Introduction to Radio Interferometry

Patrick Sheehan

Authors: Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Very Long Baseline Array

NRAO

Resolution of Observations

Angular resolution for most telescopes is ~ λ/D

- D is the diameter of the telescope
- λ is wavelength of observation

For example, Hubble Space Telescope:

- λ ~ 1um / D of 2.4m = resolution ~ 0.13"

To reach that resolution for a λ ~1mm observation, one would need a 2 km-diameter dish!

Instead, we use arrays of smaller dishes to achieve the same high angular resolution at radio frequencies

This is interferometry

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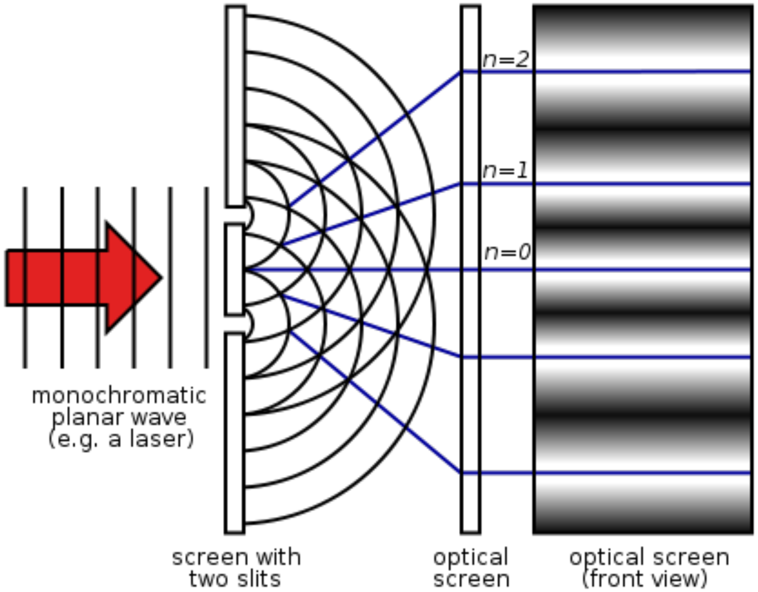
What is an interferometer?

An *interferometer* measures the interference pattern produced by multiple apertures, much like a 2-slit experiment.



*However, the interference patterns measured by radio telescopes are produced by **multiplying** - not adding - the wave signals measured at the different telescopes (i.e. apertures)

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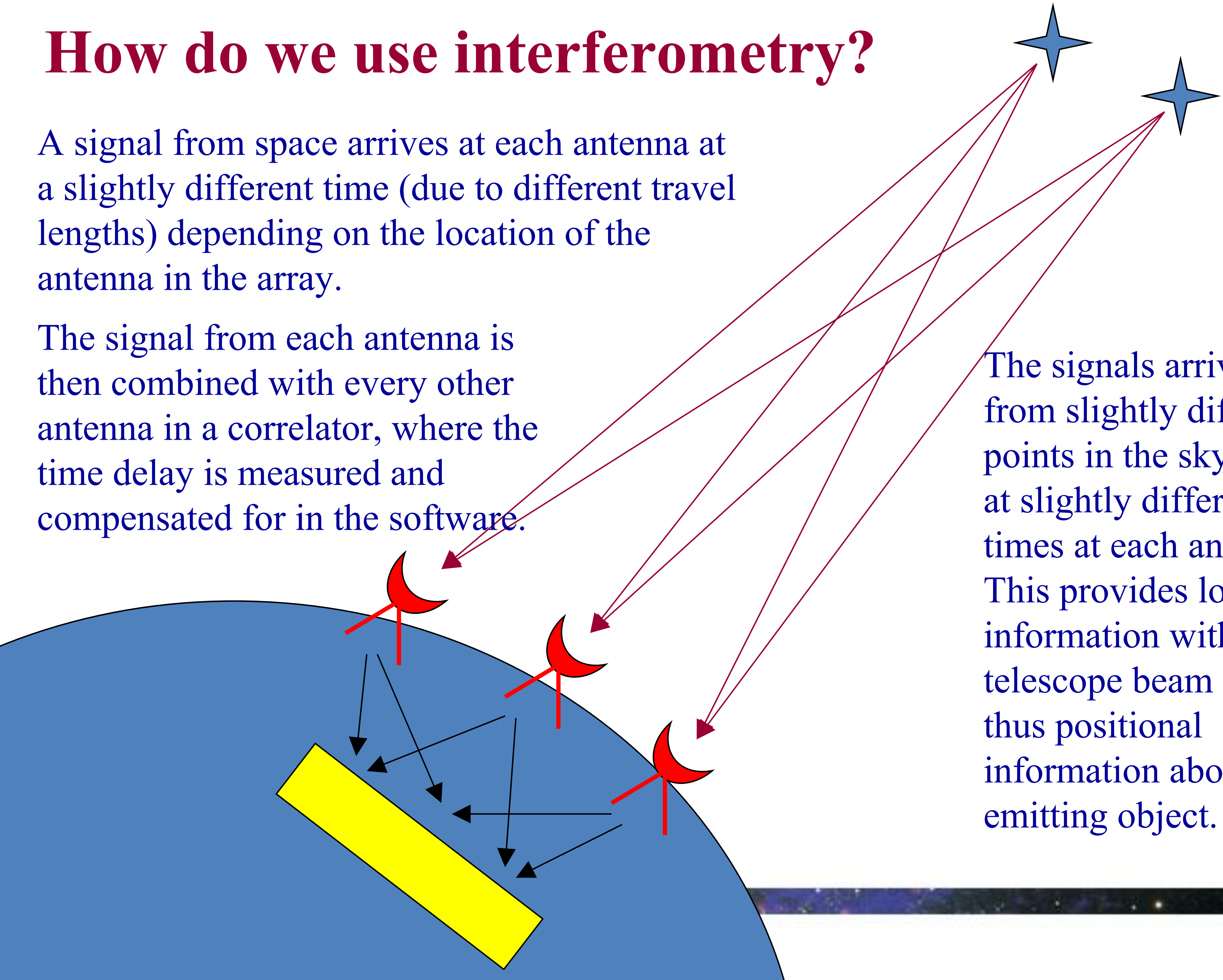
How do we use interferometry?

A signal from space arrives at each antenna at a slightly different time (due to different travel lengths) depending on the location of the antenna in the array.

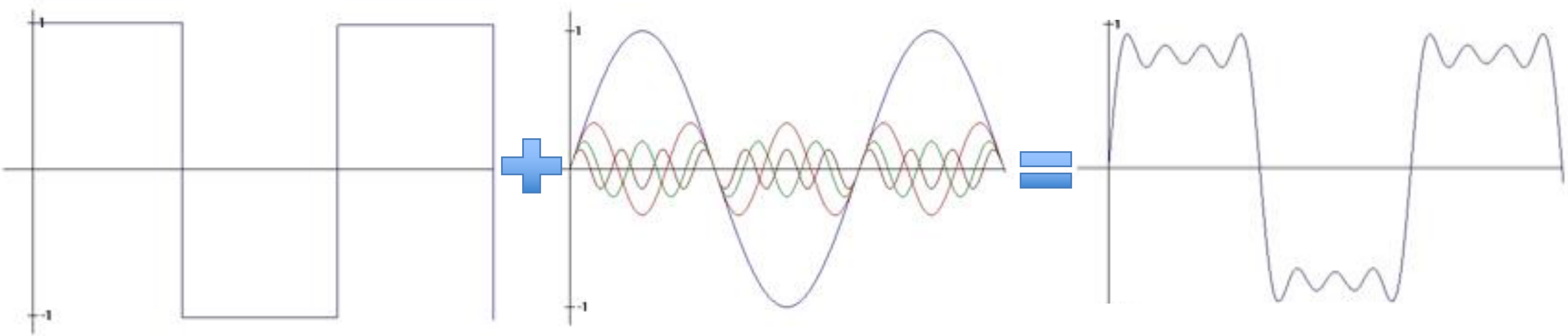
The signal from each antenna is then combined with every other antenna in a correlator, where the time delay is measured and compensated for in the software.



The signals arriving from slightly different points in the sky arrive at slightly different times at each antenna. This provides location information within the telescope beam and thus positional information about the emitting object.

The Fourier Transform

Fourier theory states that any well behaved signal (including images) can be expressed as the sum of sinusoids



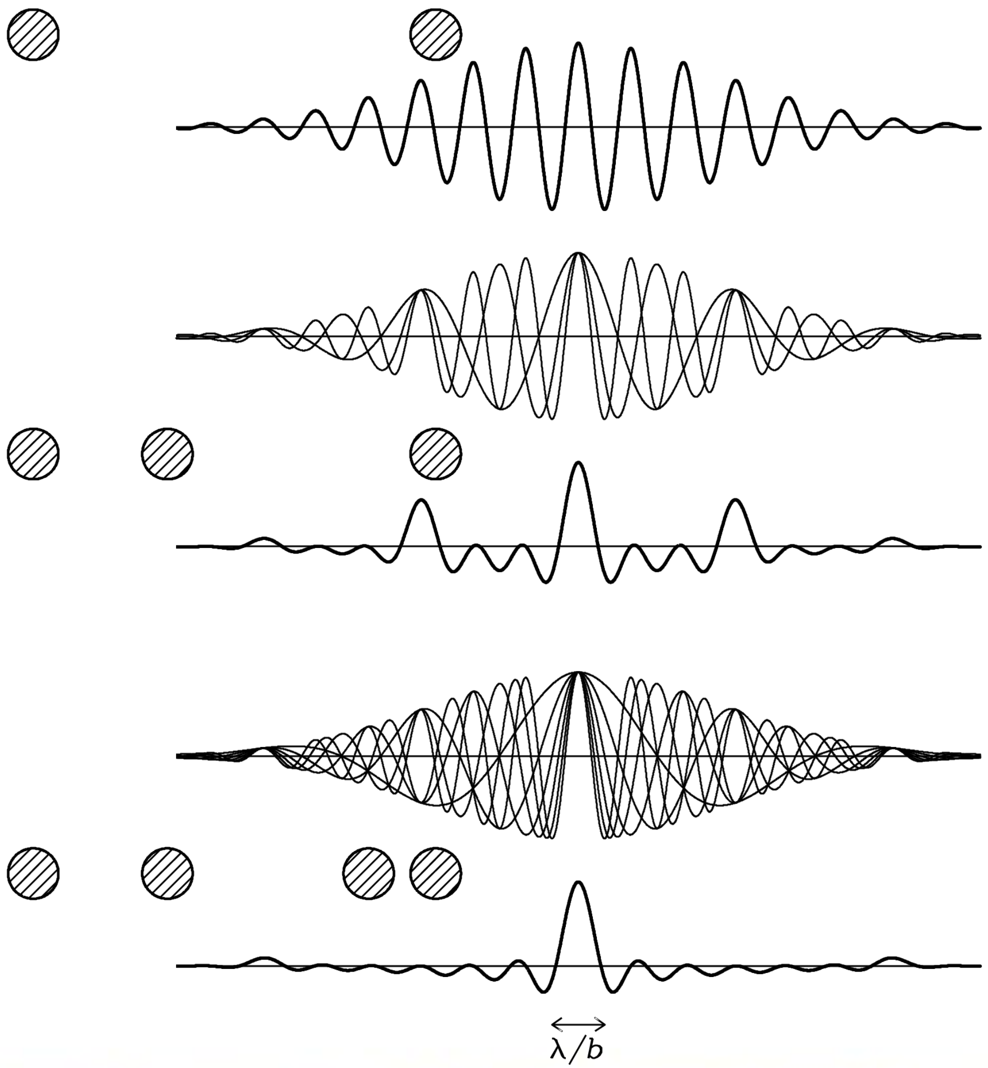
Reference signal

4 sinusoids

Sum of sinusoids & signal

- The Fourier transform is the mathematical tool that decomposes a signal into its sinusoidal components
- The Fourier transform contains *all* of the information of the original signal

An Interferometer Measures the Interference Pattern Produced by a Pair of Apertures

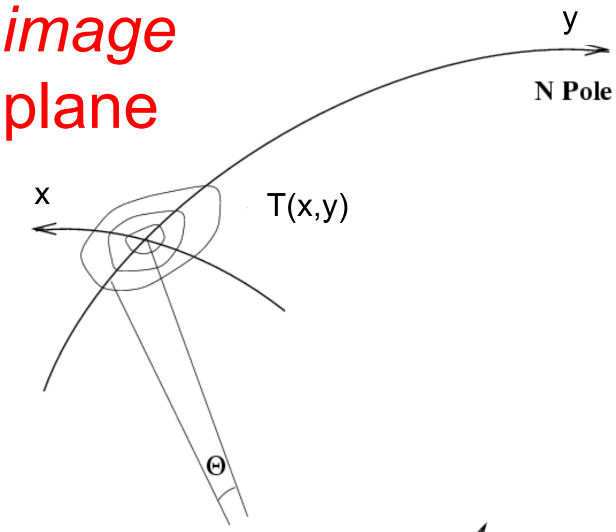


The Fourier Transform relates the measured interference pattern to the radio intensity on the sky

Fourier

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

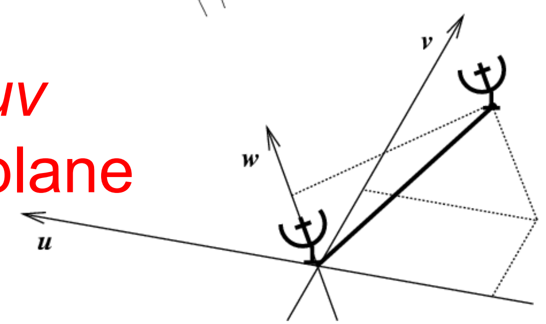
image plane



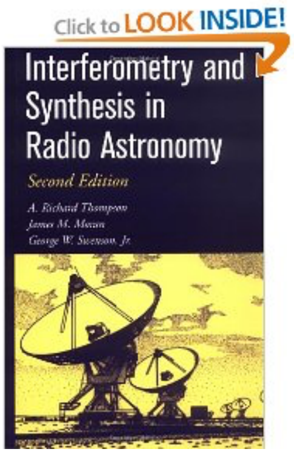
Image

$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

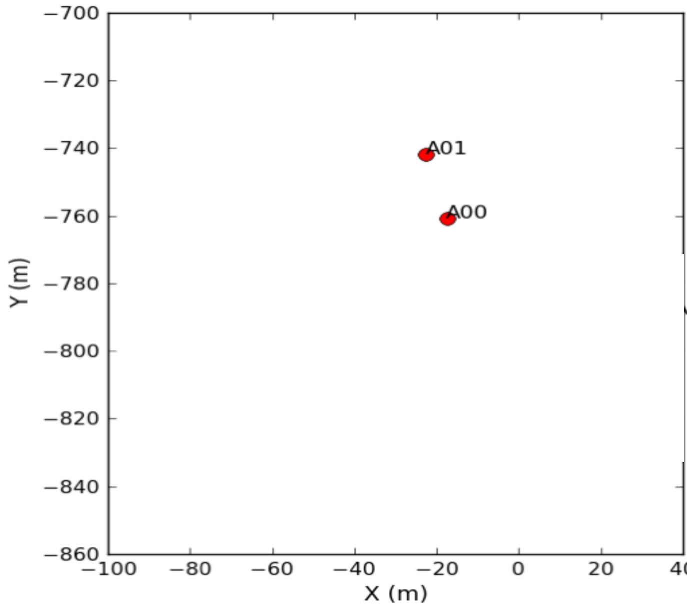
uv plane

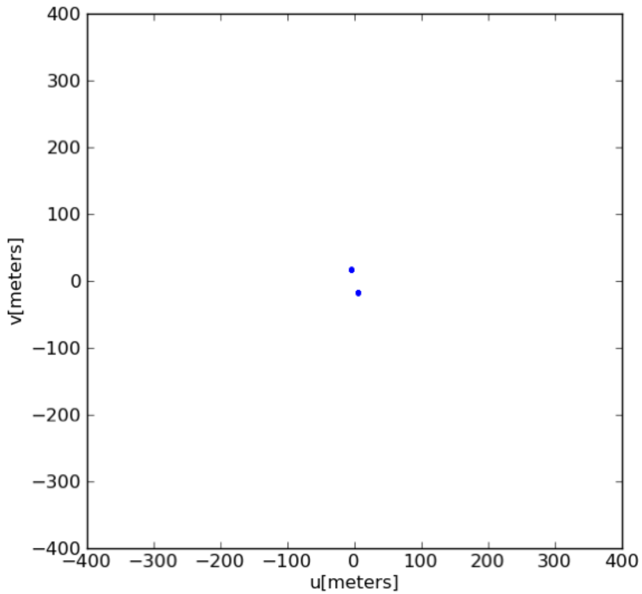


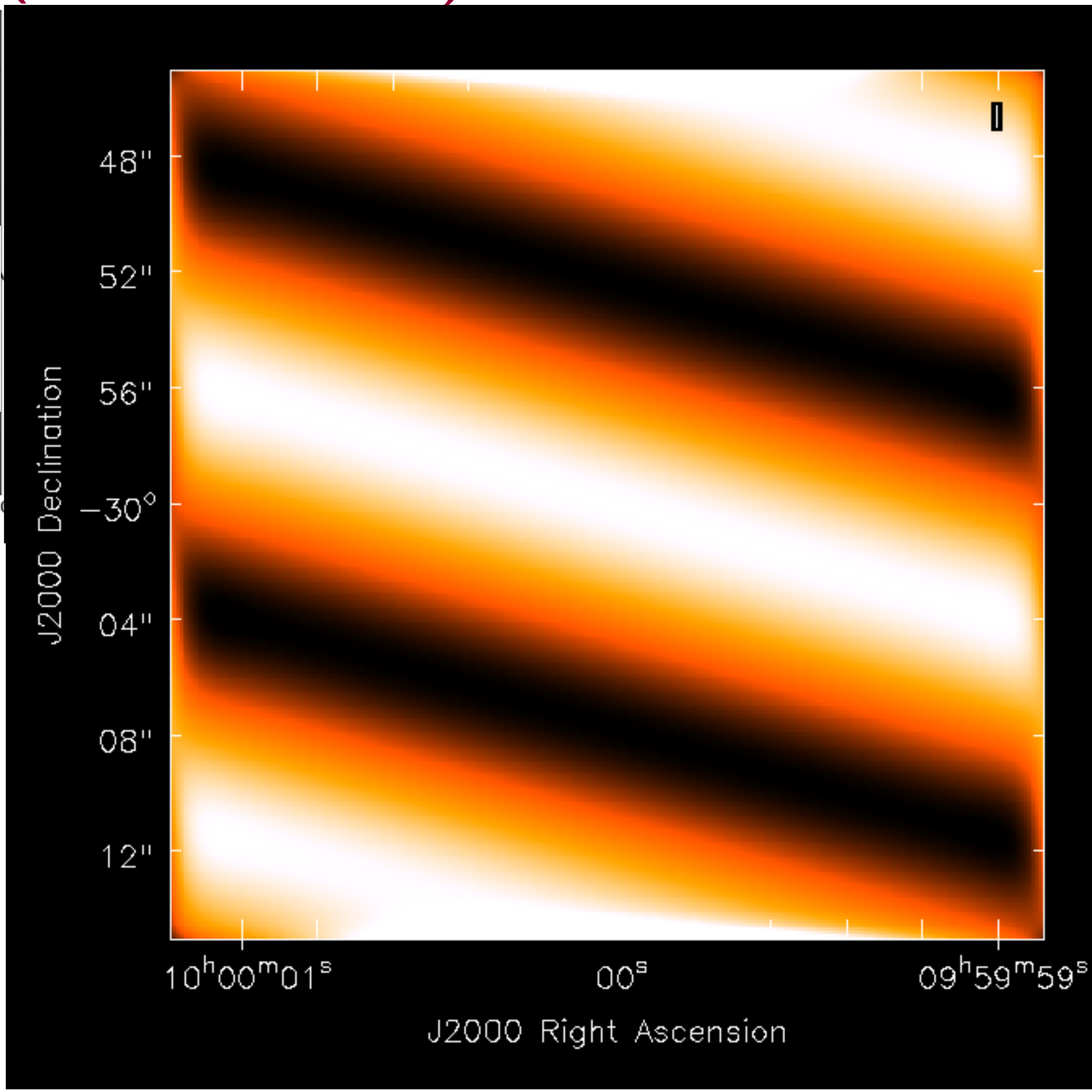
(for more info, see e.g. Thompson, Moran & Swenson)



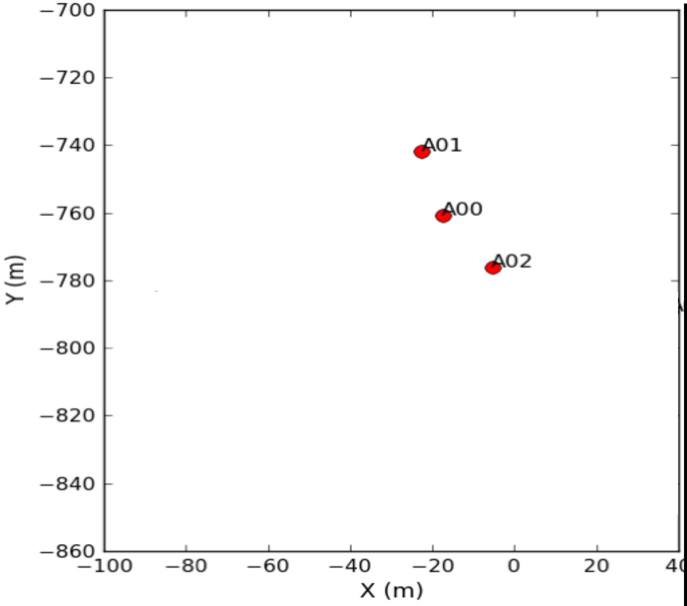
Example: Fringe pattern with 2 Antennas (one baseline)

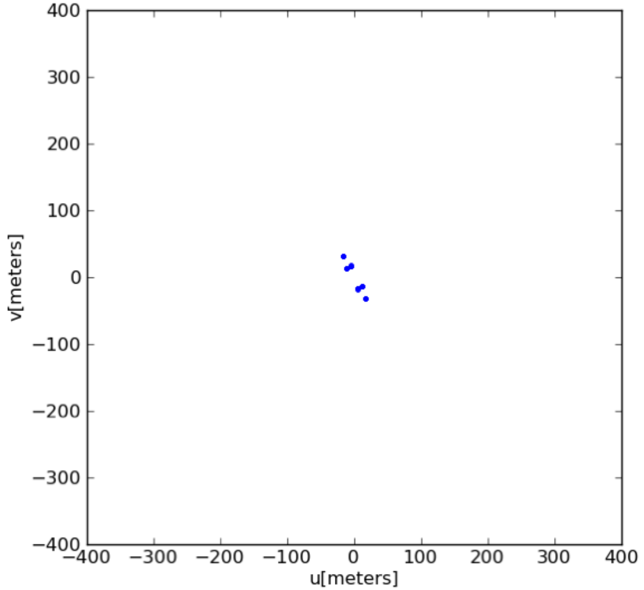


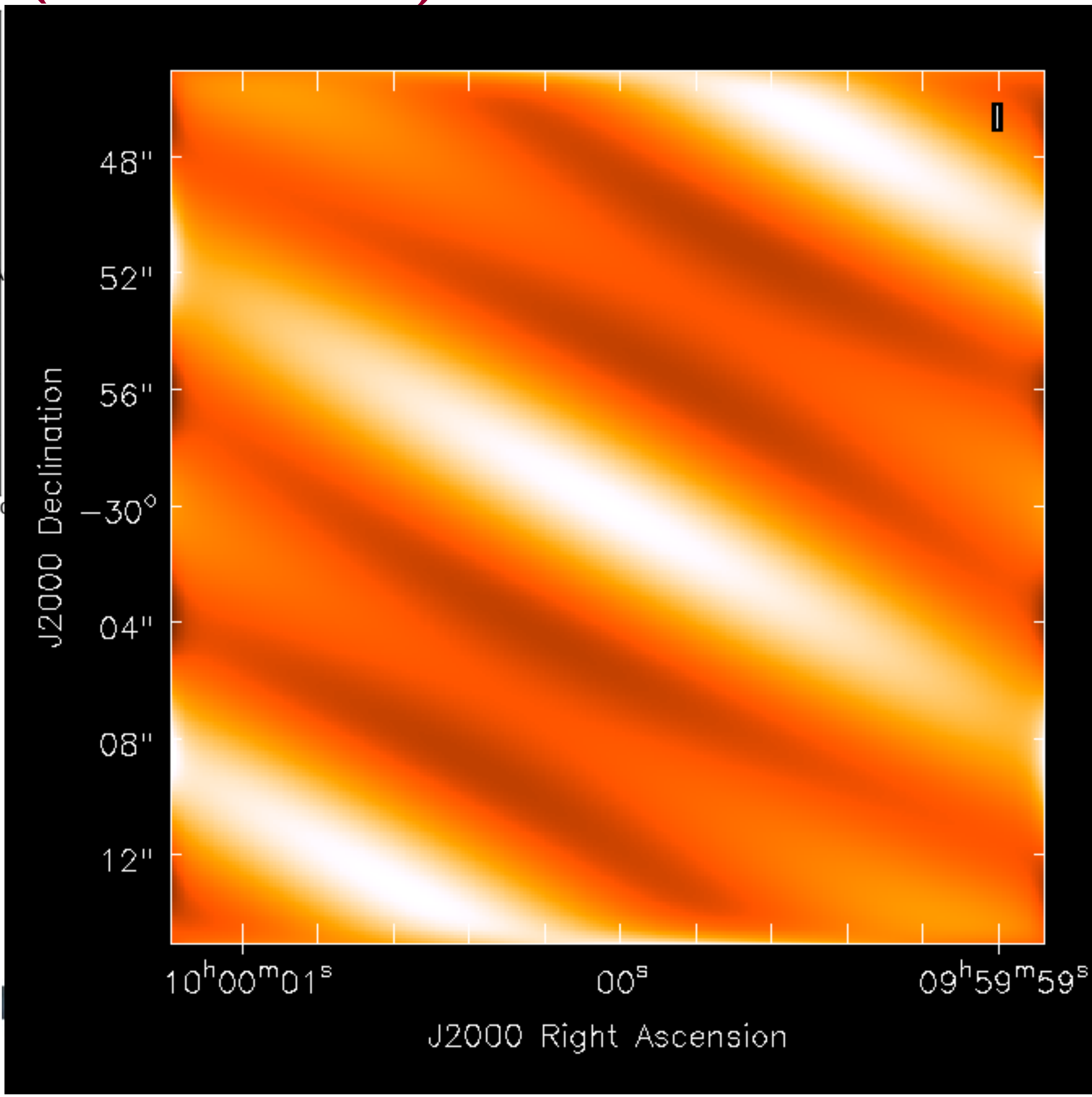




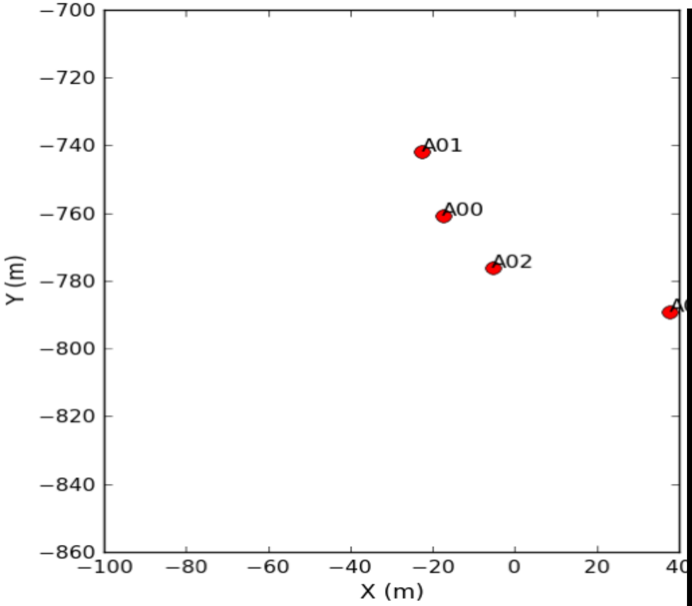
Example: Fringe pattern with 3 Antennas (3 baselines)

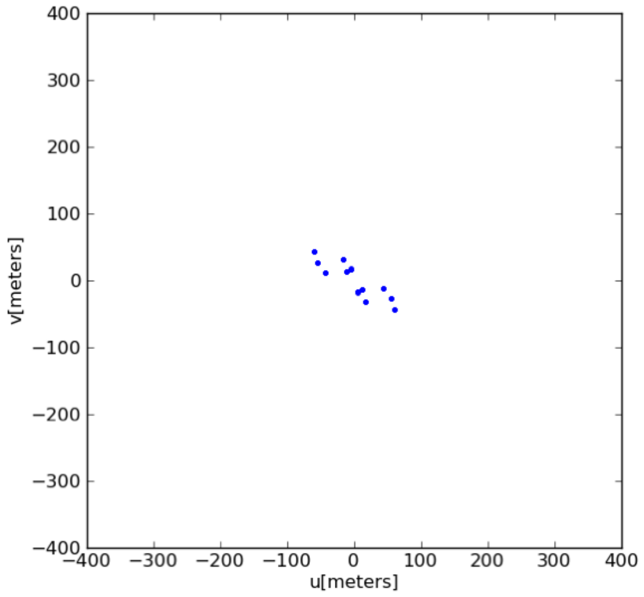


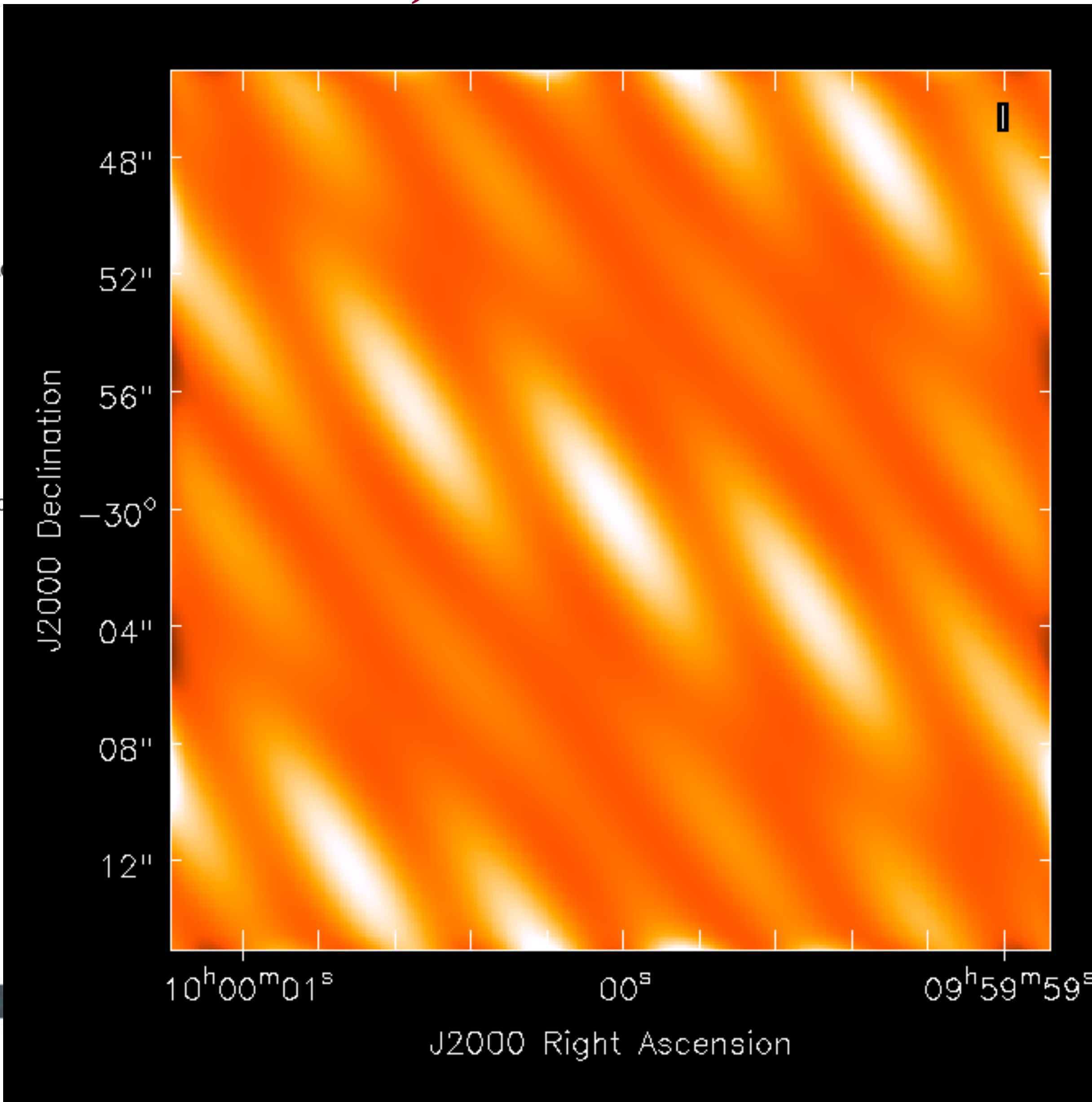




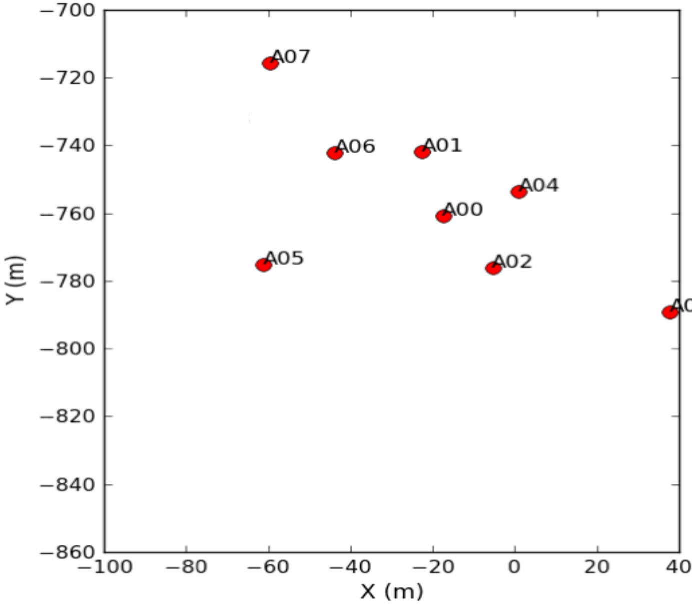
Example: Fringe pattern with 4 Antennas (6 baselines)

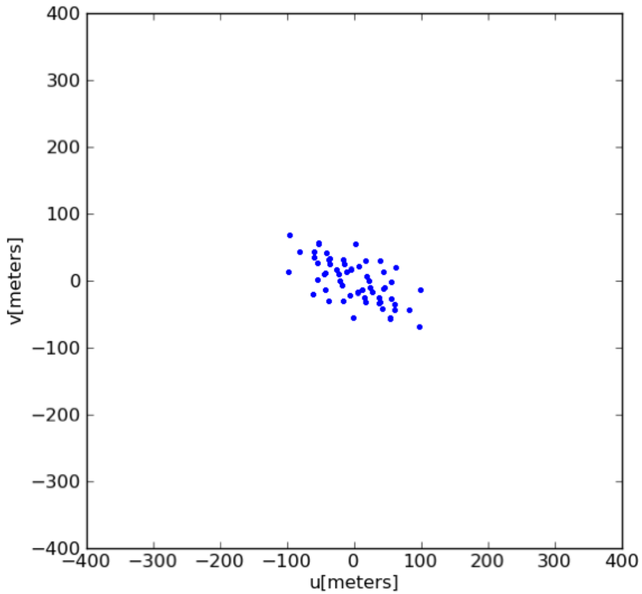


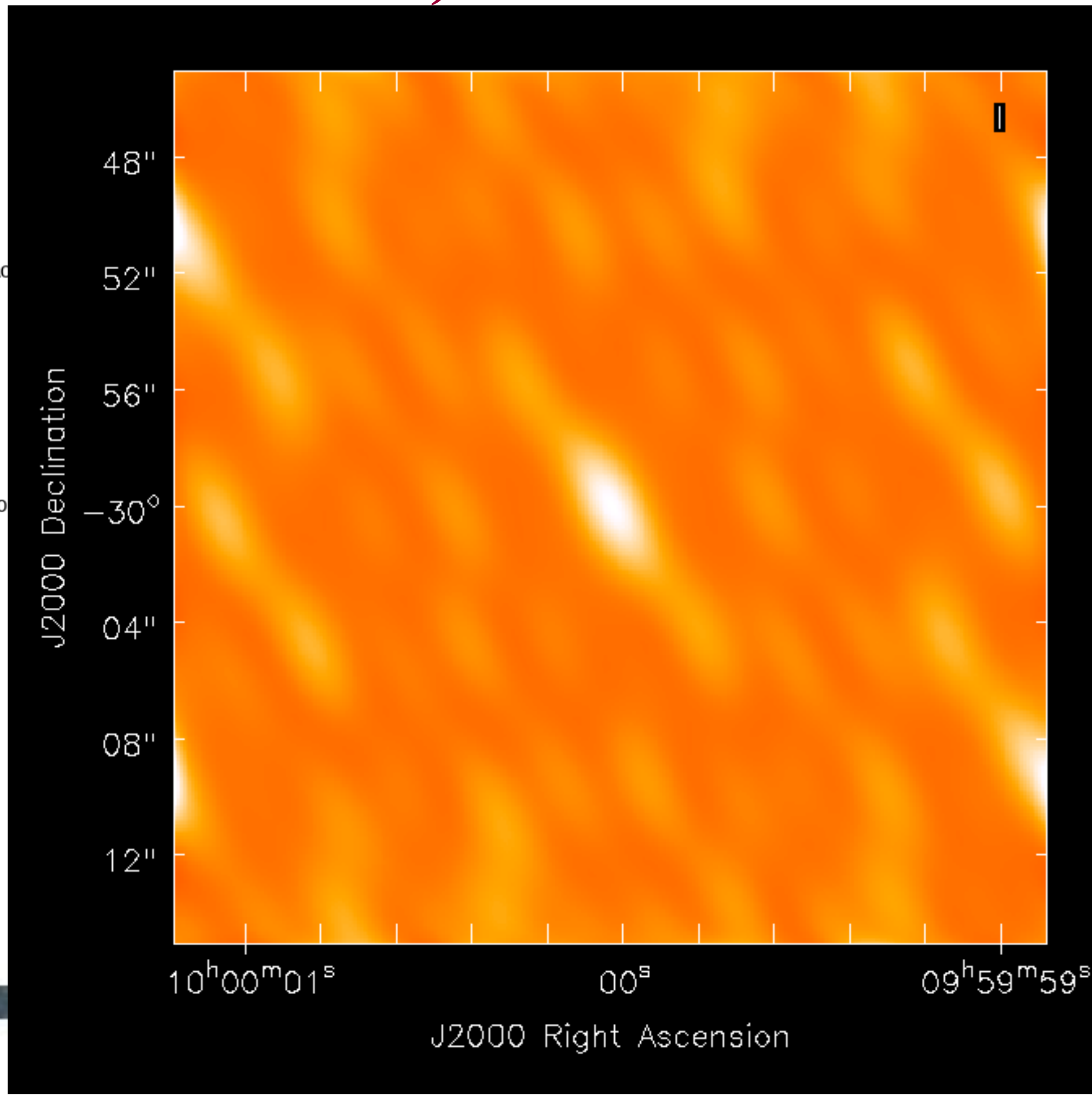




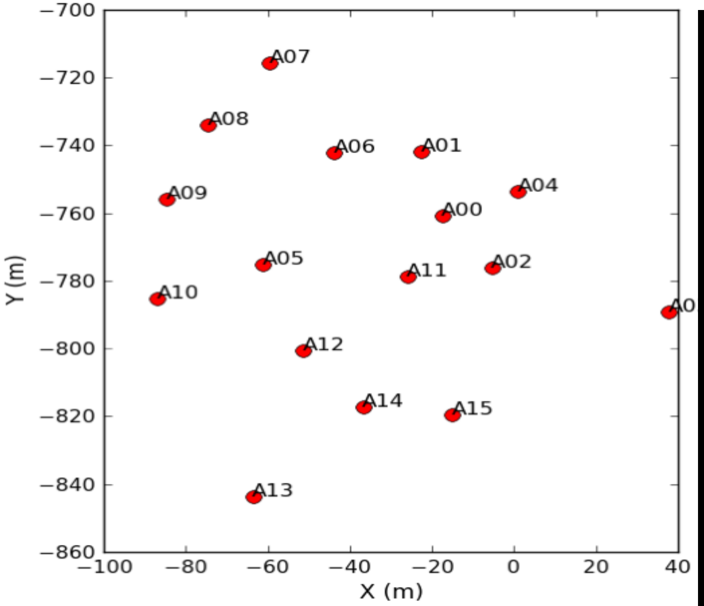
Example: Fringe pattern with 8 Antennas (28 baselines)

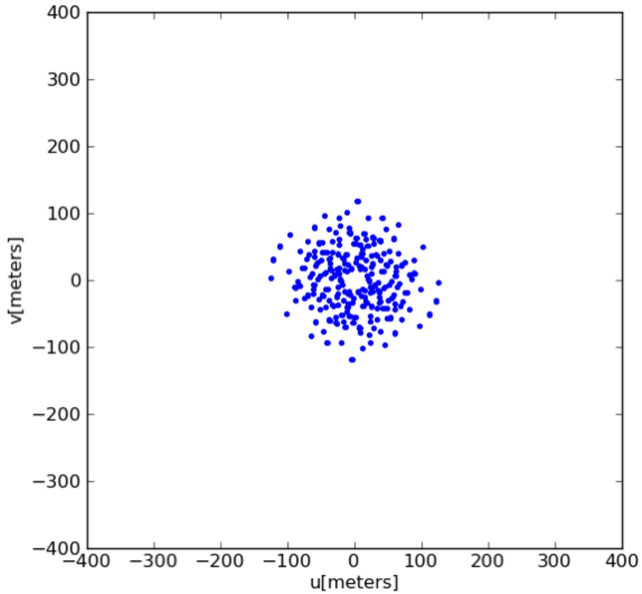


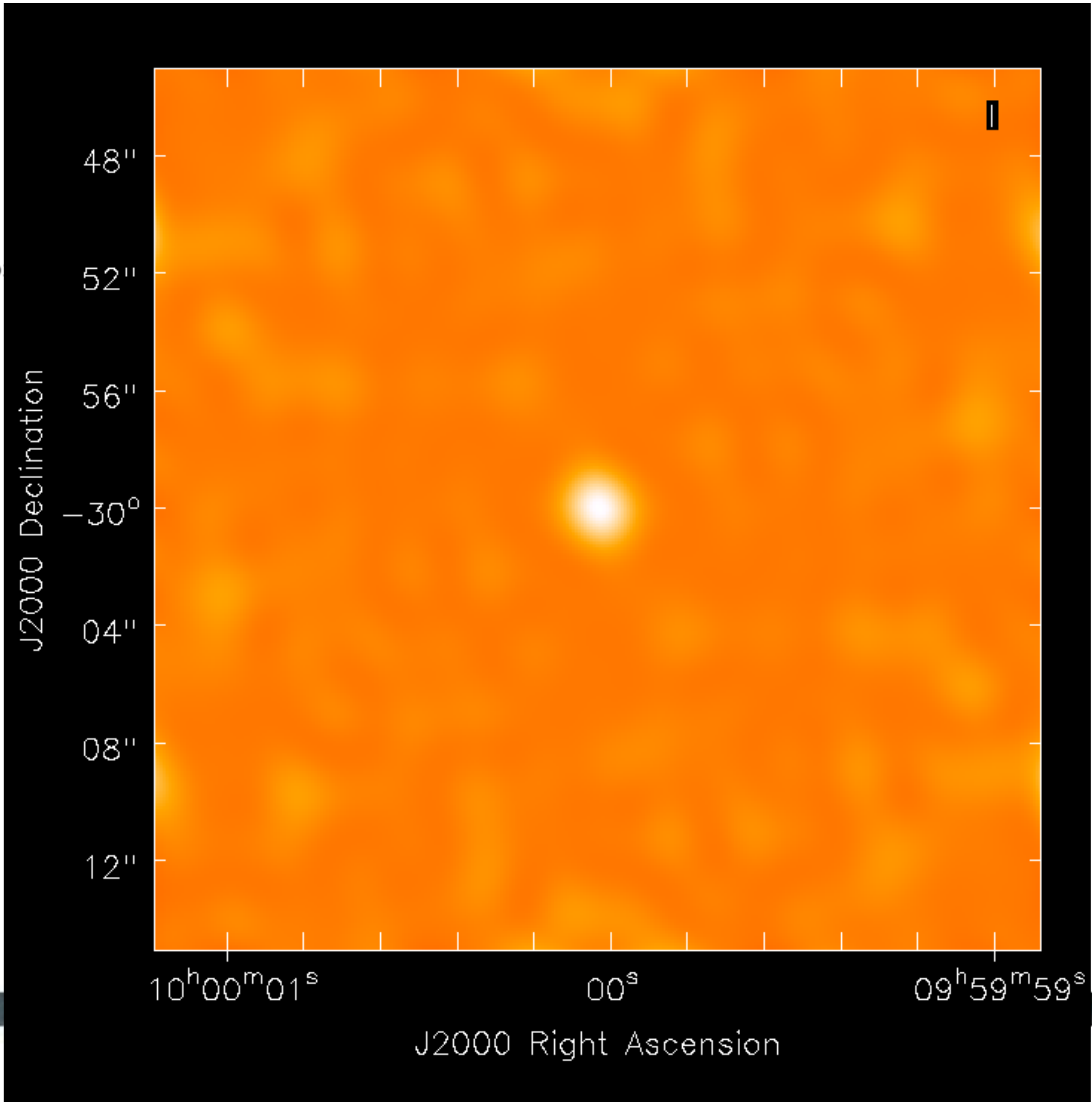




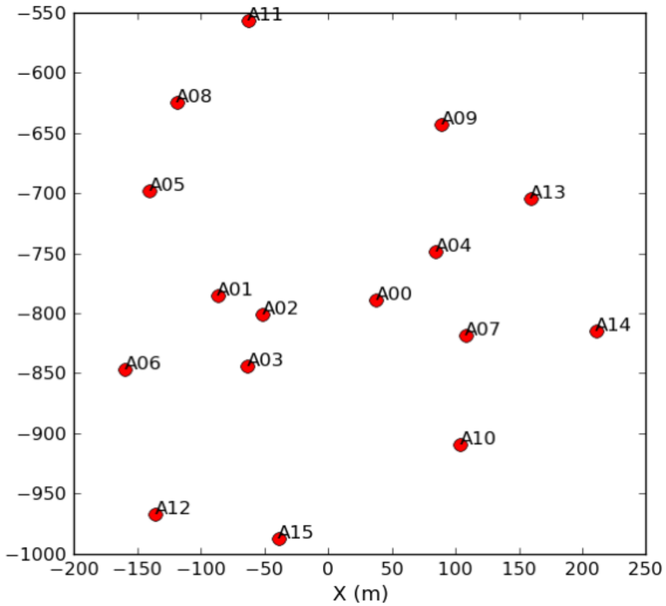
16 Antennas – Compact Configuration

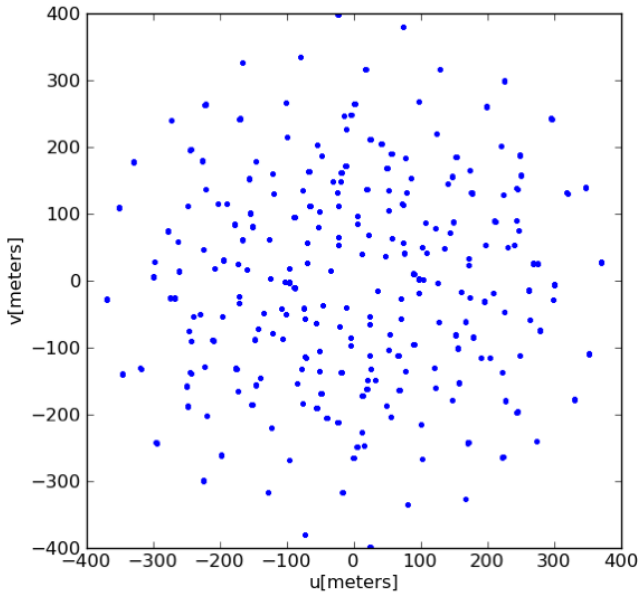


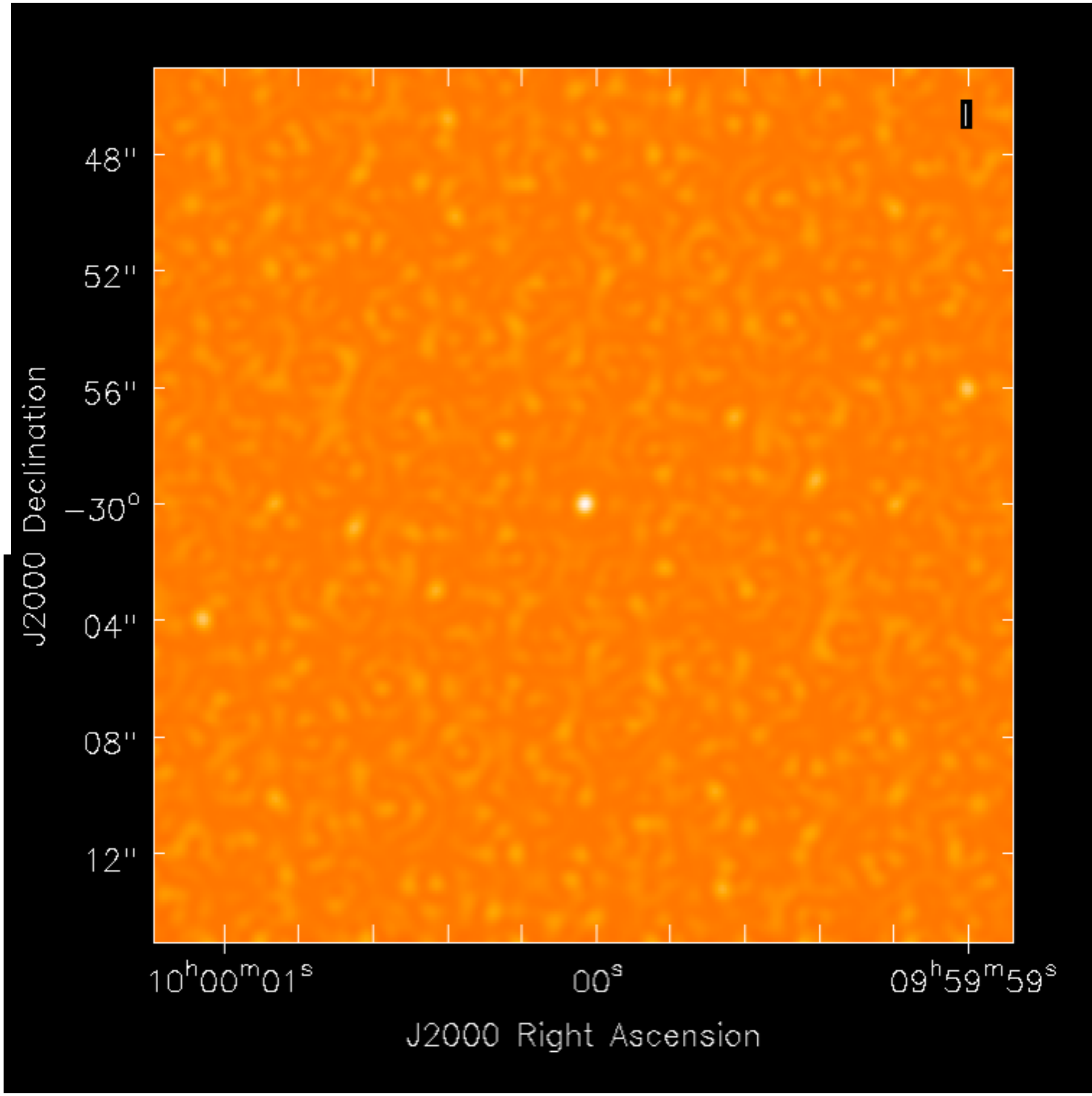




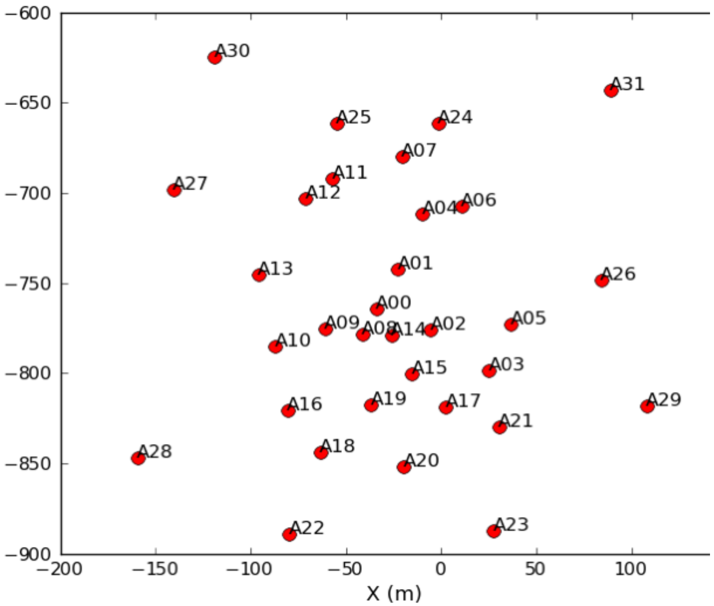
16 Antennas – Extended Configuration

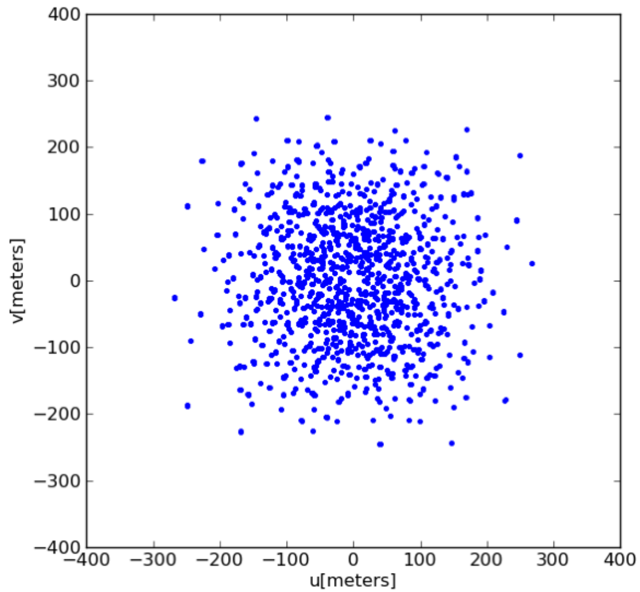


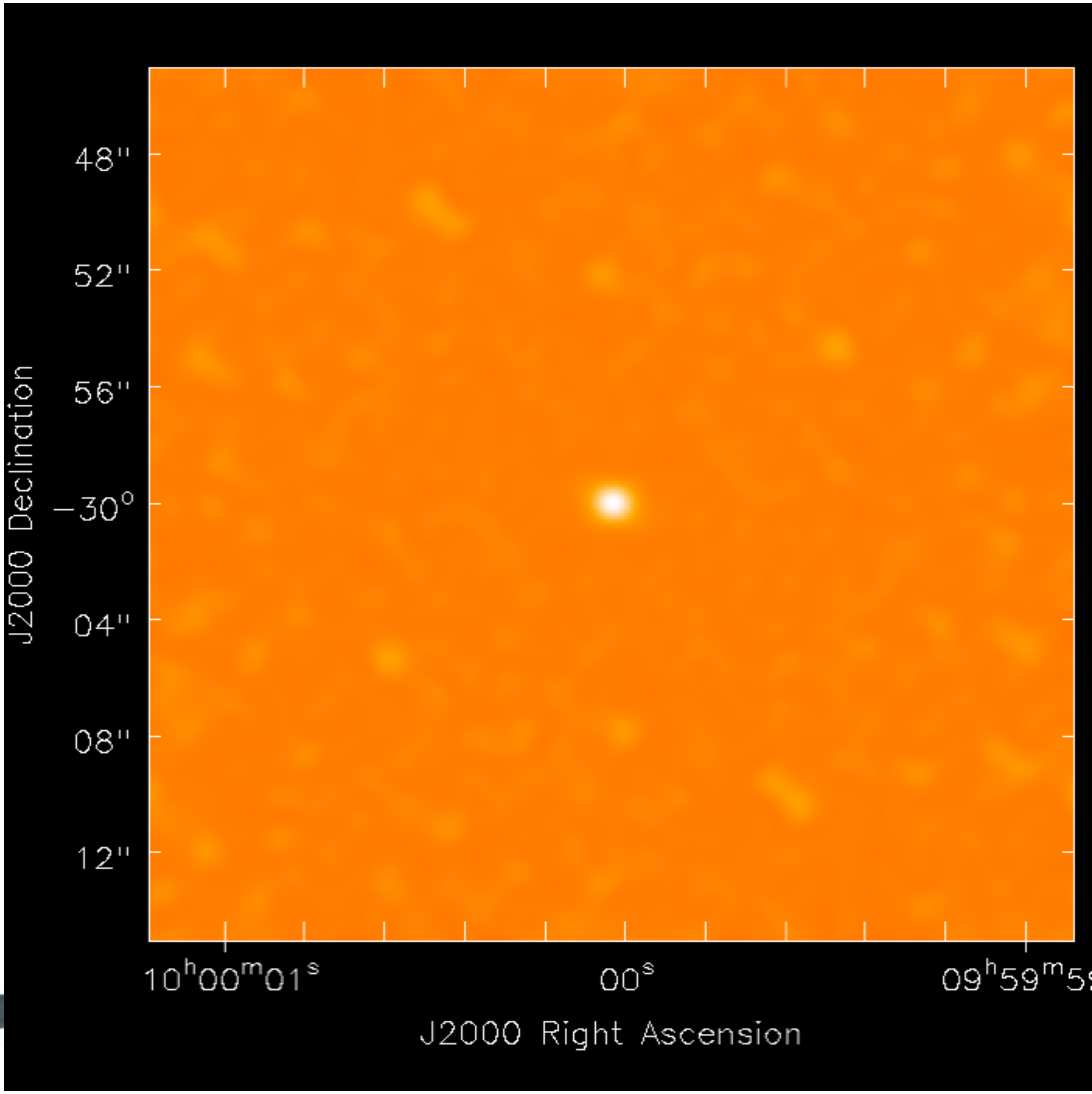




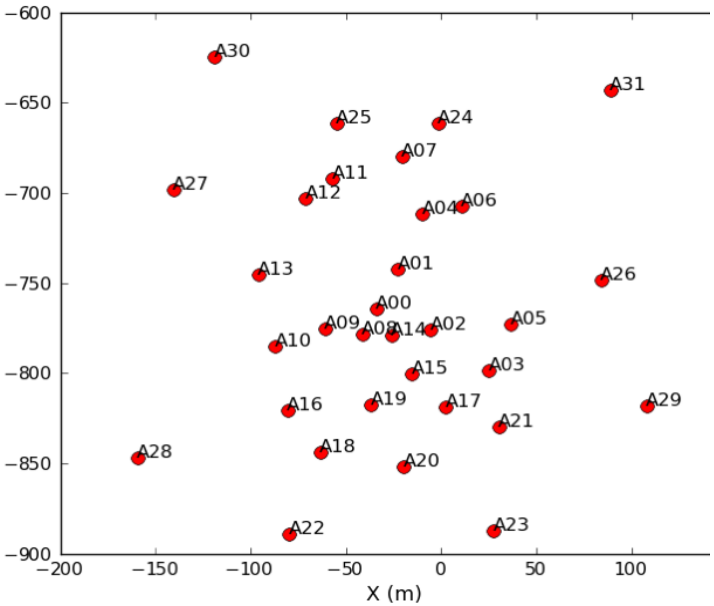
32 Antennas – Instantaneous

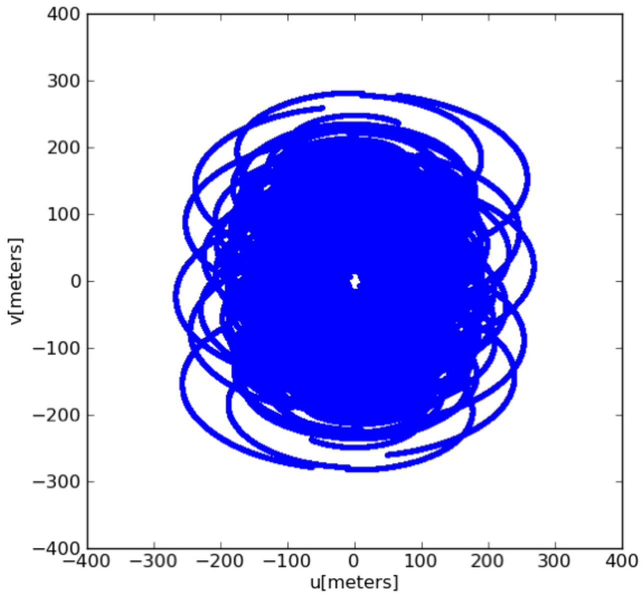


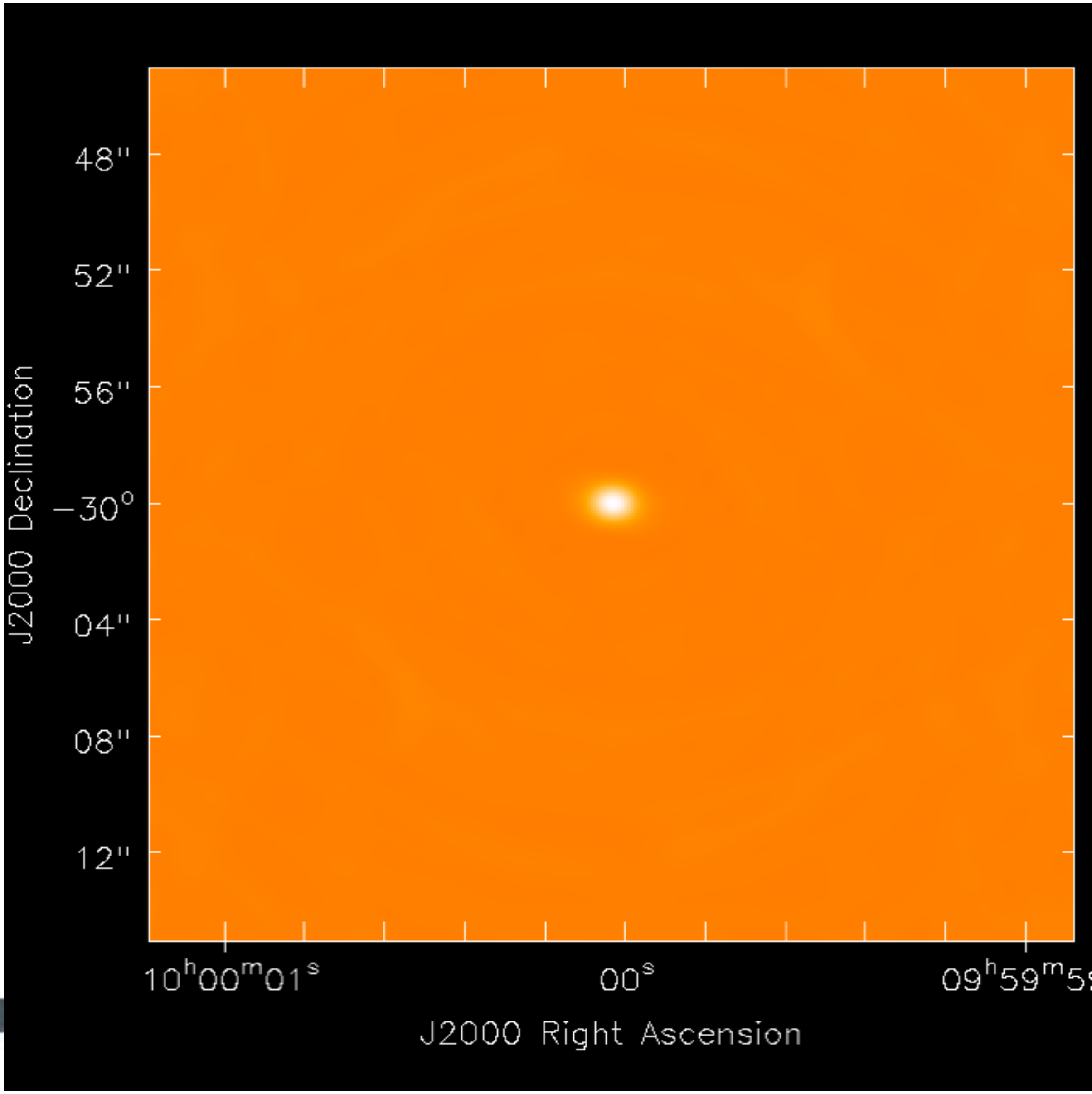




32 Antennas – 8 hours

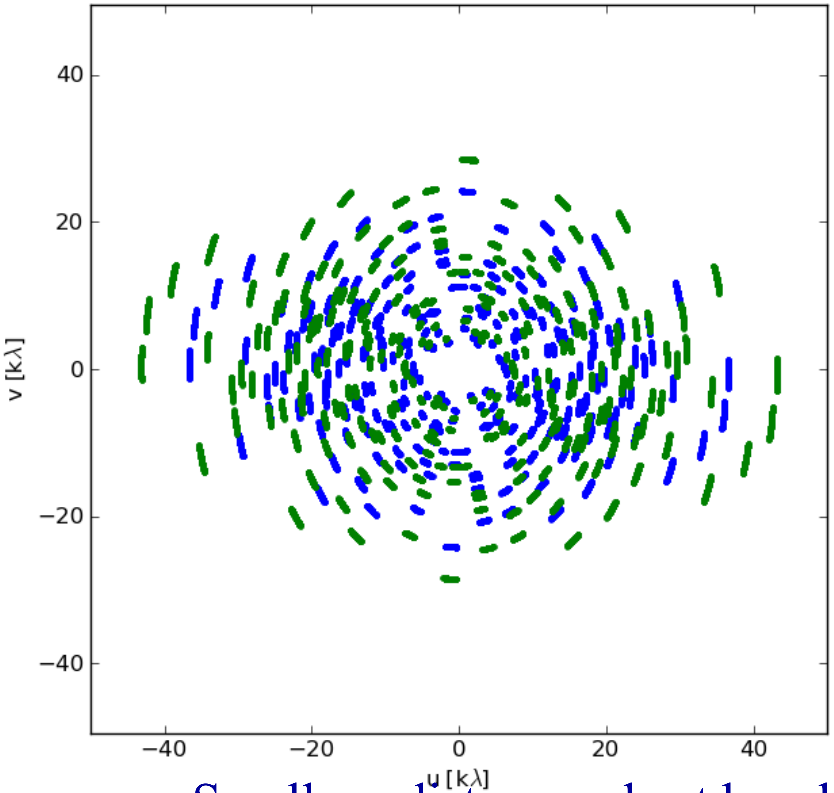


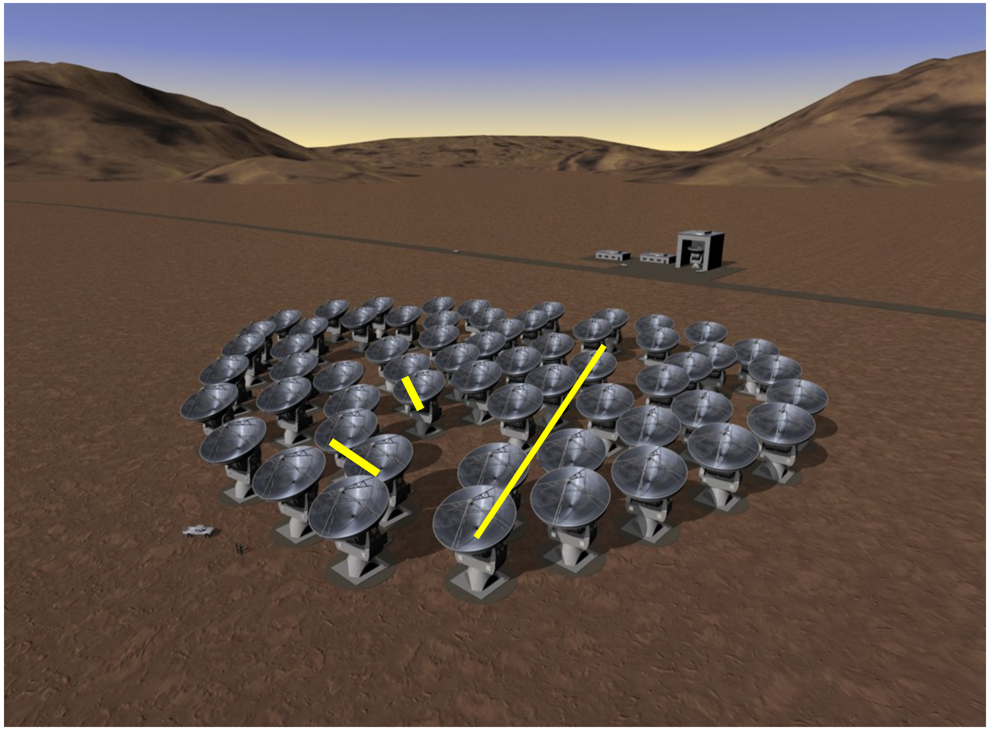




Sampling Function

Each antenna pair samples only one spot; the array cannot sample the entire Fourier/uv domain resulting in an **imperfect image**





Small uv-distance: short baselines (measure extended emission)

Long uv-distance: long baselines (measure small scale emission)

Orientation of baseline also determines orientation in the uv-plane

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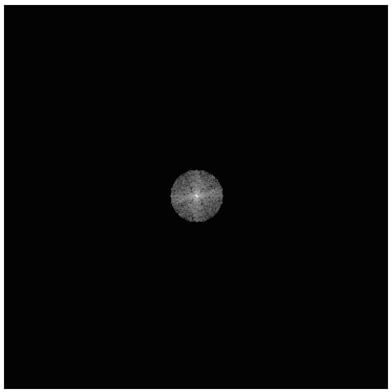
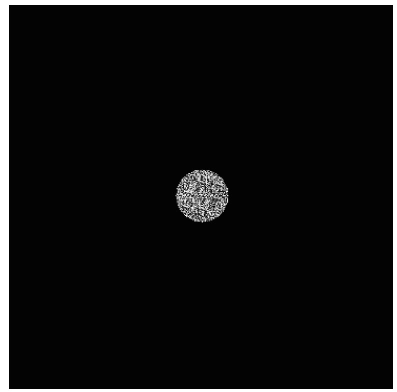
Implications of (u,v) Coverage

What does it mean if our (u,v) coverage is not complete?

V(u,v) amplitude | **V(u,v) phase** | **T(l.m)**

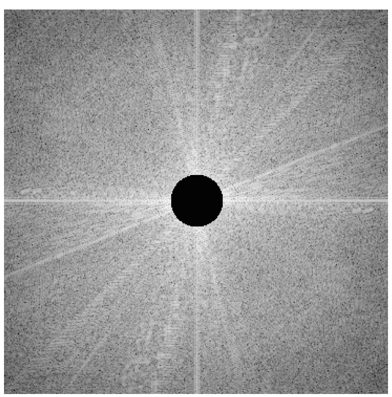
Missing High Spatial Frequencies

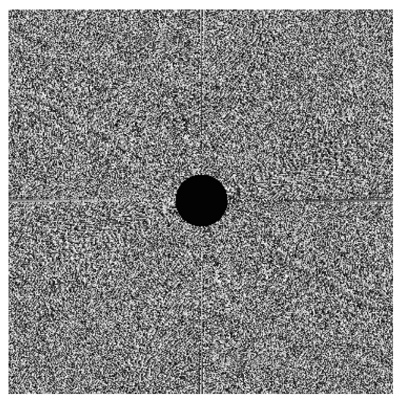




FT

Missing Low Spatial Frequencies





FT

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Characteristic Angular Scales

Angular resolution of telescope array:

- $\sim \lambda/B_{max}$, where B_{max} is the longest baseline

Maximum angular scale:

- a source is resolved if the angular size $> \lambda/B_{min}$ (B_{min} is the minimum separation between apertures)

Field of view of a single aperture (single dish):

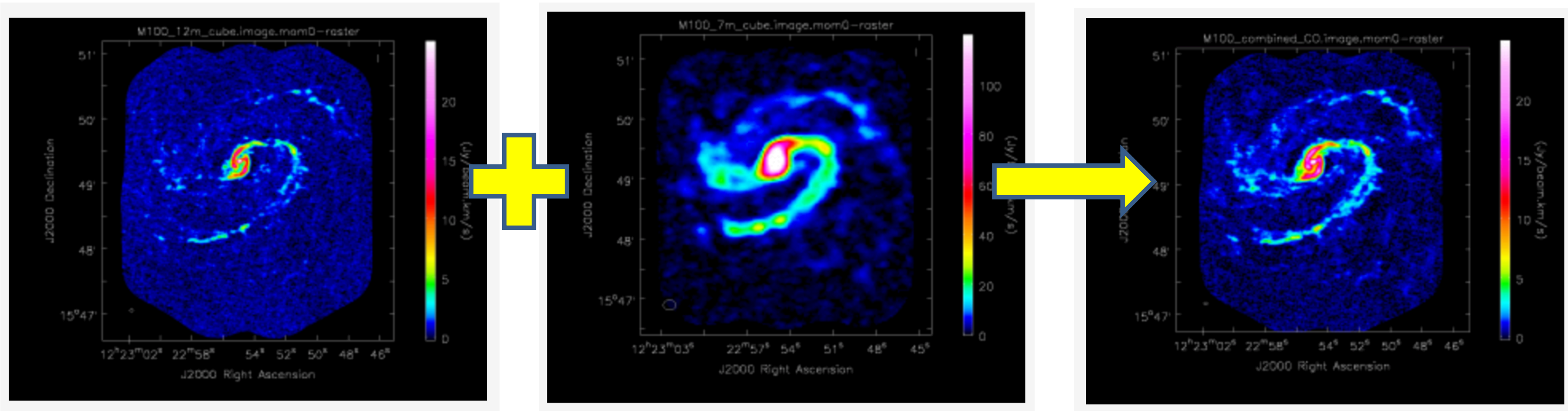
- $\sim \lambda/D$, where D is the diameter of the telescope.
- If sources are more extended than the FOV, it can be observed using multiple pointing centers in a mosaic.

An interferometer is sensitive to a range of angular sizes

$$\boldsymbol{\lambda/B_{max} < \theta < \lambda/B_{min}}$$

Since $B_{min} > D$, an interferometer is not sensitive to the large angular scales and cannot recover the total flux of resolved sources

Characteristic Angular Scales: M100



- 12m data reveals information on smaller spatial scales (denser, clumpier emission)
- 7m data reveals information on larger spatial scales (diffuse, extended emission)
- To get both: you need a combined image

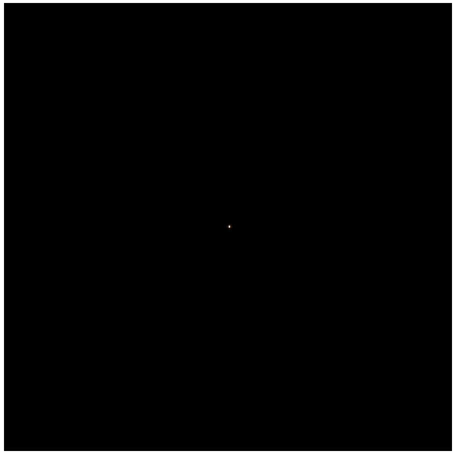
Interferometry: Spatial Scales

- The **sensitivity** is given by the number of antennas times their area
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam)
- The **resolution** is given by the largest distance between antennas (called the synthesized beam)
- The **largest angular scale** that can be imaged is given by the shortest distance between antennas

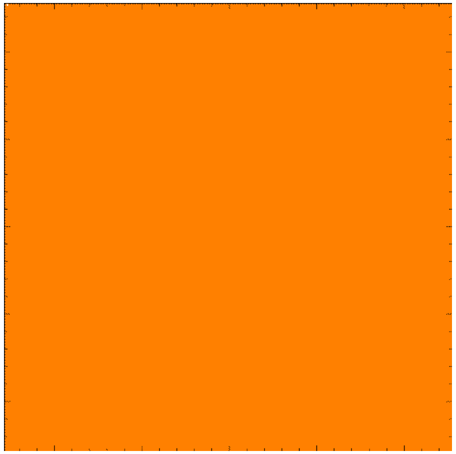
Some 2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}

δ Function

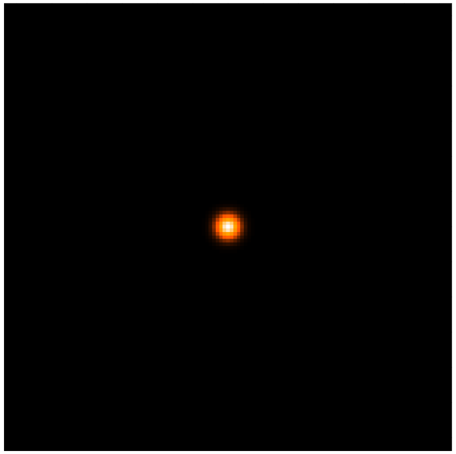


⇌



Constant

Gaussian



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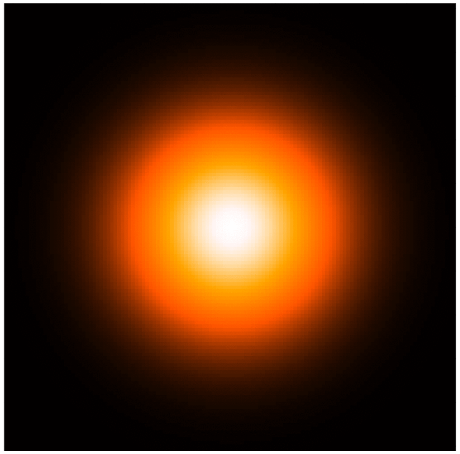


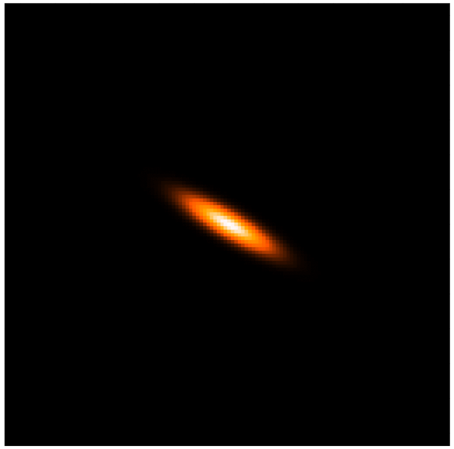
Gaussian

narrow features transform to wide features (and vice-versa)

2D Fourier Transform Pairs

T(x,y) | Amp{V(u,v)}

elliptical Gaussian

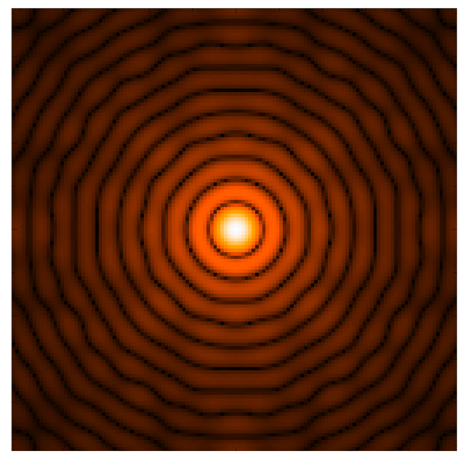


$\rightleftharpoons$

elliptical Gaussian

Disk

$\rightleftharpoons$



Bessel

sharp edges result in many high spatial frequencies

(sinc function, “ringing”, Gibbs phenomenon)

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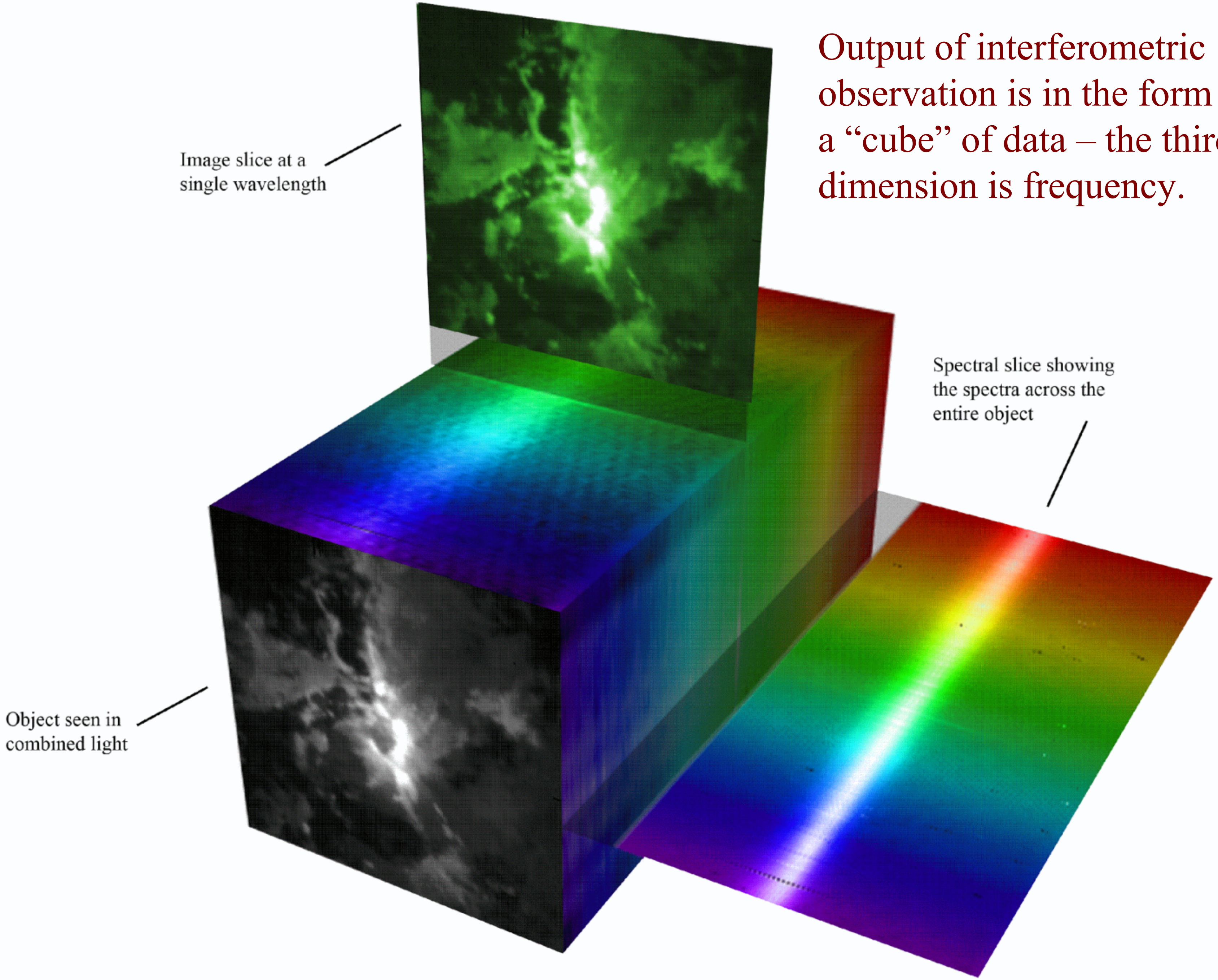
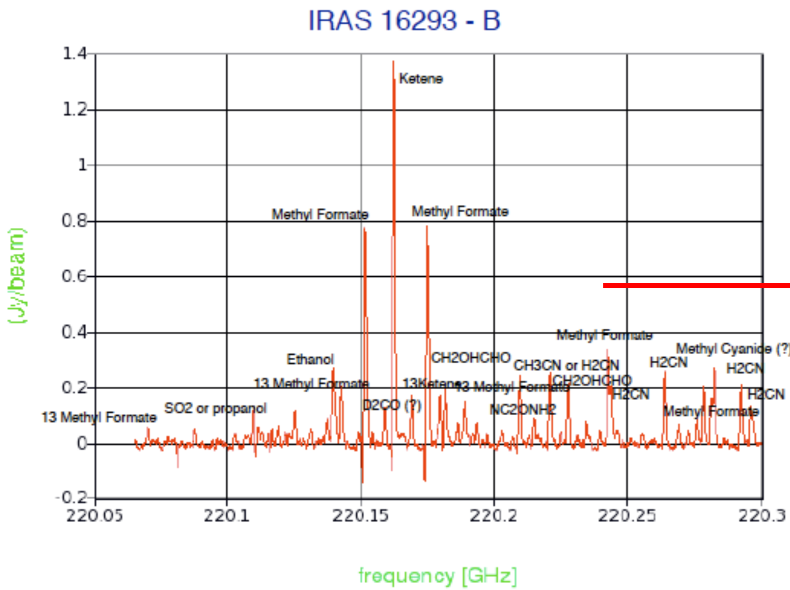
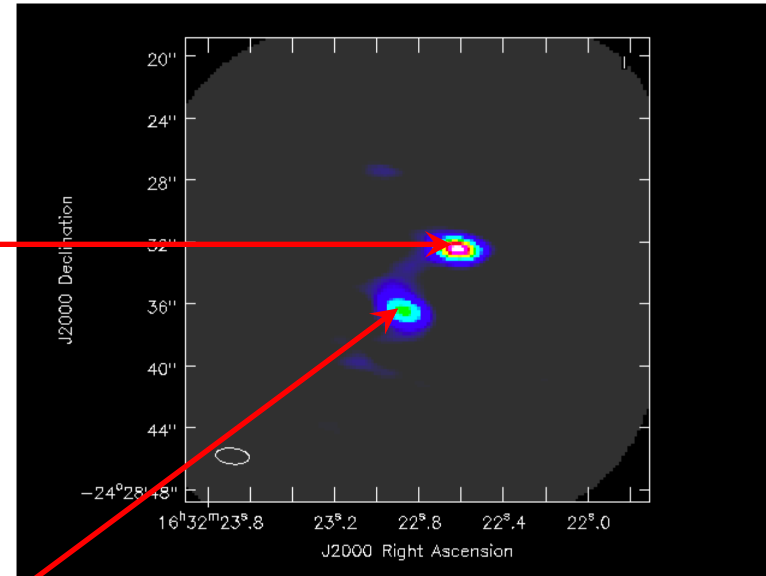
Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.



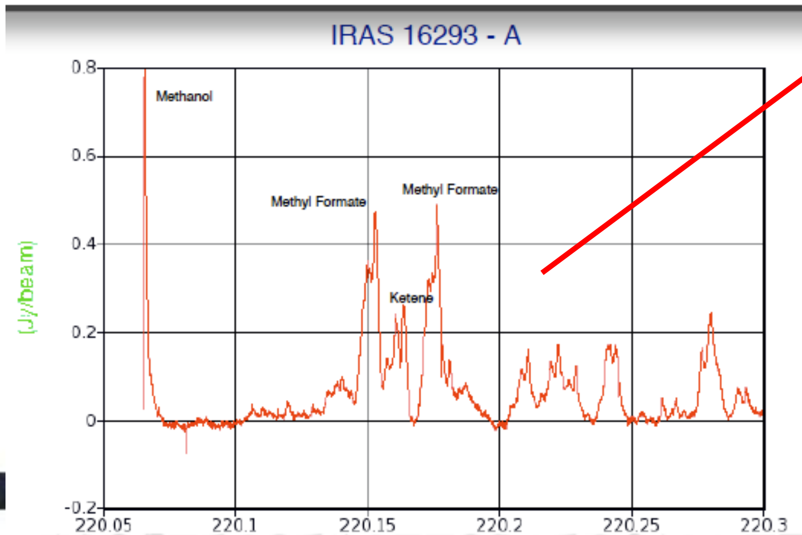
Sometimes the most interesting science lies in the third dimension

Band 6





J. Turner & ALMA CSV team



Young Low Mass Stars: IRAS16293

- Note narrow lines toward preprotostellar core B (top) with infall apparent in methyl formate and ketene lines.

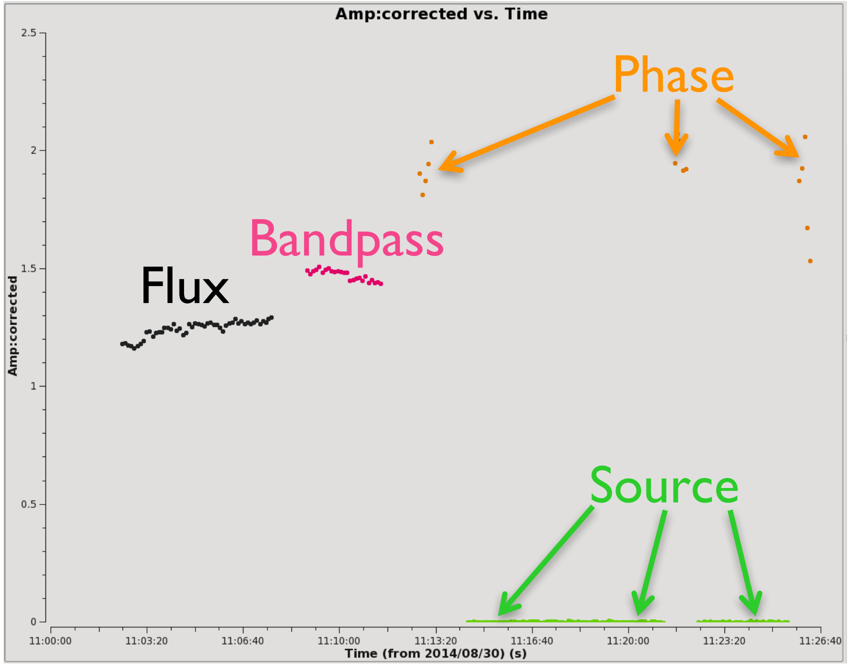
A Brief Word on Calibration

Calibration requirements (Handled by ALMA):

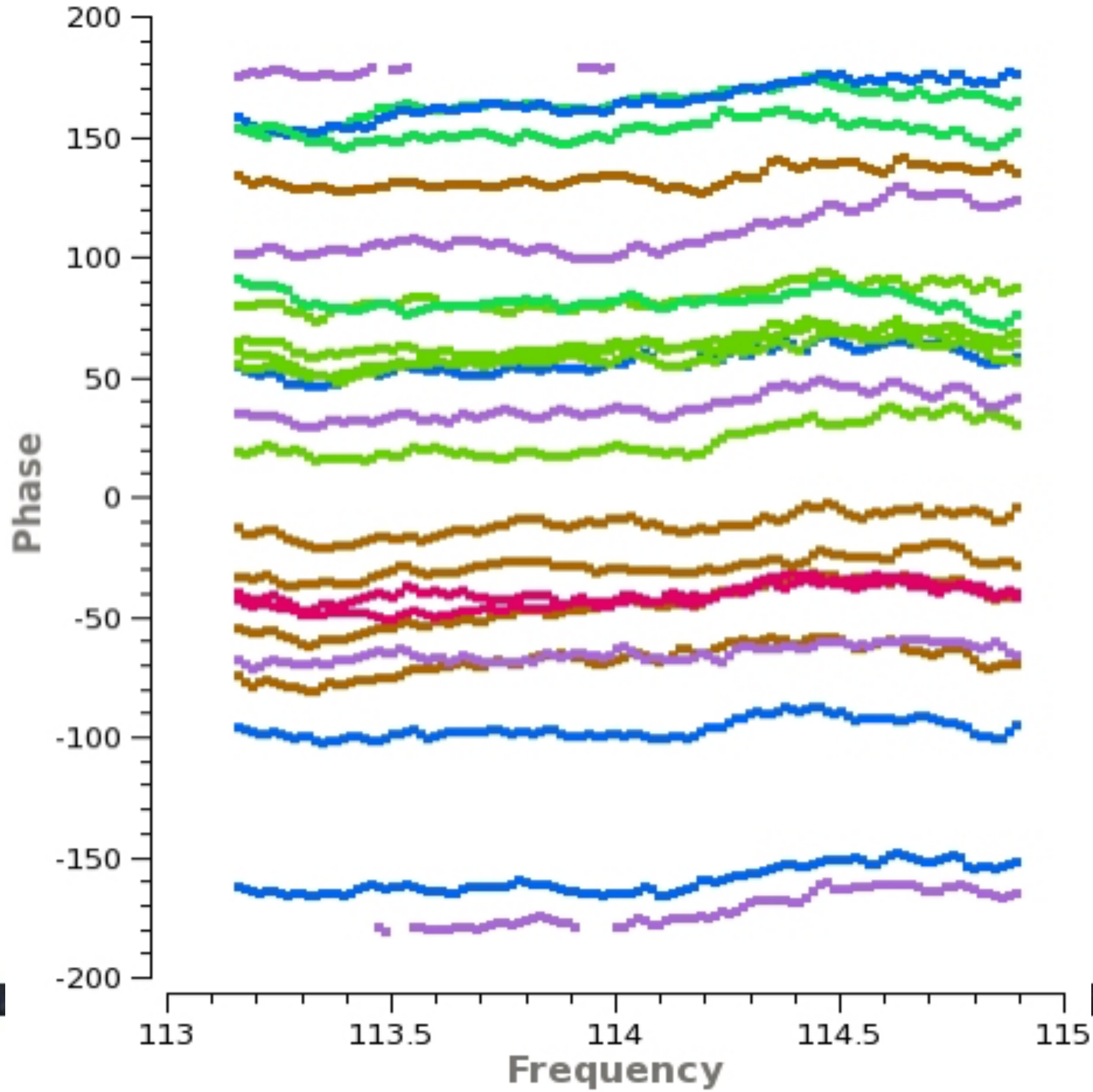
Gain calibrator
Bright quasar near science target
Solves for atmospheric and instrumental variations with time

Bandpass calibrator
Bright quasar
Fixes instrumental effects and variations vs. frequency

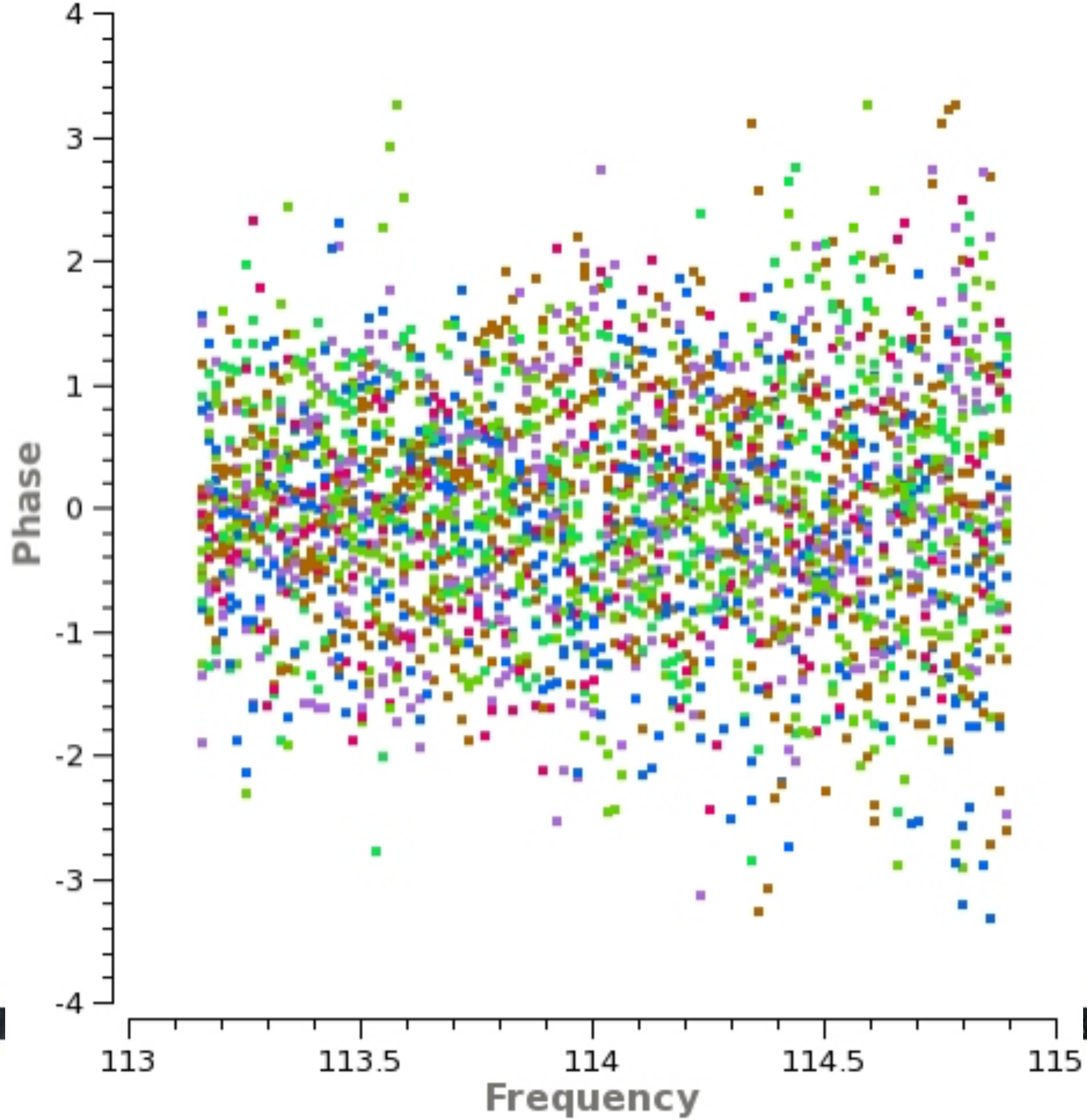
Absolute flux calibrator
Solar system object or quasar
Used to scale relative amplitudes to absolute value



Bandpass Phase vs. Frequency (Before)



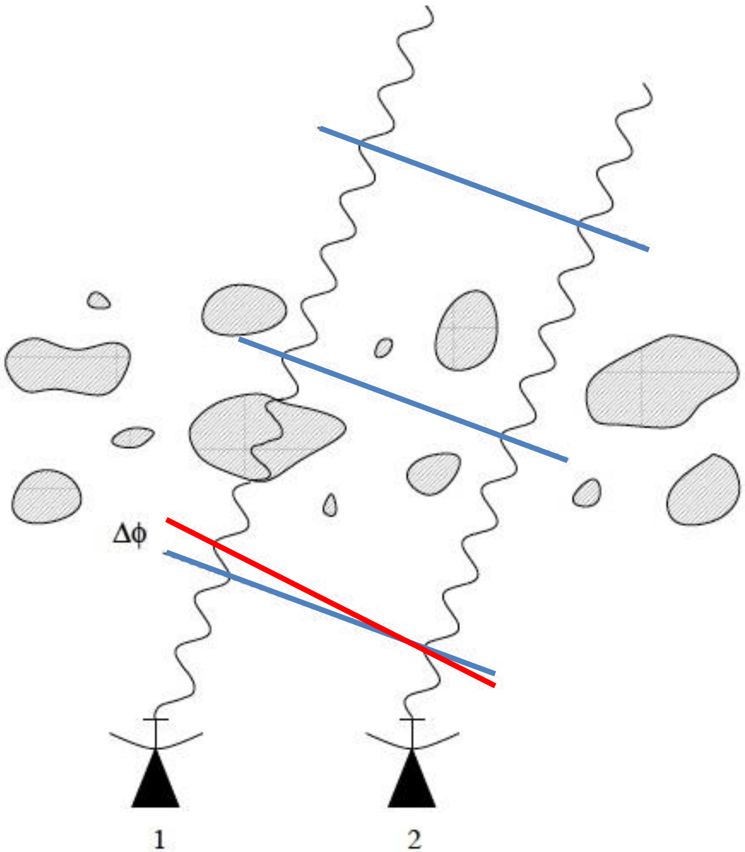
Bandpass Phase vs. Frequency (After)



Atmospheric Phase Correction

- Variations in the amount of precipitable water vapor cause phase fluctuations that result in:
  - Low coherence (loss of sensitivity)
  - Radio "seeing" of 1arcsec at 1mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

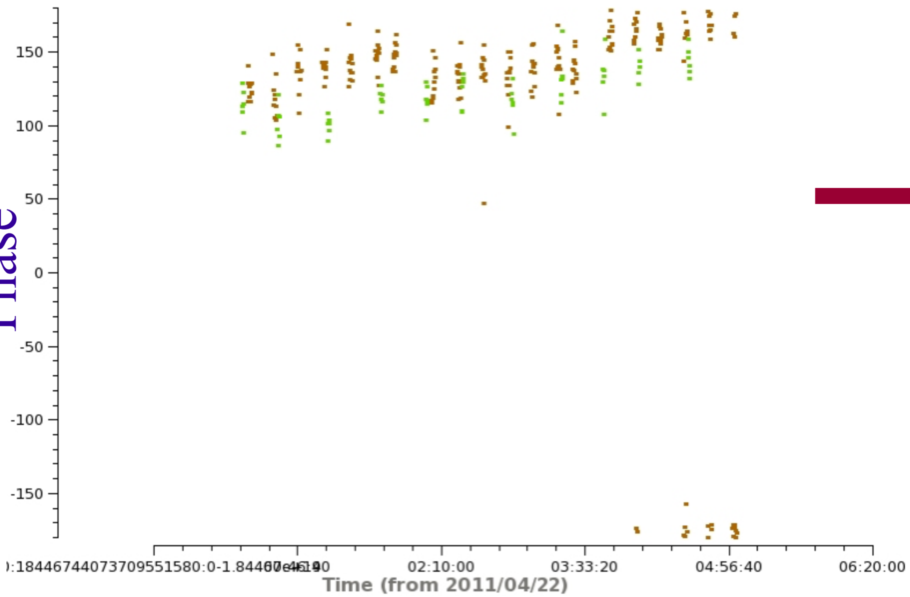
Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

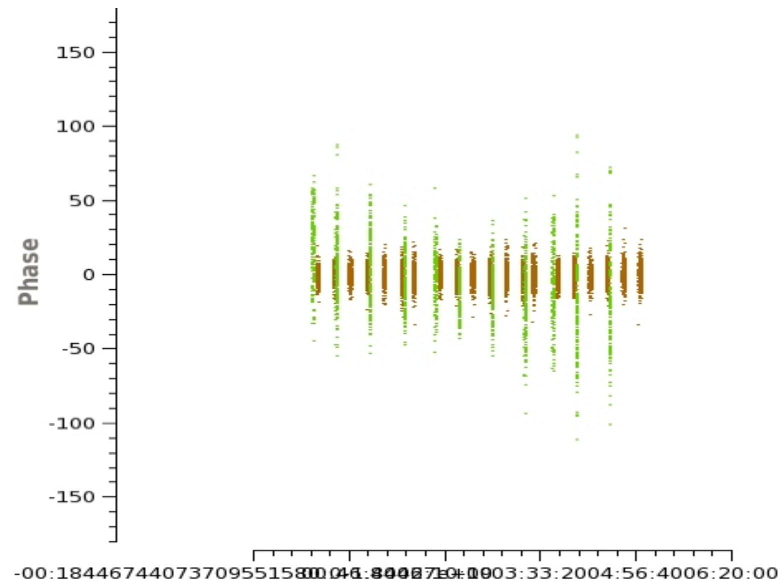


Phase Calibration

The phase calibrator must be a point source close to the science target and must be observed frequently. This provides a model of atmospheric phase change along the line of sight to the science target that can be compensated for in the data.

Phase

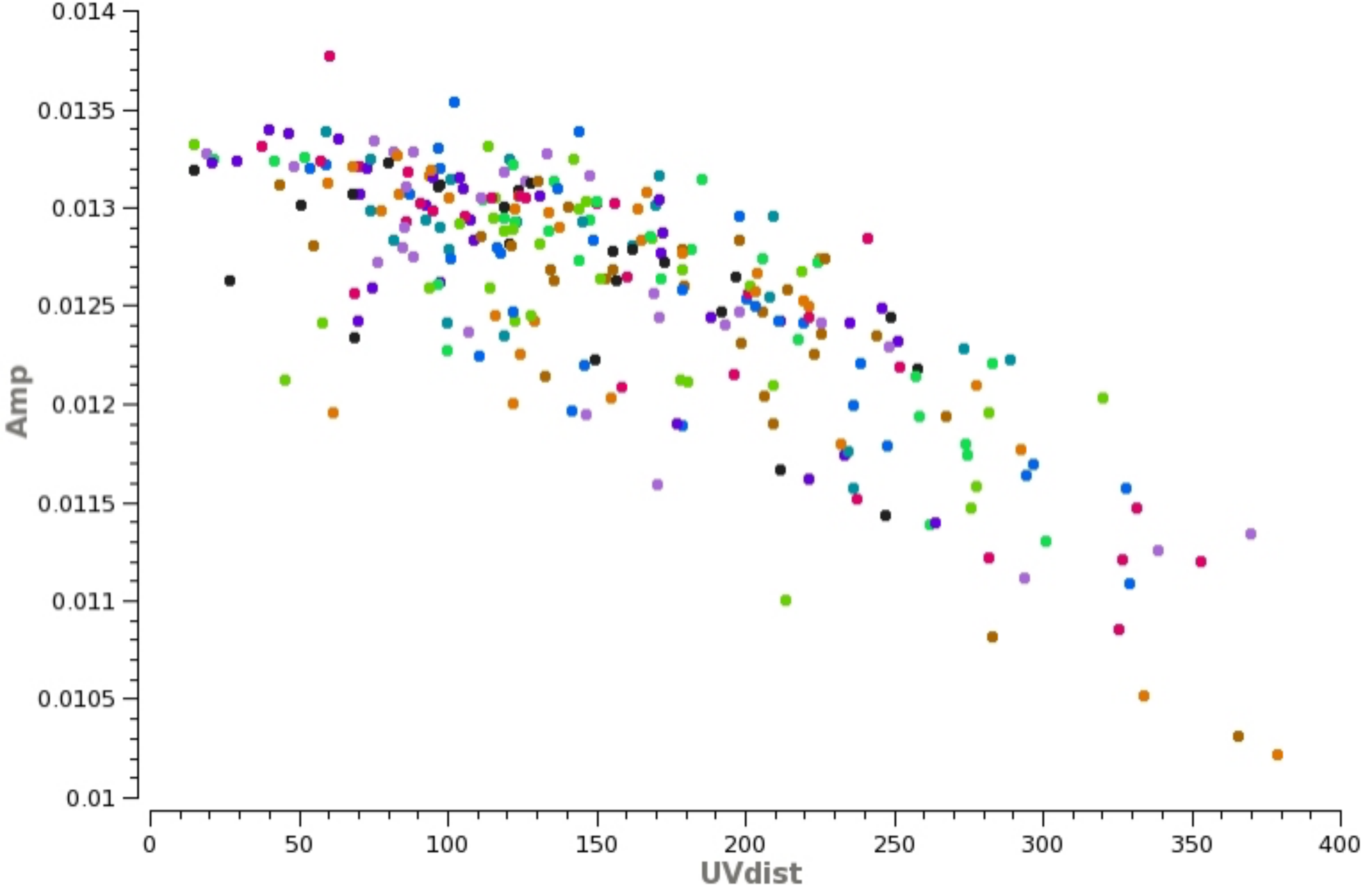




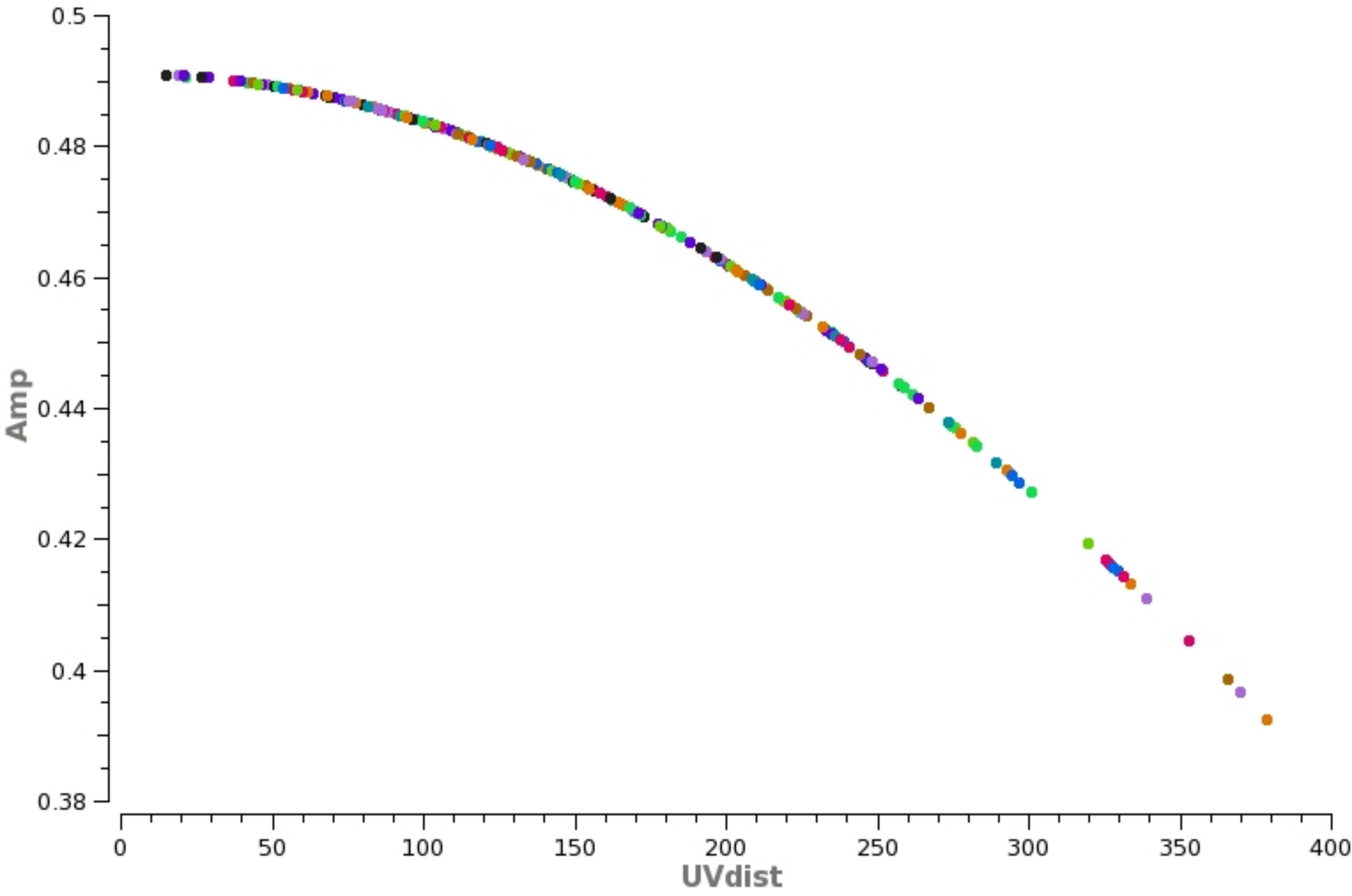
Time

Corrected using point source model

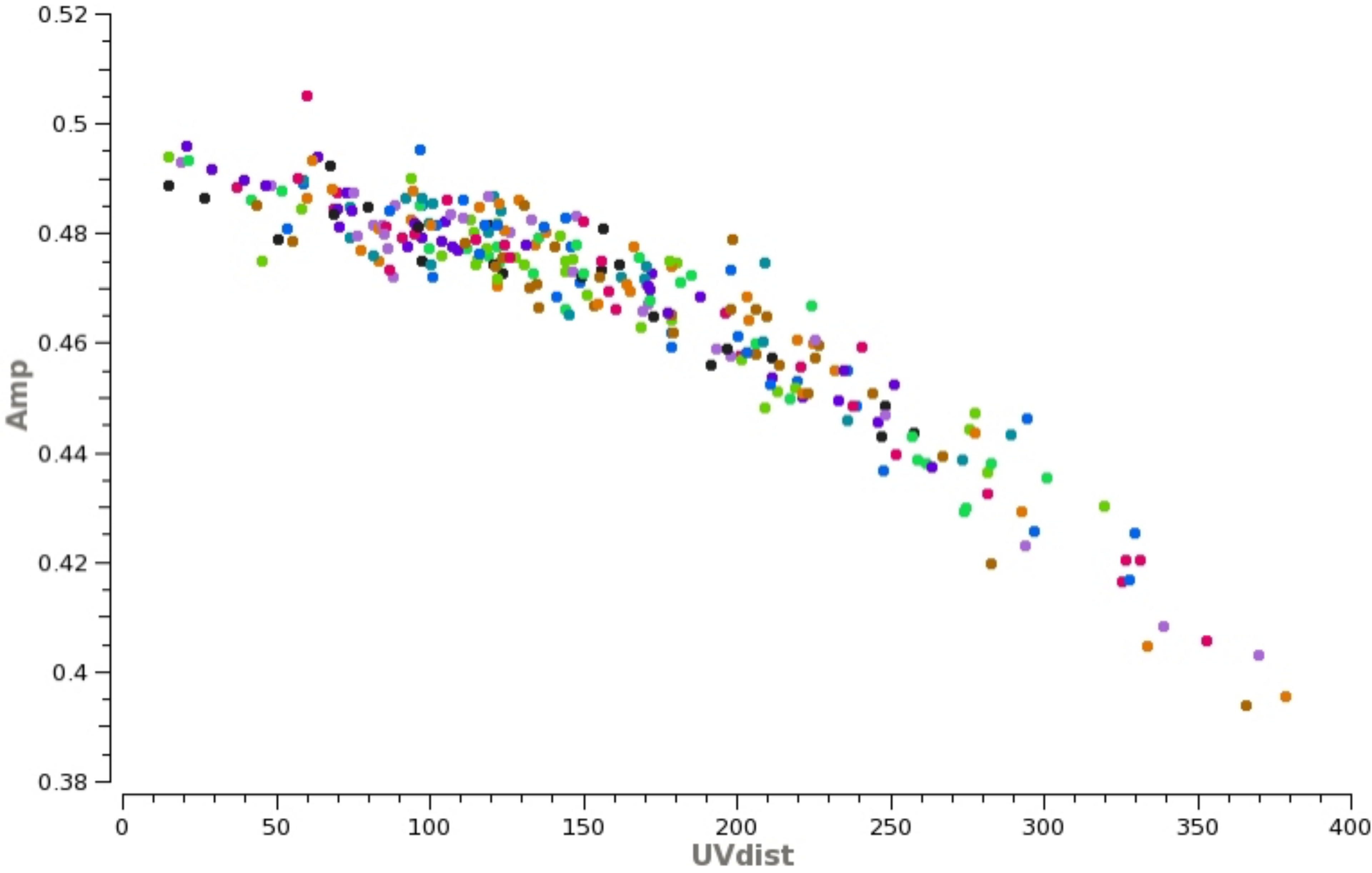
Amp-Calibrators Amp vs. uv-distance (Before)



Amp-Calibrators Amp vs. uv-distance (Model)

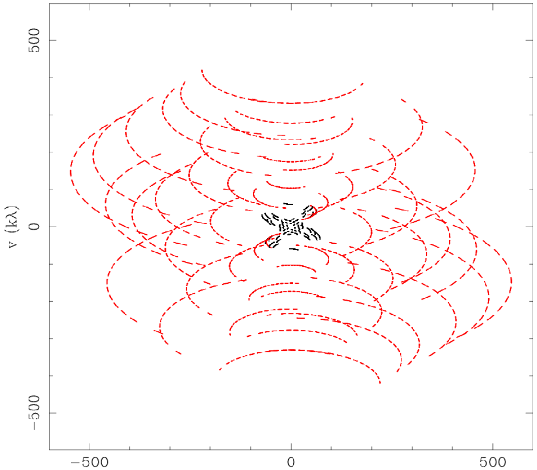


Amp-Calibrators Amp vs. uv-distance (After)

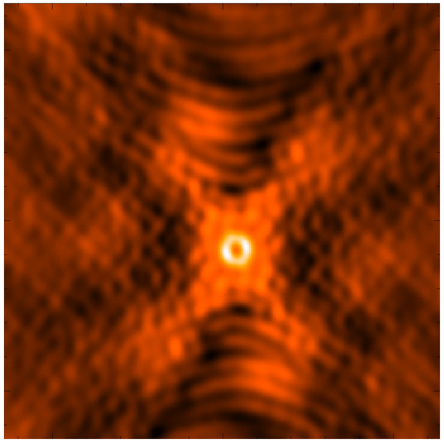


The observed (AKA dirty) image is the true image convolved with the PSF.

B(u,v)
(sampled visibilities)

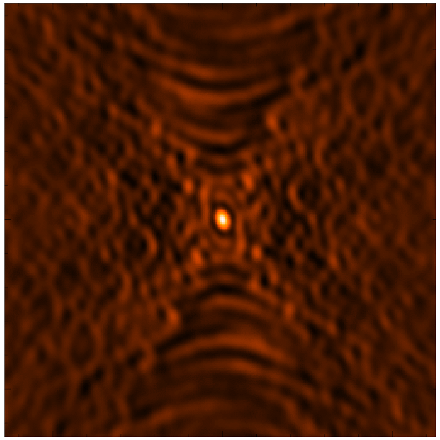


⇌ (Fourier Transform)

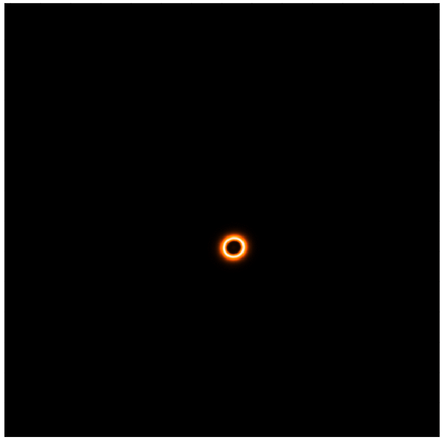


TD(x,y)
(dirty image)

b(x,y)
(dirty beam or psf)



⊗
Convolve



T(x,y)
(True sky brightness)

- **Fourier transform of sampled visibilities yields the true sky brightness convolved with the point spread function ("dirty beam").**
- **You need to deconvolve the PSF from the dirty image to reconstruct the source.**

Clean is the most common deconvolution algorithm.

Sky Model : List of delta-functions

(1) Construct the observed (dirty) image and PSF

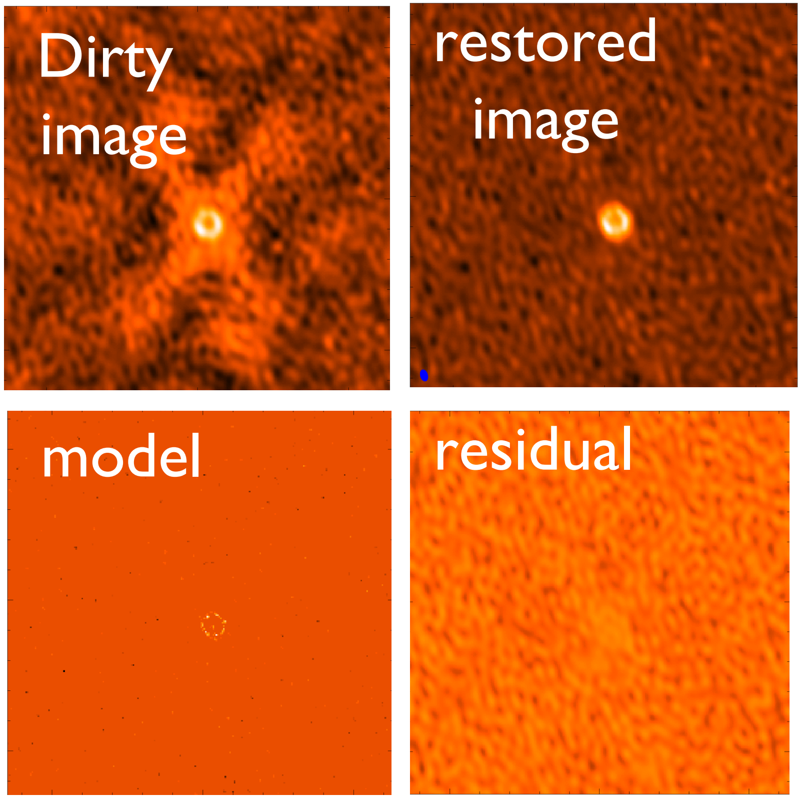
(2) Search for the location of peak amplitude.

(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



Choices: what and how much PSF to subtract and when to stop

Adapted from slide by Urvashi Rau

Some good references

- Thompson, A.R., Moran, J.M., Swensen, G.W. 2004 “Interferometry and Synthesis in Radio Astronomy”, 2nd edition (Wiley-VCH)
- 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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http://www.almaobservatory.org

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