Introduction to Radio Interferometry

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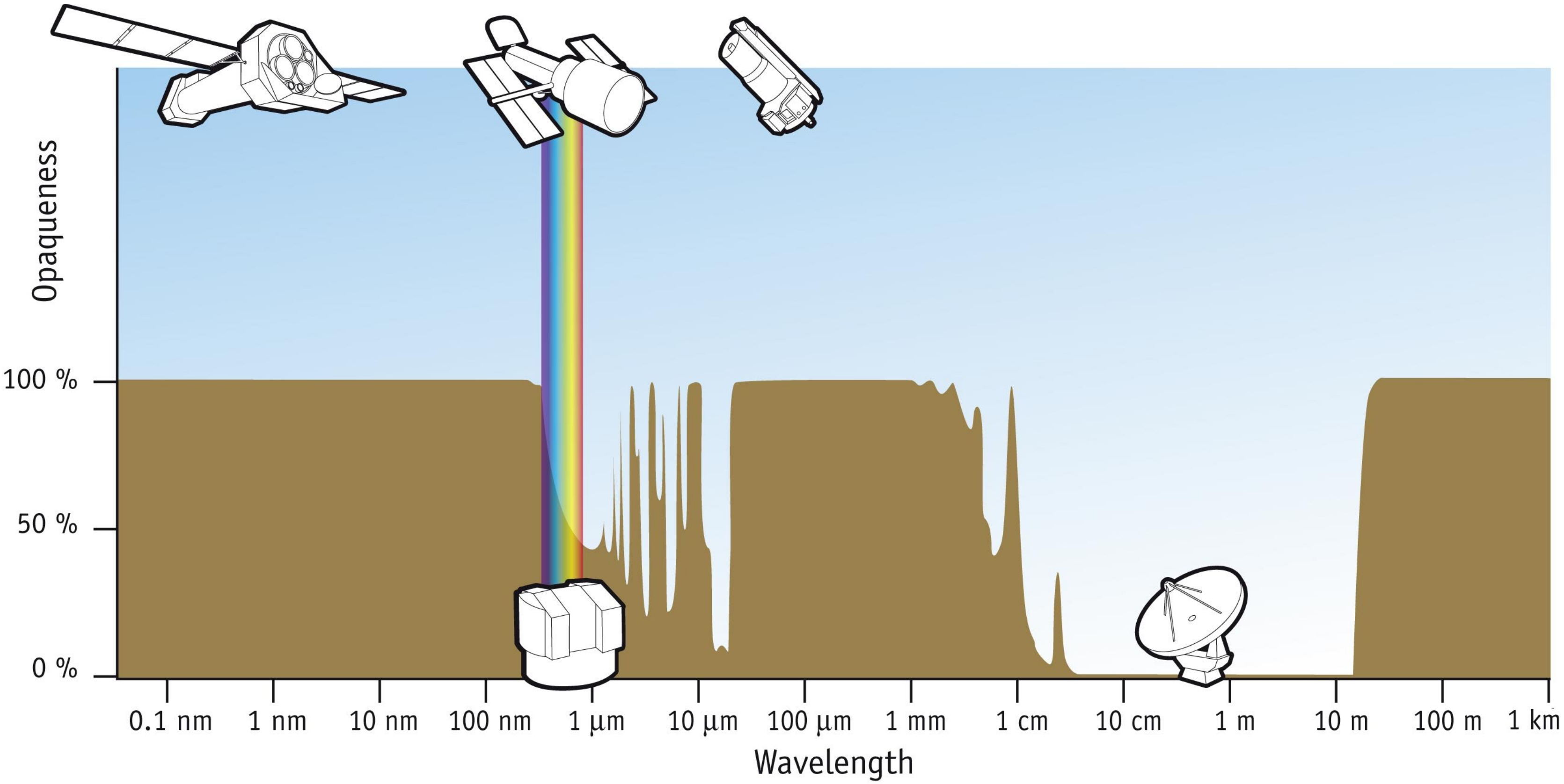
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Very Long Baseline Array

Radio Astronomy

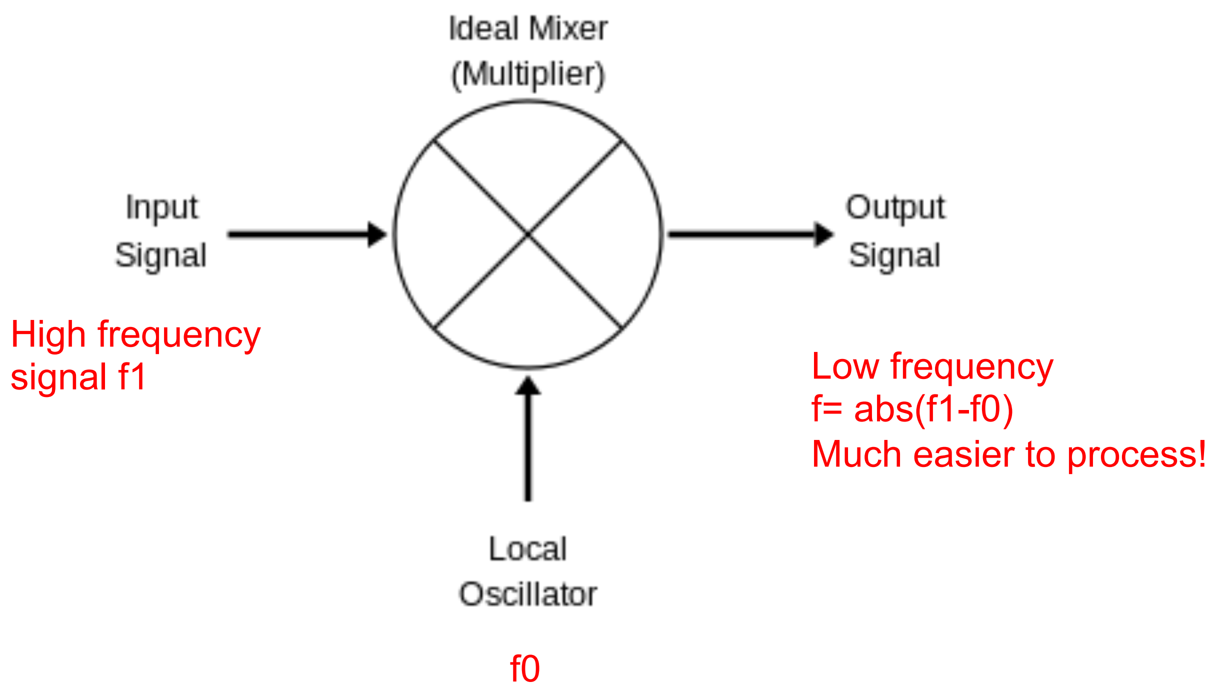
- Old definition



- Now refer to telescopes using heterodyne technology

What is heterodyne?

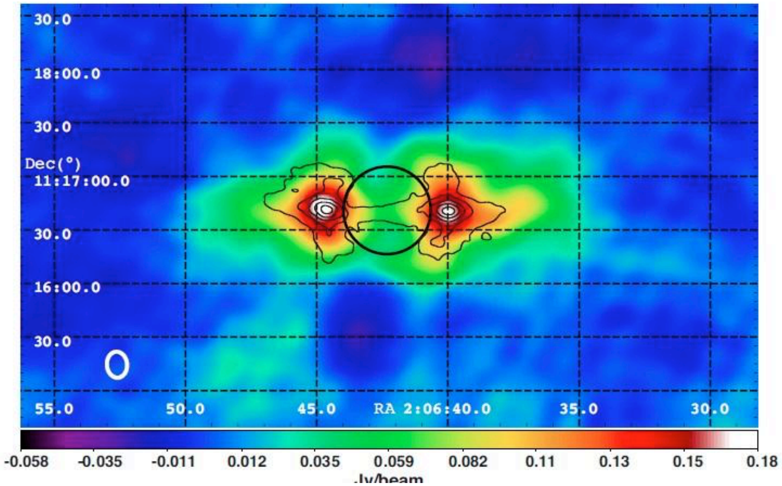
In a heterodyne receiver, observed sky frequencies are converted to lower frequency signals by mixing with a signal artificially created by a Local Oscillator. The output can then be amplified and analyzed more easily while retaining the original phase and amplitude information.

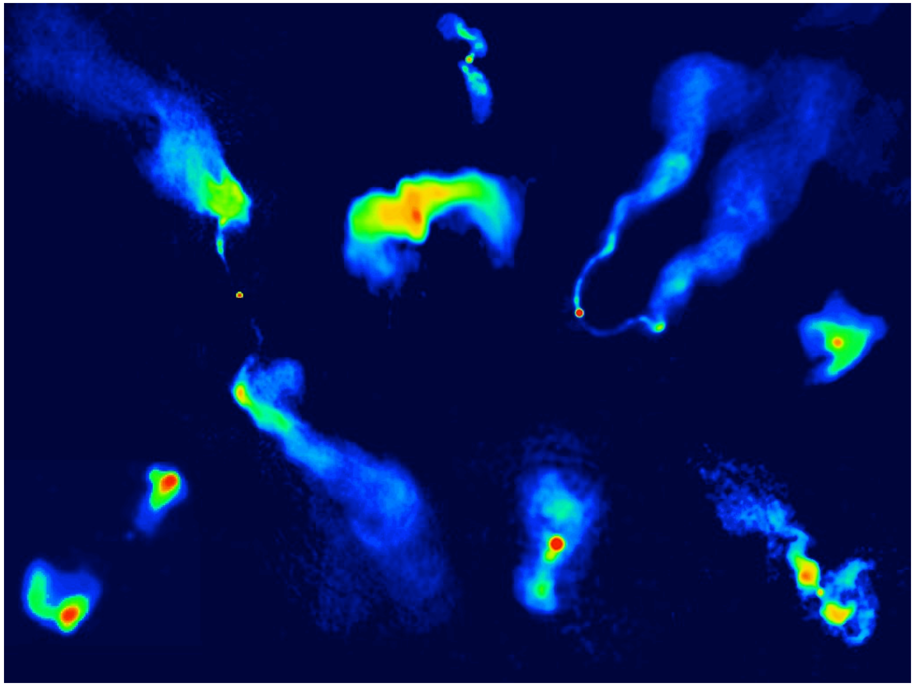


Long wavelength means no glass mirrors

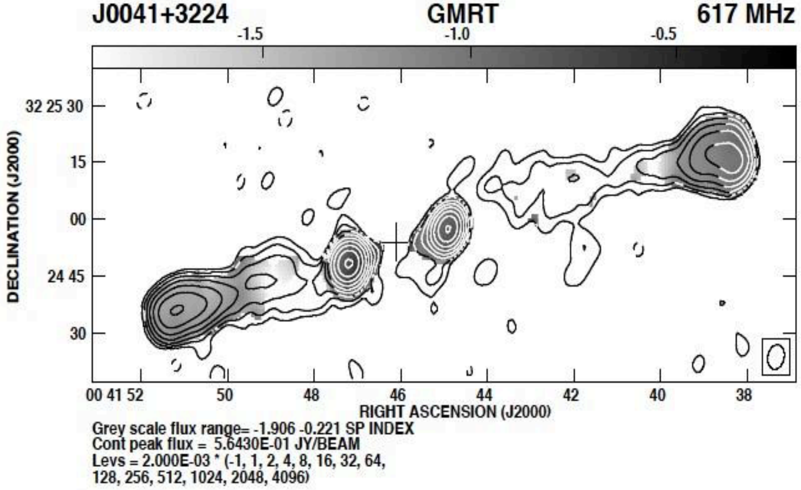
What can we observe? (MHz-GHz range)

Jupiter's radiation belt at 100MHz





Relic emission from old radio galaxies



Synchrotron emission from extended radio galaxies (5 GHz)

Images from NRAO Image Gallery: http://images.nrao.edu/

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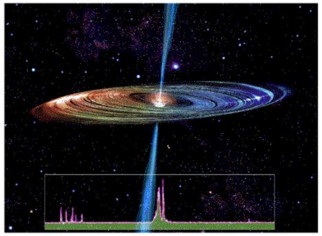
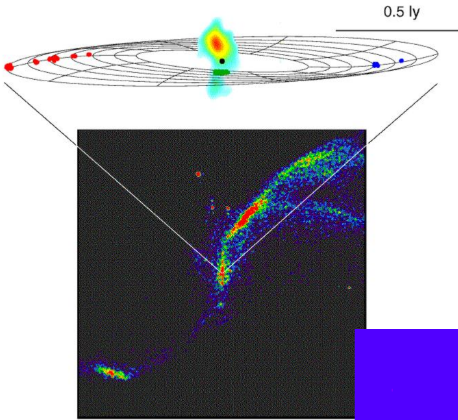
http://images.nrao.edu/

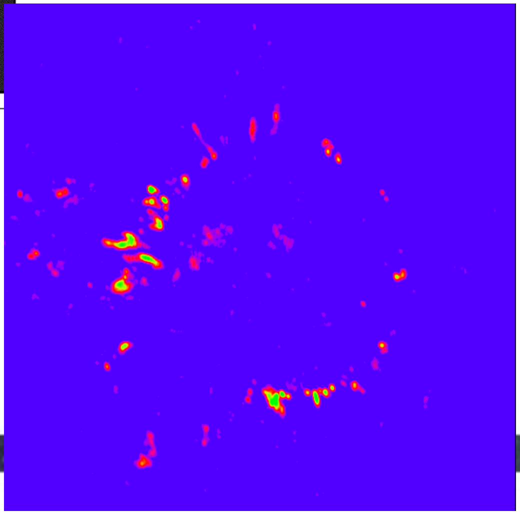
What can we observe?

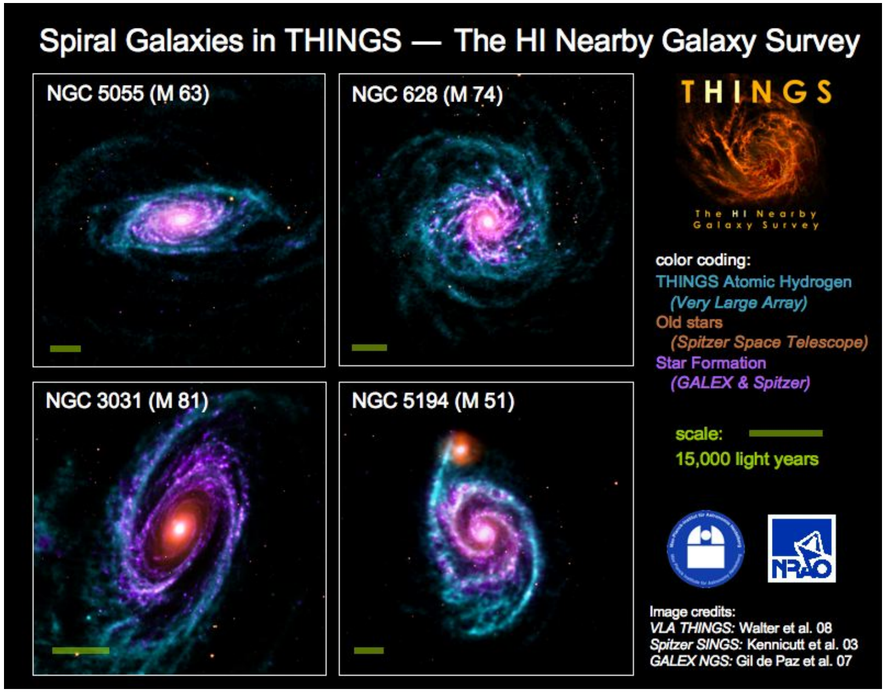
At low frequencies (MHz-GHz):


NGC 4258

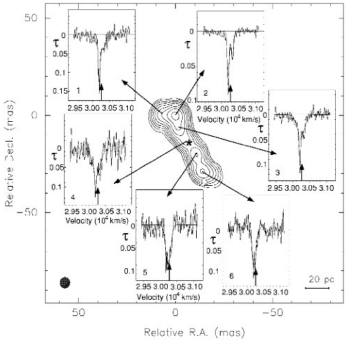


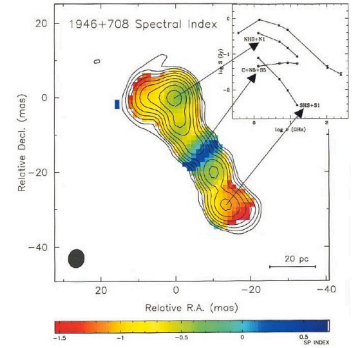
H_2O, OH or SiO masers in galaxies and stars





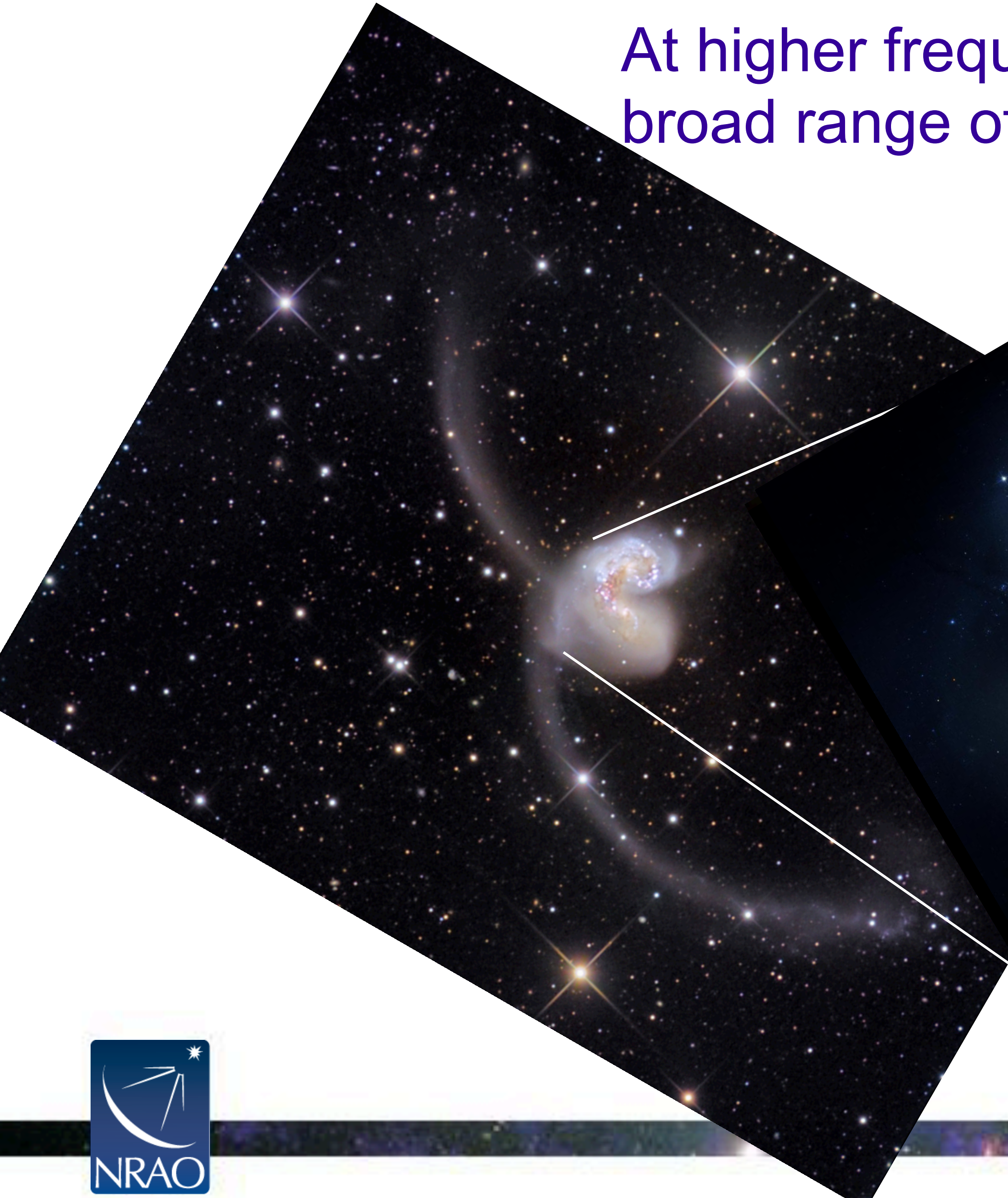
HI emission and absorption, free-free absorption in galaxies

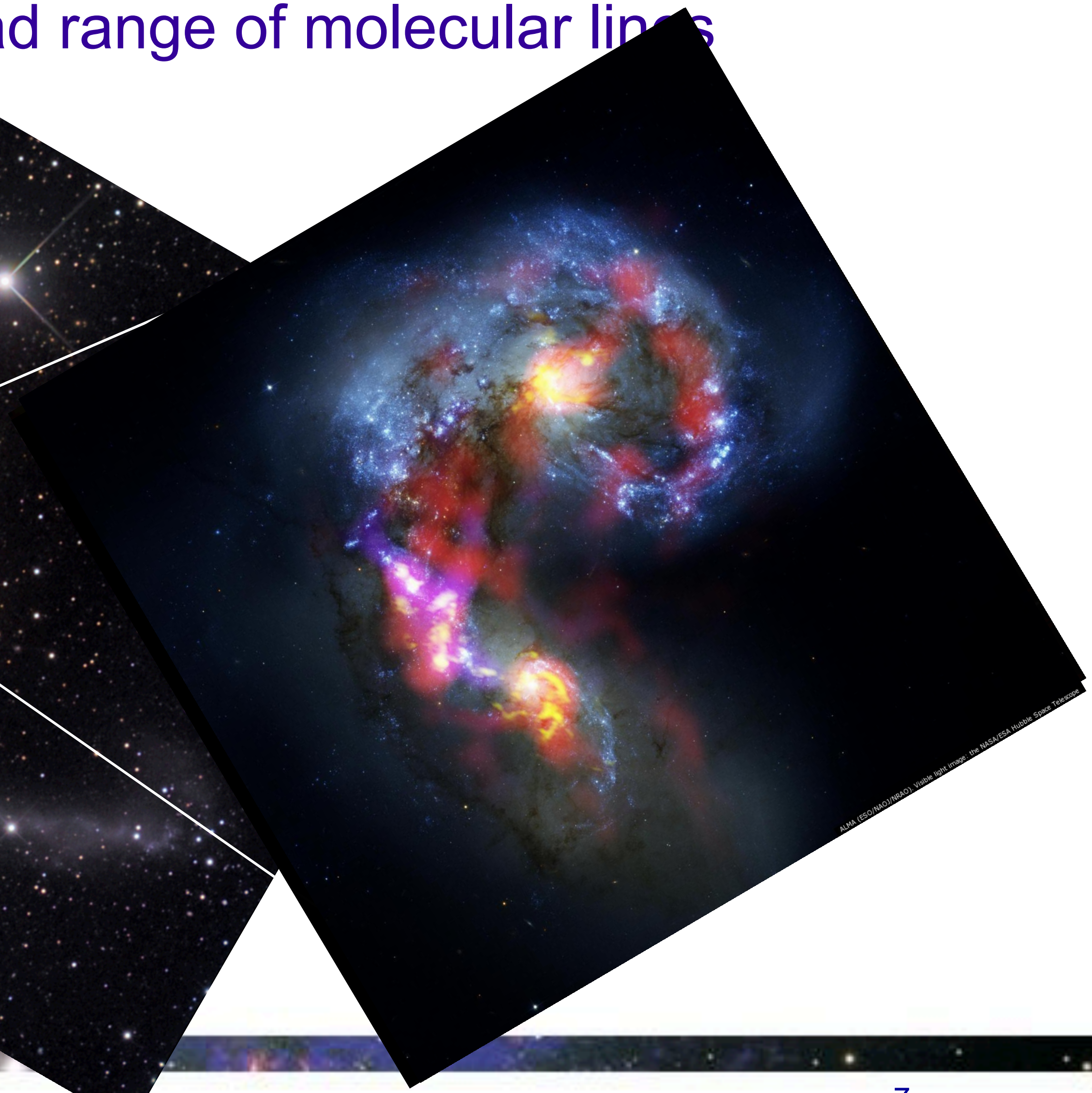




What can we observe?

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





Challenges to observe at radio wavelengths

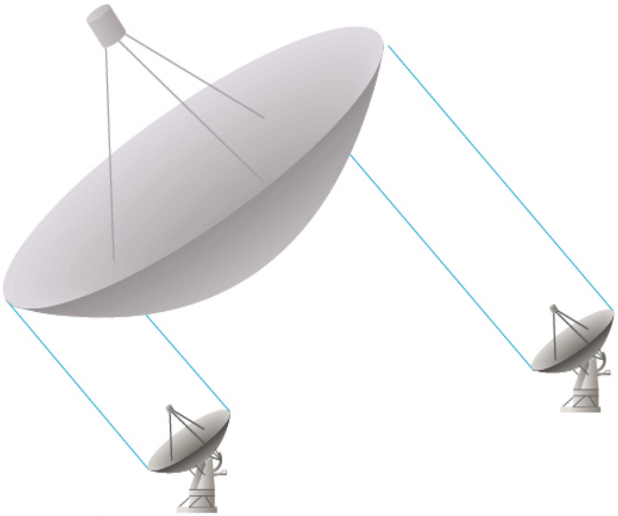
- Angular resolution for most telescopes is ~ λ/D
- e.g. Hubble Space Telescope:
  - λ ~ 1um / D of 2.4m ~ 0.13”

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

A smart technique is interferometry!

Interferometry

An interferometer consists of two or more separate telescopes that combine their signals, offering a resolution equivalent to that of a telescope of diameter equal to the largest separation between its individual elements.

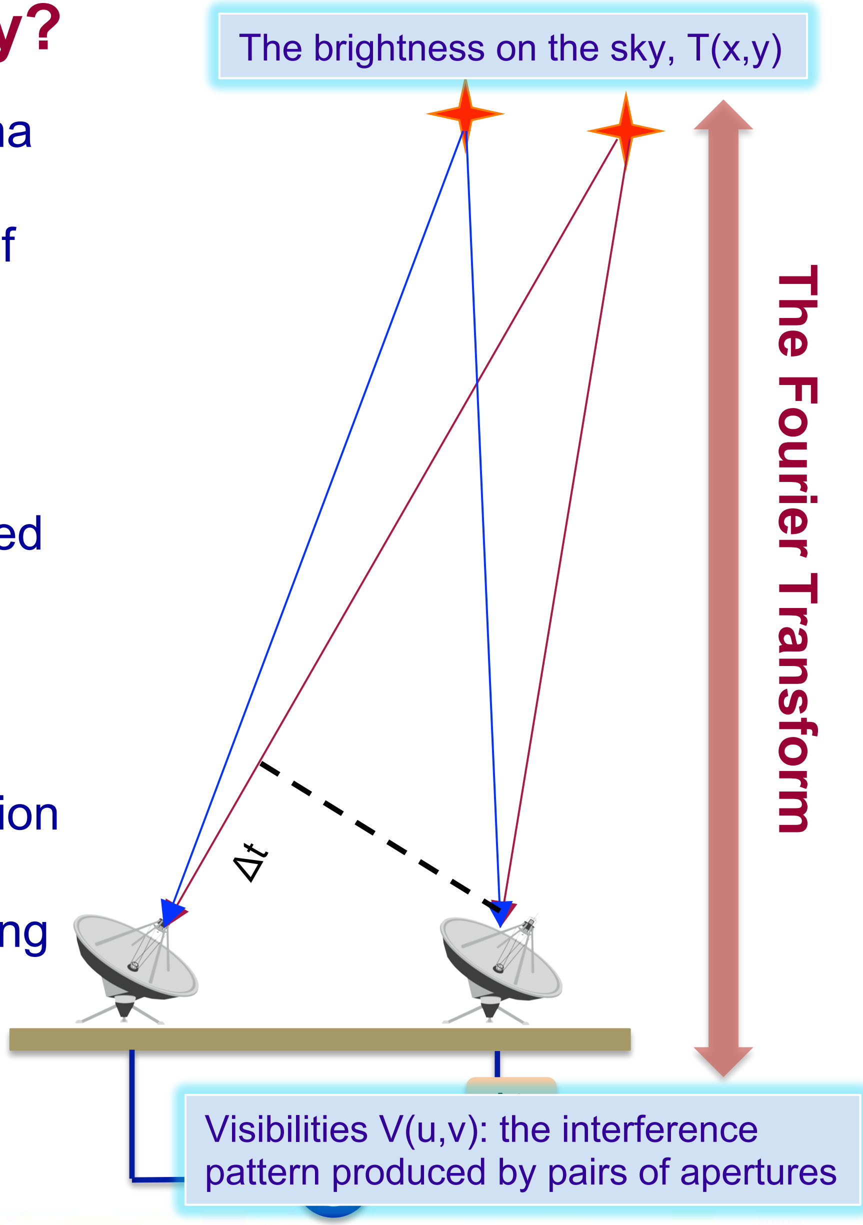


How do we use interferometry?

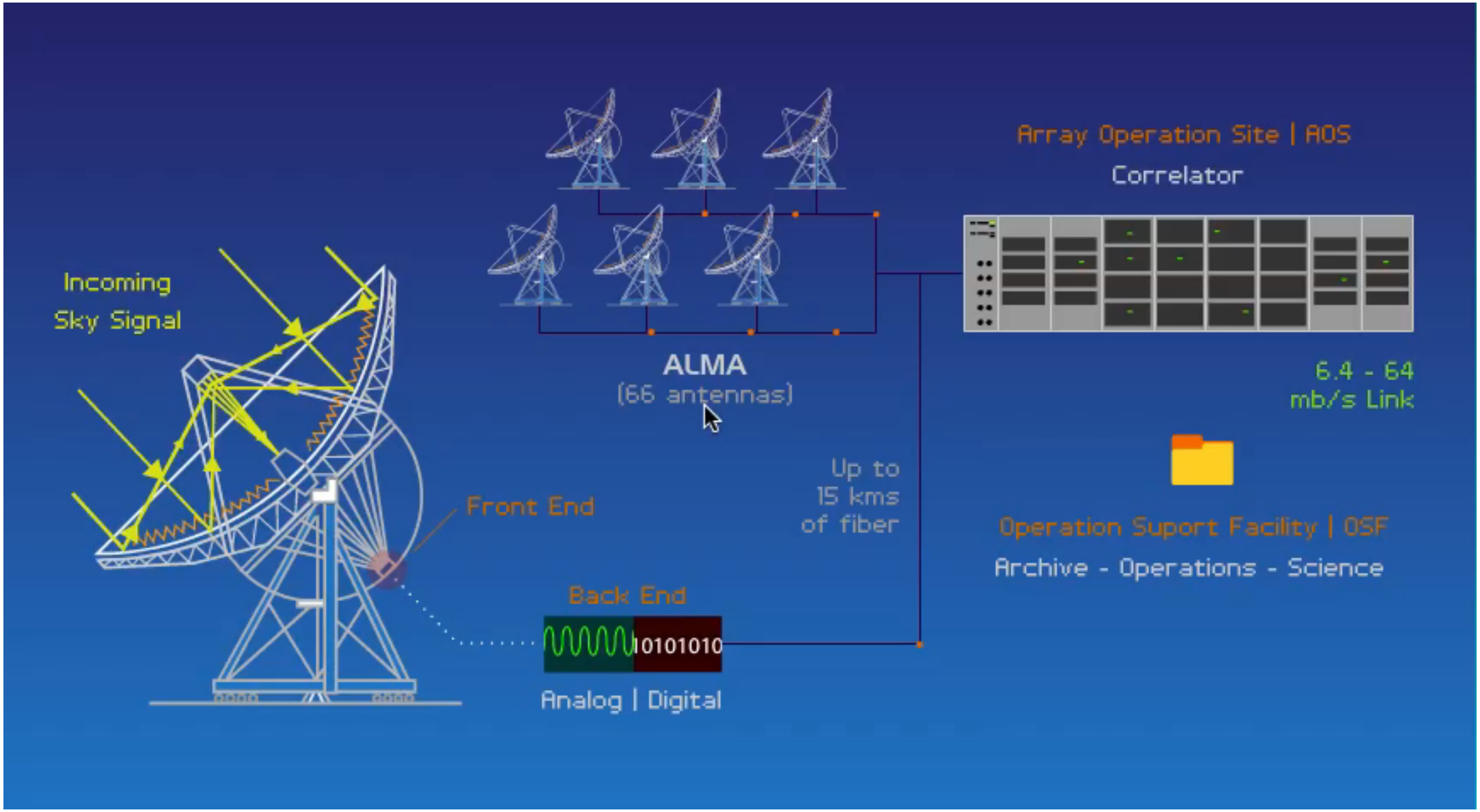
A signal from space arrives at each antenna at a slightly different time (due to different travel lengths) depending on the location of the antenna in the array.

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.



An interferometer in action



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

1. An interferometer measures the interference pattern produced by pairs of apertures.

2. The interference pattern is directly related to the source brightness:
   - For small fields-of-view: the complex visibility, $V(u,v)$, is the 2D Fourier transform of the brightness on the sky, $T(x,y)$

(van Cittert-Zernike theorem)

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

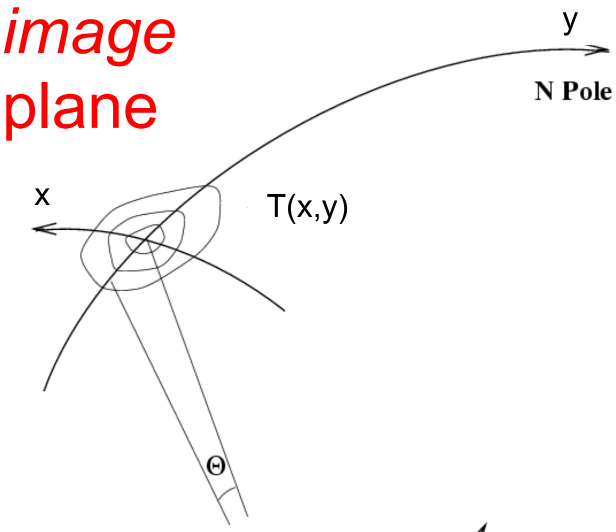
Fourier space/

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

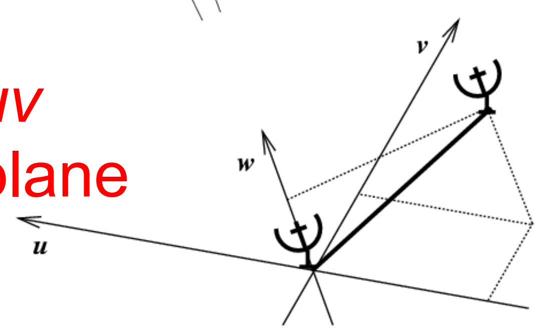
Image space/

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

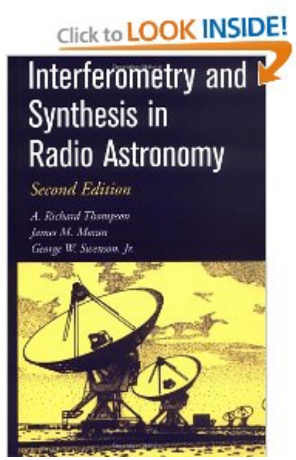
image plane



uv plane



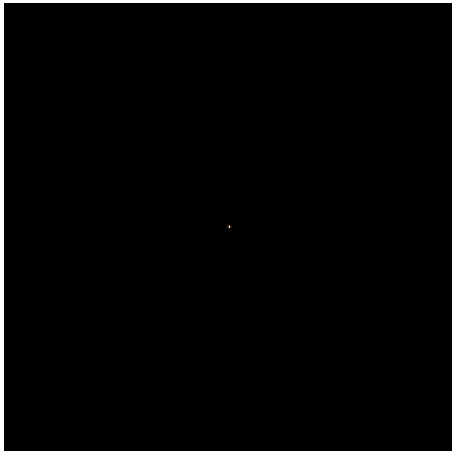
(for more info, see e.g. Thompson, Moran & Swenson)



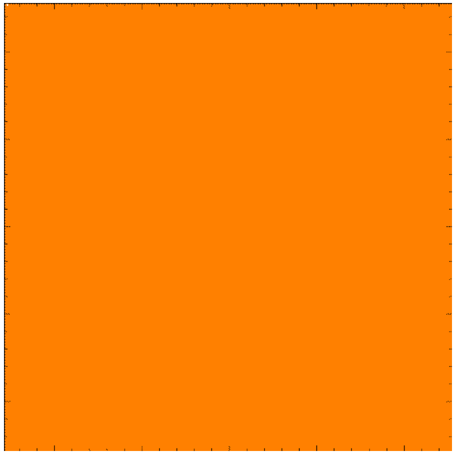
Some 2D Fourier Transform Pairs

$T(x,y)$ $\qquad$ $Amp\{V(u,v)\}$

δ Function

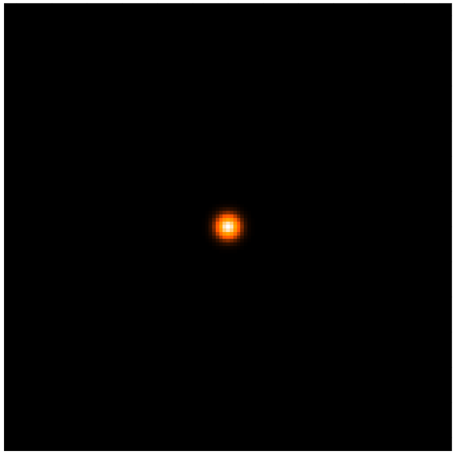


$\rightleftharpoons$



Constant

Gaussian



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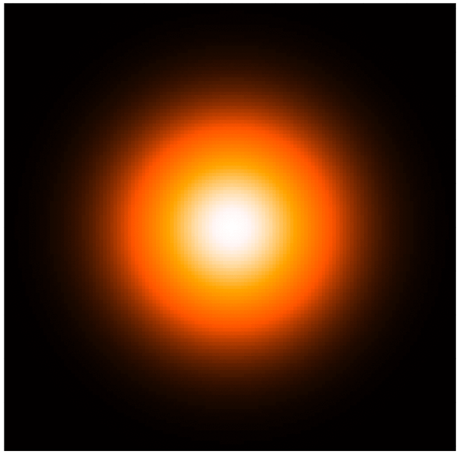


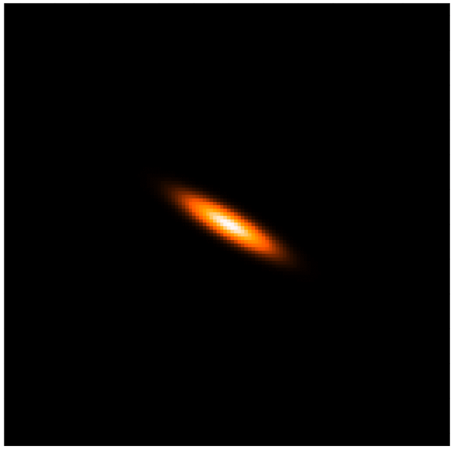
Gaussian

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

2D Fourier Transform Pairs

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

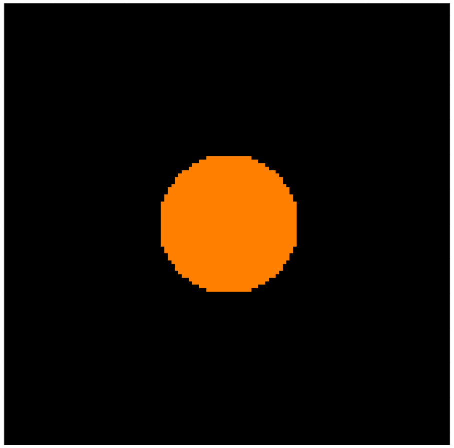
elliptical Gaussian



$\rightleftharpoons$

elliptical Gaussian

Disk



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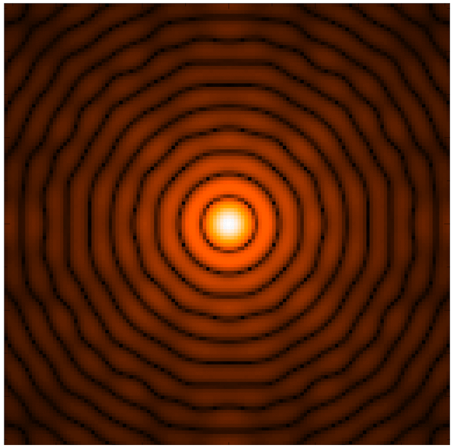


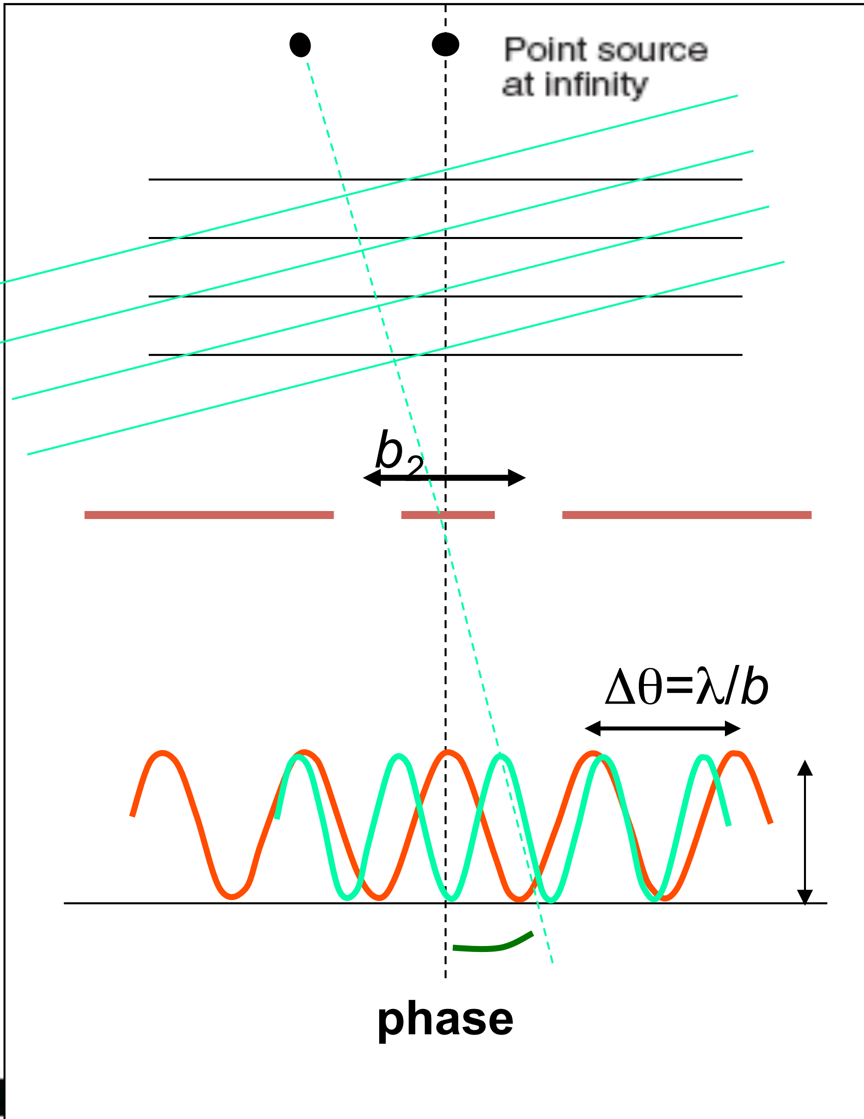
Bessel

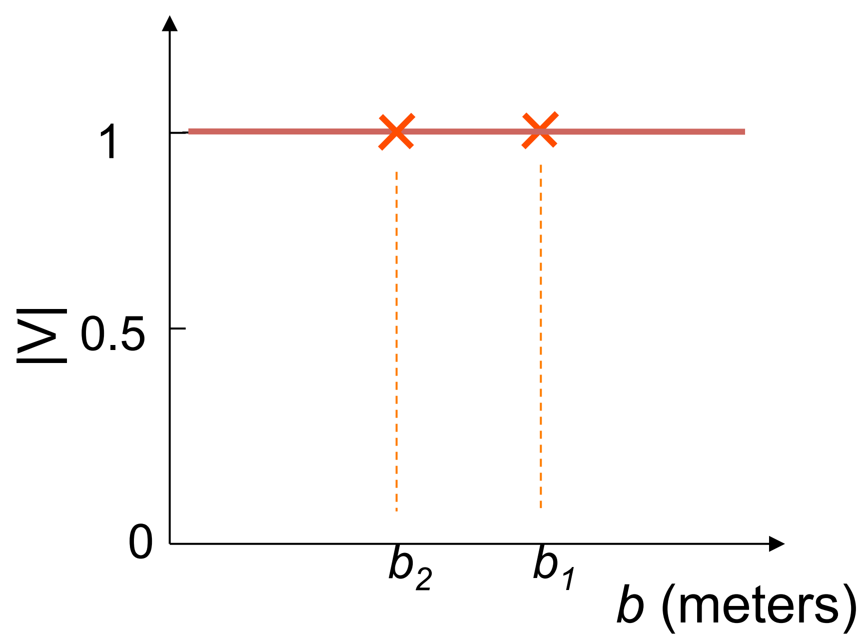
sharp edges result in many high spatial frequencies

(sinc function, “ringing”, Gibbs phenomenon)

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





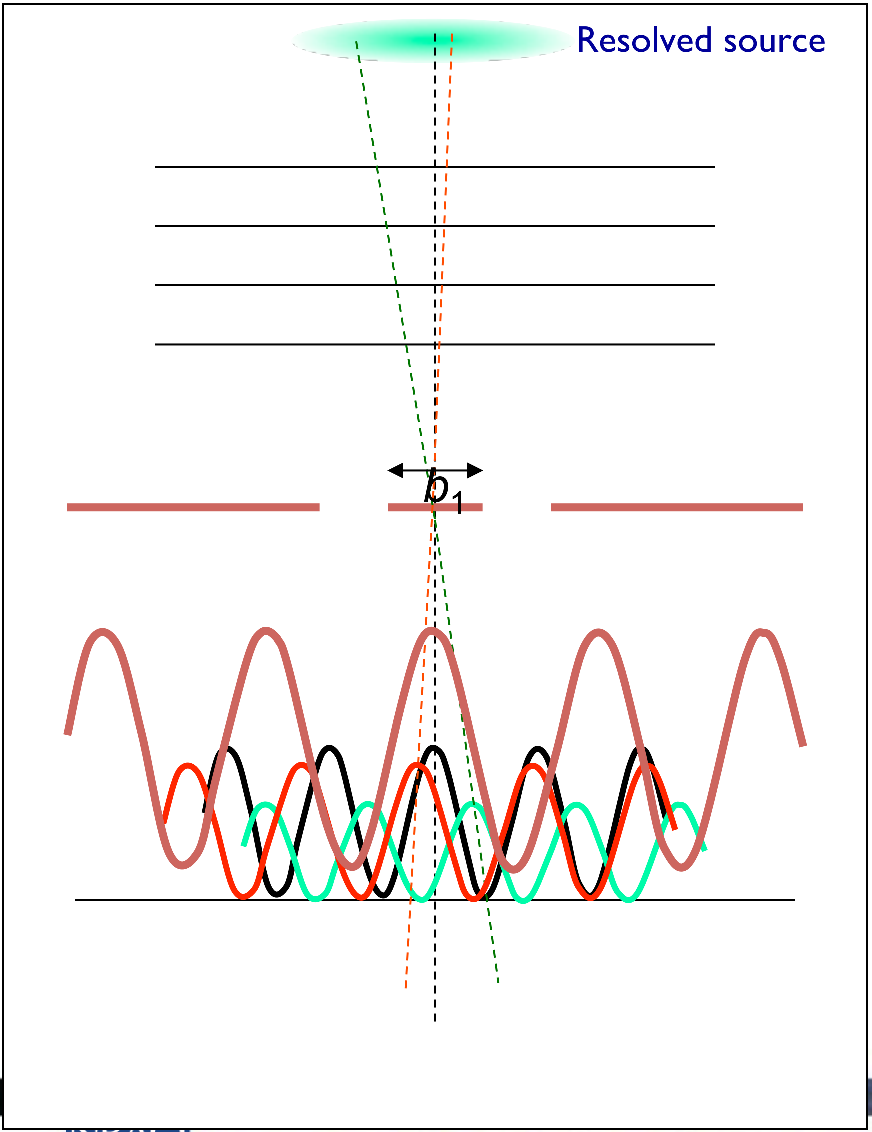
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

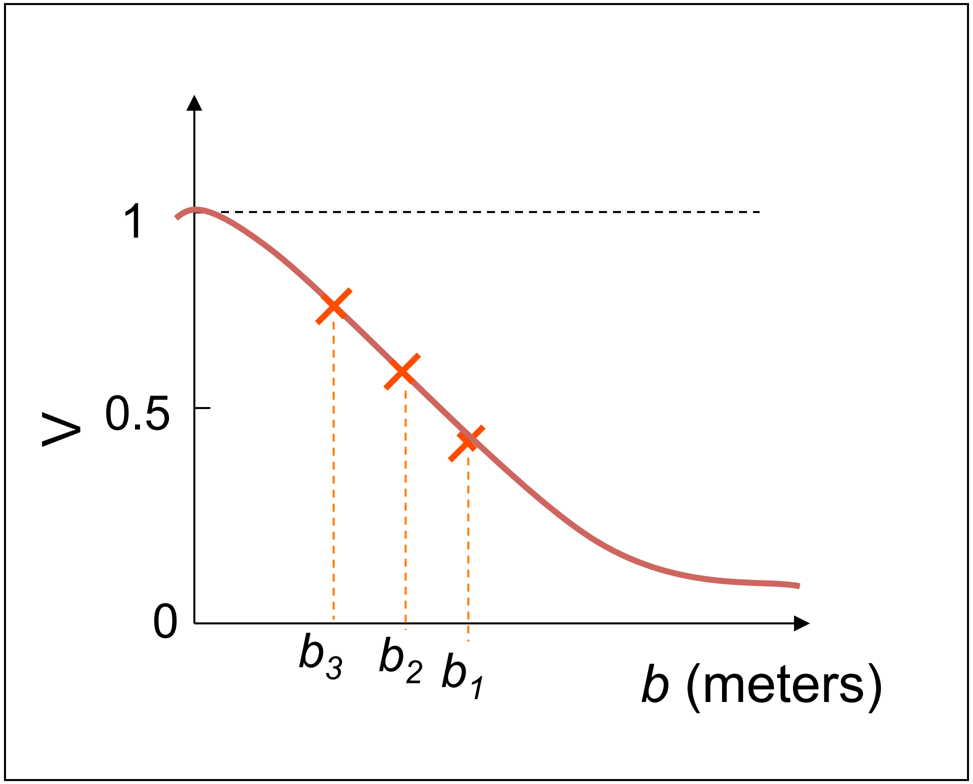
The visibility is a **complex** quantity:

- **amplitude** tells "how much" of a certain frequency component
- **phase** tells "where" this component is located

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





$$|V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

Understanding the observational strategy

Interferometry basics

- The **sensitivity** is given by the number of antennas times their area
- 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
- 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)

Characteristic Angular Scales

Angular resolution of telescope array:

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

The largest 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):

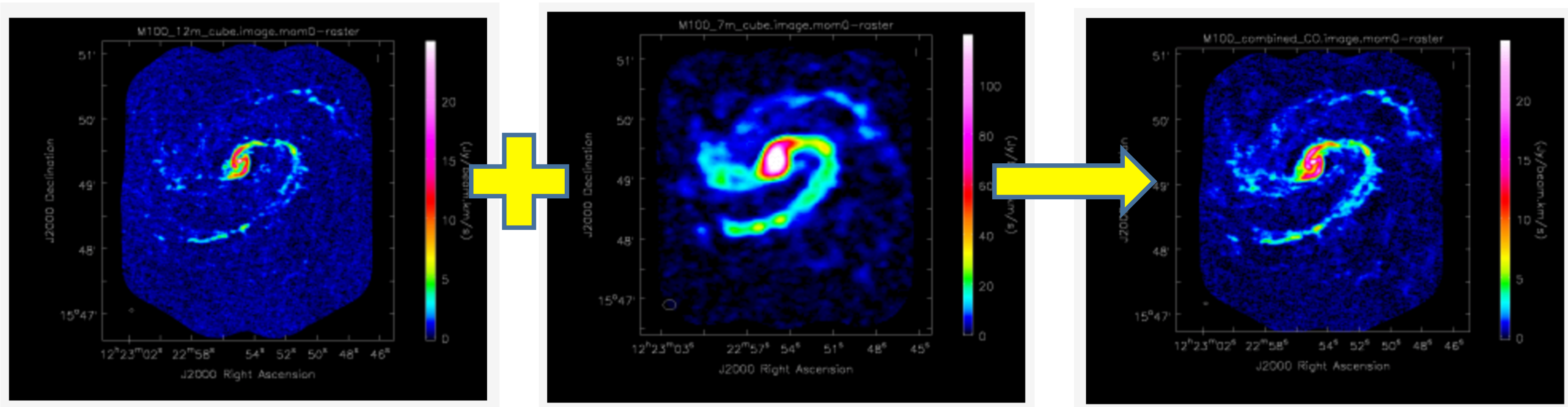
- $\sim \lambda/D$, where D is the diameter of the telescope.
- If sources are more extended than the FOV, it can be observed using multiple pointing centers in a mosaic.

An interferometer is sensitive to a range of angular sizes

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

NRAO

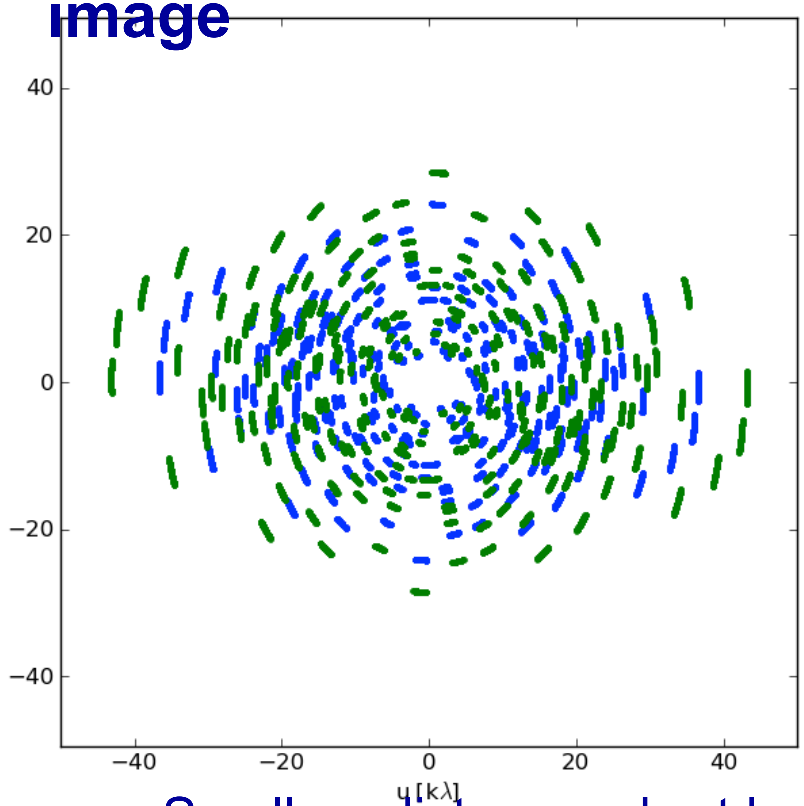
Characteristic Angular Scales: M100

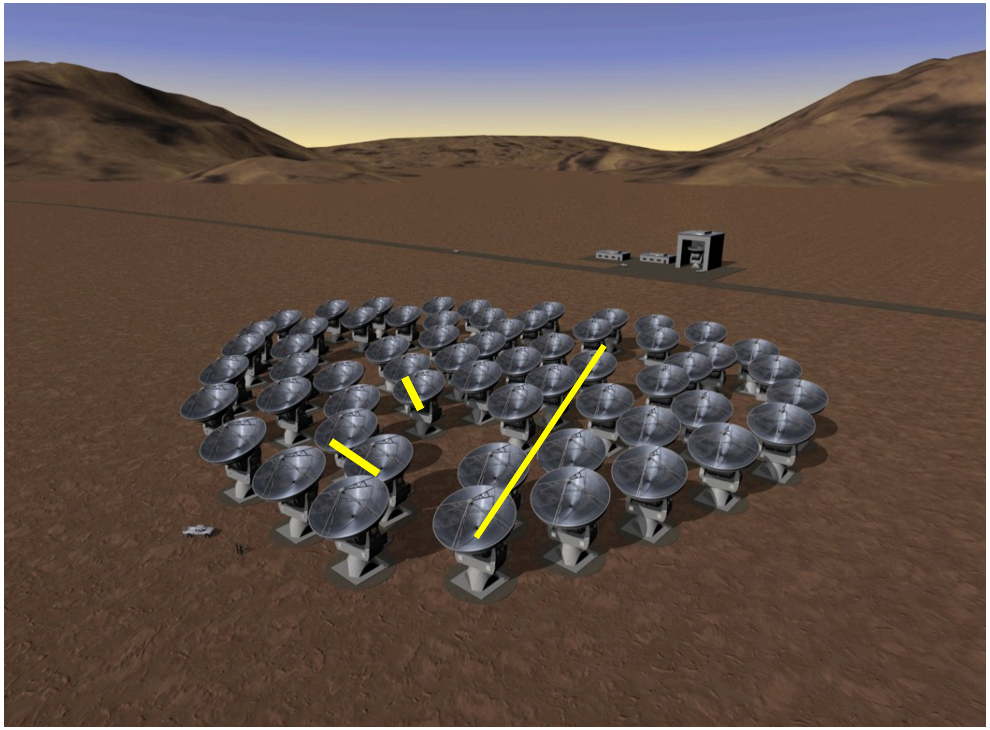


- 12m data reveals information on smaller spatial scales (denser, clumpier emission)
- 7m data reveals information on larger spatial scales (diffuse, extended emission)
- To get both: you need a combined image

Sampling Function

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

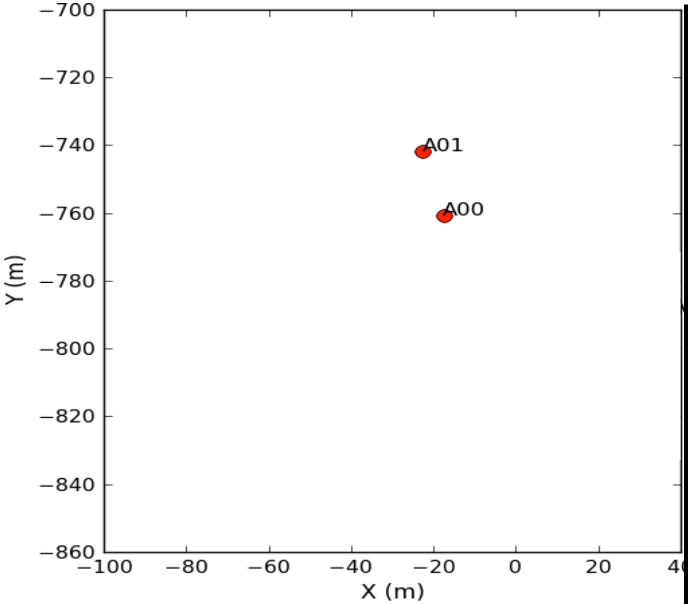


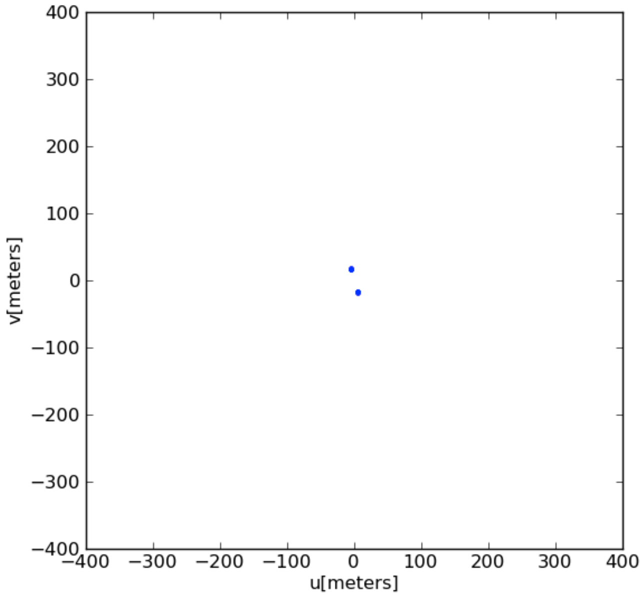


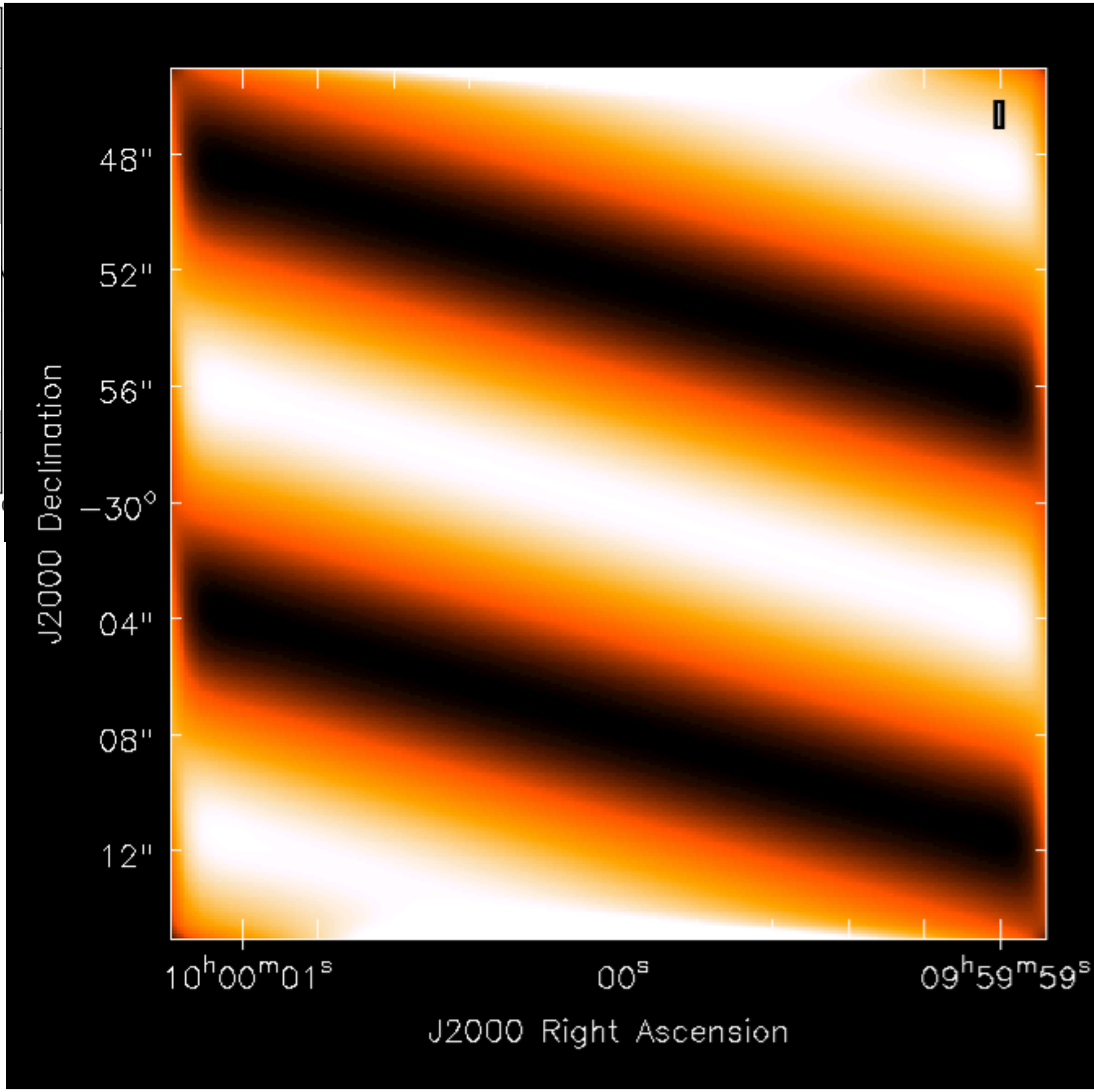
Small uv-distance: short baselines (measure extended emission)
Long uv-distance: long baselines (measure small scale emission)
Orientation of baseline also determines orientation in the uv-plane

NRAO

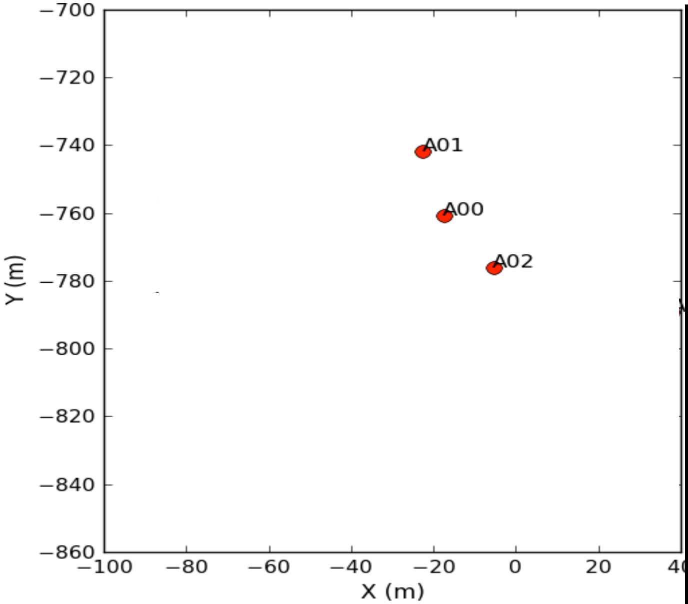
Example: Fringe pattern with 2 Antennas

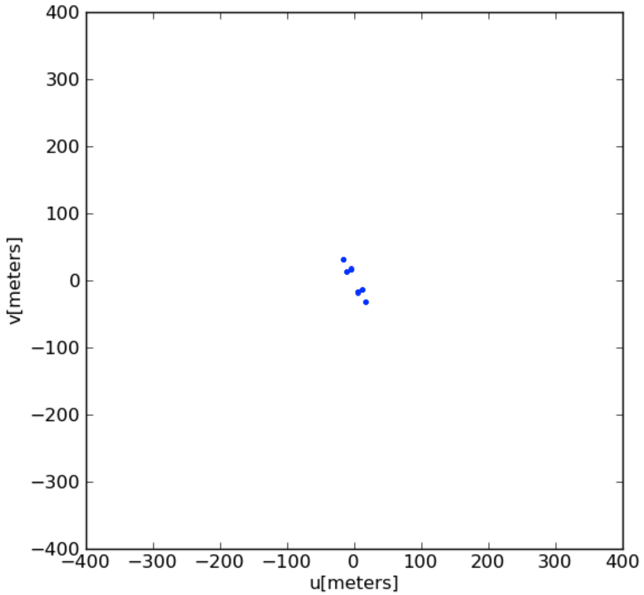


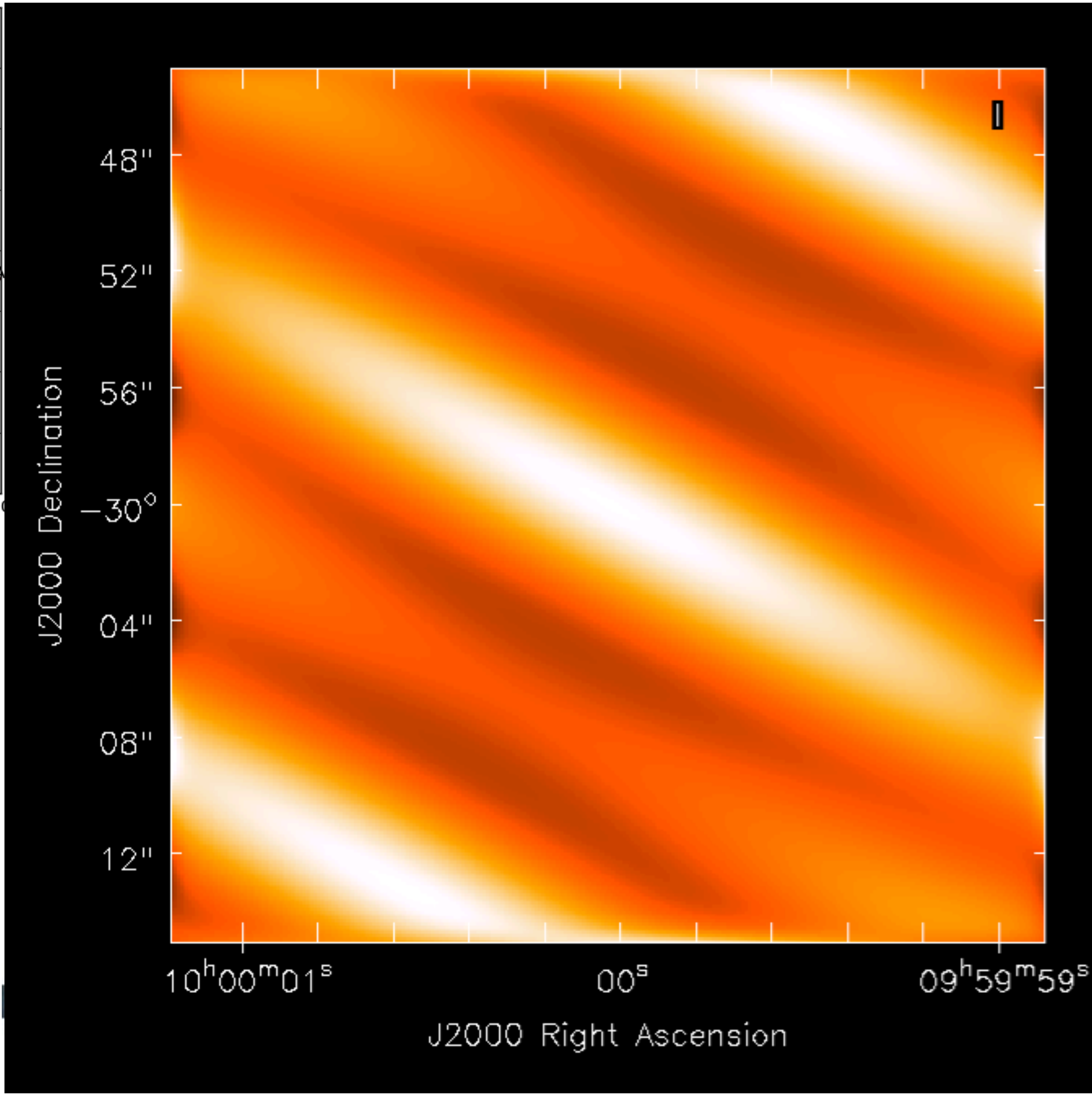




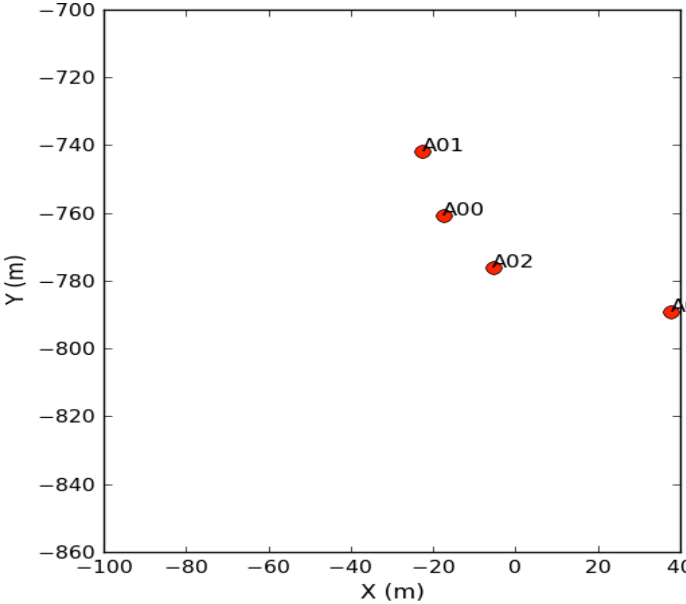
Example: Fringe pattern with 3 Antennas

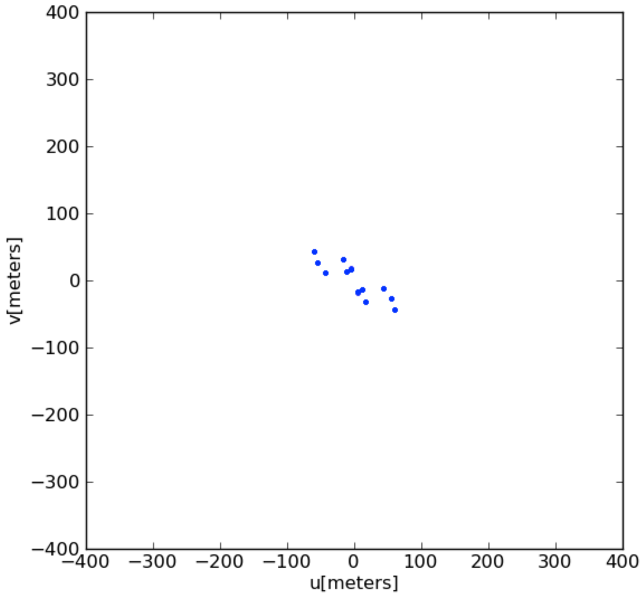


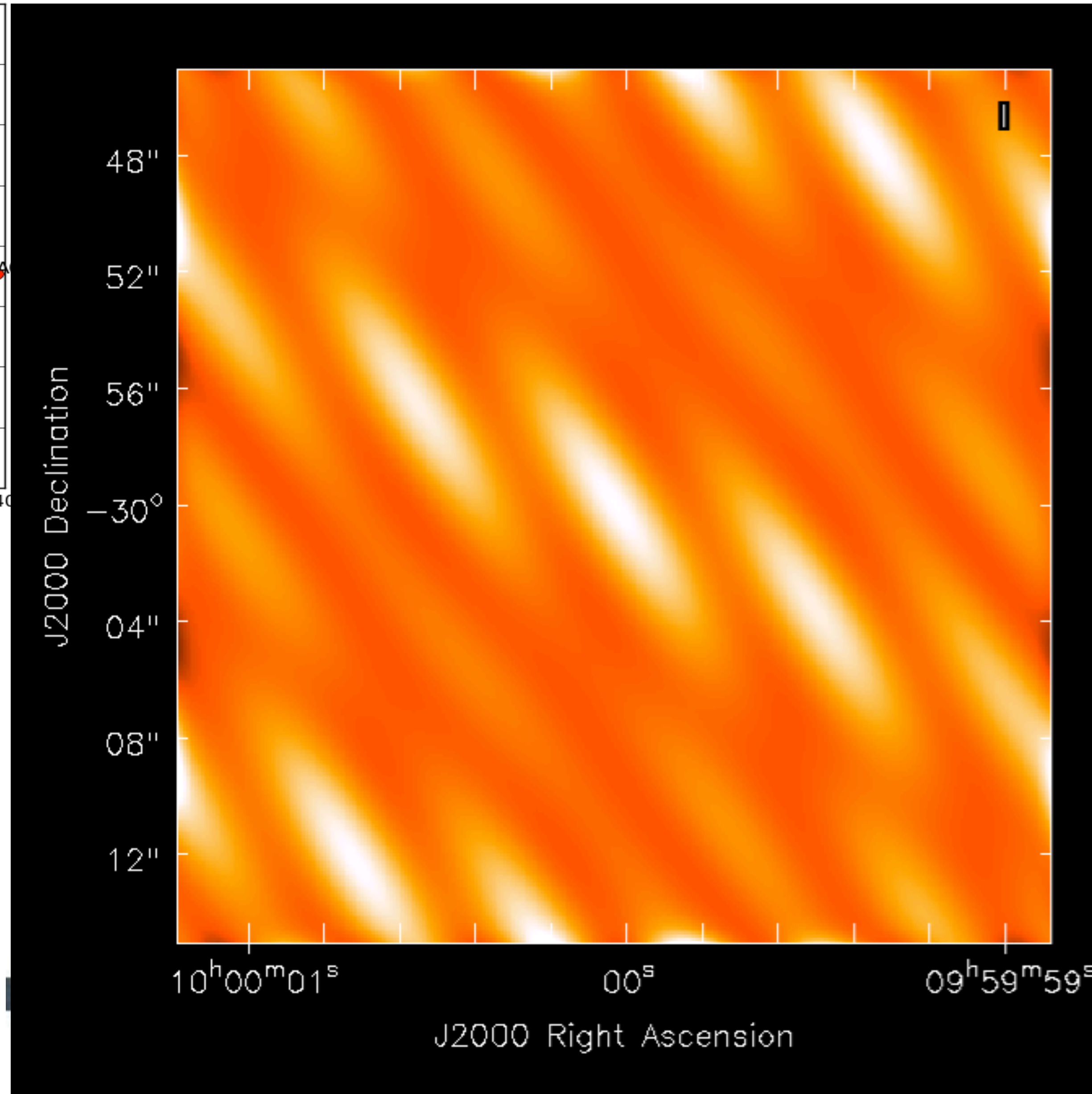




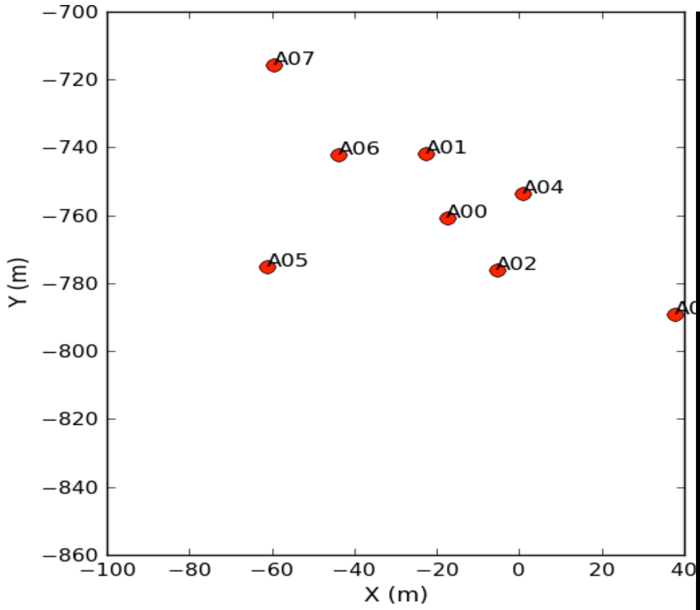
Example: Fringe pattern with 4 Antennas

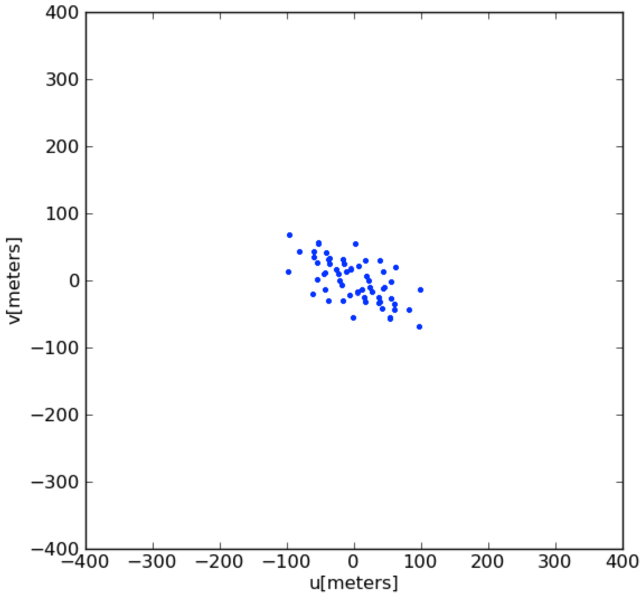


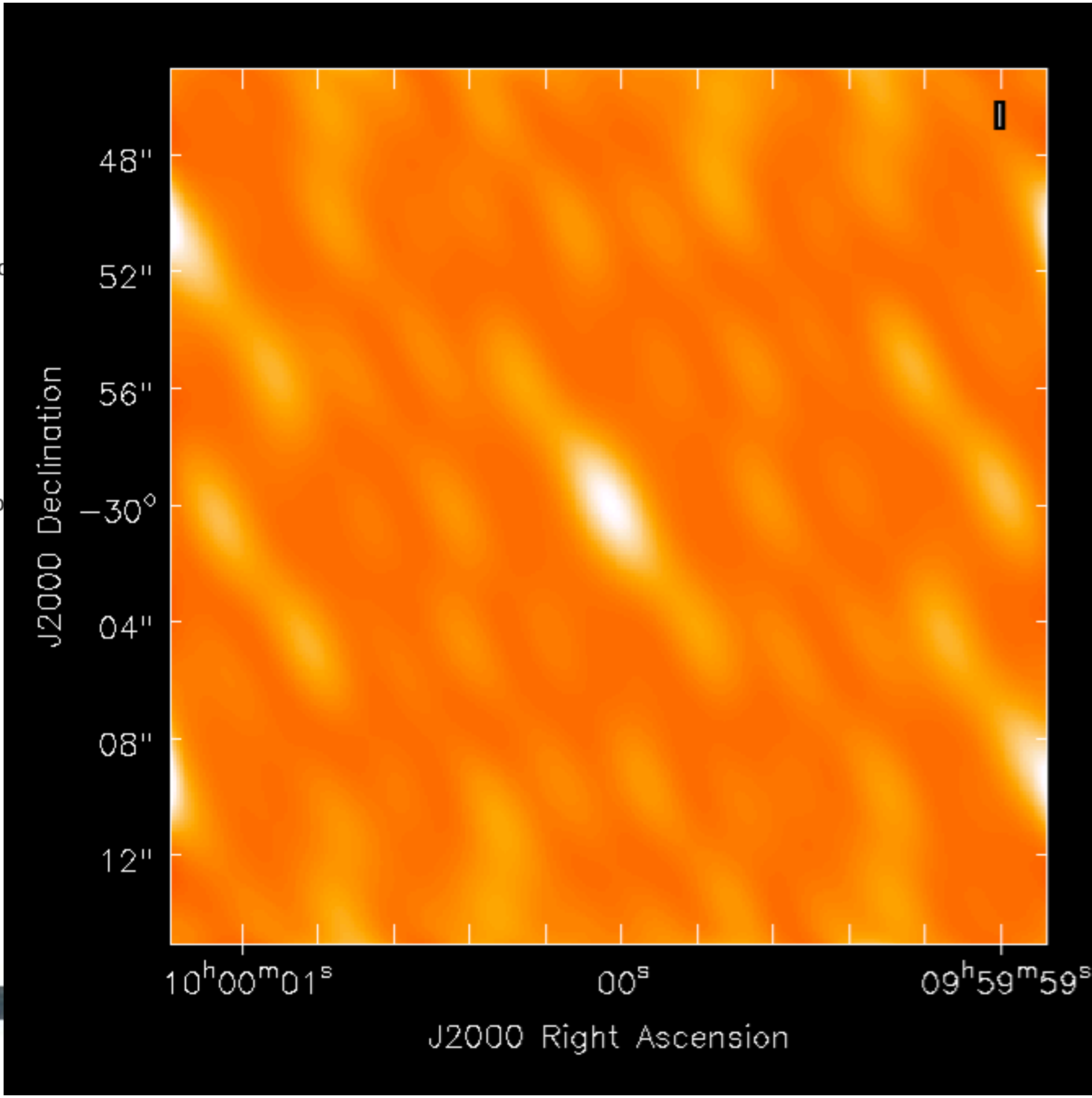




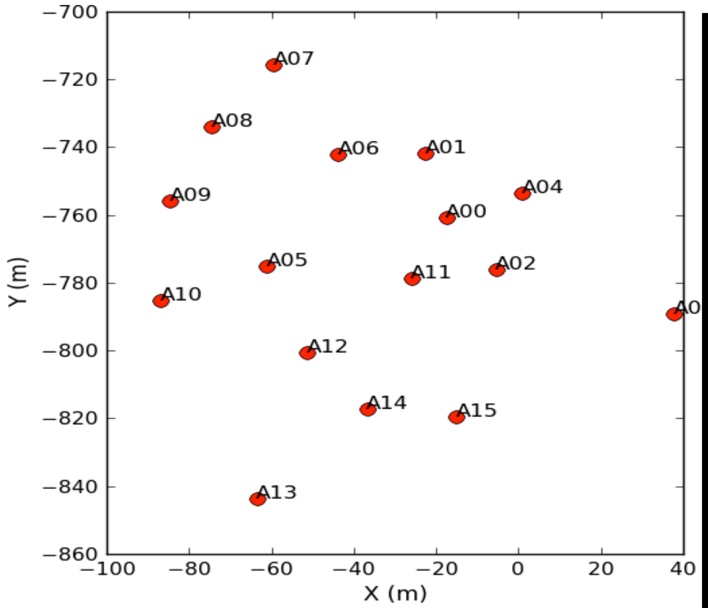
Example: Fringe pattern with 8 Antennas

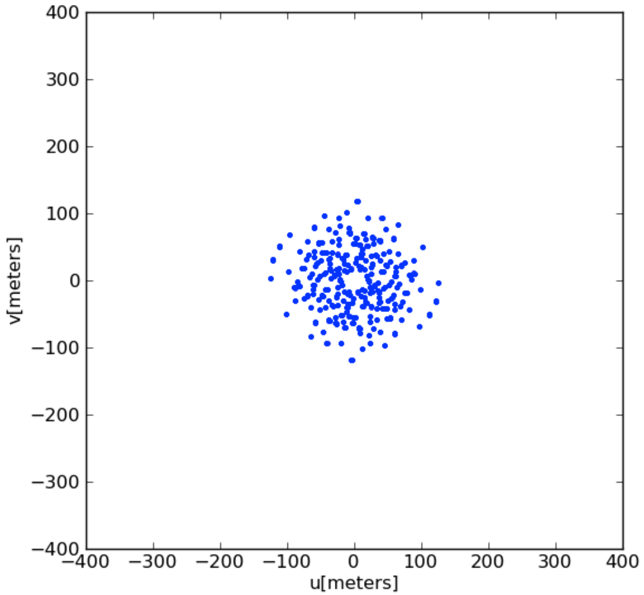


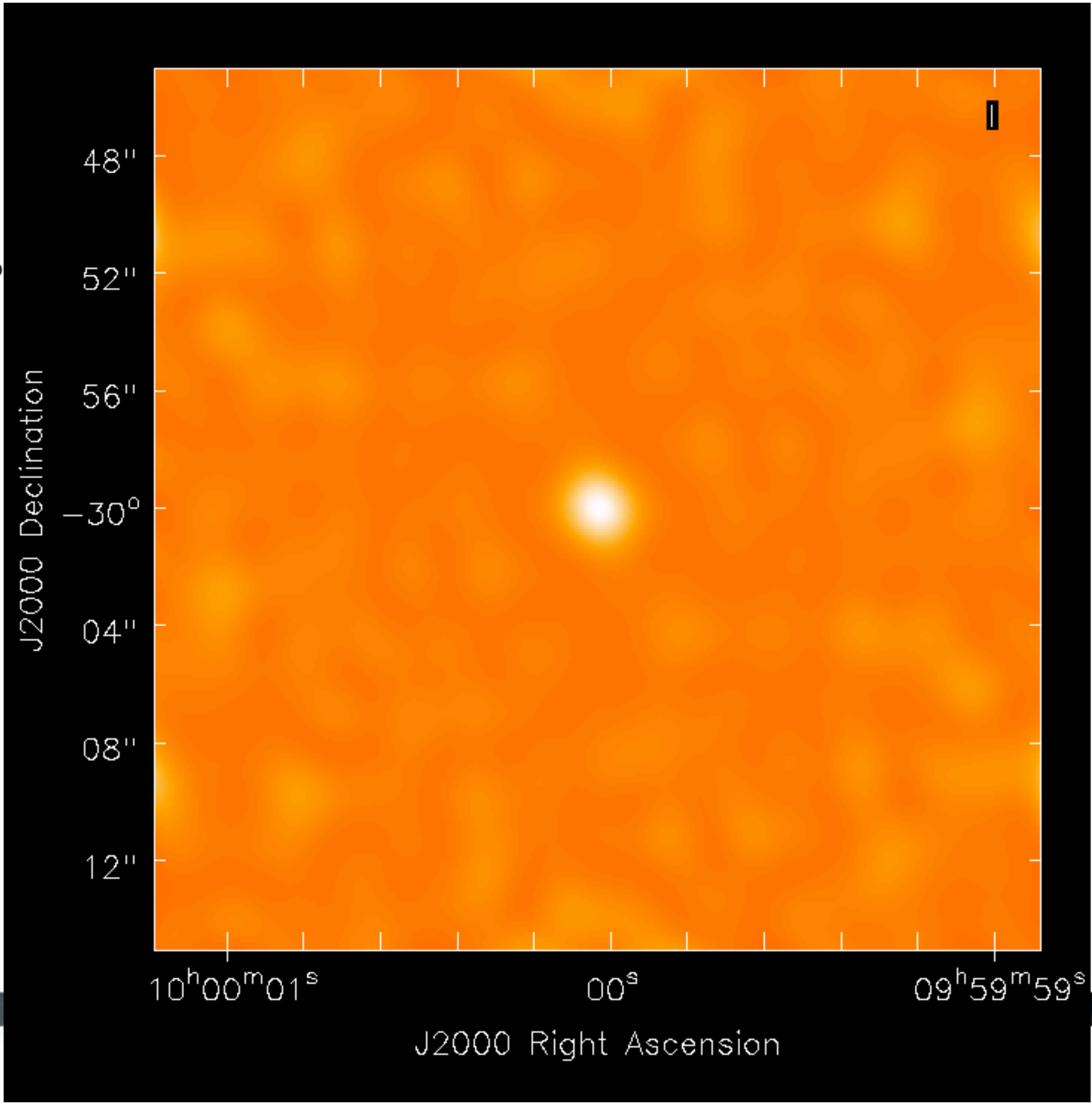




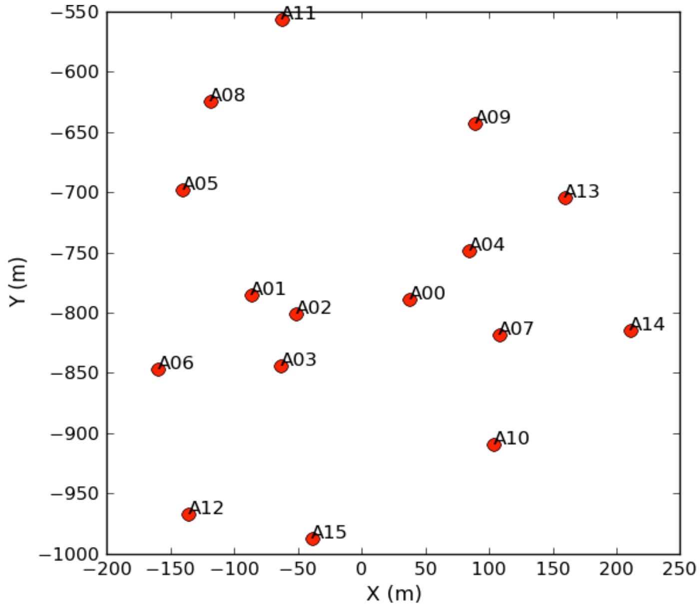
16 Antennas – Compact Configuration

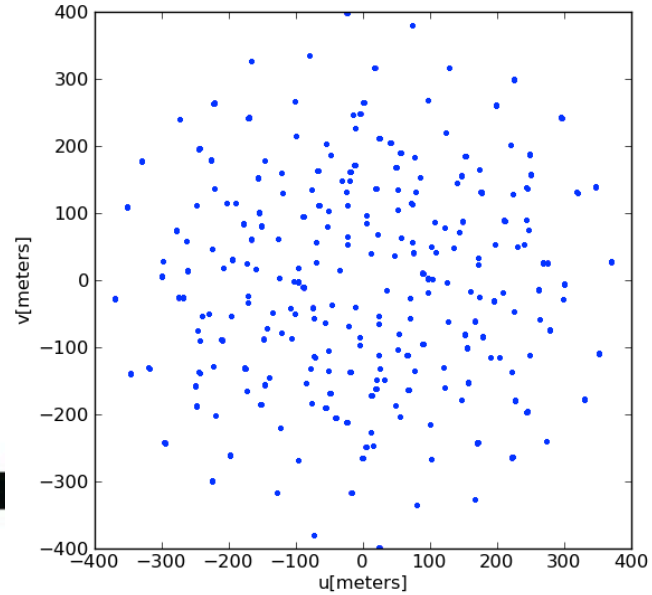


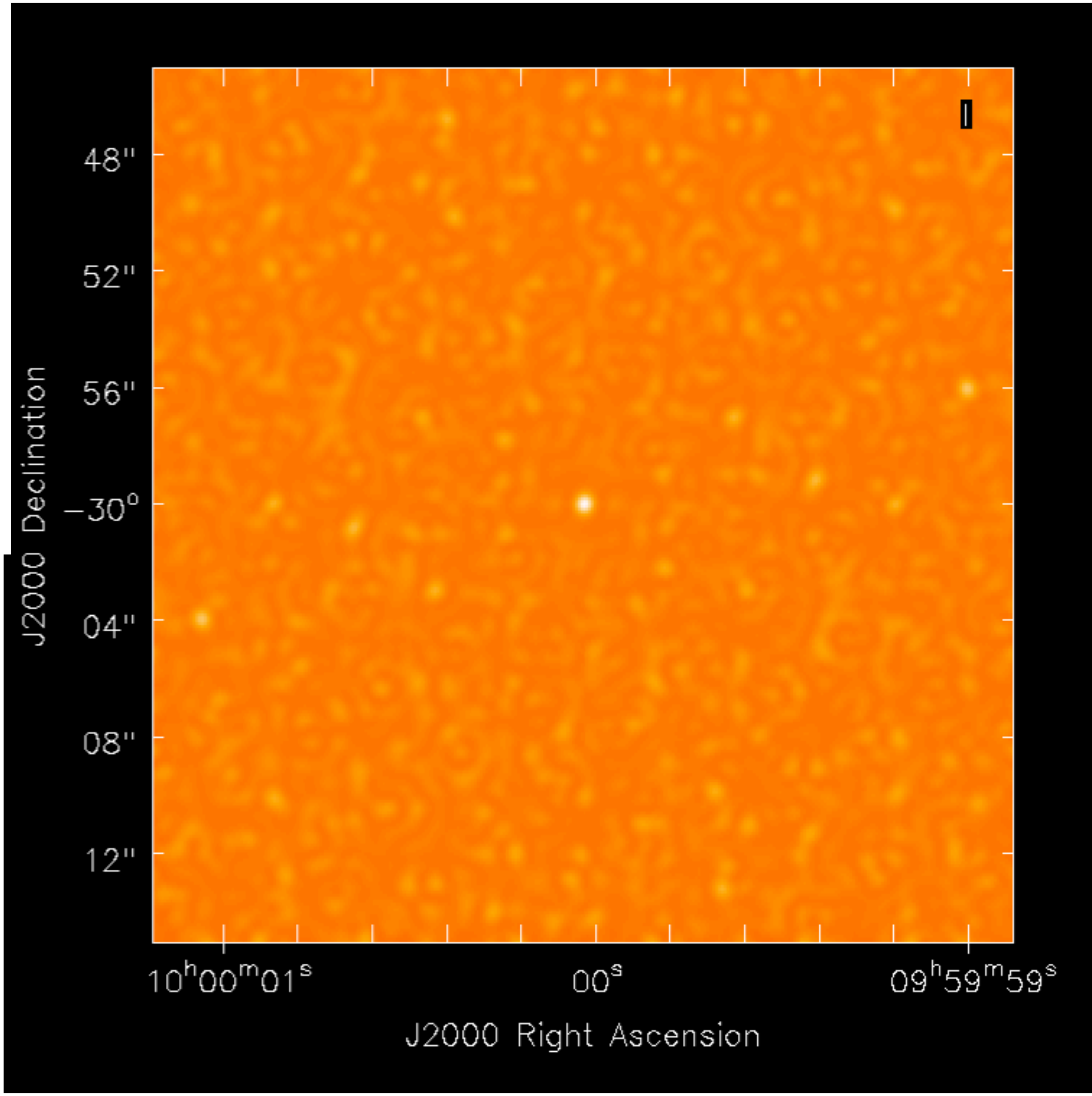




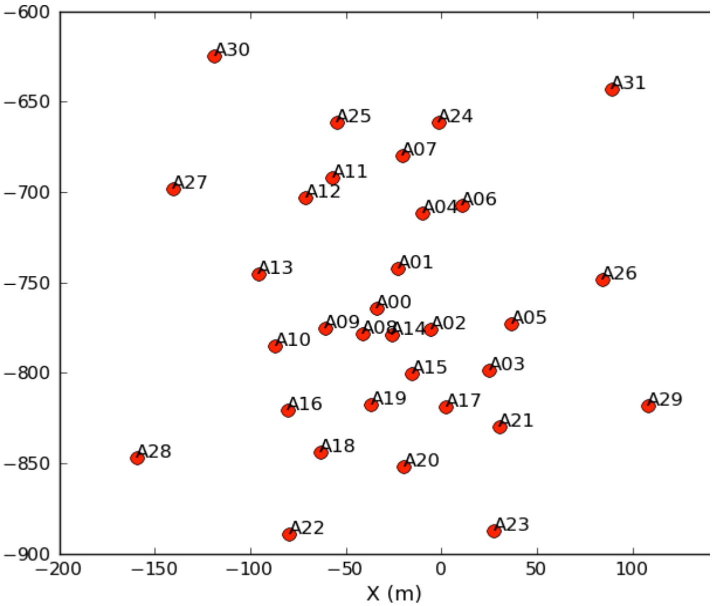
16 Antennas – Extended Configuration

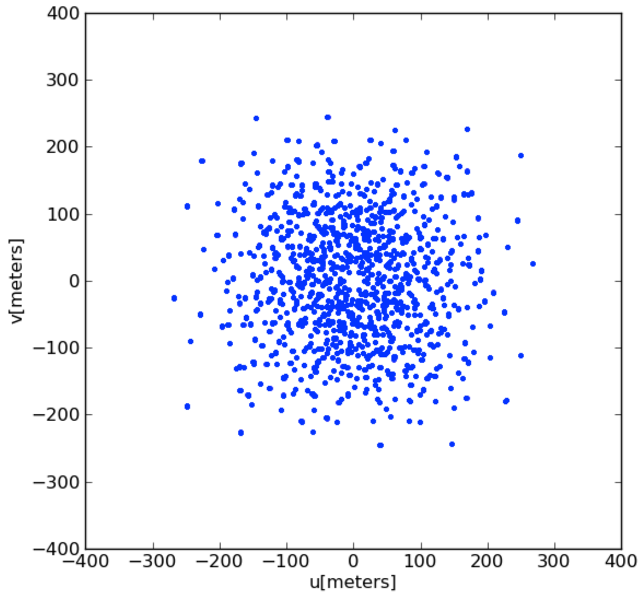


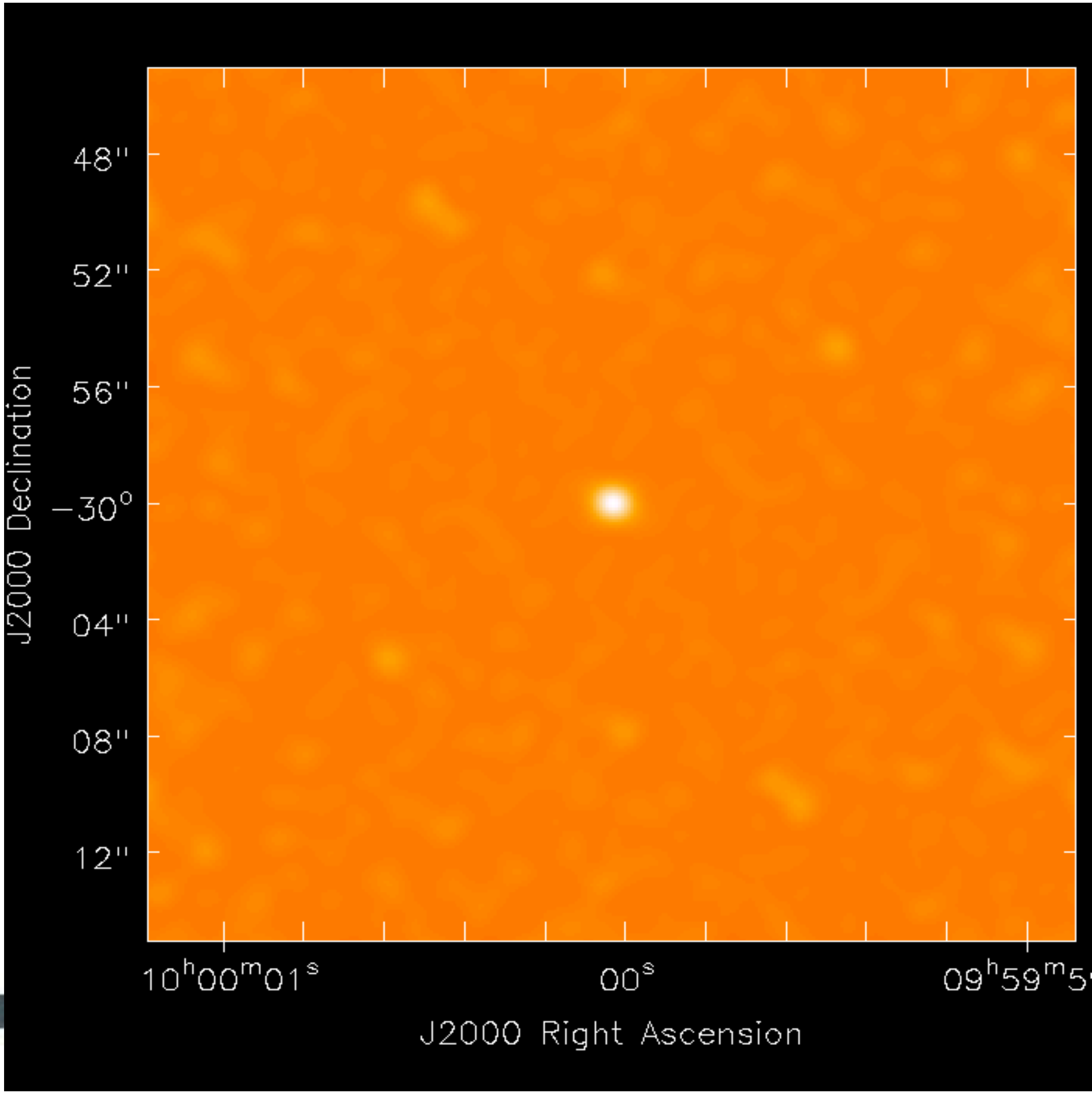




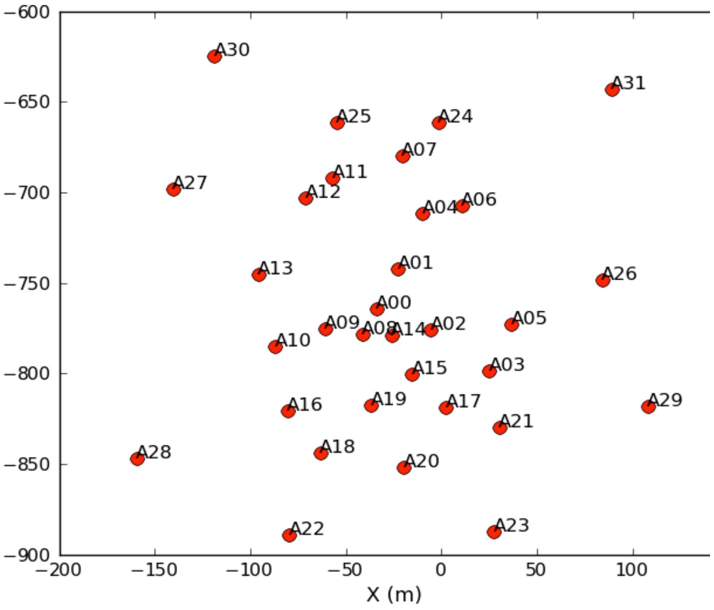
32 Antennas – Instantaneous

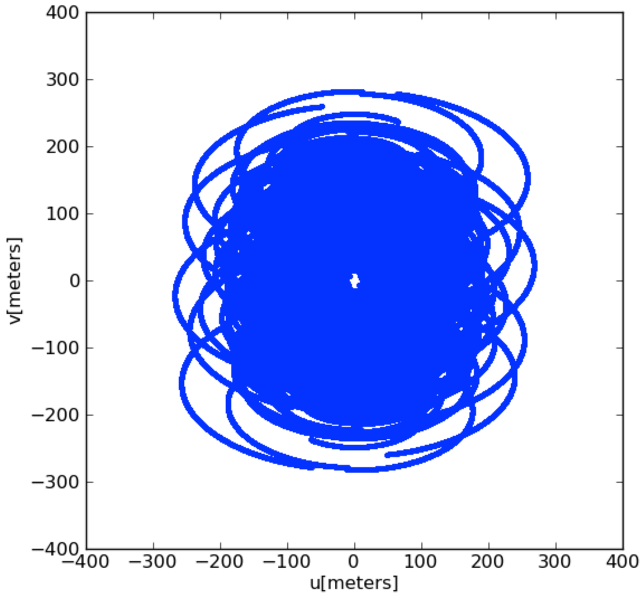


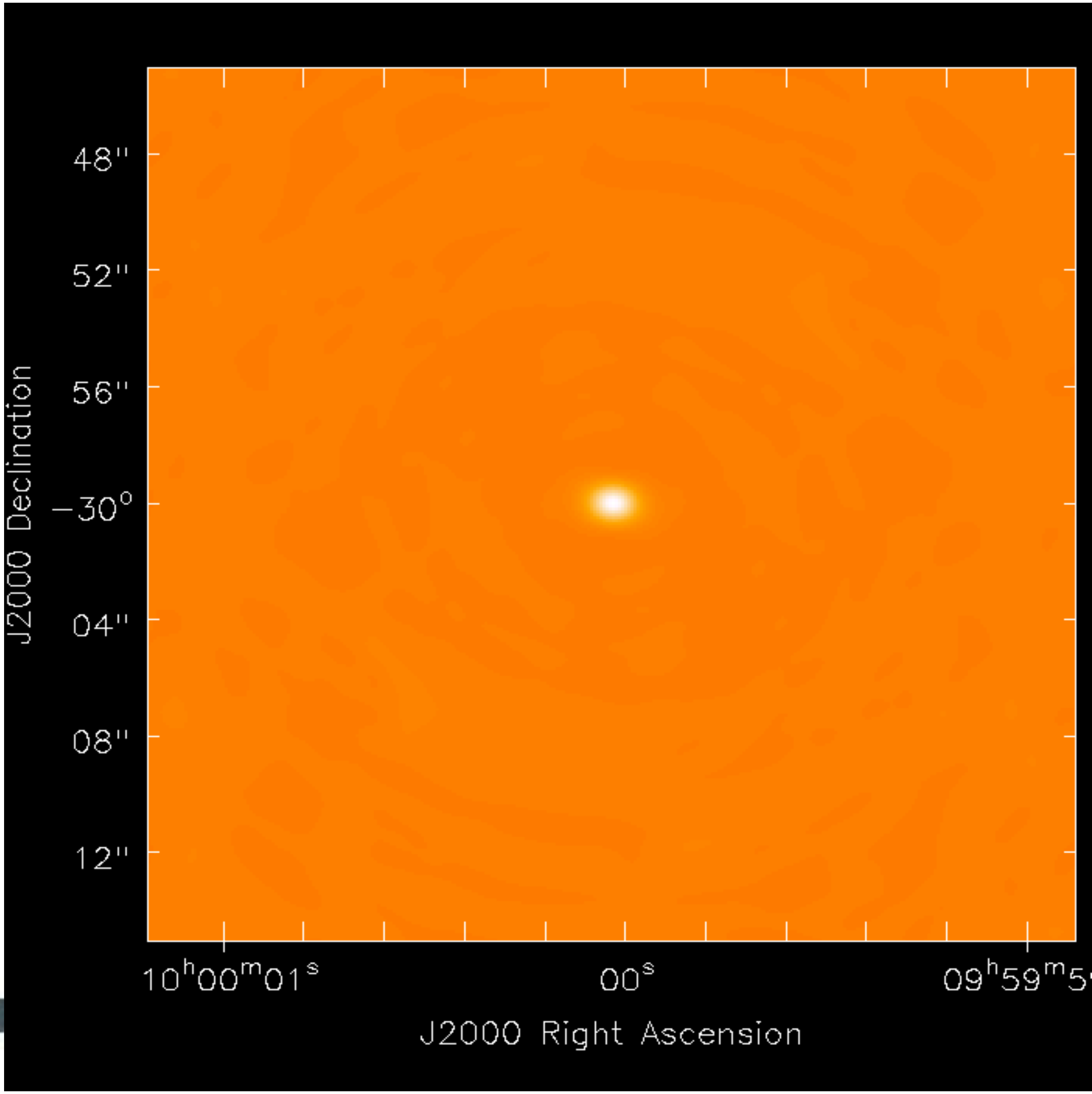




32 Antennas – 8 hours



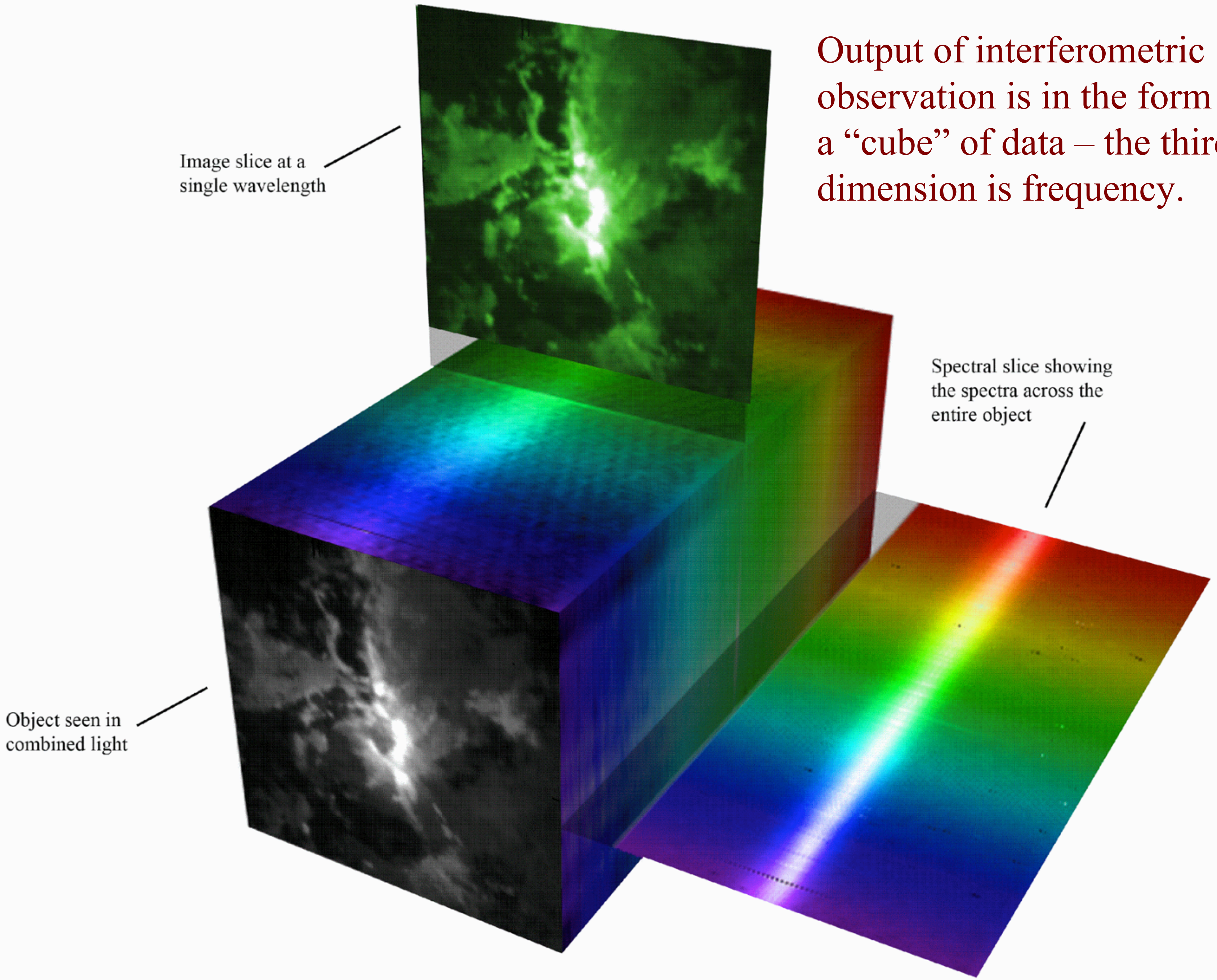




uv coverage: why the central hole?

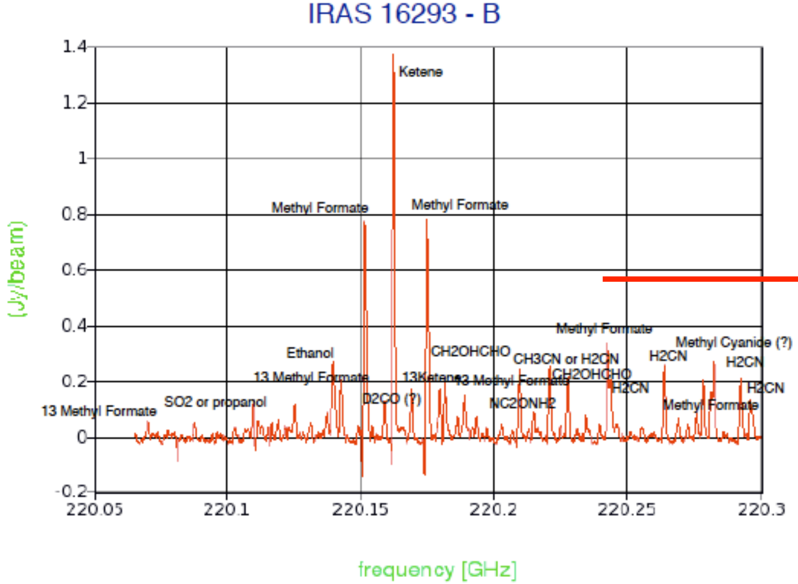
- The central hole in the sampling of the uv plane arises due to **short baselines**
- The largest angular scale that an interferometer is sensitive to is given by the shortest distance between 2 antennas.
- The field of view is given by the beam of a single antenna.
- A single antenna diameter will 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 or we can fill in the information with 7m observations or ultimately single dish data.

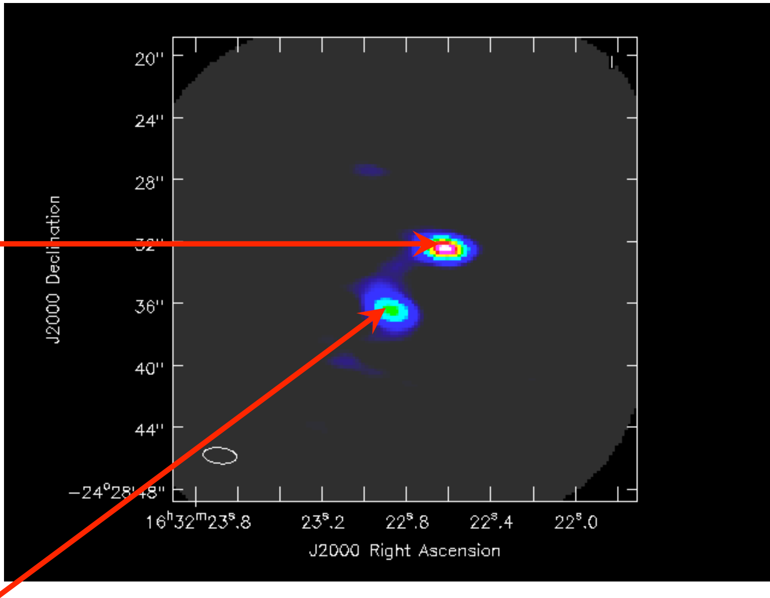
Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.



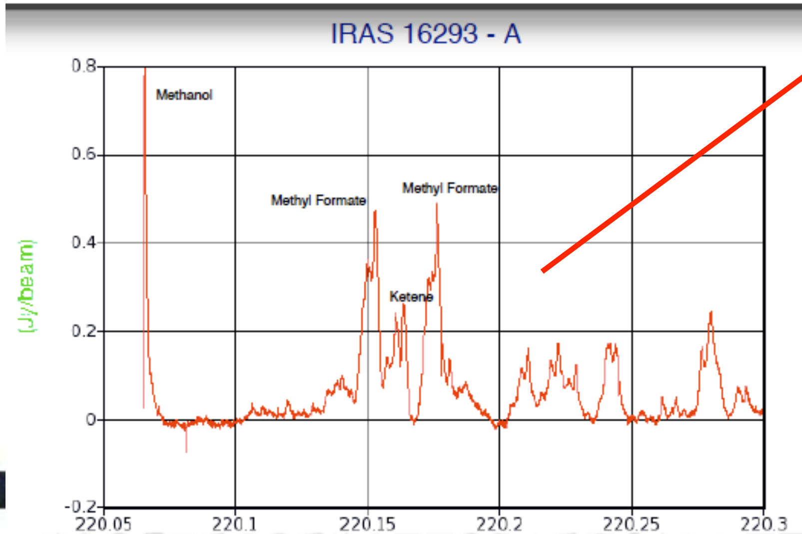
Sometimes the most interesting science lies in the third dimension

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.

Understanding the observational processes

Measuring the visibility

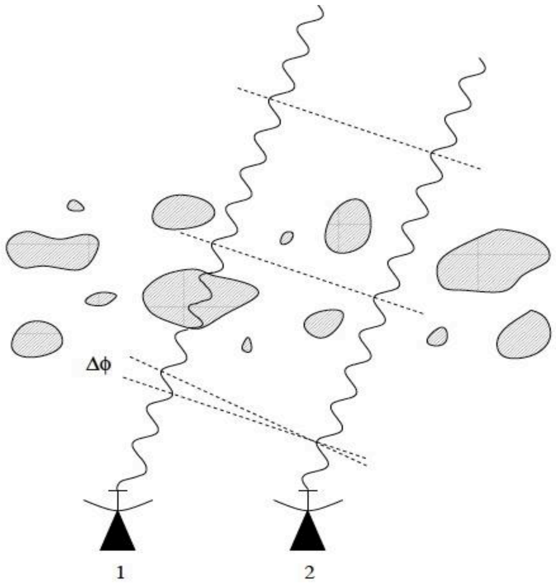
Calibration formula:

$$\tilde{V}_{\nu}(u,v) = G_{\nu}(u,v)V_{\nu}(u,v) + \eta_{\nu}(u,v)$$

G(u,v) = complex gain, i.e., amplitude and phase gains, depending on time and frequency

Due to the atmosphere, i.e., different optical path and atmospheric opacity, and to the instrumental response to the astronomical signal.

η(u,v) = random complex noise



Data Calibration

Basic idea: observe sources with known flux, shape and spectrum to derive the response of the instrument.

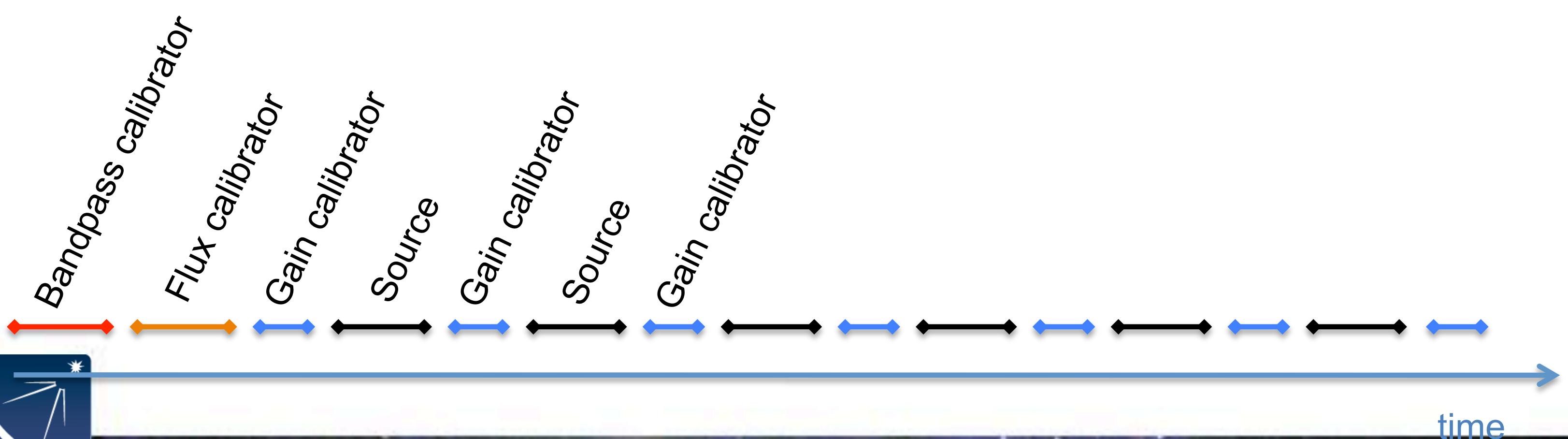
Bandpass calibration:
what does it do? It compensates for the change of gain with frequency.
How does it work? A strong source with a flat spectrum (i.e., bandpass calibrator) is observed (usually once during the track). Bandpass calibration is generally stable across the track.

Phase calibration:
What does it do? It compensates for relative temporal variation of the phase of the correlated signal on different antennas (or baselines).
How does it work?
- using Water Vapor Radiometers
-a strong source with known shape (preferably a point source) is observed every few minutes. If the gain calibrator is a point source, than the gain are derived assuming that the intrinsic phase is 0.

Data Calibration

Basic idea: observe sources with known flux, shape and spectrum to derive the response of the instrument.

Amplitude calibration:
What does it do? It compensates for atmospheric opacity and loss of signal within the interferometer (e.g., pointing errors).
How does it work? A source with known flux is observed. This can be a planet for which accurate models exists, or a *stable* radio source, which has been independently calibrated using, e.g., a planet. Accuracies < 15% in the absolute flux are challenging and might required specific observing strategies.



Observing Strategy

Choose your array by largest angular scale of target

- Interferometers act as spatial filters - shorter baselines are sensitive to larger targets, so remember:
  - Spatial scales larger than the smallest baseline cannot be imaged
  - Spatial scales smaller than the largest baseline cannot be resolved

Calibration Requirements (Handled by ALMA):

- Gain calibrator: solves for atmospheric and instrumental variations with time.
  - Usually a bright quasar **near** science target
- Bandpass calibrator: fixes instrumental effects and variations vs frequency
  - Usually a bright quasar
- Absolute flux calibrator: used to scale relative amplitudes to absolute value
  - Usually a solar system object or quasar

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

NRAO

For more info:

http://www.almaobservatory.org

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Republic of Chile. ALMA is funded by ESO on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and by NINS in cooperation with the Academia Sinica (AS) in Taiwan and the Korea Astronomy and Space Science Institute (KASI). ALMA construction and operations are led by ESO on behalf of its Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.