Introduction to Radio Interferometry

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Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

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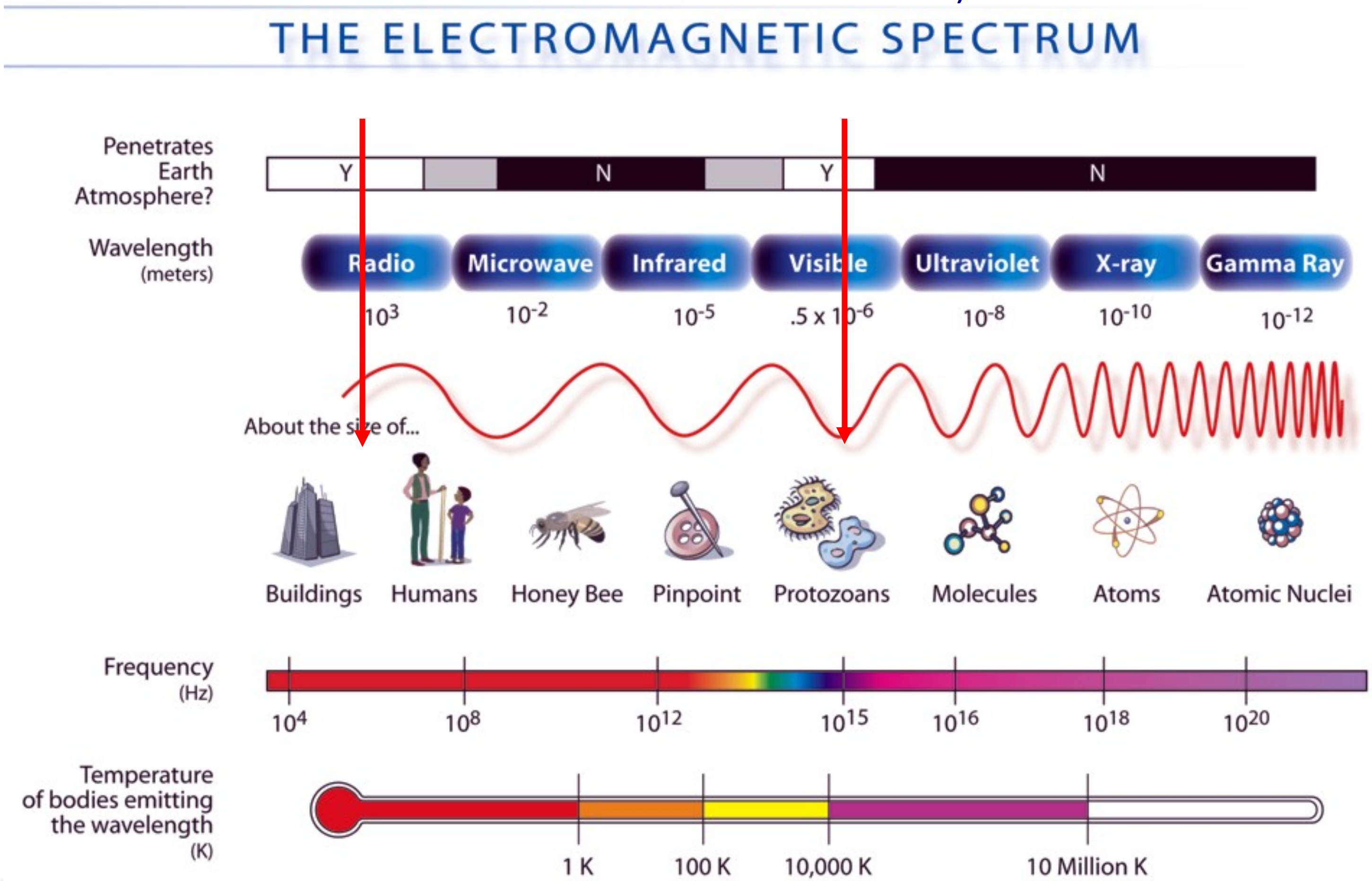
Radio Astronomy

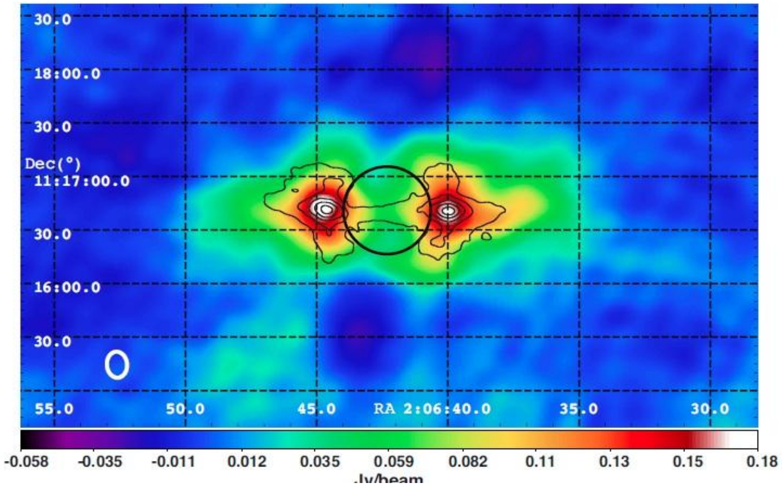
(Now used to refer to most telescopes using heterodyne technology, which extends to the microwave)



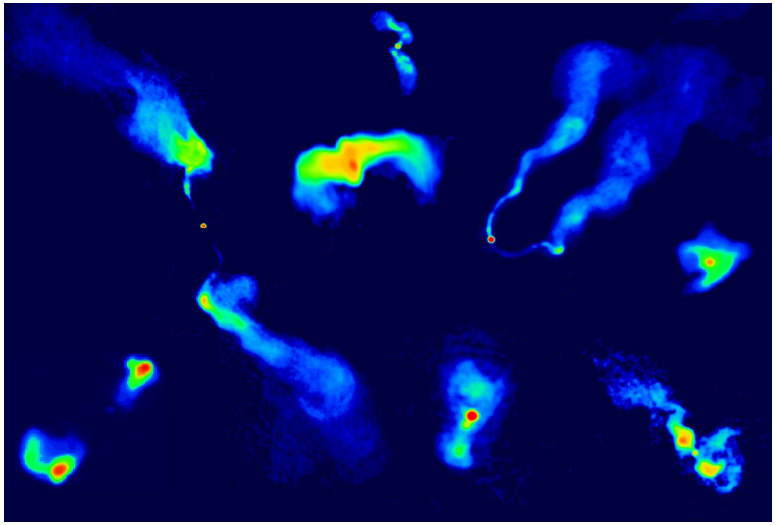
Long wavelength means no glass mirrors

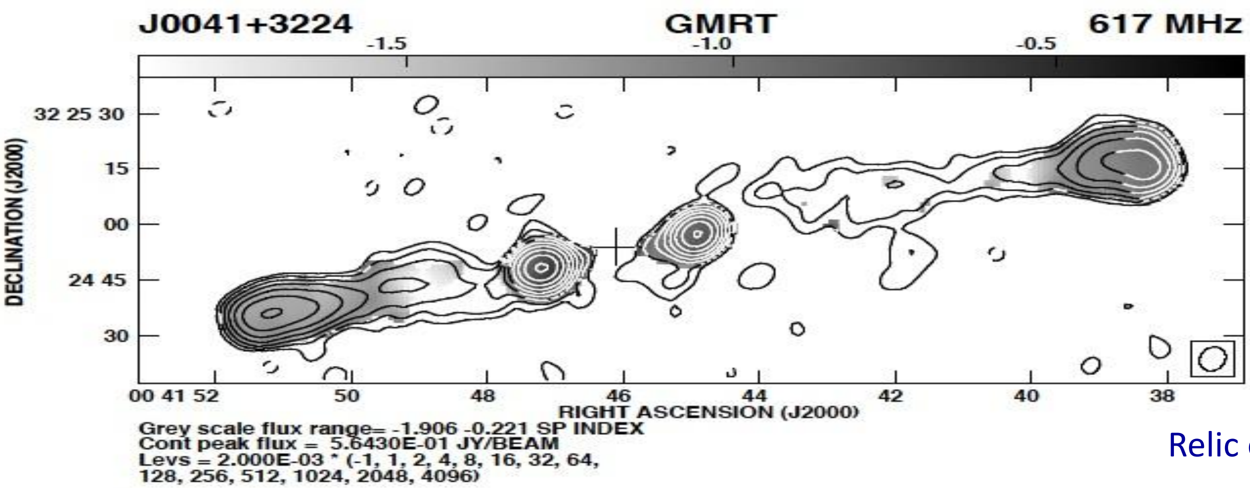
What can we observe? (MHz-GHz range)

Jupiter's radiation belt at 100MHz



Synchrotron emission from extended radio galaxies (5 GHz)





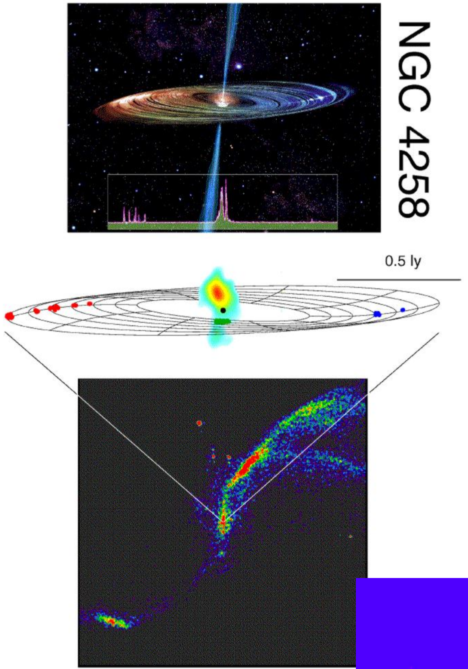
Images from NRAO Image Gallery: https://p

Relic emission from old radio galaxies

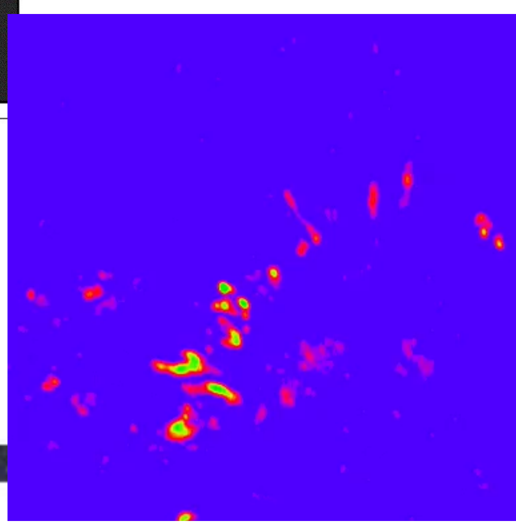
Images from NRAO Image Gallery:
https://public.nrao.edu/gallery/

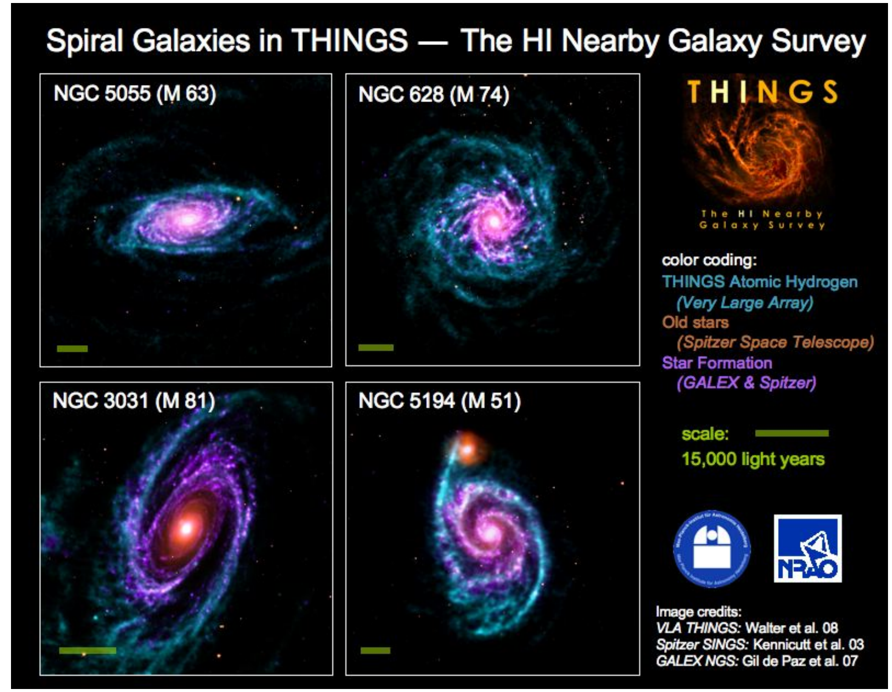
What can we observe?

At low frequencies (MHz-GHz):

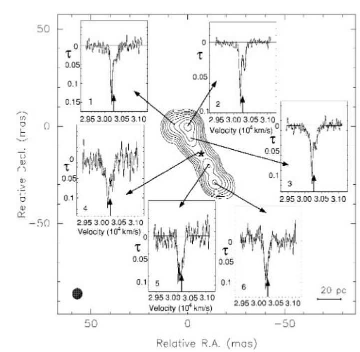


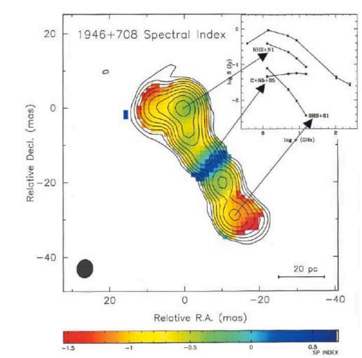
H_2O, OH or SiO masers in galaxies and stars





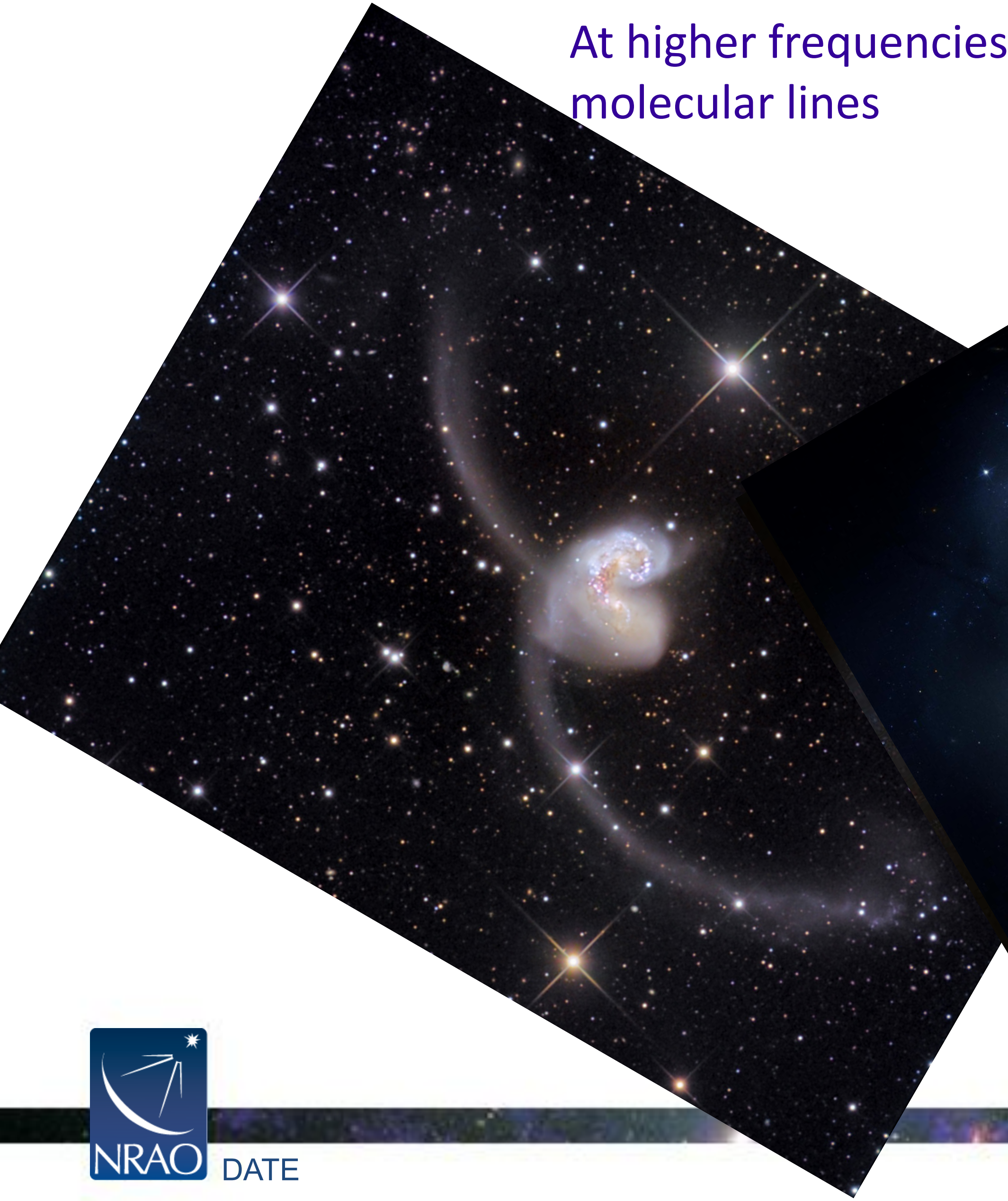
HI emission and absorption, free-free absorption in galaxies





What can we observe?

At higher frequencies we can observe a broad range of molecular lines



Images from NRAO Image Gallery: https://public.nrao.edu/gallery/

High Resolution Data is Important

Angular resolution for most telescopes is ~ λ/D

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

For the Hubble Space Telescope:

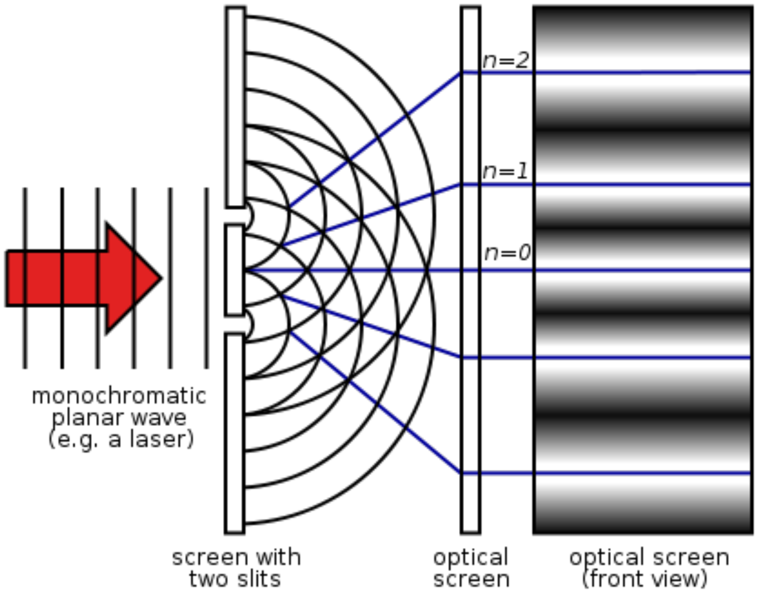
λ ~ 1um / D of 2.4m = resolution ~ 0.13"

To reach that resolution at λ ~1mm, we would need ~2 km-diameter dish!

Instead, we use arrays of smaller dishes to achieve that high angular resolution at radio wavelengths

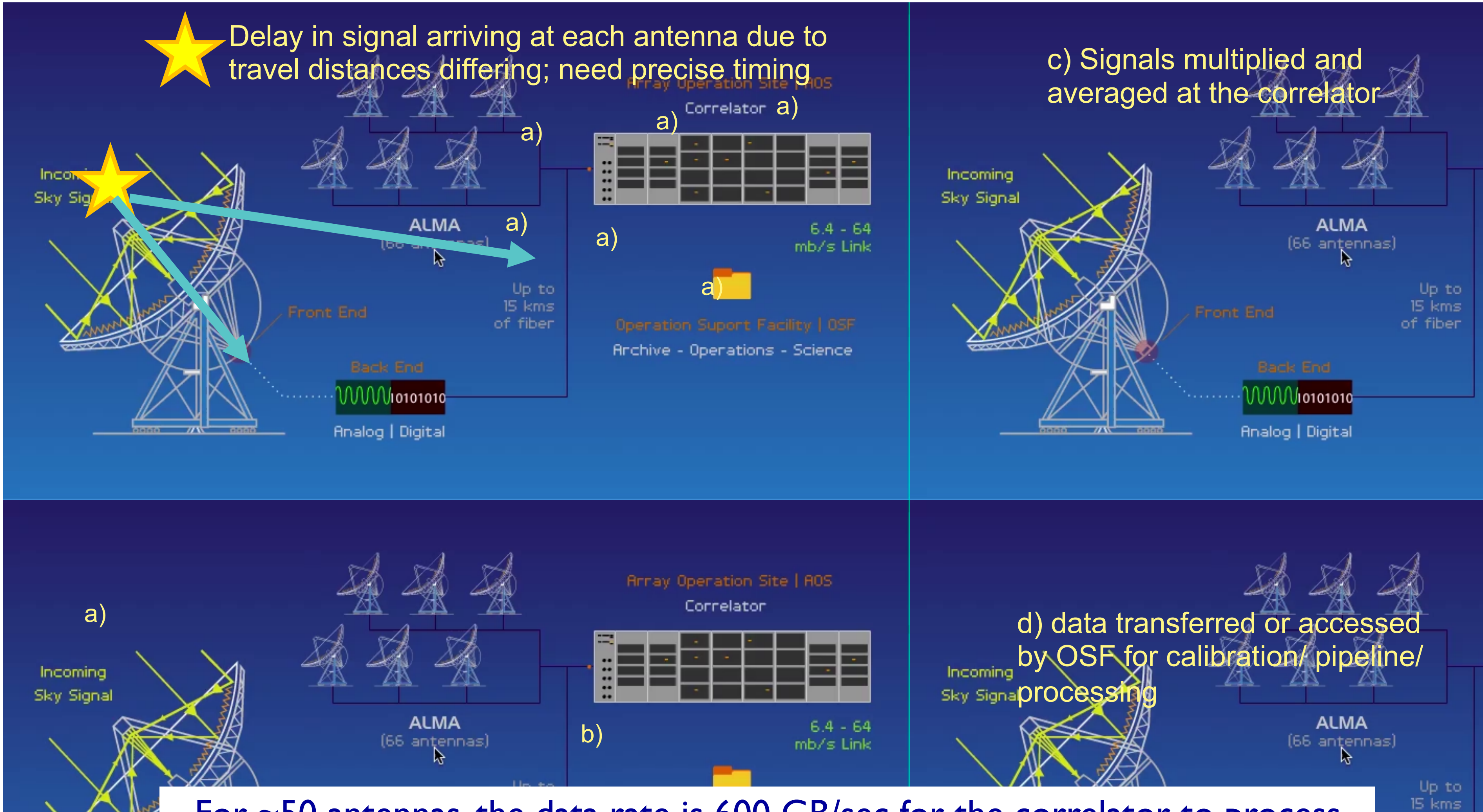
What is an interferometer?

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



In astronomy, *radio interferometry* works in reverse:
by multiplying the input from two telescopes (aka two apertures), we can receive information from the sky in the spots illuminated by an interference pattern

An Interferometer In Action



For ~50 antennas, the data rate is 600 GB/sec for the correlator to process

Planning Your Observation

Interferometers act as spatial filters - shorter baselines are sensitive to larger targets, so remember …

Spatial scales smaller than the largest baseline (B_{max}) cannot be resolved

Spatial scales larger than the smallest baseline (B_{min}) cannot be imaged

Angular resolution of telescope array:

$\sim \lambda/B_{max}$ (B_{max} = longest baseline)

Maximum angular scale:

$\sim \lambda/B_{min}$ (B_{min} = shortest distance between antennas)

Field of view (FOV):

$\sim \lambda/D$ (D = antenna diameter)

BUT sources more extended than the FOV can be observed using multiple pointing centers in a mosaic

Visibility and Sky Brightness

The van Cittert-Zernike theorem

- **Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)**

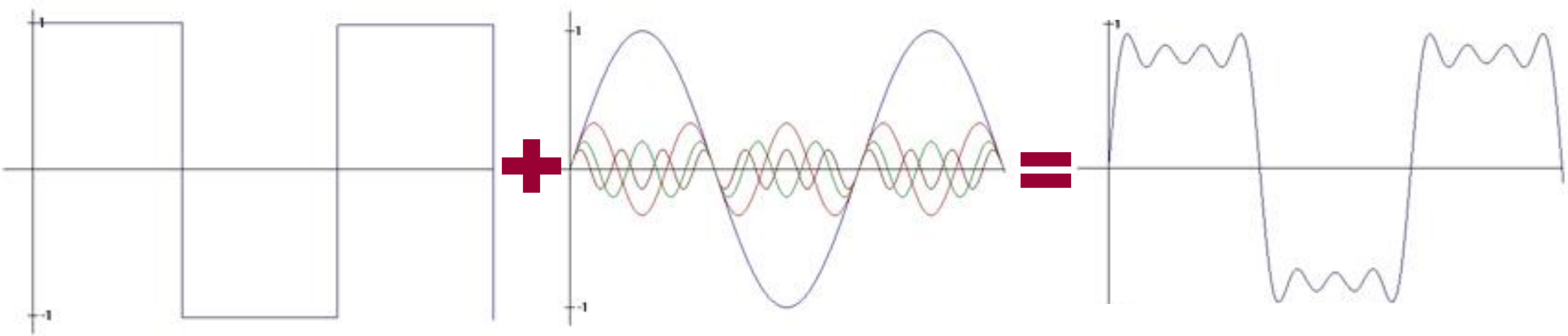
$$V(u,v) \xrightarrow{\text{FT}} T(x,y)$$

V(u,v) = the complex visibility function $= \iint T(x,y)e^{2\pi i(ux+vy)}dxdy$

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

Introducing 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

Visibility and Sky Brightness

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

Fourier space/domain

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

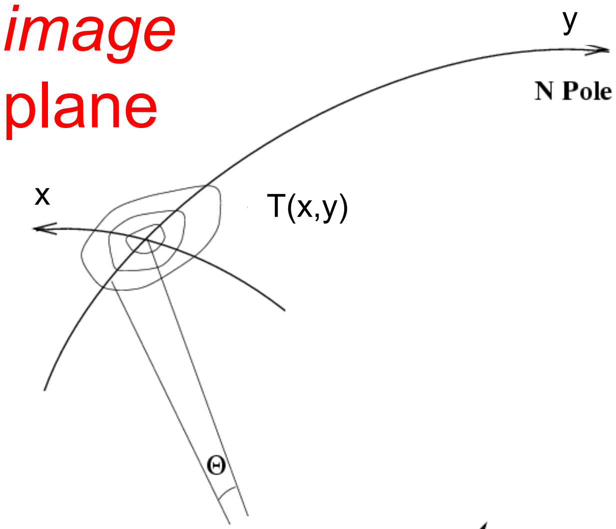
Complex visibility function

Image space/domain

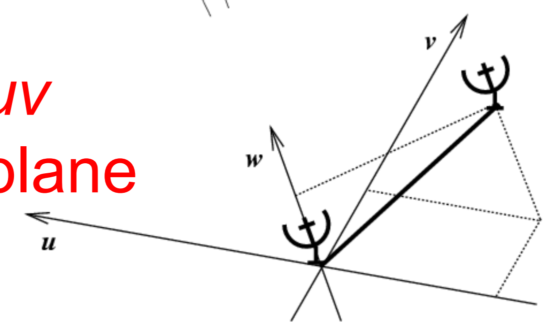
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

Sky brightness distribution

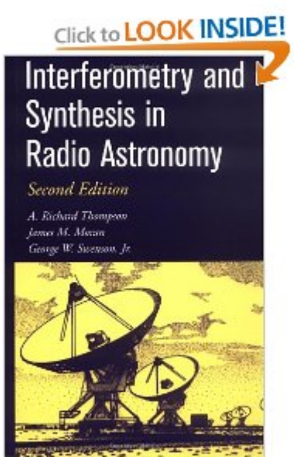
image plane



uv plane



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



What Are Visibilities?

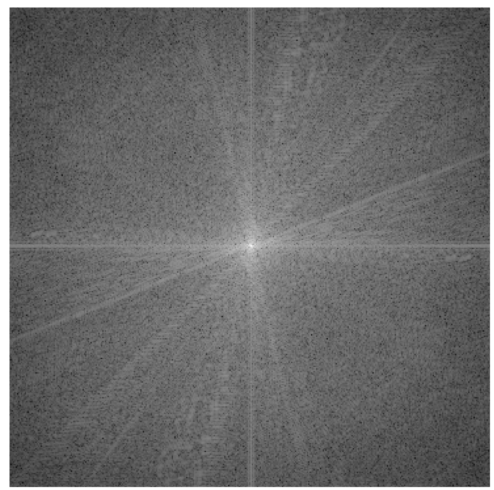
Each V(u,v) contains information on T(x,y) everywhere

Each V(u,v) is a complex quantity

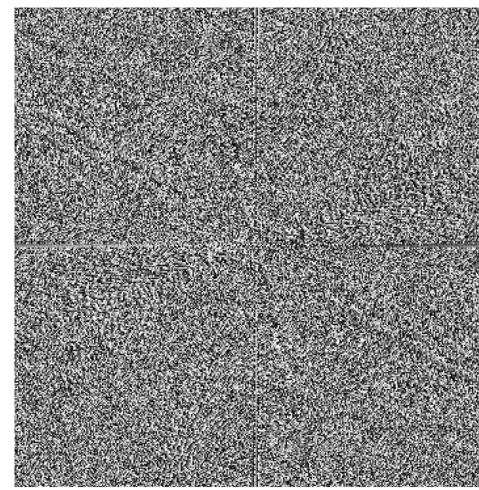
Expressed as (real, imaginary) or (amplitude, phase)

T(x,y)

FT →



V(u,v) amplitude



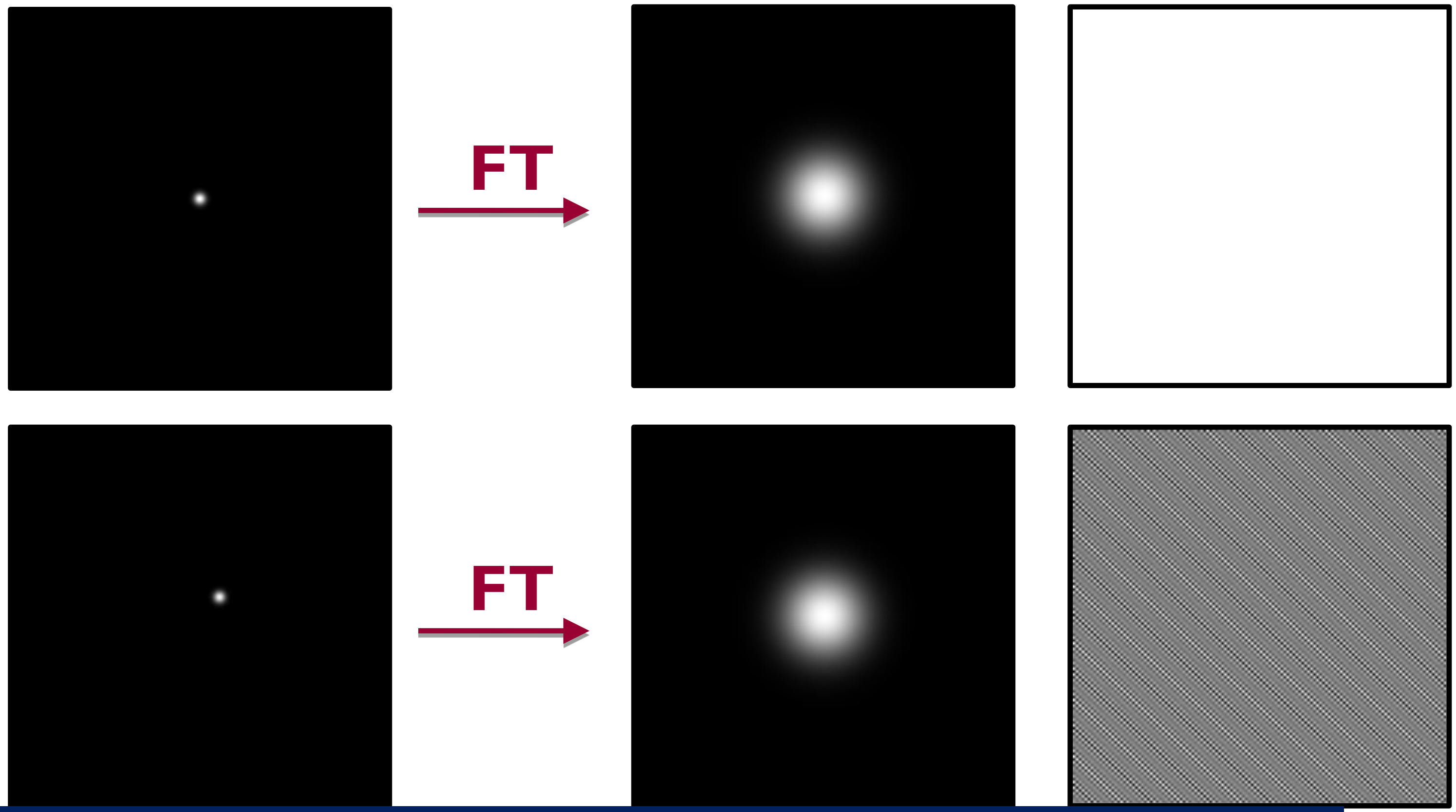
V(u,v) phase

Examples of 2D Fourier Transforms

T(x,y) | V(u,v) amplitude | V(u,v) phase

Centered Gaussian

Offset Gaussian



Rules of the Fourier Transform:

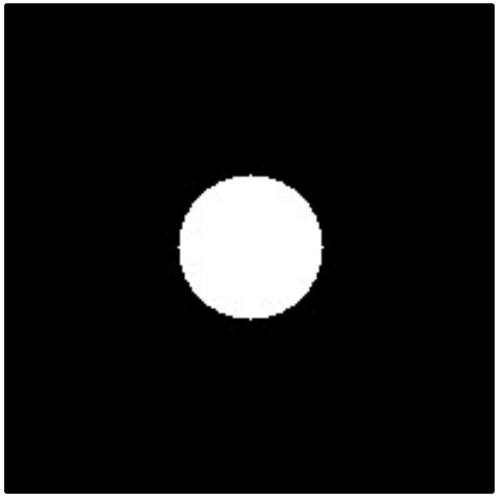
Amplitude tells you 'how much' of a spatial frequency

Phase tells you 'where' the spatial frequency is

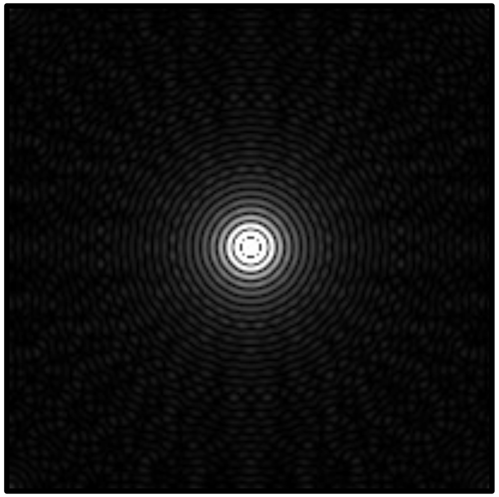
Examples of 2D Fourier Transforms

T(x,y) | **V(u,v) amplitude**

Uniform Disk

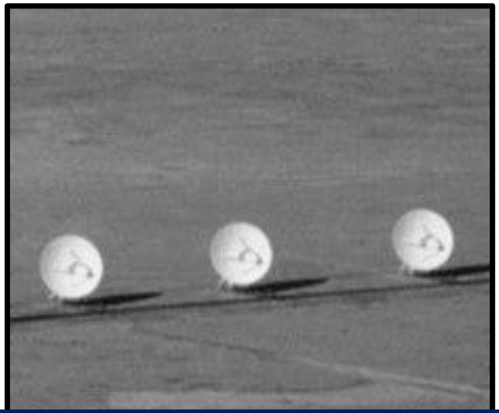


FT →

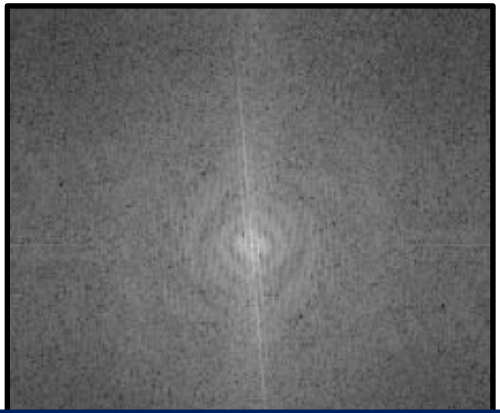


Bessel Function

VLA Antennas



FT →



Bessel Function!

Rules of the Fourier Transform:
Sharp features (edges) result in many high spatial features

Basics of Aperture Synthesis

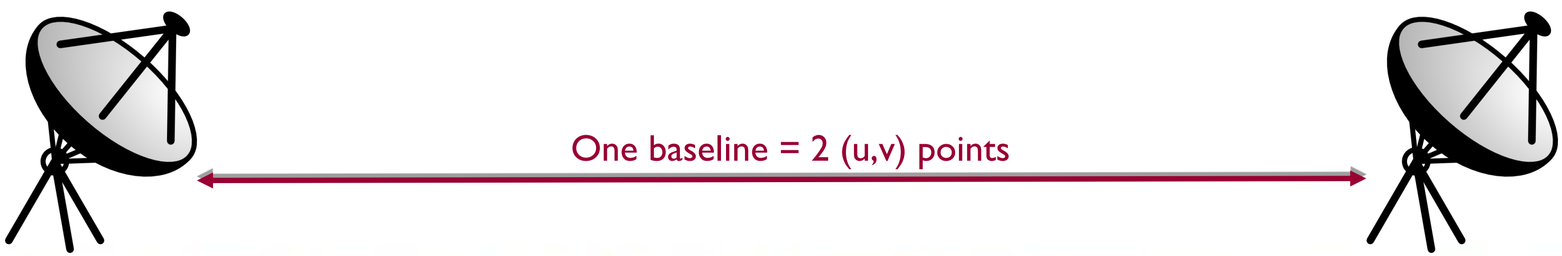
Idea: Sample V(u,v) at an enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{max},v_{max})

One pair of antennas = one baseline

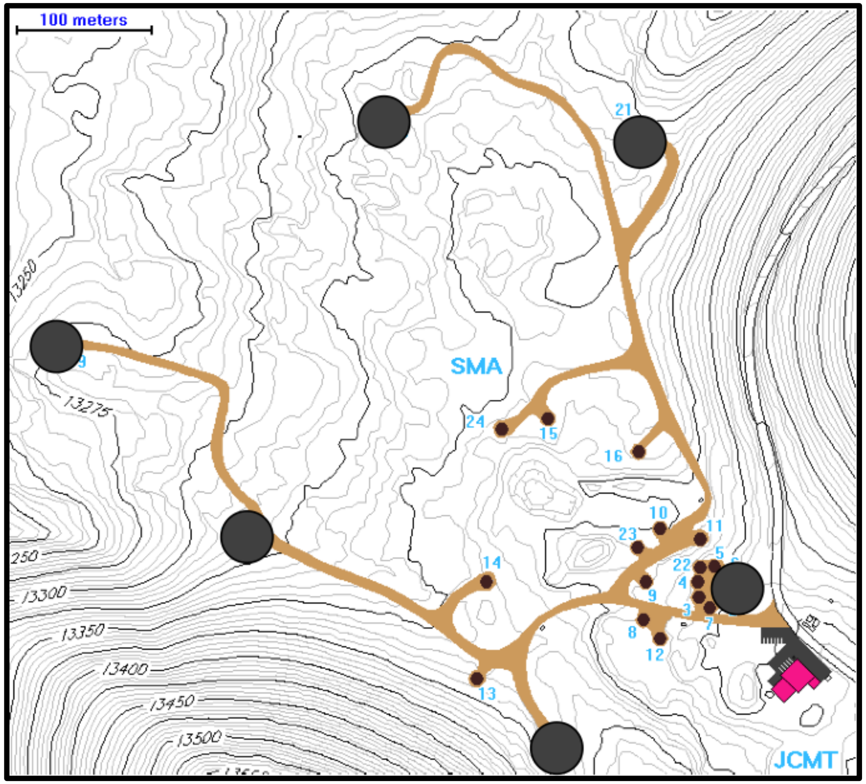
For **N antennas**, we get **N(N-1) samples** at a time

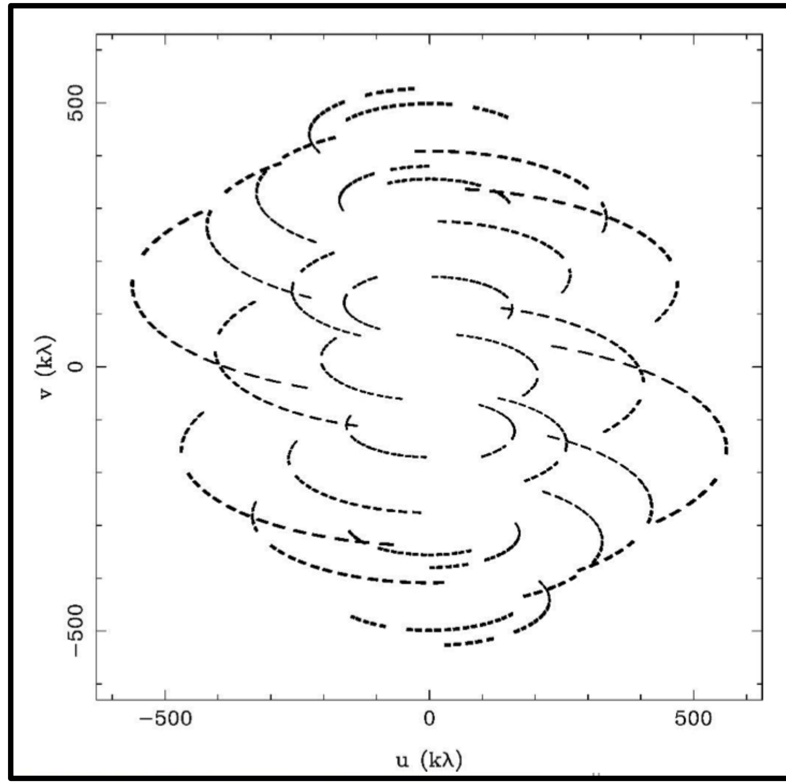
How do we fill in the rest of the (u,v) plane?

1. Earth's rotation
2. Reconfigure physical layout of N antennas



(u,v) Plane Sampling



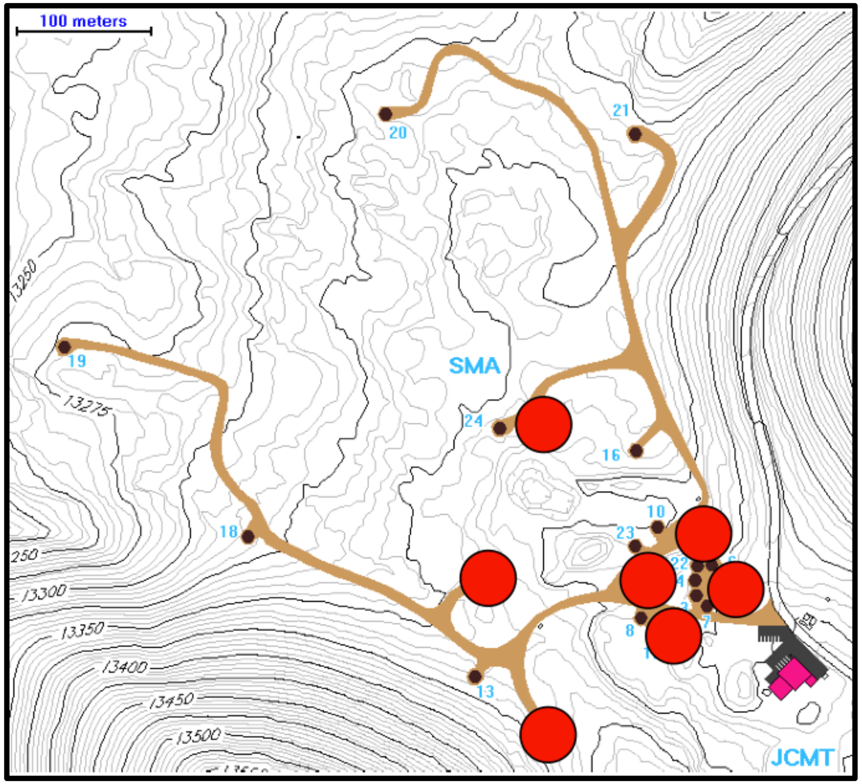


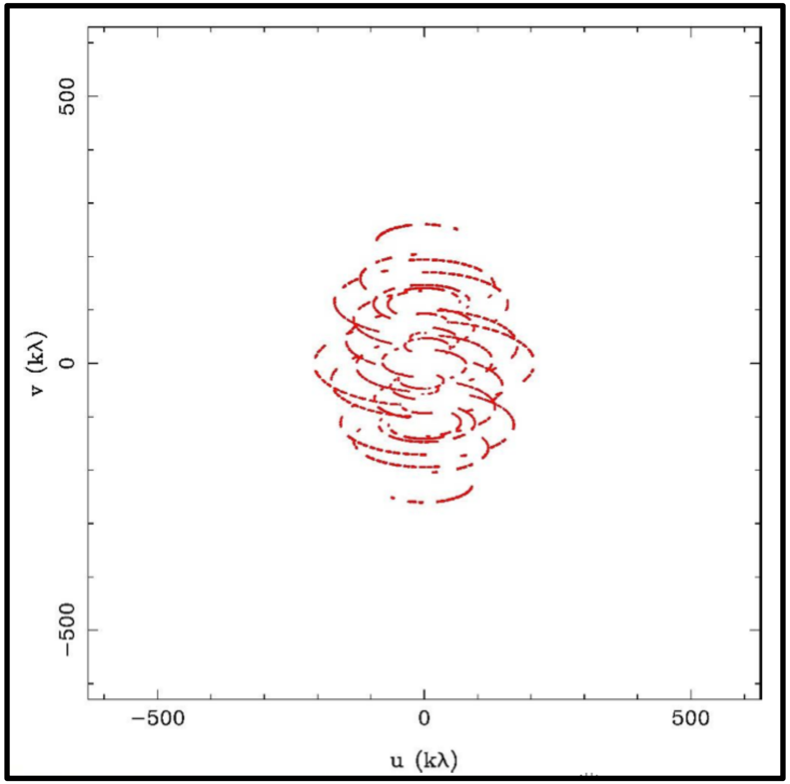
Very Extended SMA configuration

(most extended baselines)

345 GHz, DEC = +22

(u,v) Plane Sampling



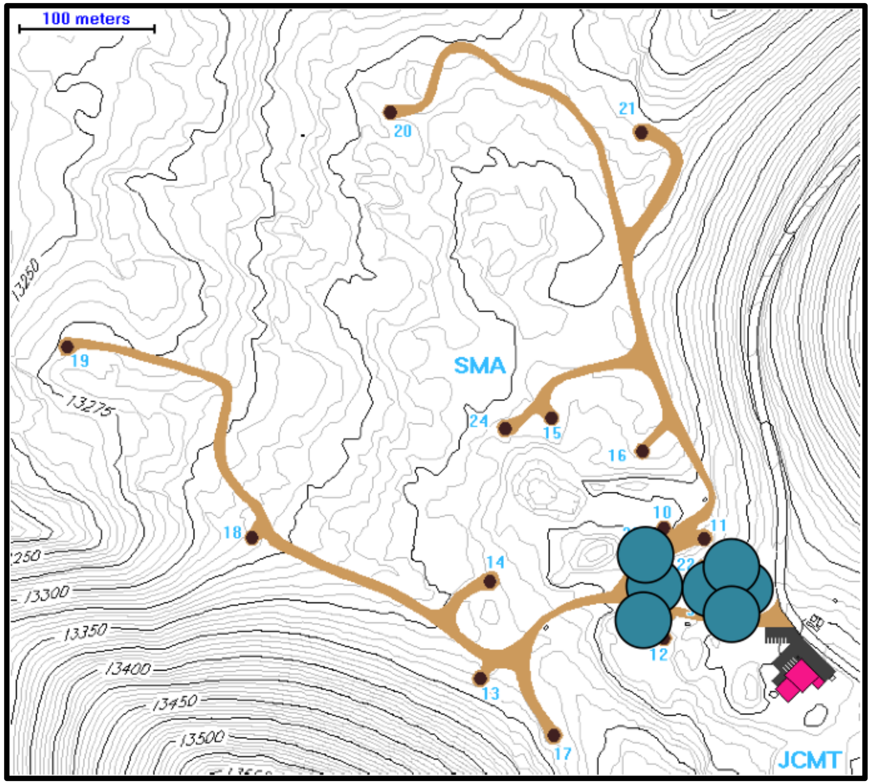


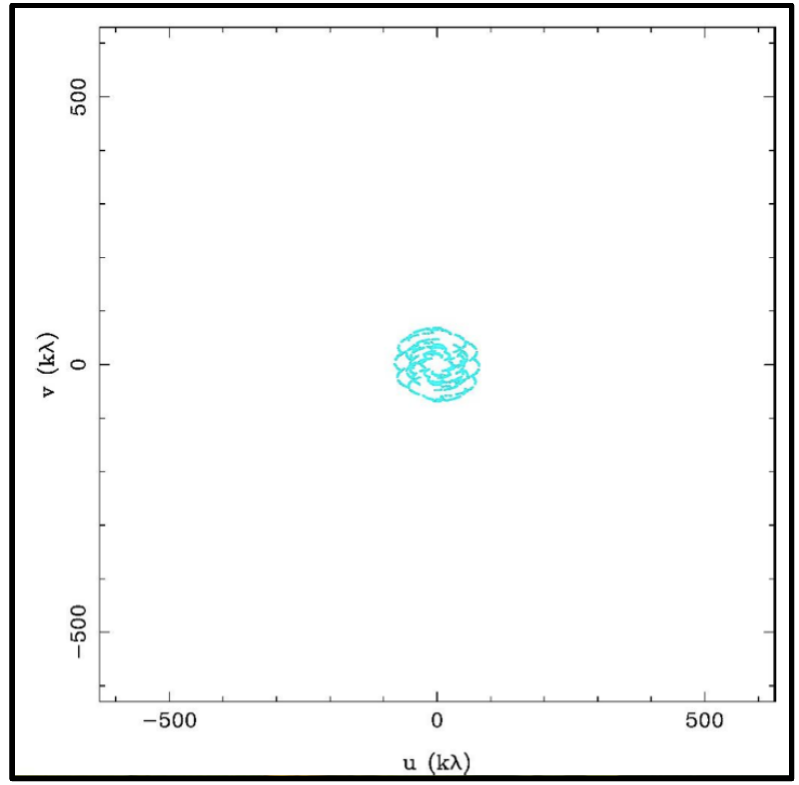
Extended SMA configuration

(extended baselines)

345 GHz, DEC = +22

(u,v) Plane Sampling



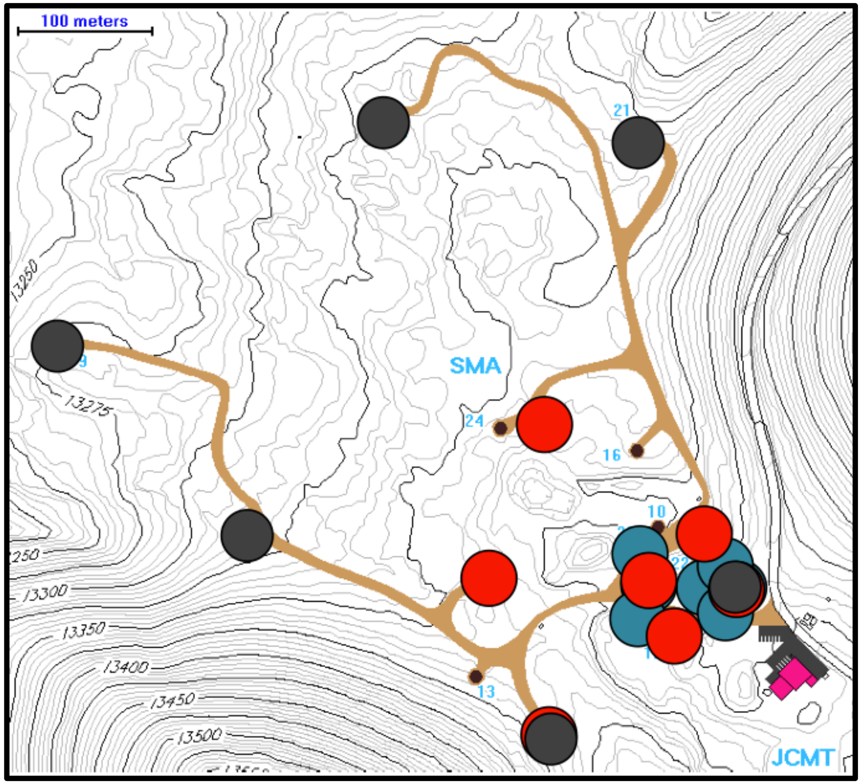


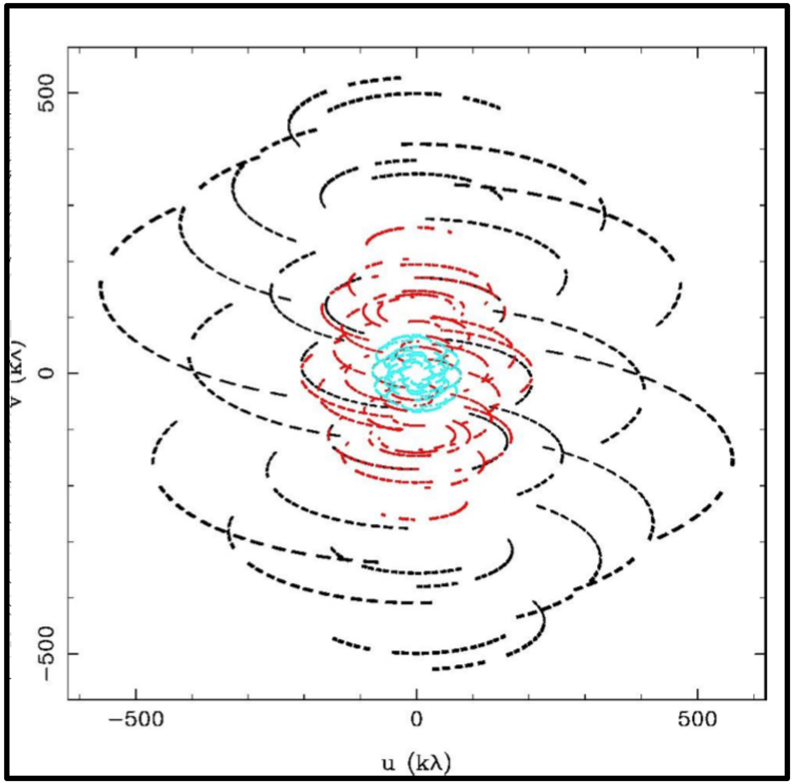
Compact SMA configuration

(compact baselines)

345 GHz, DEC = +22

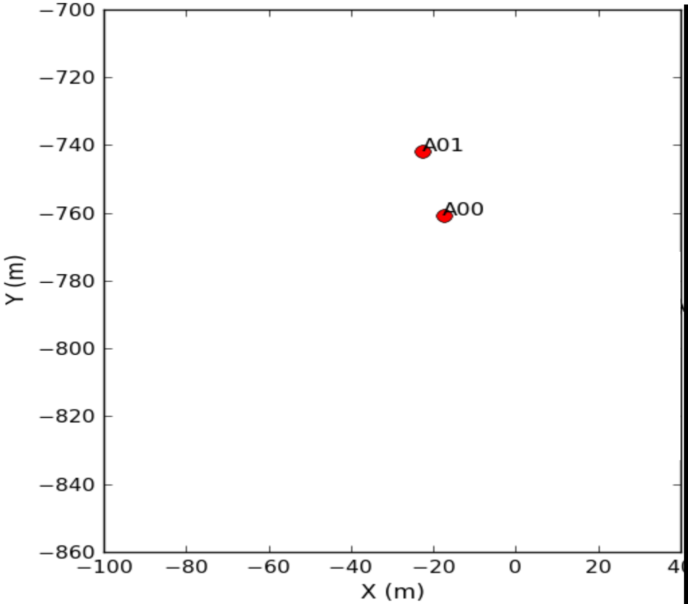
(u,v) Plane Sampling

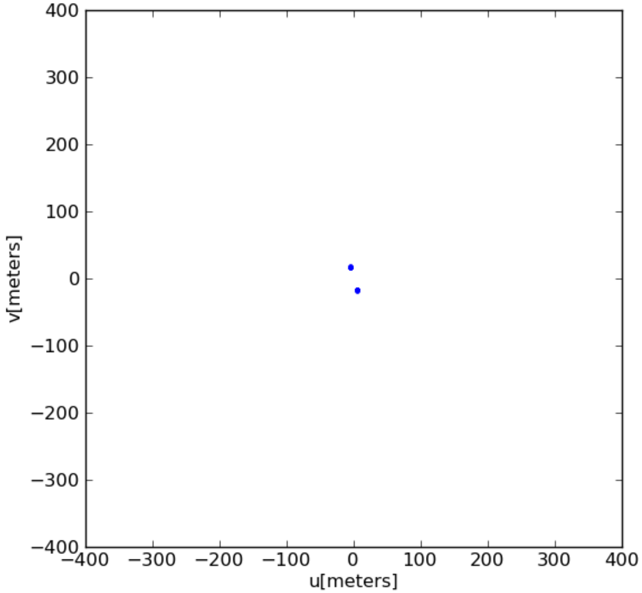


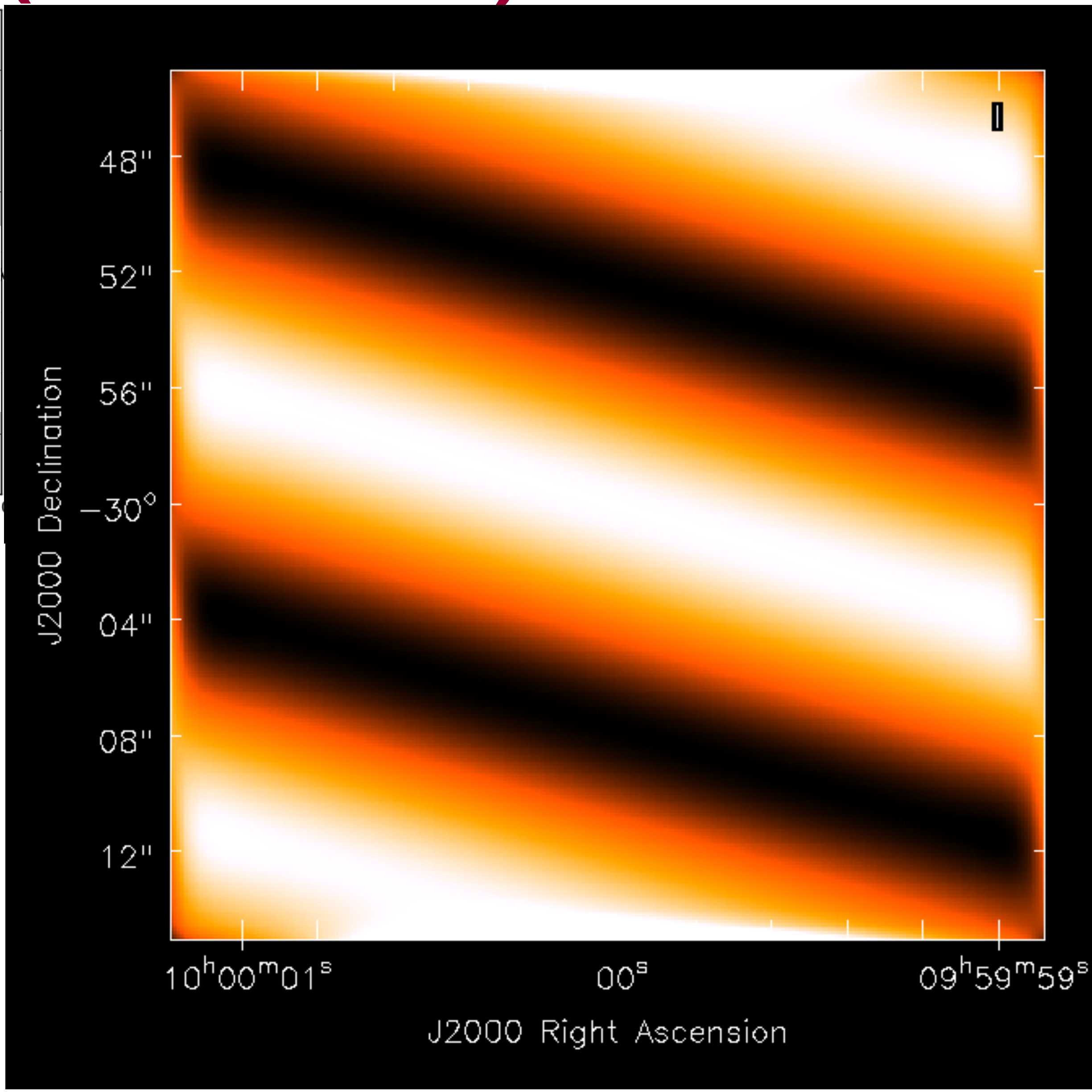


Combine multiple configurations to get the most complete coverage of the (u,v) plane

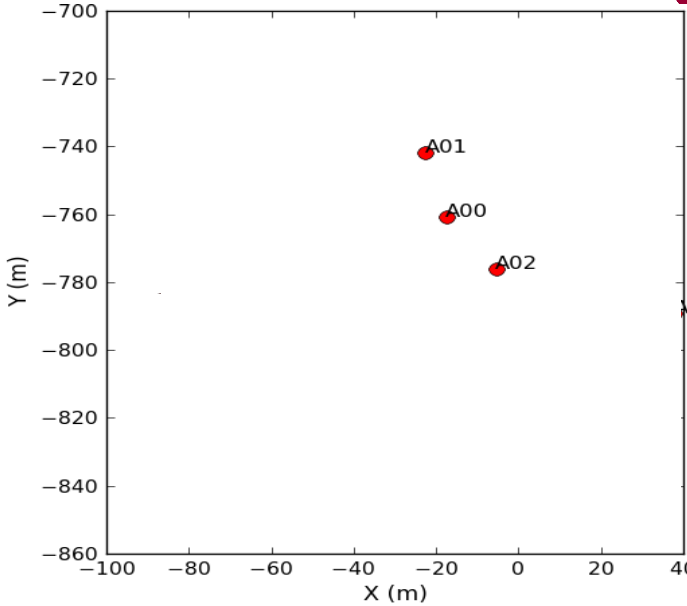
Example: Fringe pattern with 2 Antennas (one baseline)

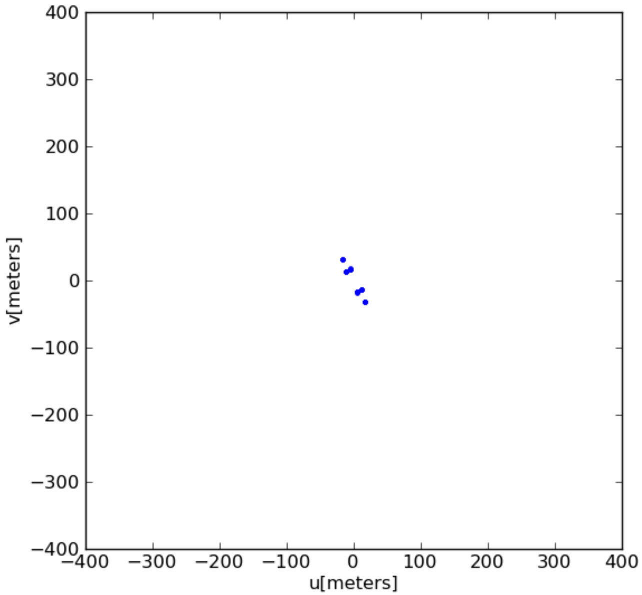


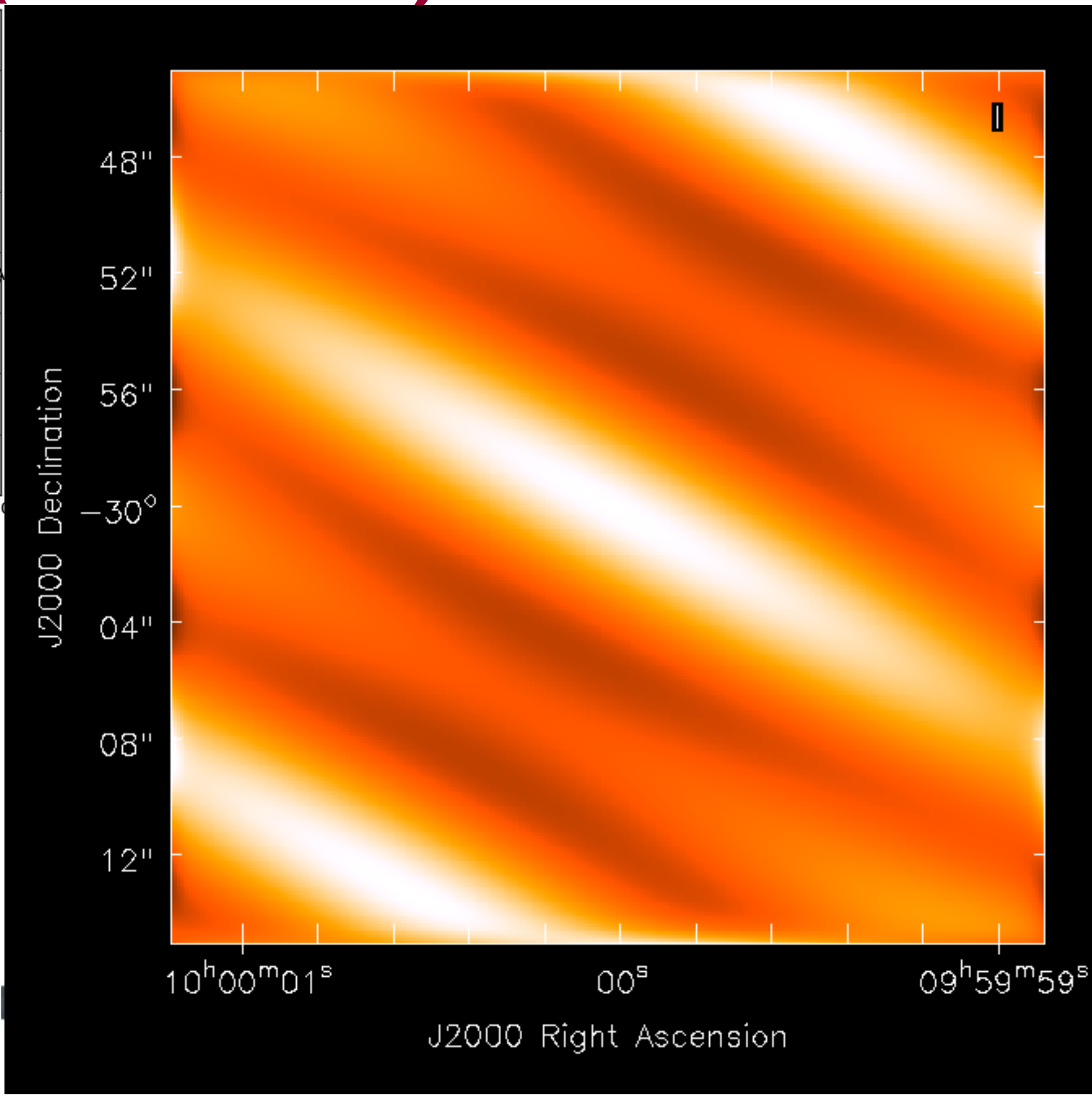




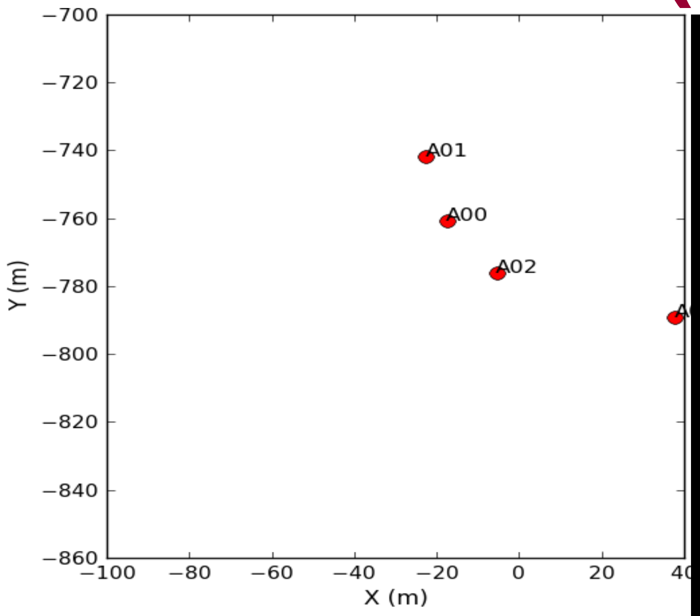
Example: Fringe pattern with 3 Antennas (3 baselines)

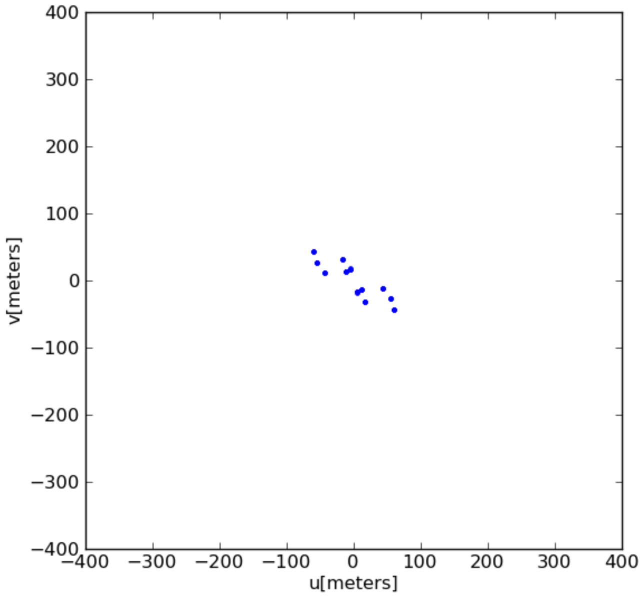


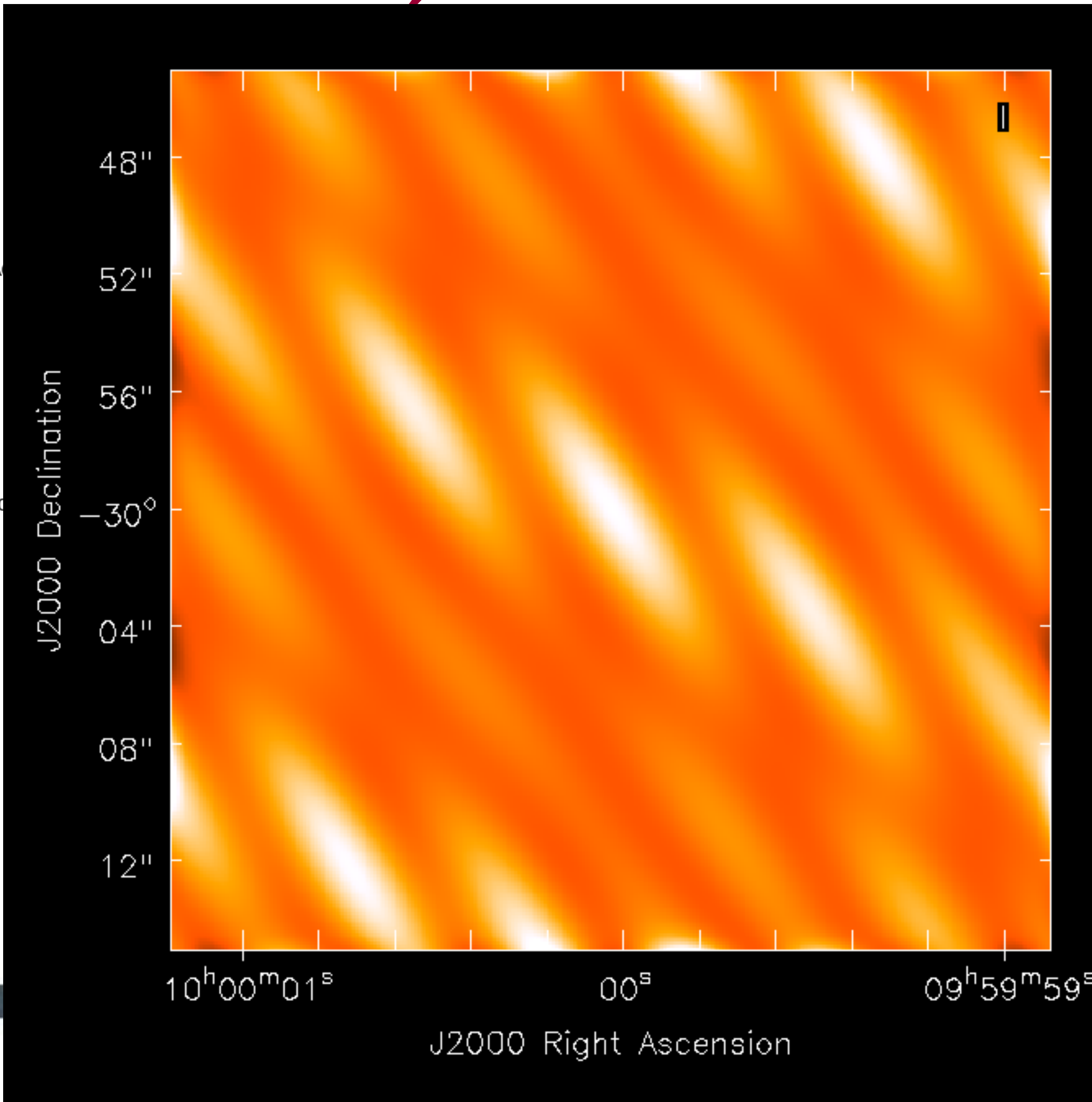




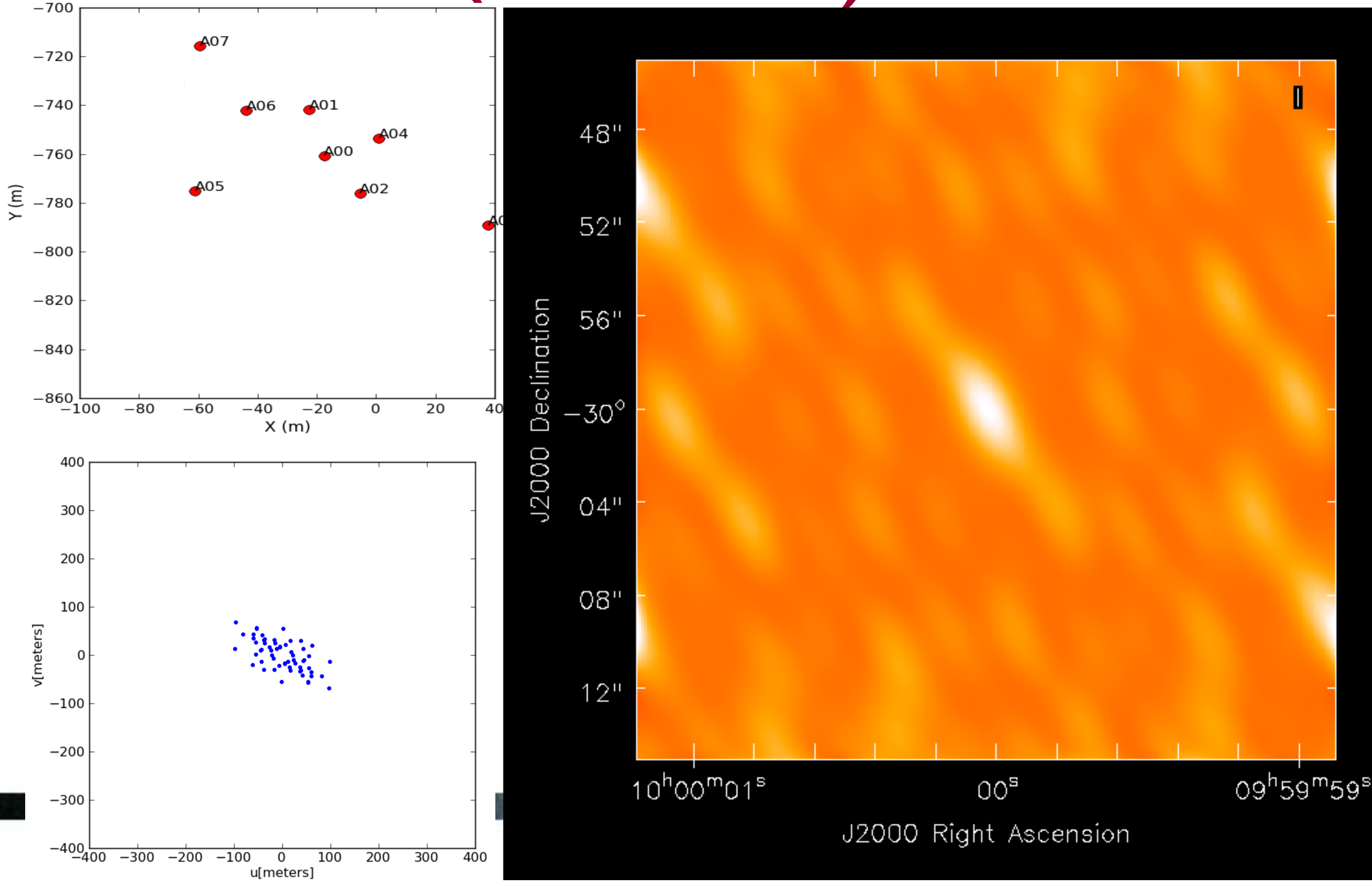
Example: Fringe pattern with 4 Antennas (6 baselines)



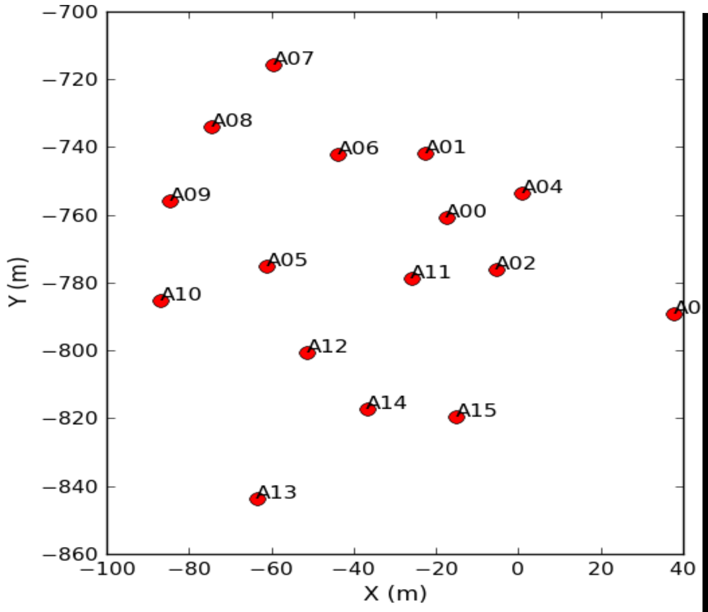


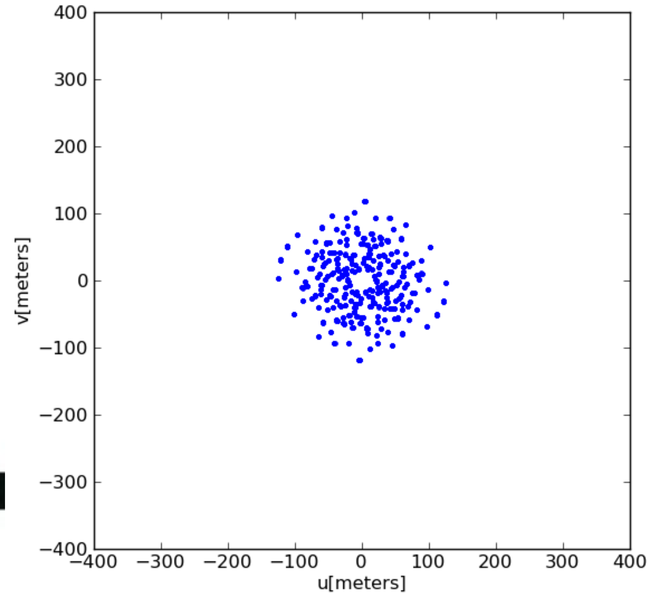


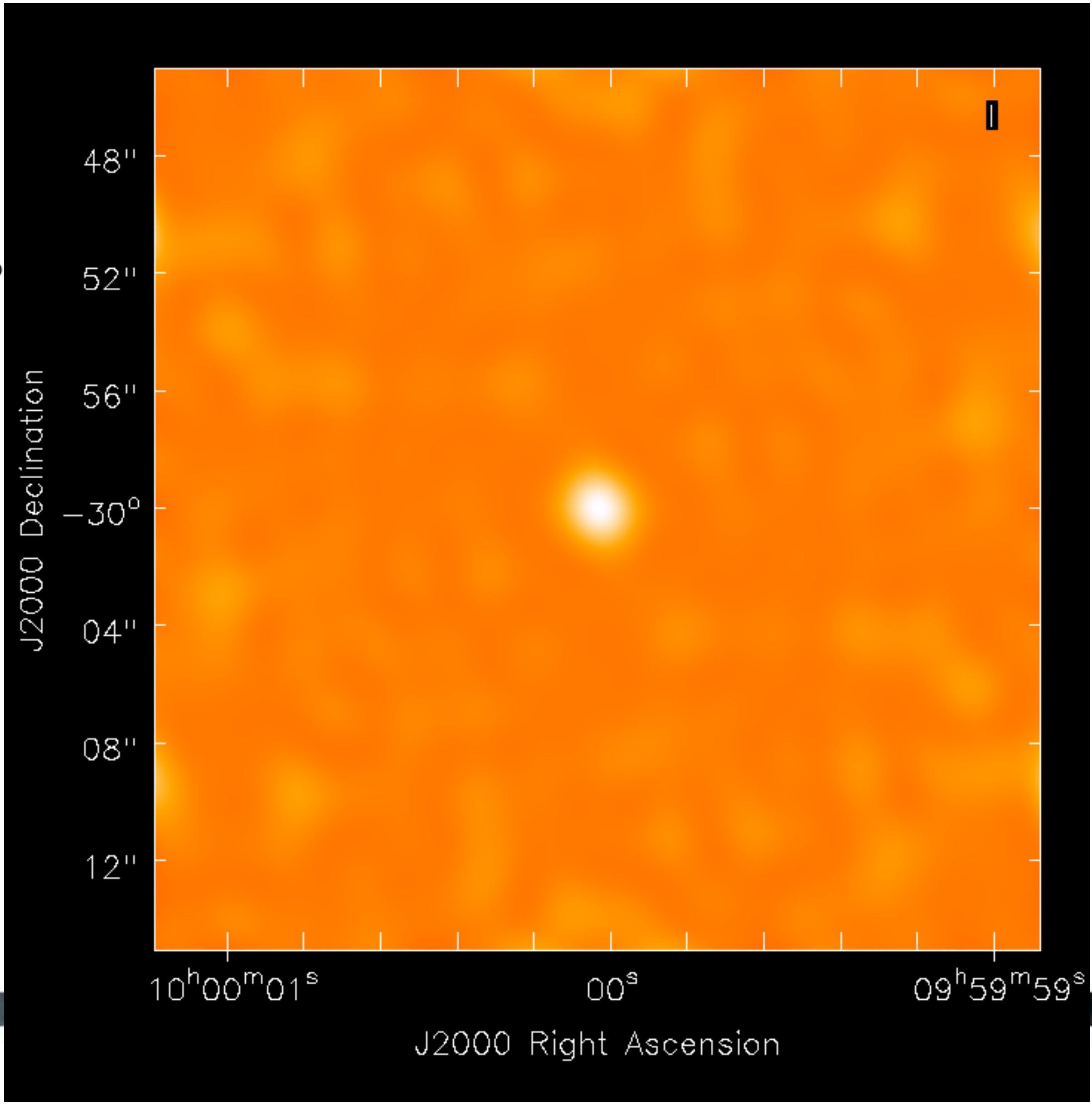
Example: Fringe pattern with 8 Antennas (28 baselines)



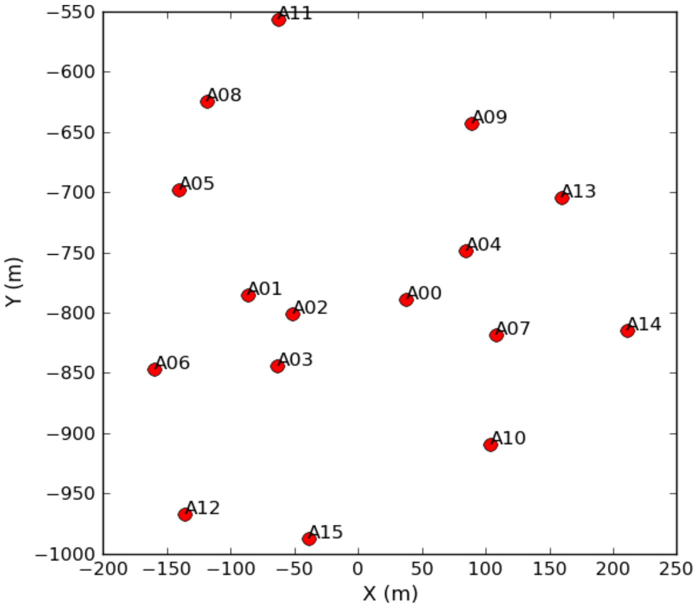
16 Antennas – Compact Configuration

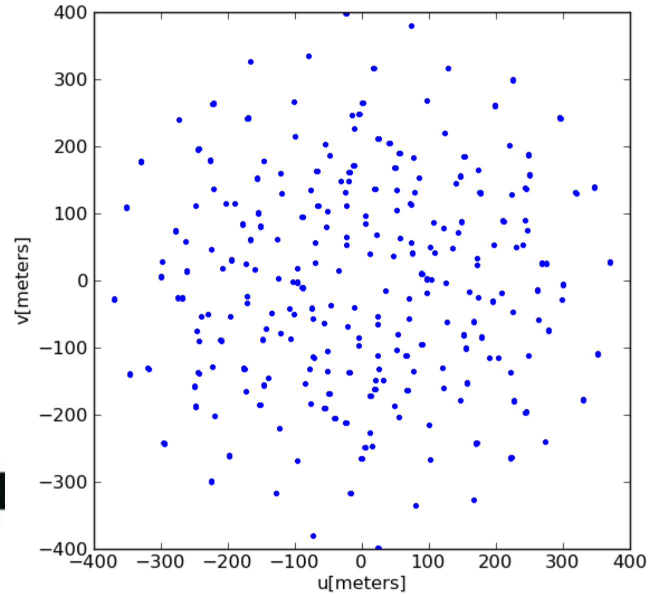


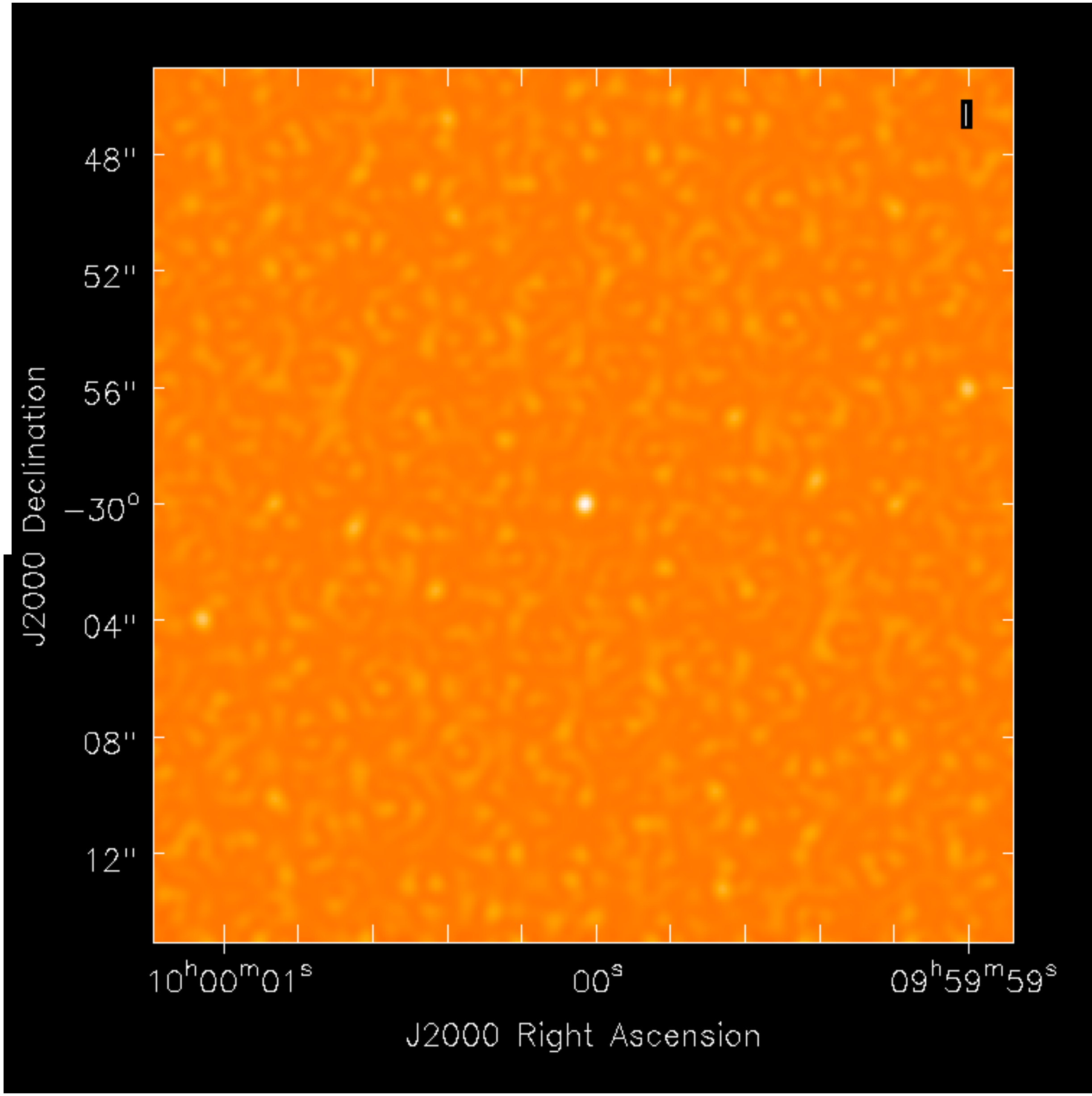




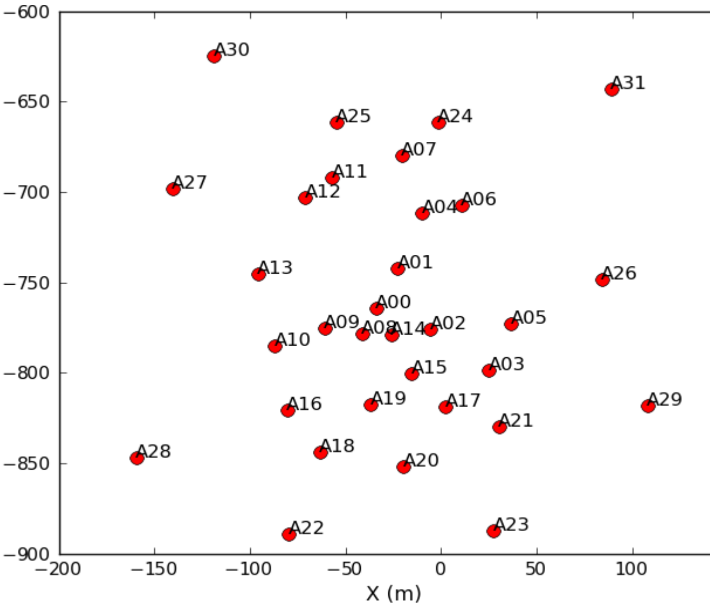
16 Antennas – Extended Configuration

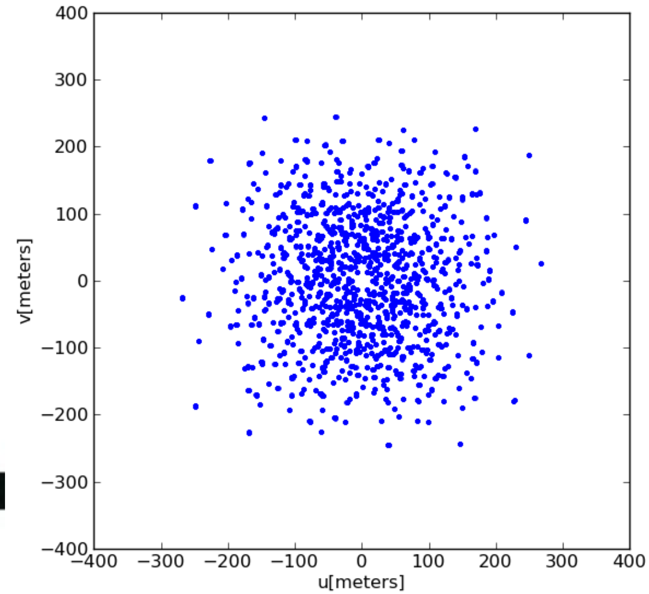


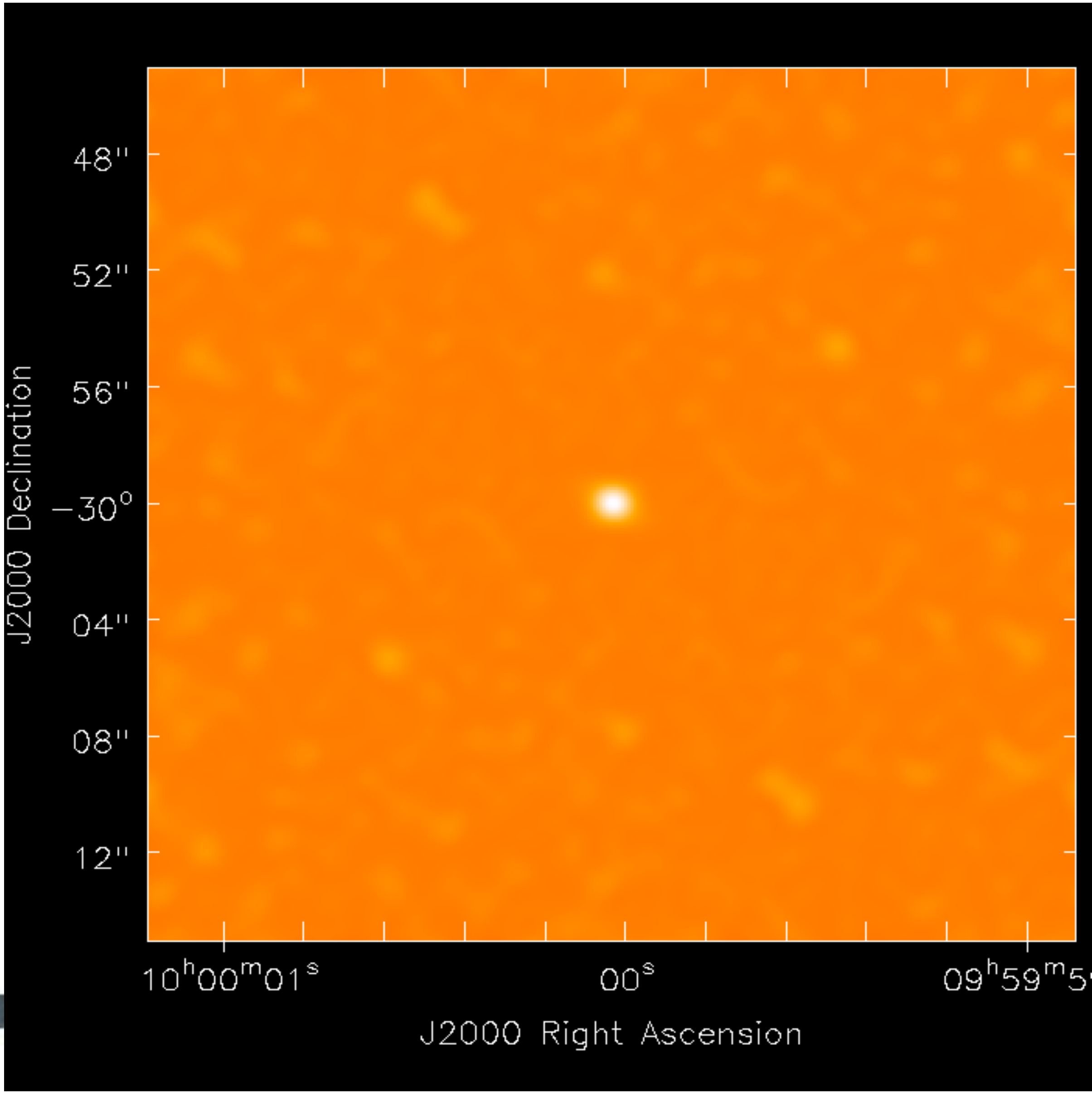




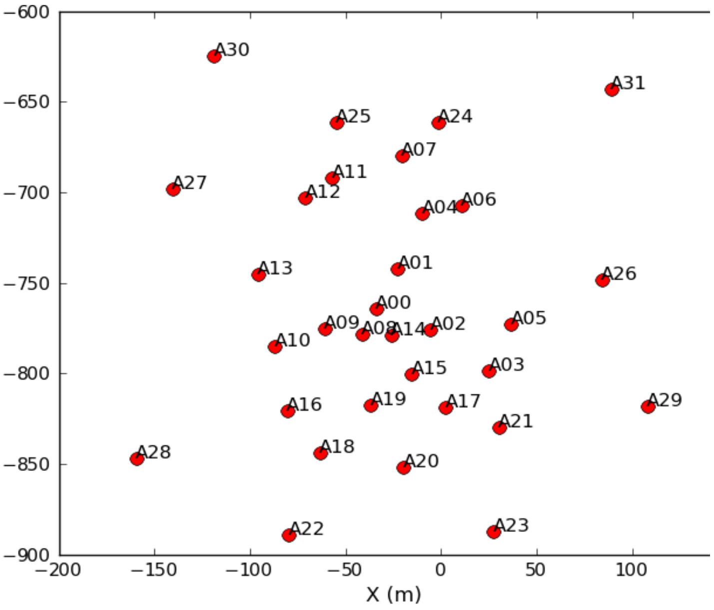
32 Antennas – Instantaneous

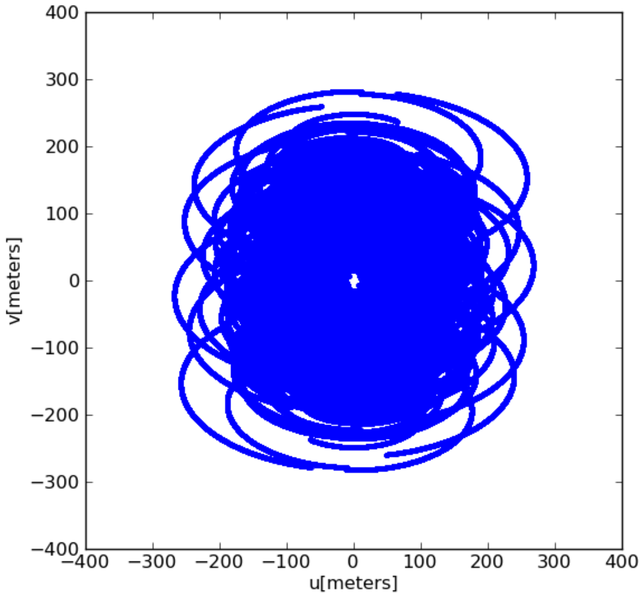


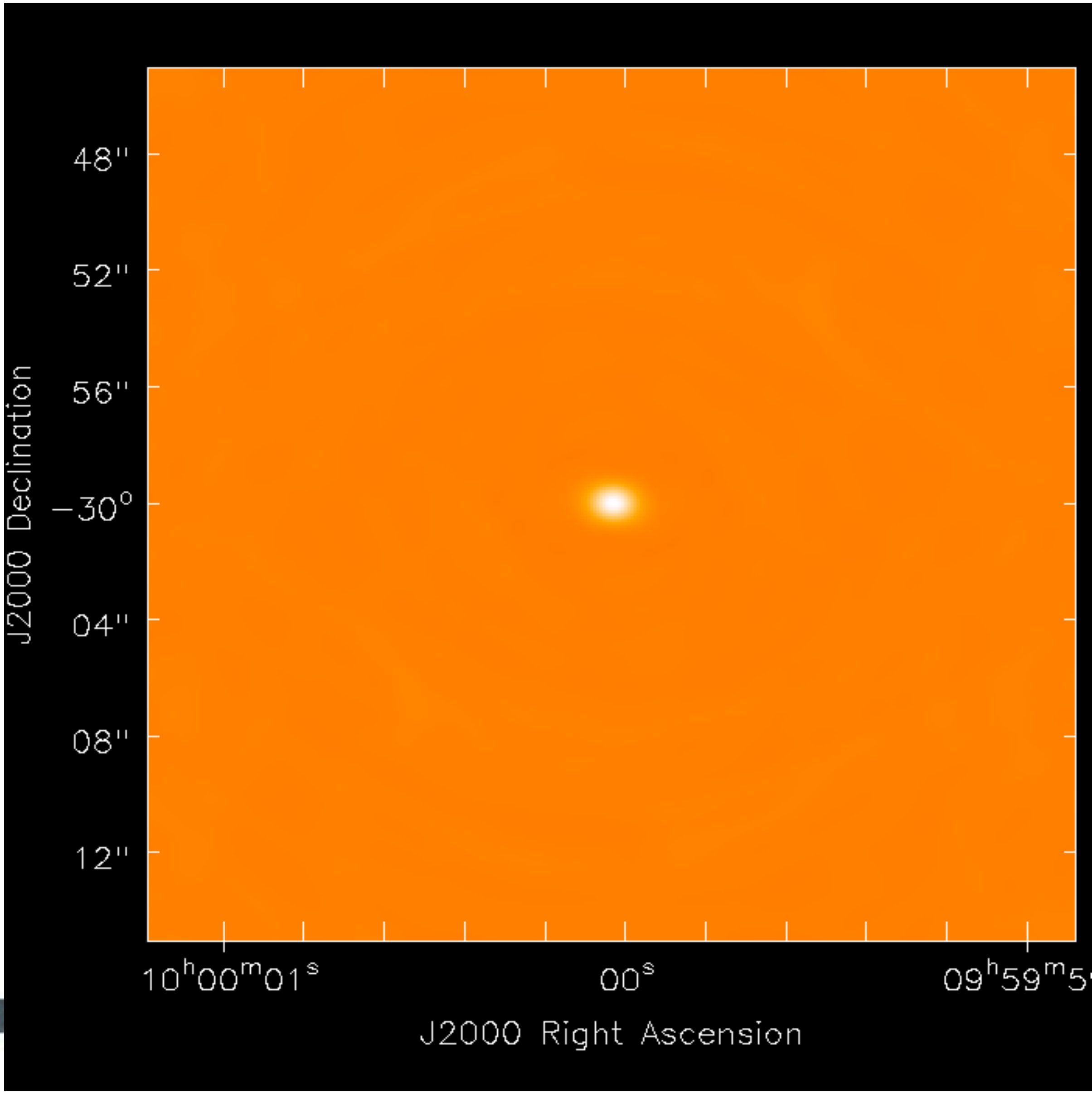




32 Antennas – 8 hours

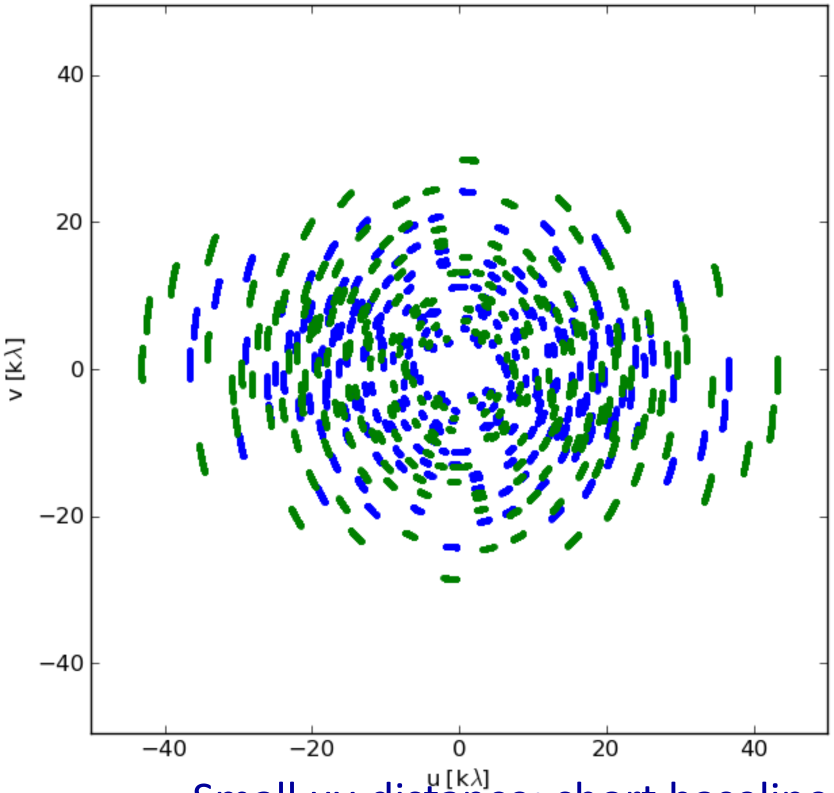


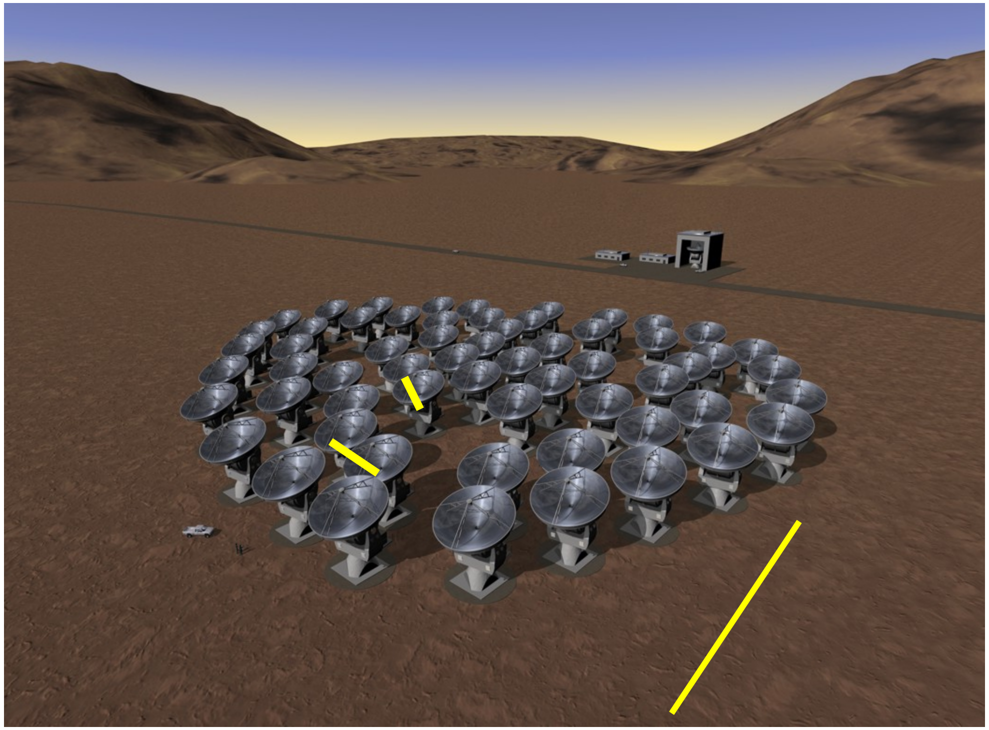




Sampling Function

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





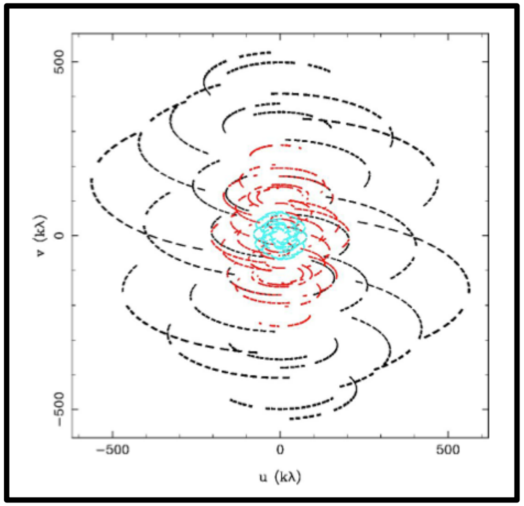
Small uv-distance: short baselines (measure extended emission)

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

Orientation of baseline also determines orientation in the uv-plane

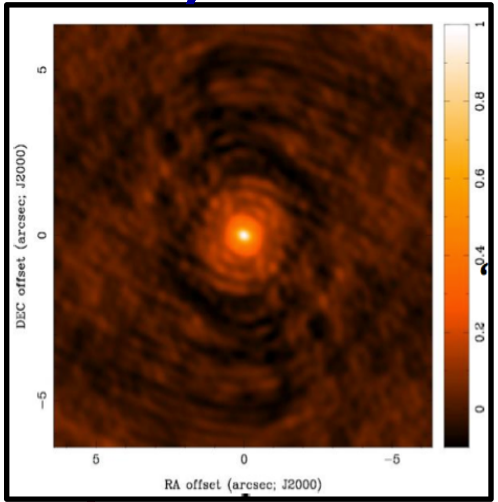
The Dirty Beam

S(u,v)



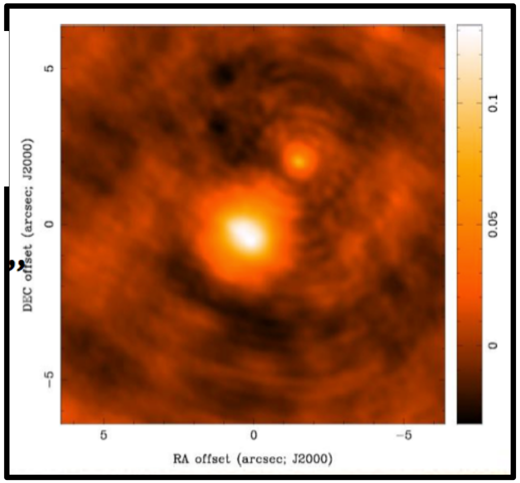
FT →

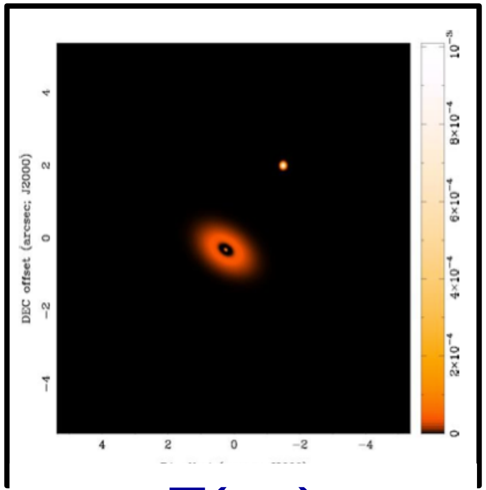
s(x,y)
"Dirty Beam"



*** (Convolution)**

$T_D(x,y)$
"Dirty Image"





T(x,y)

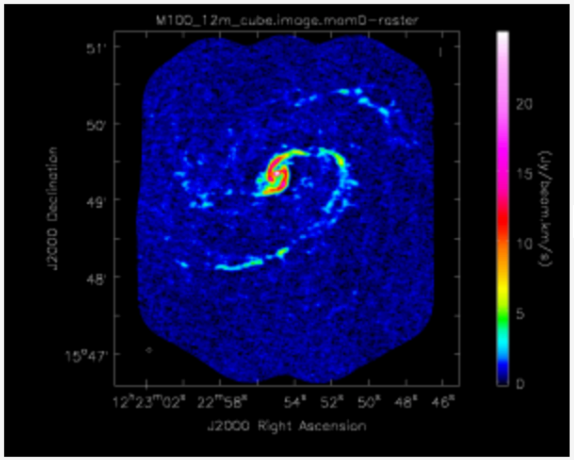
uv coverage: why the central hole?

- The central hole in the sampling of the uv plane arises due to **short baselines**
- The largest angular scale that an interferometer is sensitive to is given by the shortest distance between 2 antennas.
- The field of view is given by the beam of a single antenna.
- A single antenna diameter will always be < the shortest distance between two antennas.
- So the field of view is always > the largest angular scale
- If your source is extended, you will always have some flux at short spacings (i.e. extended emission) that is not recovered.

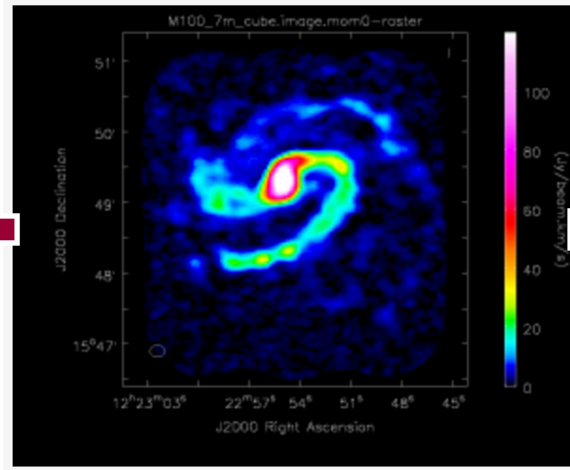
- **Solutions:** We can extrapolate to these shorter spacings after our observations are taken (see ALMA Data Products) or we can fill in the information with 7m observations or ultimately single dish data.

Characteristic Angular Scales: M100

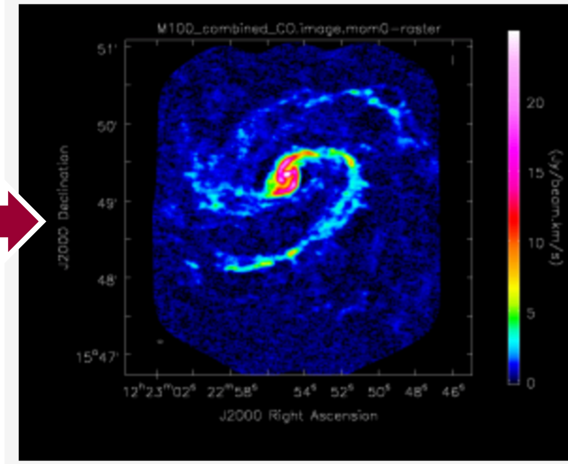
ALMA 12m



ACA 7m



Combined

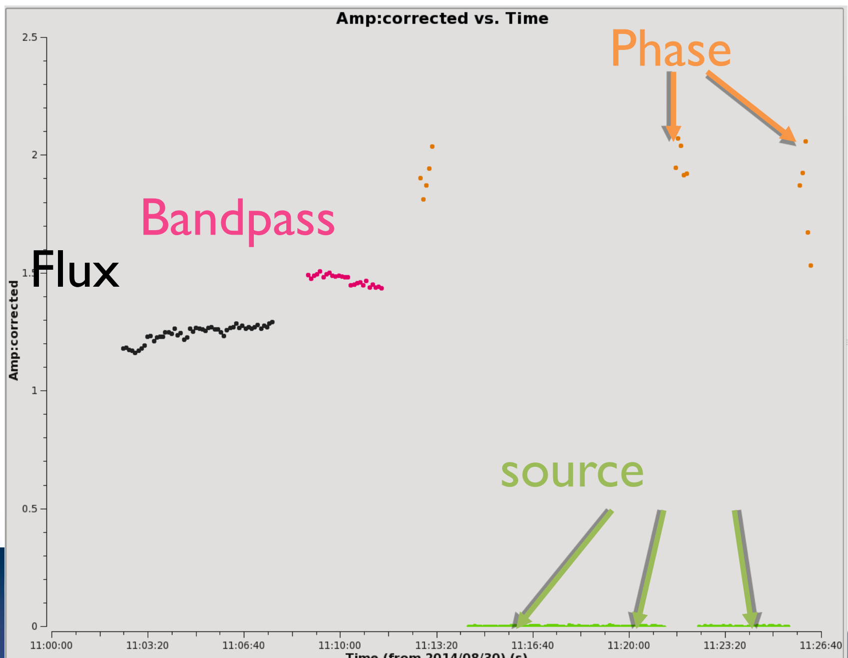


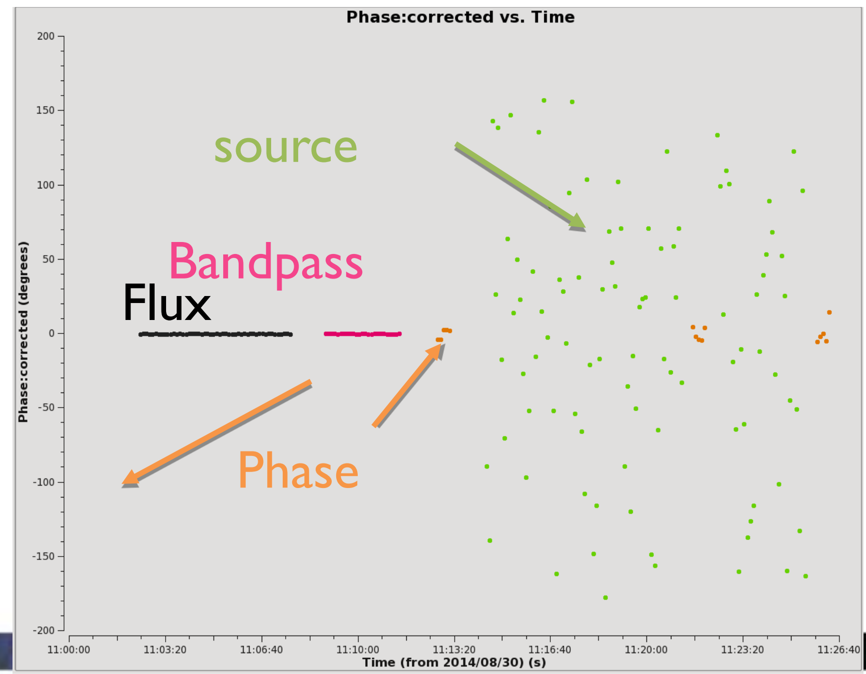
ALMA 12m shows smaller spatial scales (denser, clumpier emission)
ACA 7m data shows larger spatial scales (diffuse, extended emission)

To get both — you need a combined image!

A Brief Word on Calibration

- Calibration is the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations. For interferometric visibilities we need:
  - Bandpass cal (correct frequency-dependent telescope response)
  - Phase and amplitude gain cal (remove effects of atmospheric water vapor and correct time-varying phases/amplitudes)
  - Set absolute flux scale
- CALIBRATION IS HANDLED BY ALMA; DETAILS IN IMAGING WITH CASA TALK





Good Future References

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Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 “Synthesis Imaging in Radio Astronomy” (San Francisco: ASP)

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www.iram.fr/IRAMFR/IS/IS2008/archive.html

Good Future References

NRAO Synthesis Imaging Workshop

https://science.nrao.edu/science/meetings/2018/16th-synthesis-imaging-workshop/16th-synthesis-imaging-workshop-lectures

http://www.cvent.com/events/17th-synthesis-imaging-workshop/event-summary-0d59eb6cd1474978bce811194b2ff961.aspx

Examples of UV coverage from Ian Czekala

https://drive.google.com/file/d/1fy3edrJNATo175WopB49-3mZ7QeZPK5O/view

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