Introduction to Radio Interferometry

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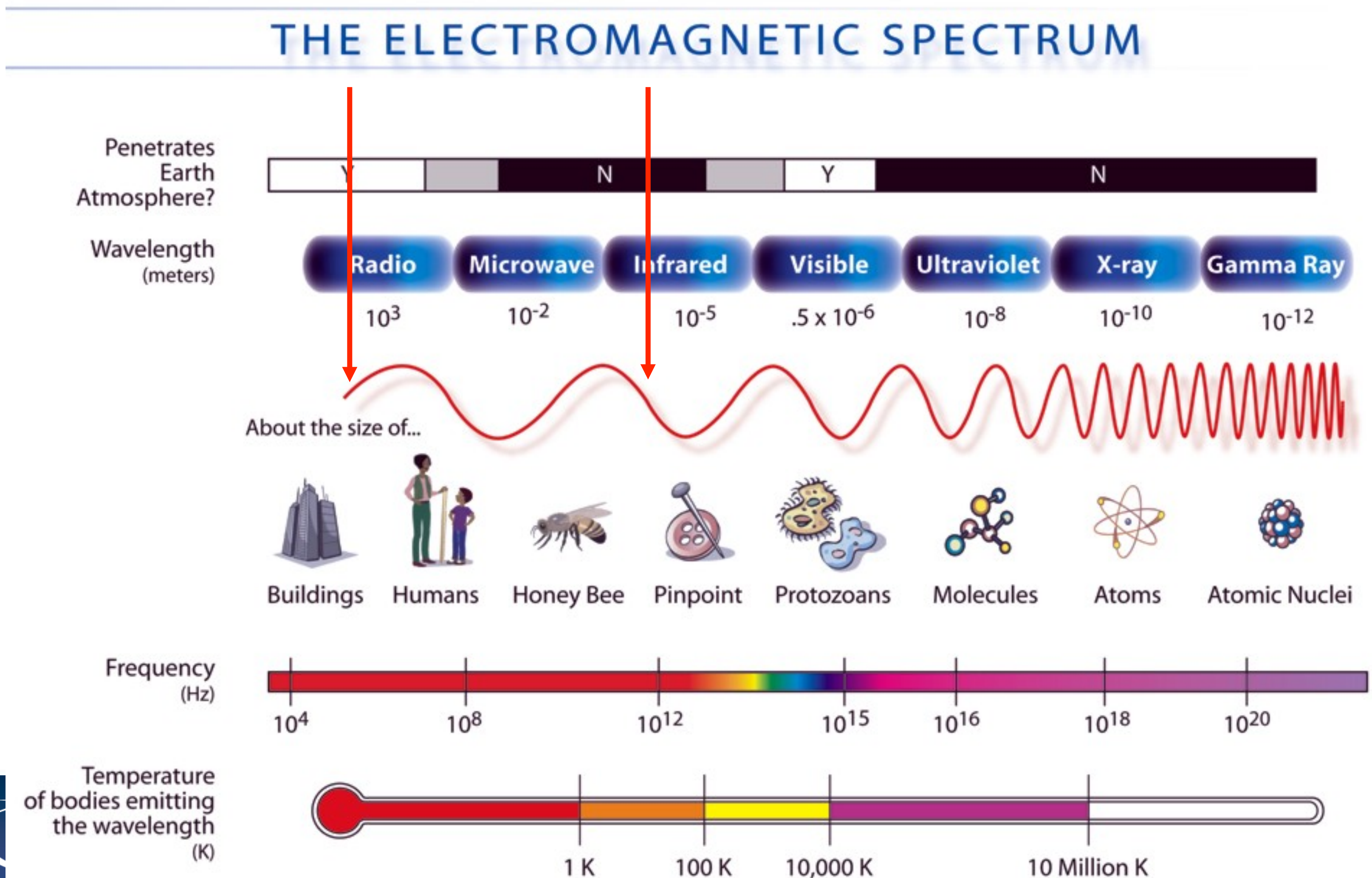
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

Radio Astronomy

Now used to refer to most telescopes using heterodyne technology



What is heterodyne?

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, and it means we retain phase information as well as amplitude.

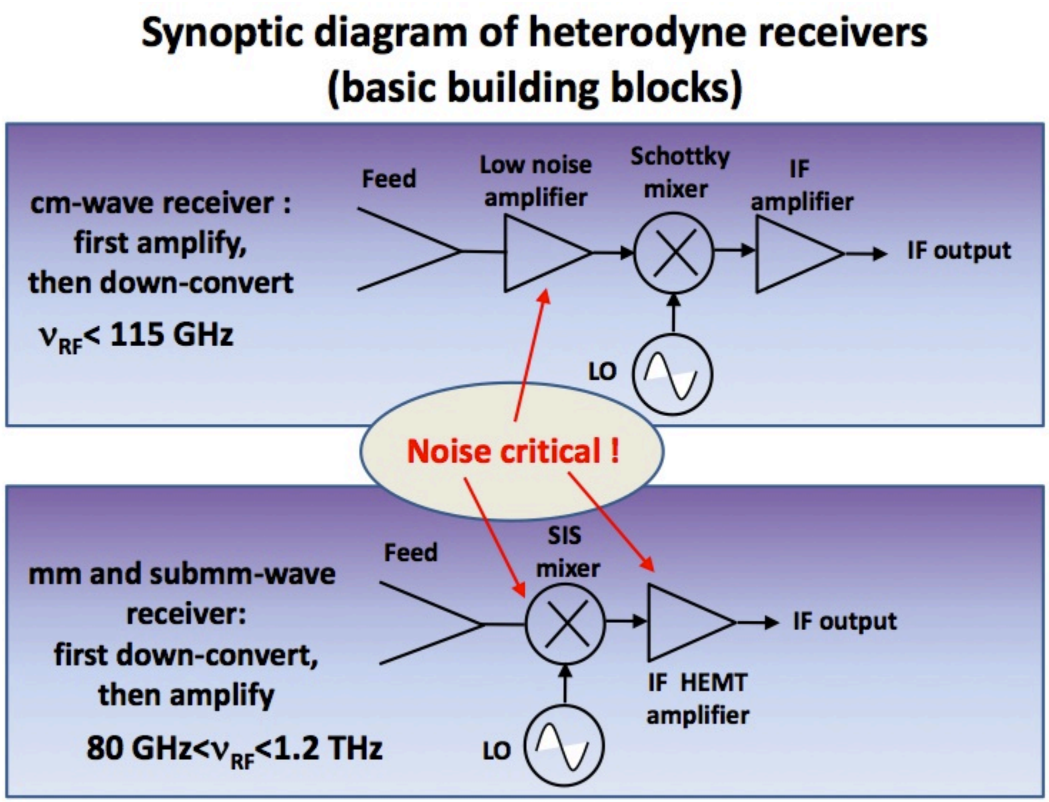
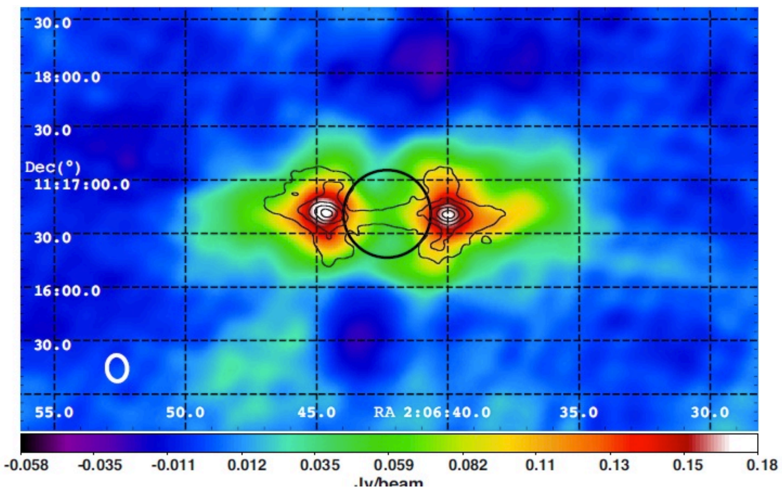


Image from Alessandro Navarrini (IRAM)

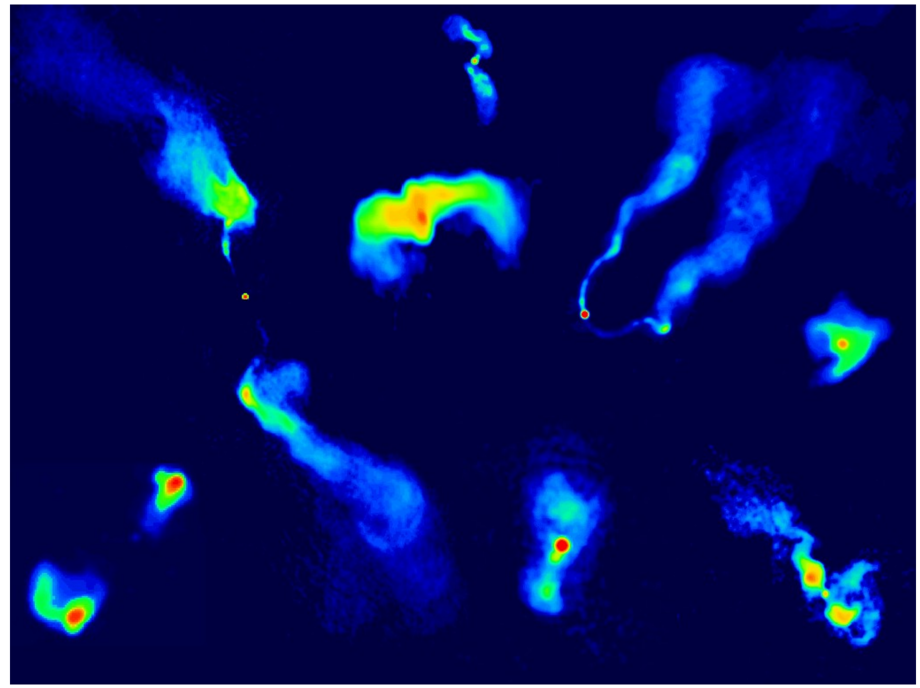
Long wavelength means no glass mirrors

What should we observe?

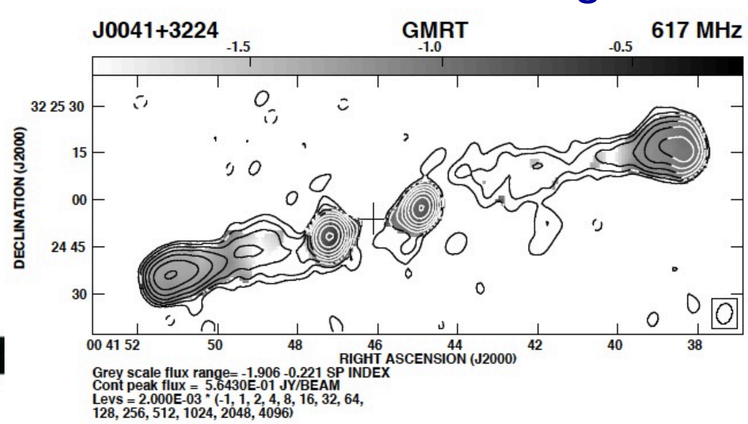
At low frequencies (MHz-GHz):



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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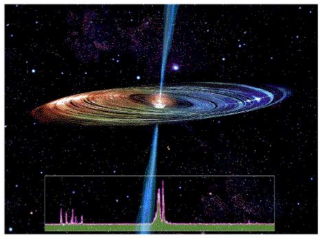
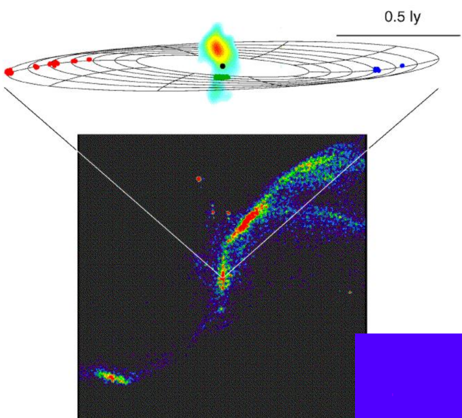
  http://images.nrao.edu/

What should we observe?

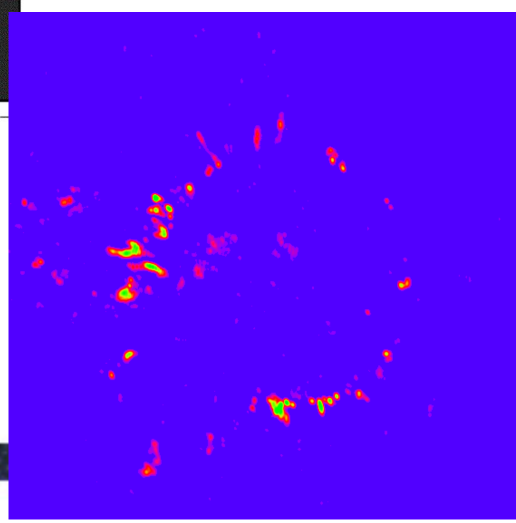
At low frequencies (MHz-GHz):

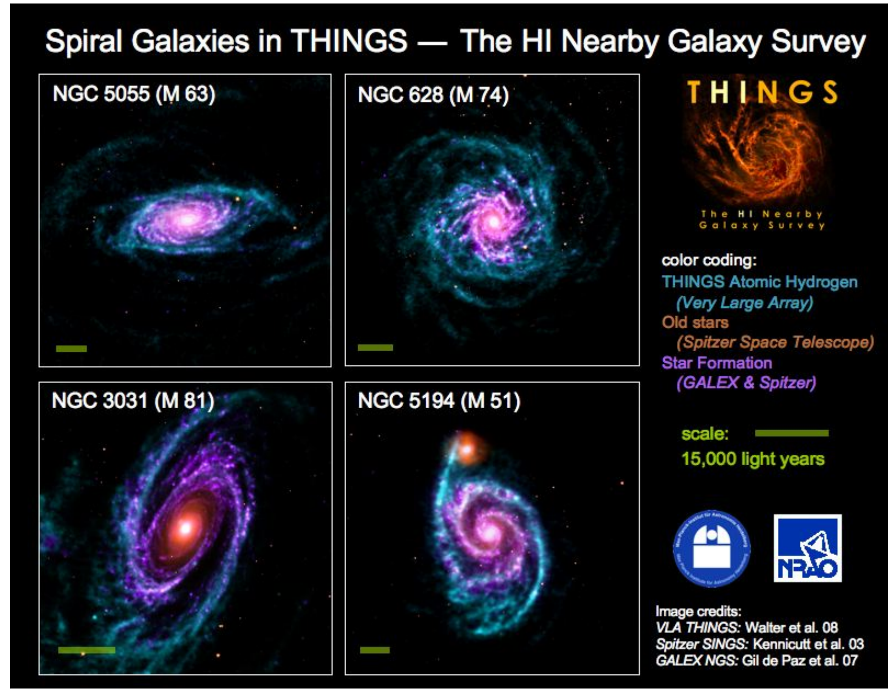


NGC 4258

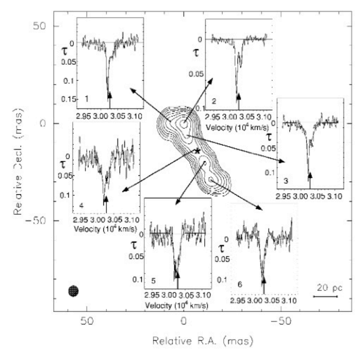


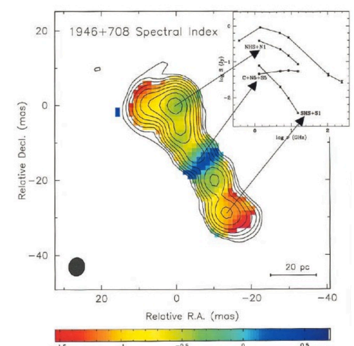
H_2O, OH or SiO masers in galaxies and stars





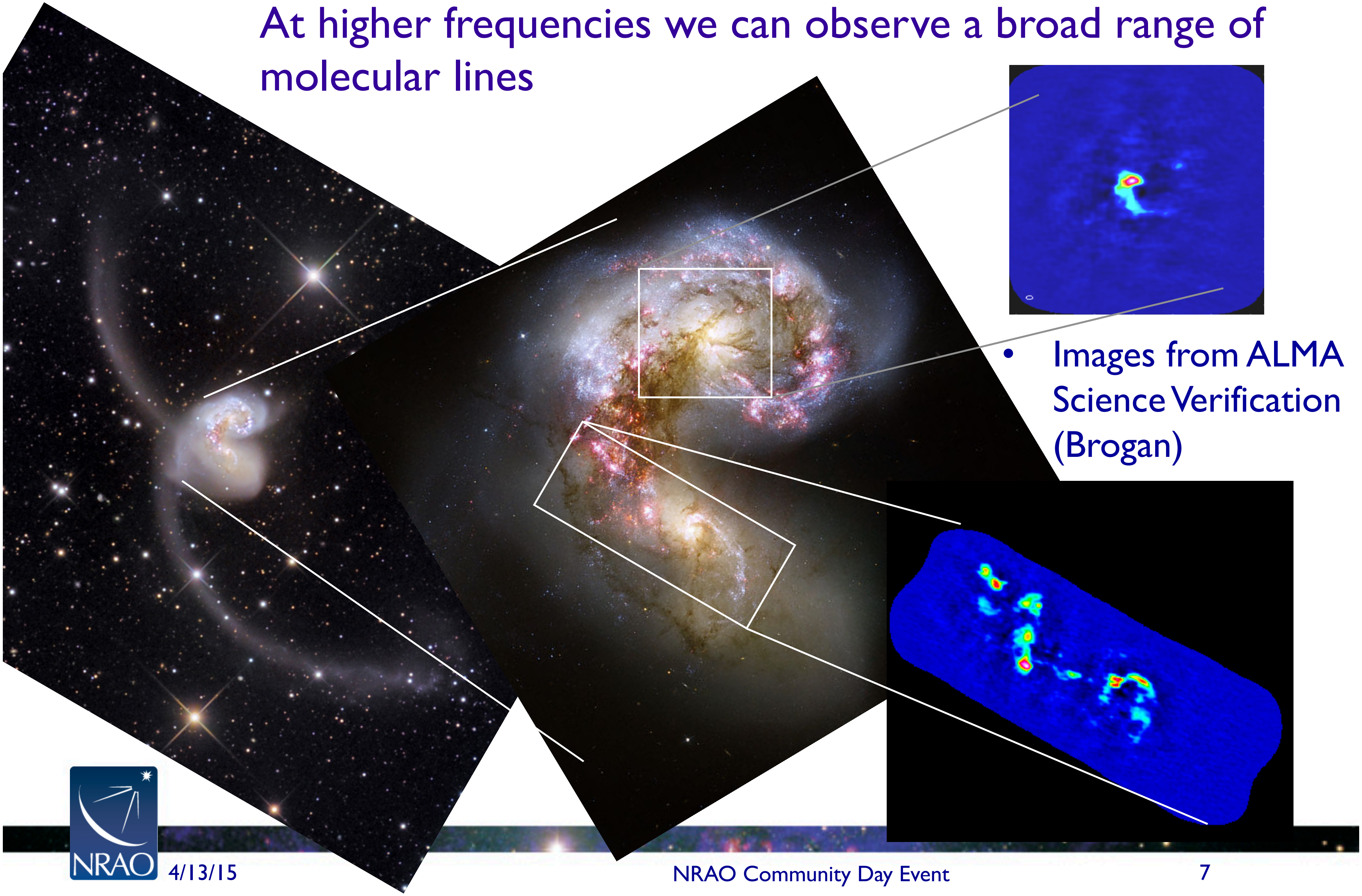
HI emission and absorption, free-free absorption in galaxies





What should we observe?

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



- Images from ALMA Science Verification (Brogan)

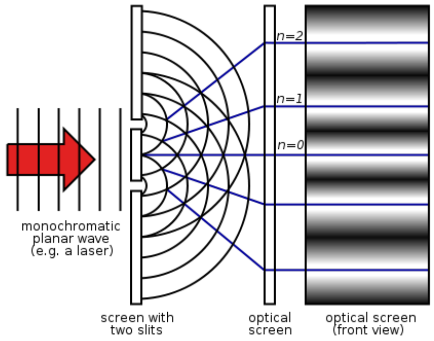
Resolution of Observations

- Angular resolution for most telescopes ~ λ/D
  - D is the diameter of the telescope, λ is wavelength of observation
- Hubble Space Telescope resolution ~ 0.13”
  - $D = 2.4m$, $\lambda \sim 1um$
- For 1mm wavelength observations, one would need a 2km-diameter antenna to reach this resolution
- Instead, we use arrays of smaller telescopes to achieve high angular resolution in radio astronomy

This is interferometry

What is an interferometer?

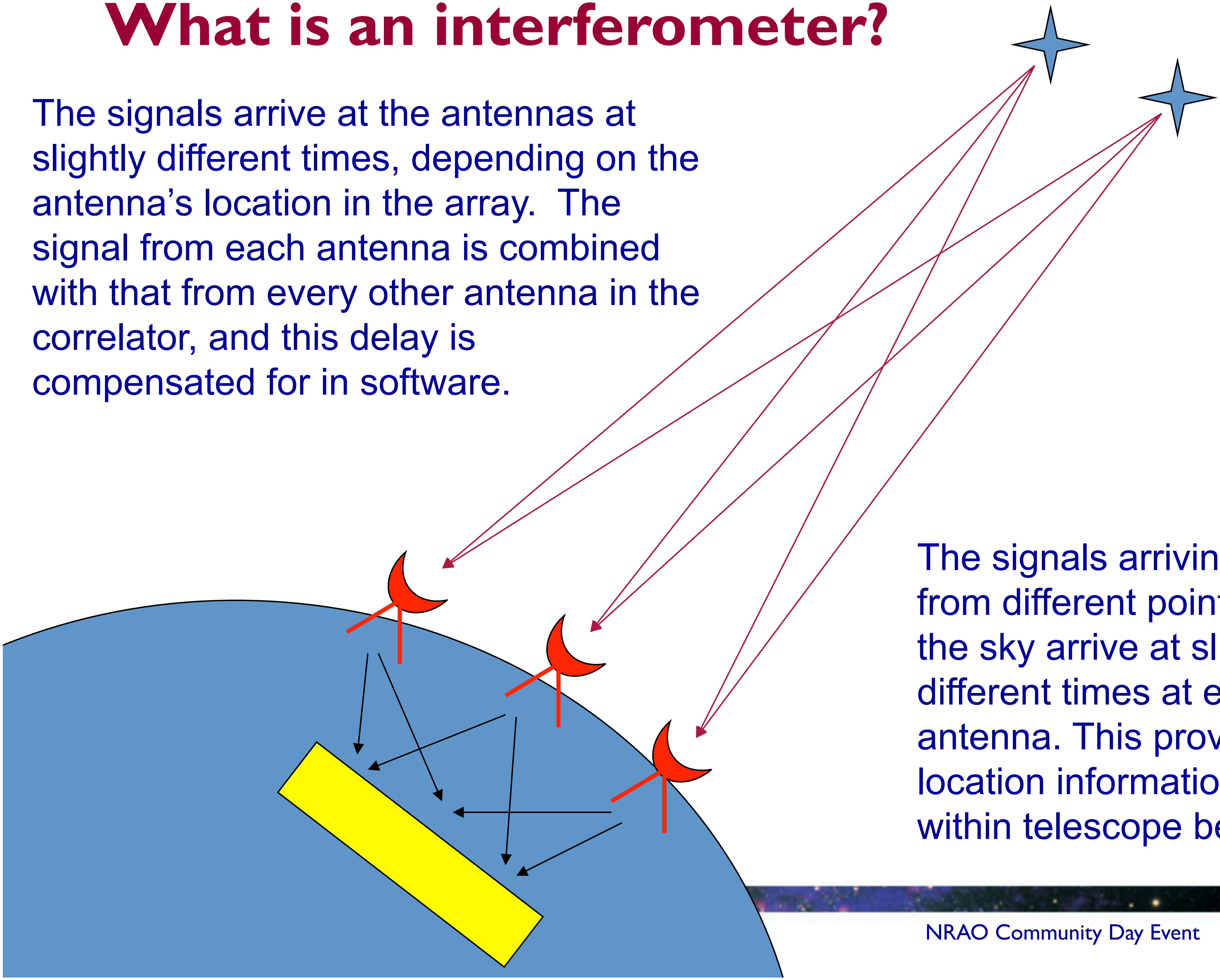
- An interferometer measures the interference pattern produced by multiple apertures, like a 2-slit experiment.



- Note: Radio interferometers typically produce "interference pattern" by multiplying, not adding, signal measured at different telescopes (apertures)

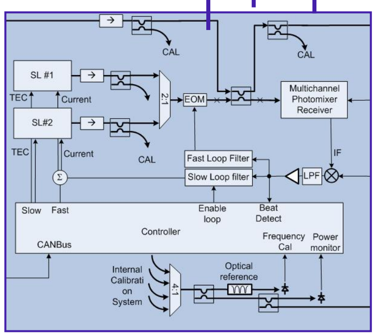
What is an interferometer?

The signals arrive at the antennas at slightly different times, depending on the antenna's location in the array. The signal from each antenna is combined with that from every other antenna in the correlator, and this delay is compensated for in software.



The signals arriving from different points in the sky arrive at slightly different times at each antenna. This provides location information within telescope beam.

Practical Details

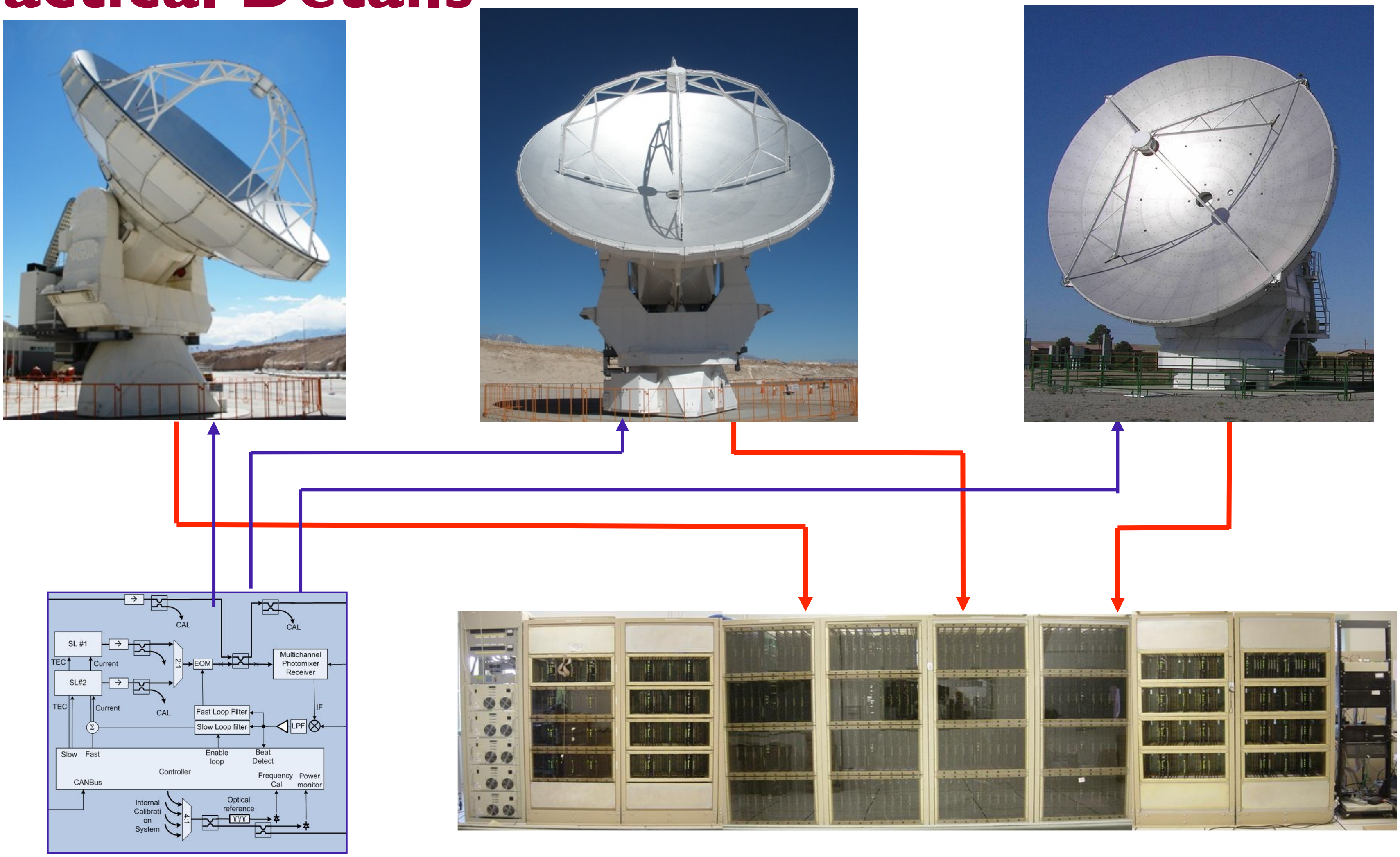


Precise determination of arrival times requires exquisite timing

- One-wavelength error at band 10 = 1picosec
- Need << wavelength timing precision

Common time reference distributed to all antennas (LO)

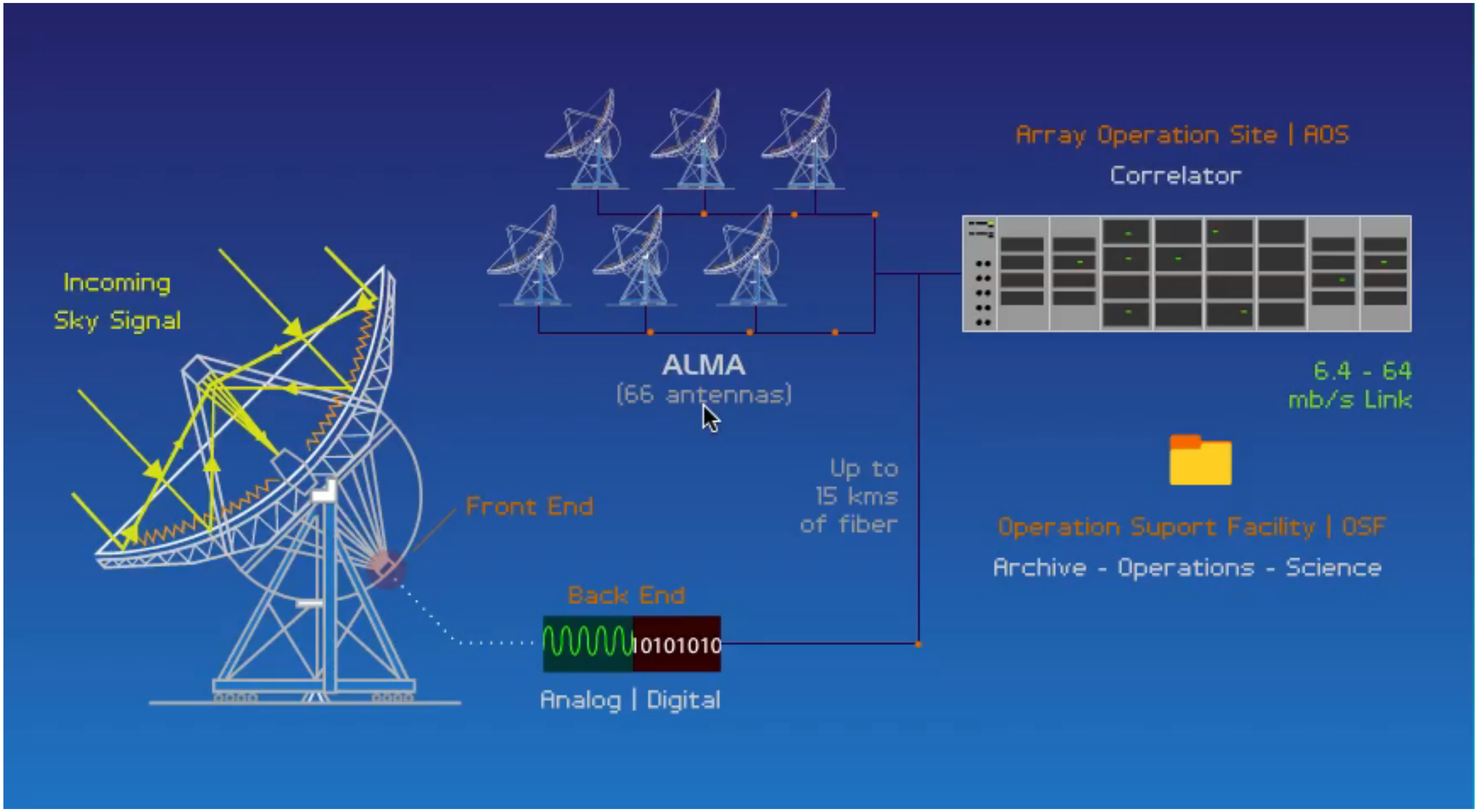
Practical Details



Signal from each antenna digitized and sent to correlator for multiplication, averaging

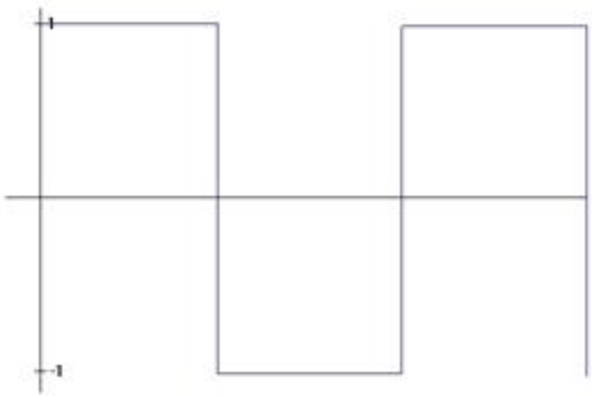
50 antennas = 600 GB/sec for correlator to process

An interferometer in action

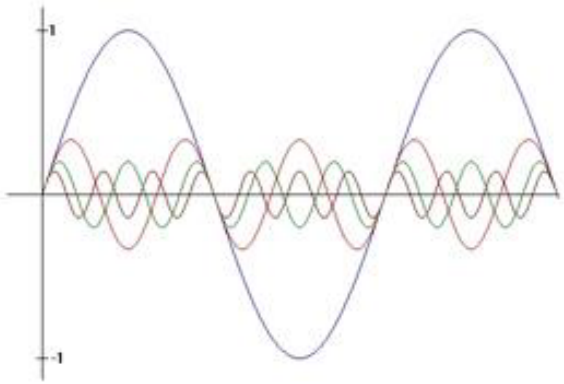


The Fourier Transform

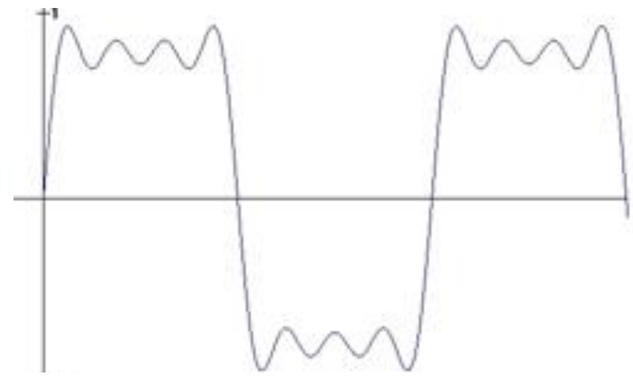
Fourier theory states that any well behaved signal (including images) can be expressed as the sum of sinusoids



Reference signal



4 sinusoids



Sum of sinusoids

- 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

The Fourier Transform relates the interference pattern to the 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. In particular, 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 interference pattern to the intensity on the sky

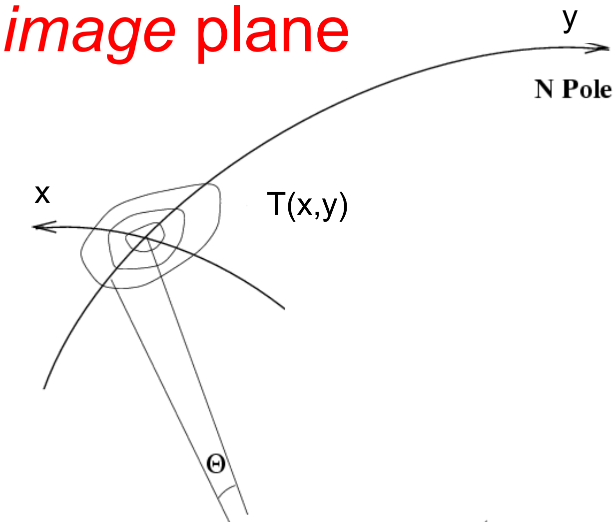
Fourier space/domain

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

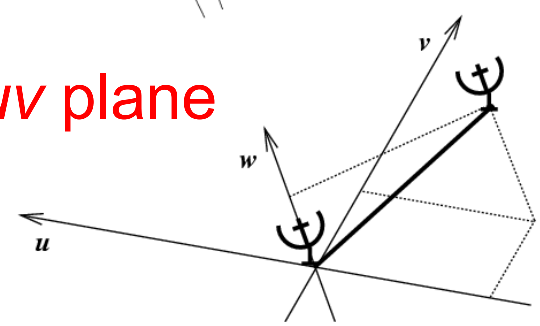
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

Image space/domain

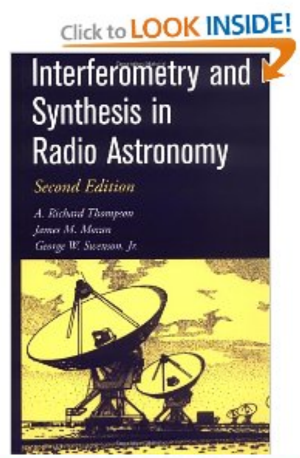
image plane



uv plane



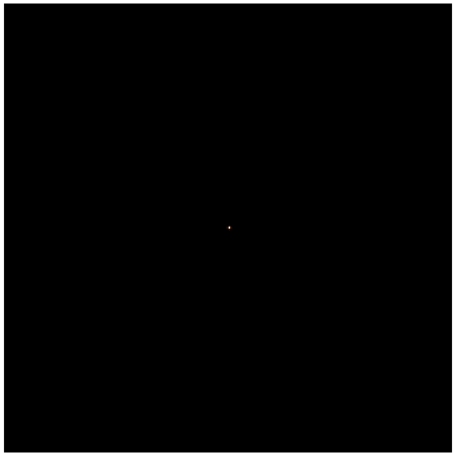
(for more info, see e.g. Thompson, Moran & Swenson)



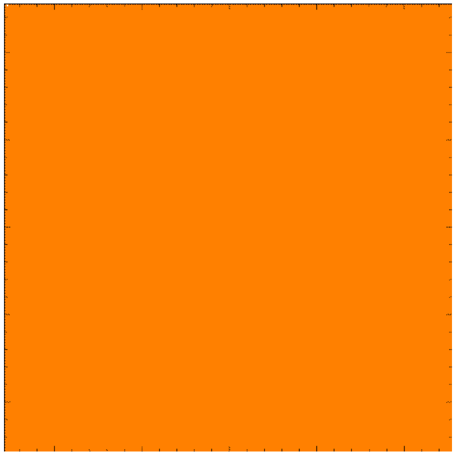
Some 2D Fourier Transform Pairs

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

δ Function

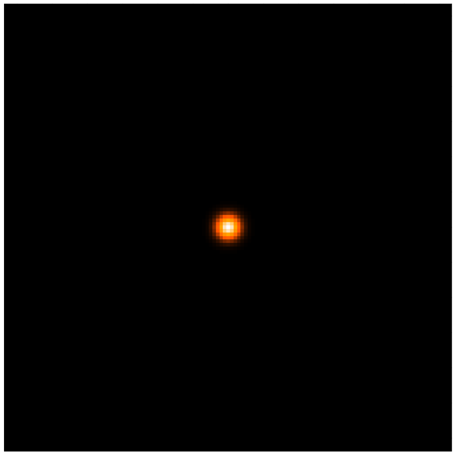


$\rightleftharpoons$



Constant

Gaussian



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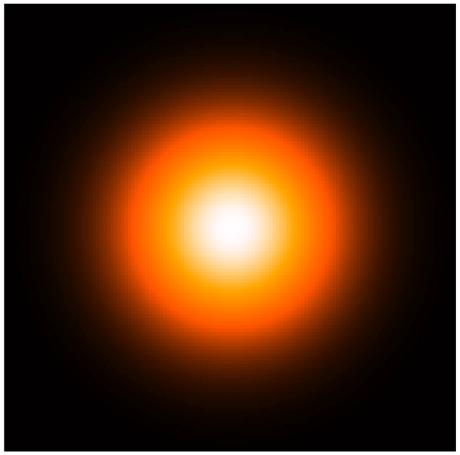


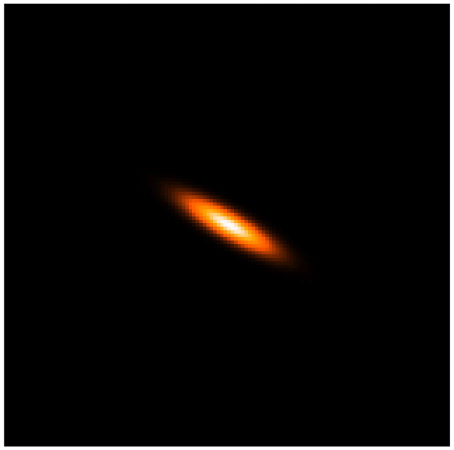
Gaussian

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

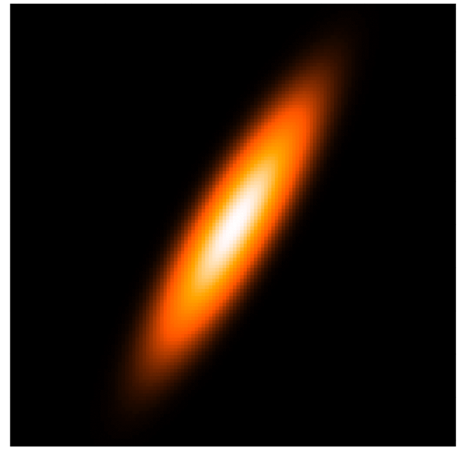
2D Fourier Transform Pairs

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

elliptical Gaussian



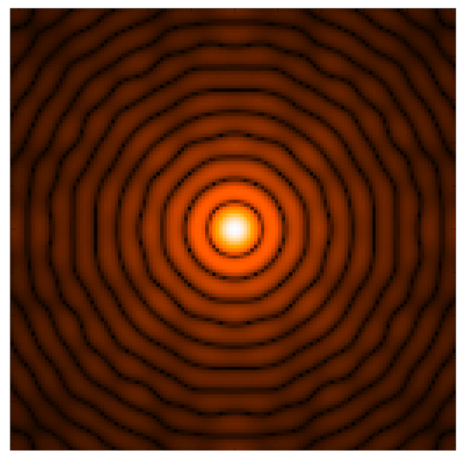
$\rightleftharpoons$



elliptical Gaussian

Disk

$\rightleftharpoons$



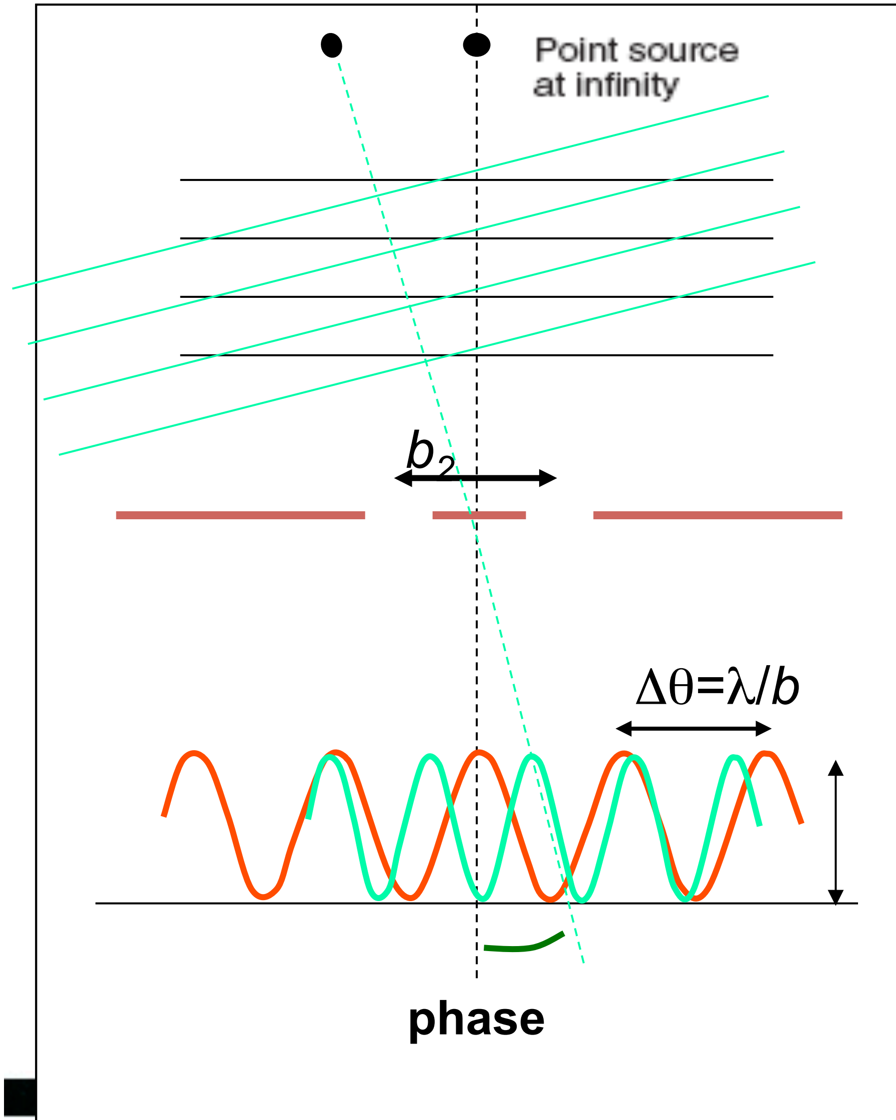
Bessel

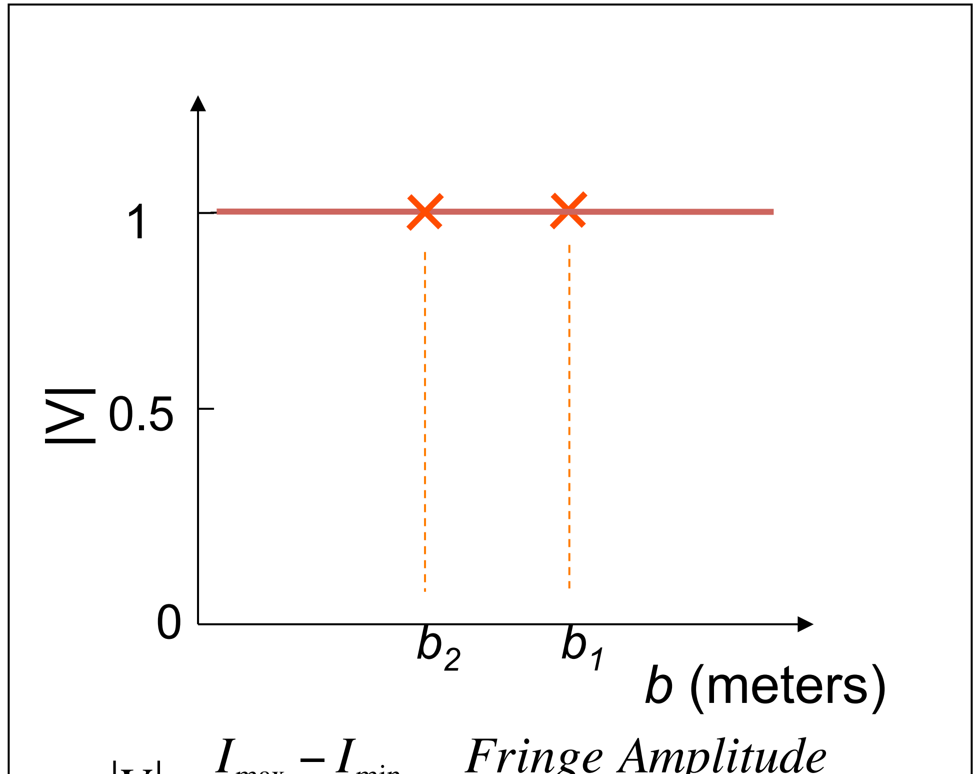
NRAO

sharp edges result in many high spatial frequencies
(sinc function, "ringing", Gibbs phenomenon)

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





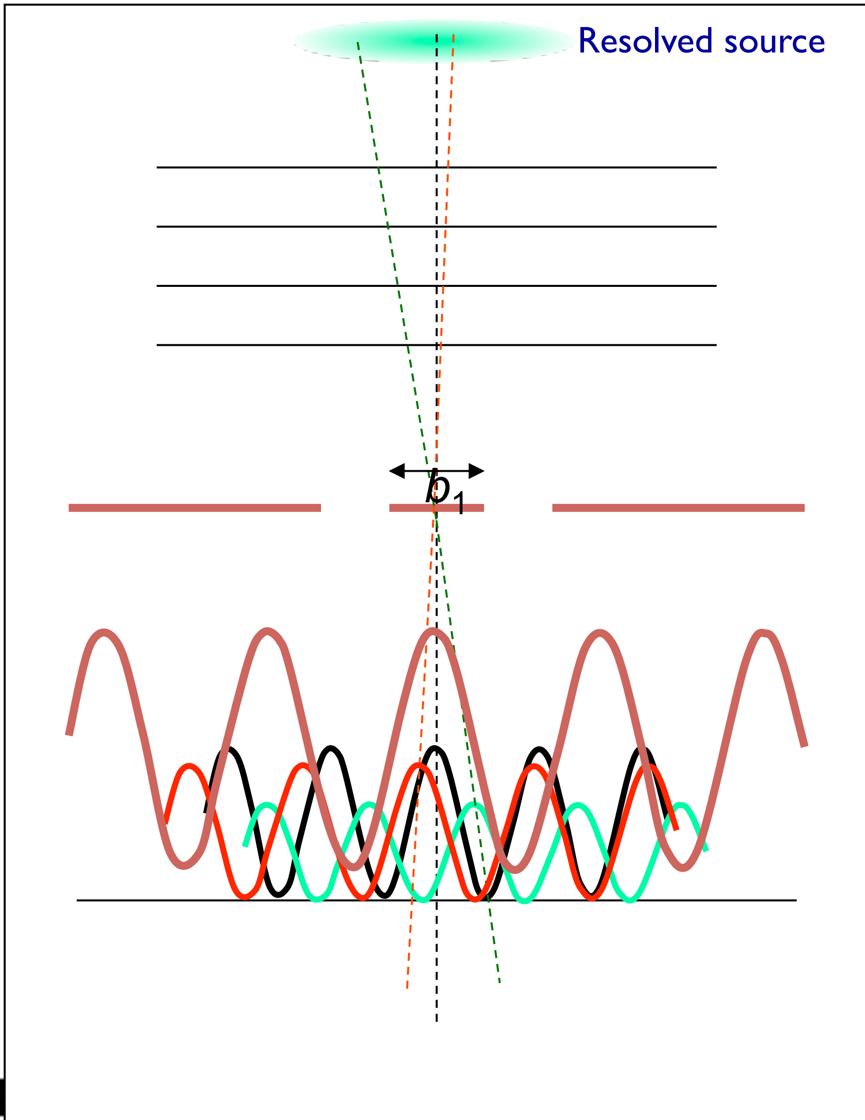
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

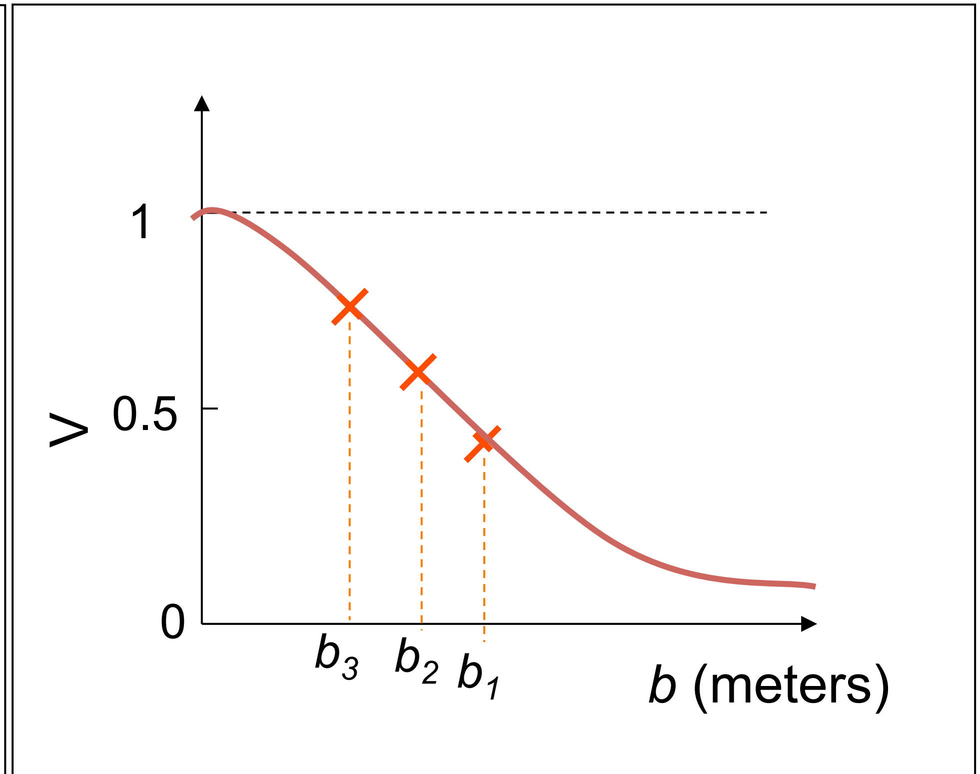
The visibility is a **complex** quantity:

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

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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

Characteristic Angular Scales

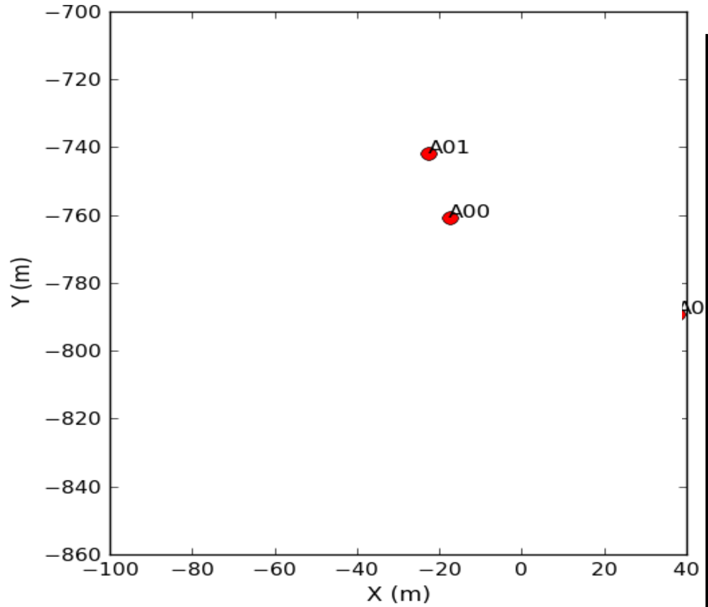
- Angular resolution
  - ~ λ/B_{max} , where B_{max} is the longest baseline
- Maximum angular scale
  - the source is resolved if $\theta>\lambda/B_{min}$, where B_{min} is the minimum separation between apertures.
- Field of view of the single aperture
  - ~ λ/D, where D is the diameter of the telescope.
  - Sources more extended than the field of view can be observed using multiple pointing centers in a mosaic.

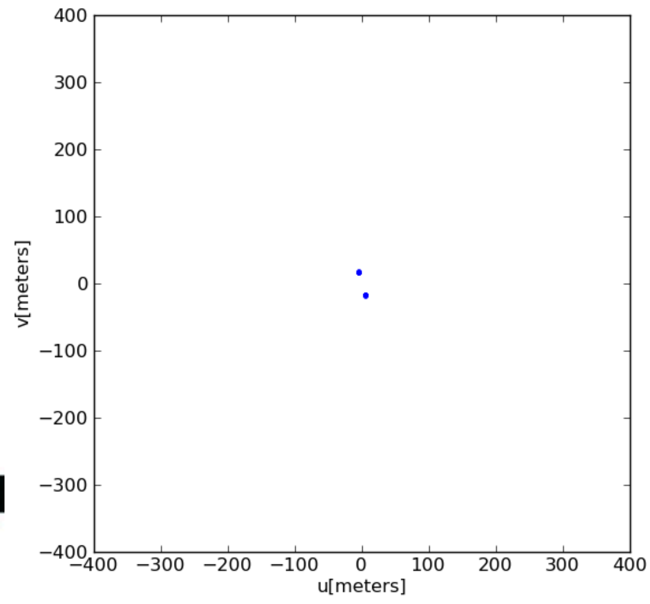
An interferometer is sensitive to a range of angular sizes

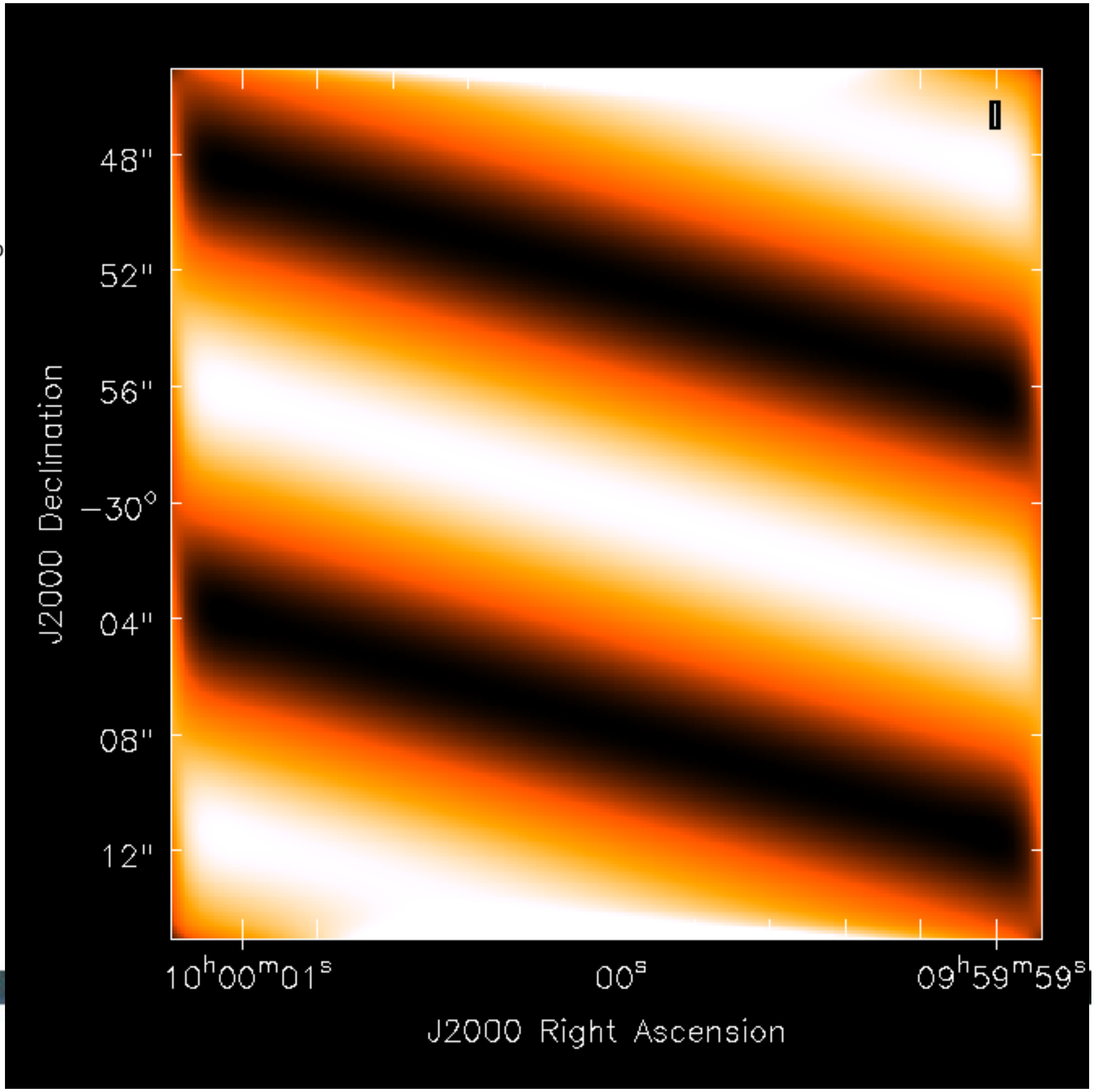
$$\lambda/B_{max} < \theta < \lambda/B_{min}$$

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

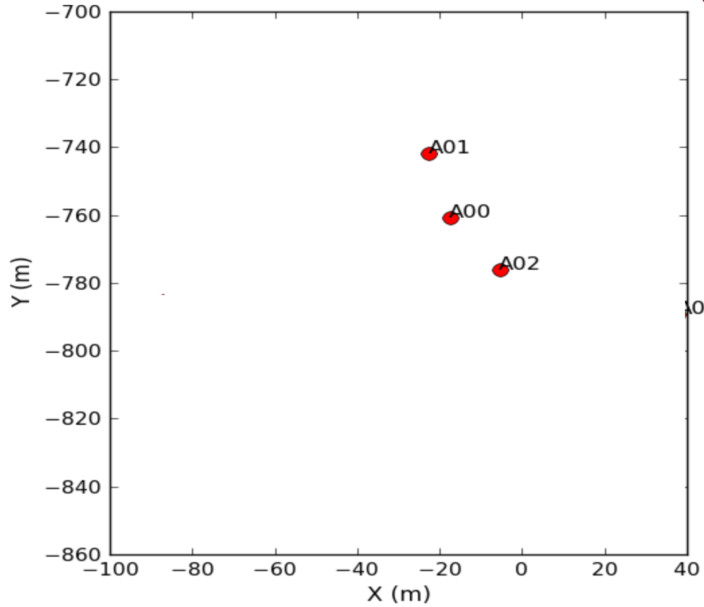
Example: Fringe pattern with 2 Antennas (1 baseline)

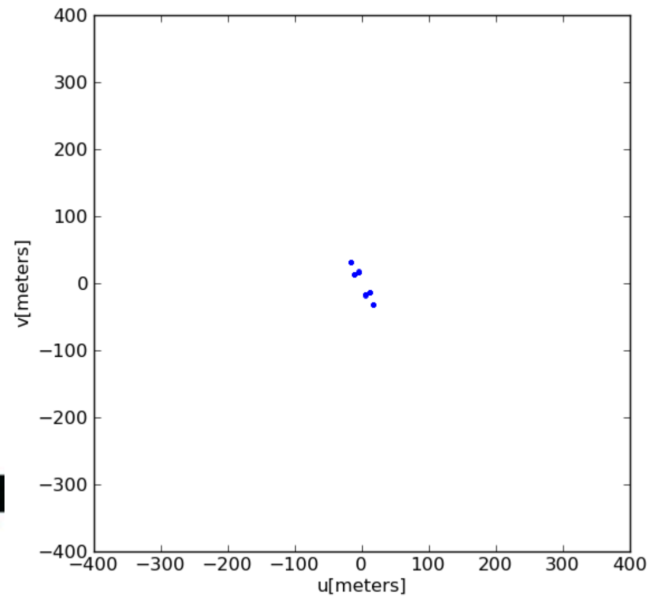


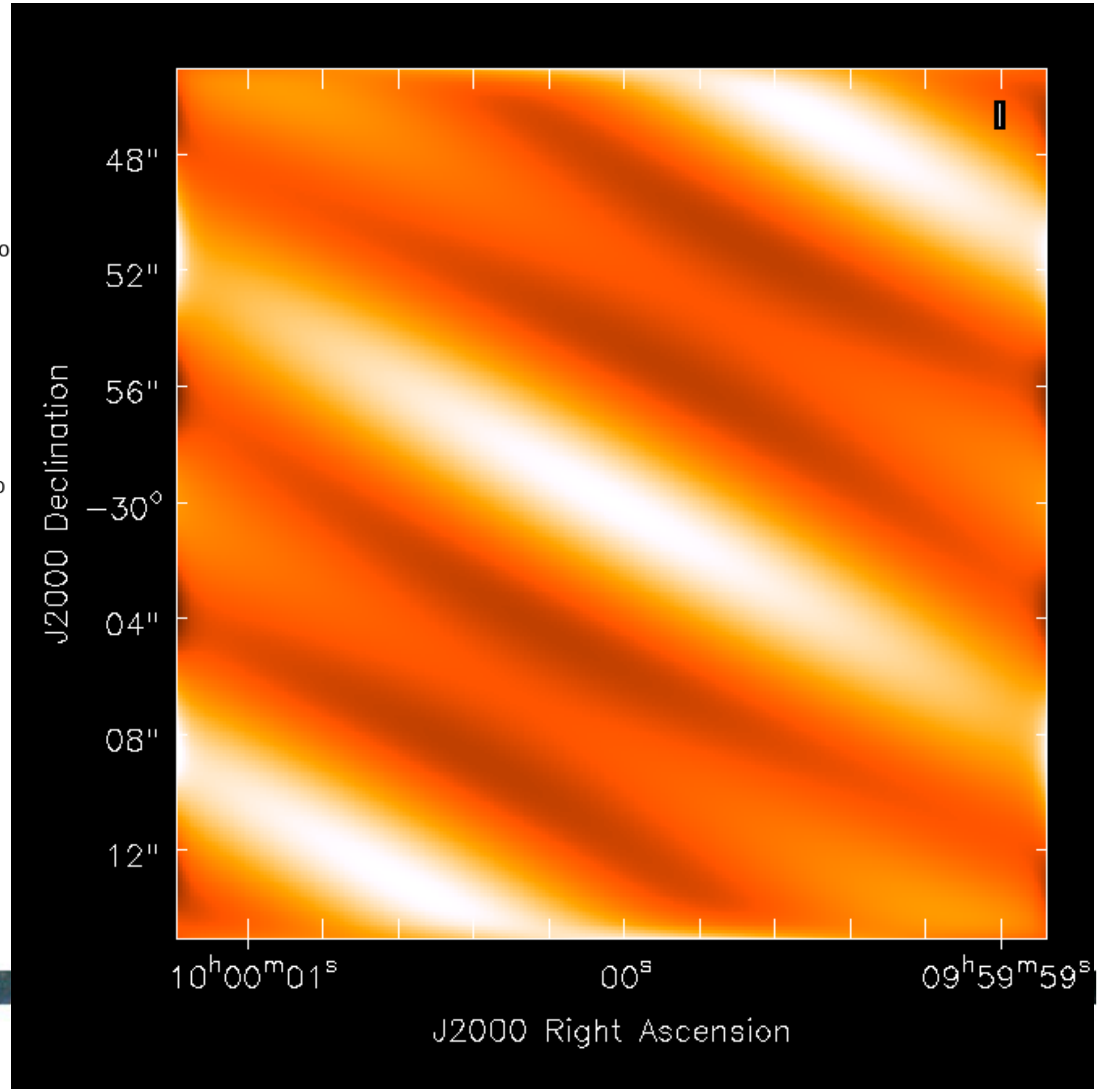




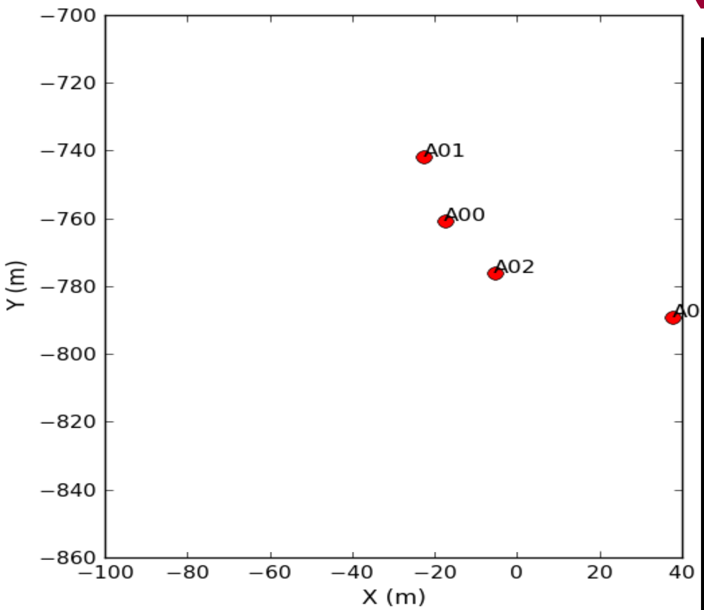
Example: Fringe pattern with 3 Antennas (3 baselines)

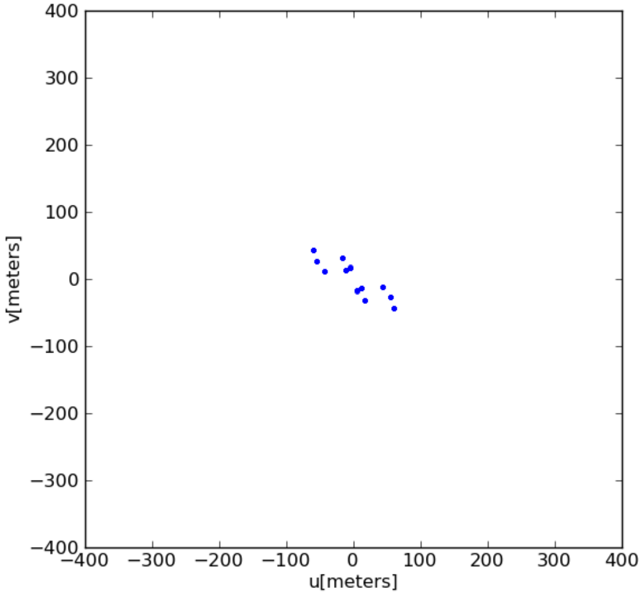


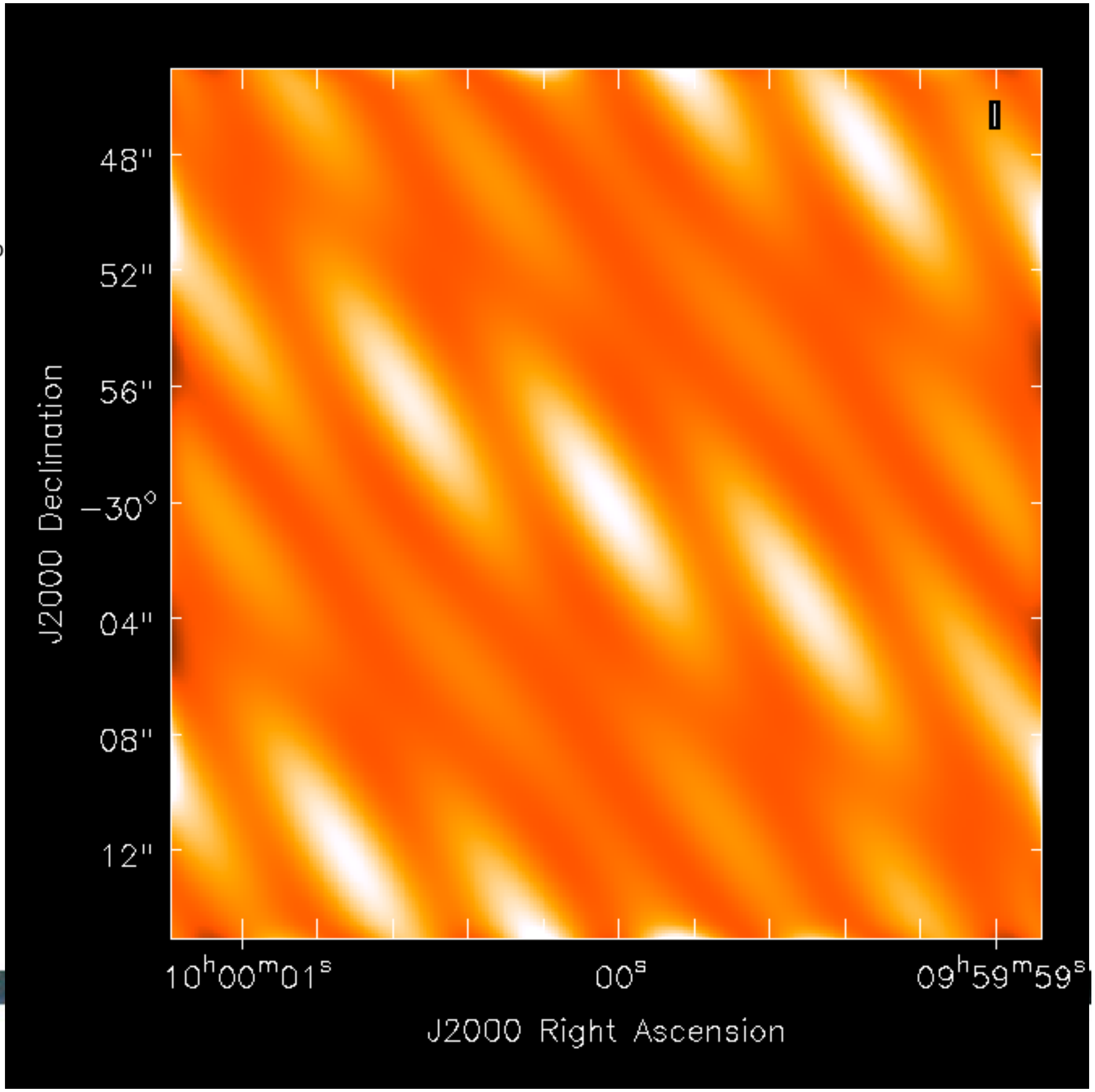




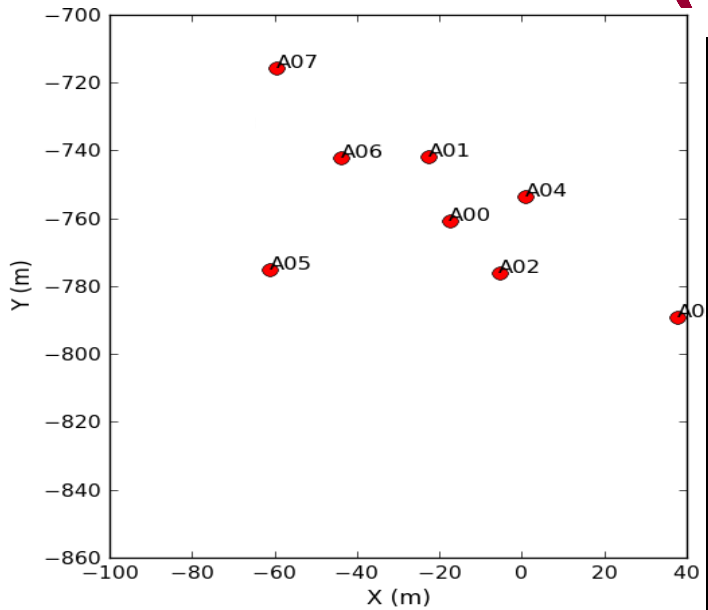
Example: Fringe pattern with 4 Antennas (6 baselines)

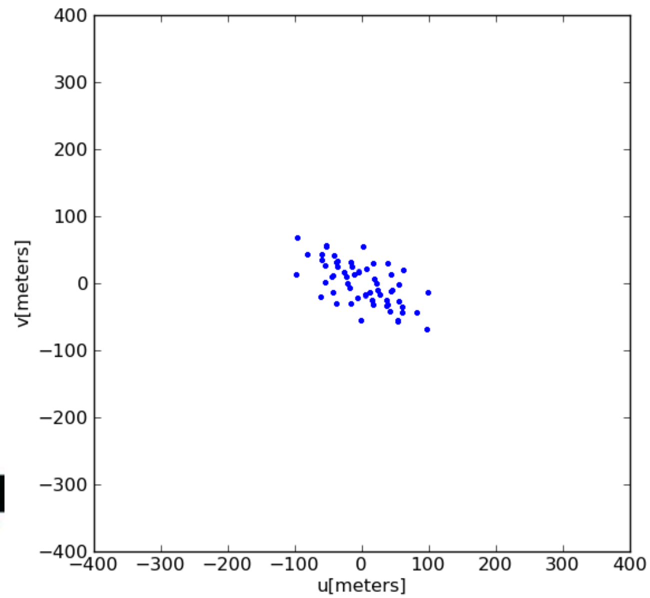


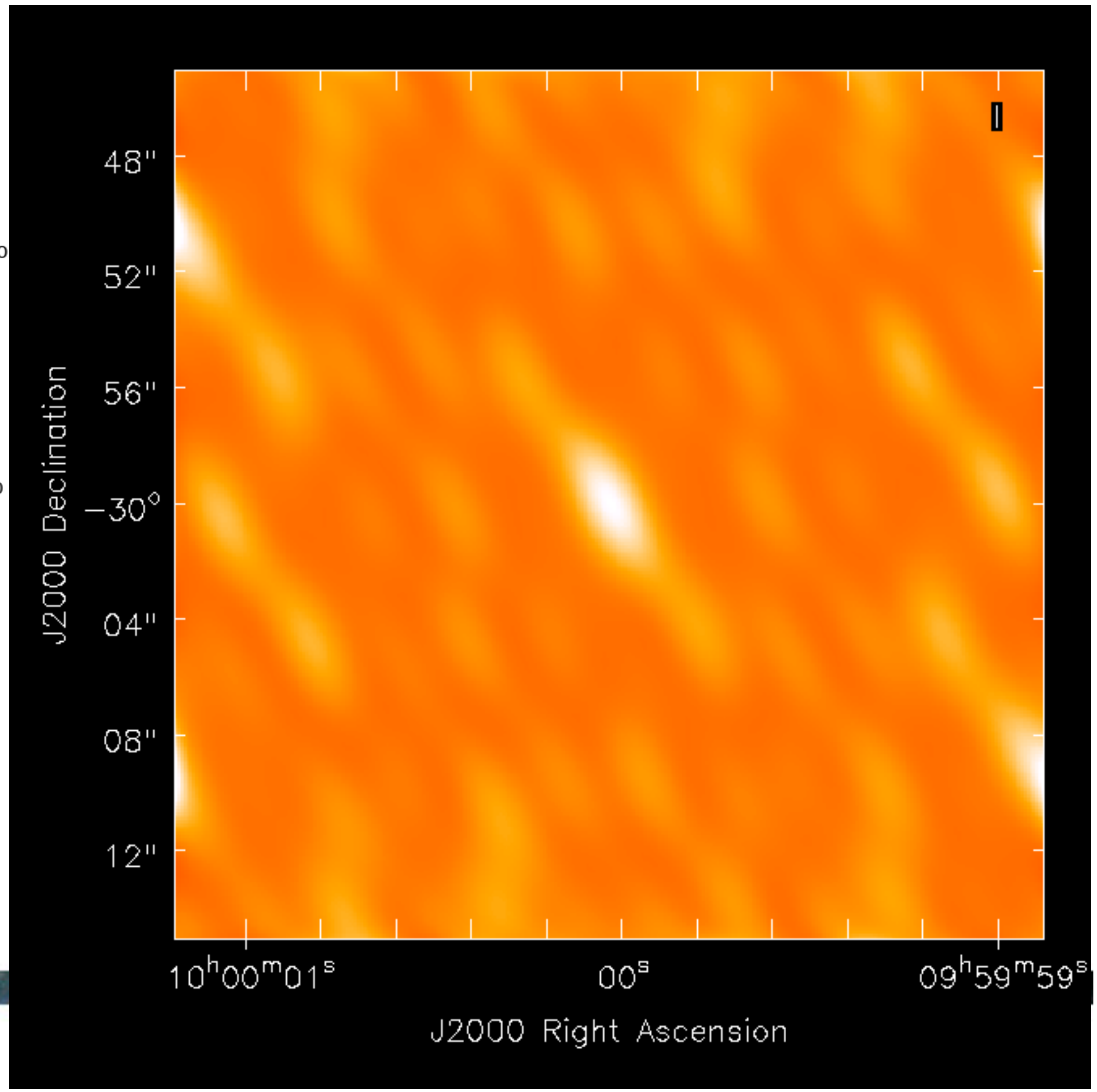




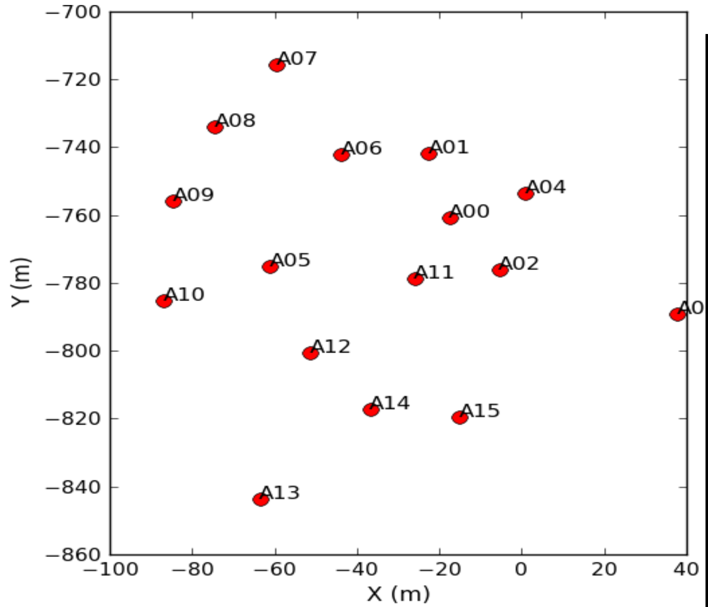
Example: Fringe pattern with 8 Antennas (28 baselines)

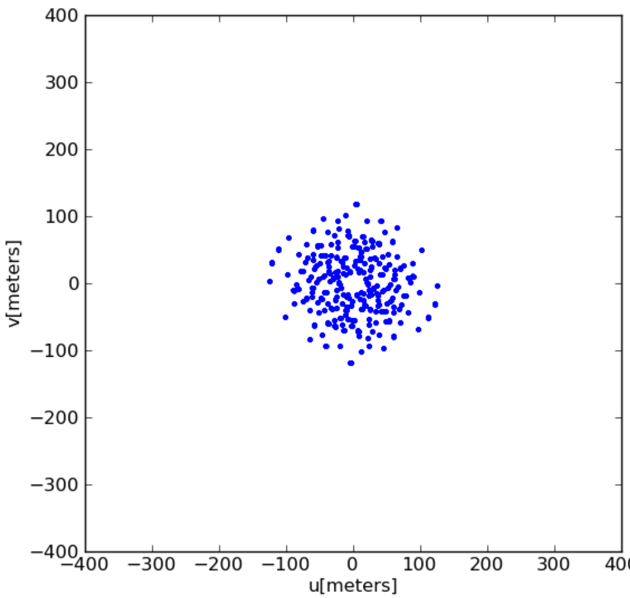


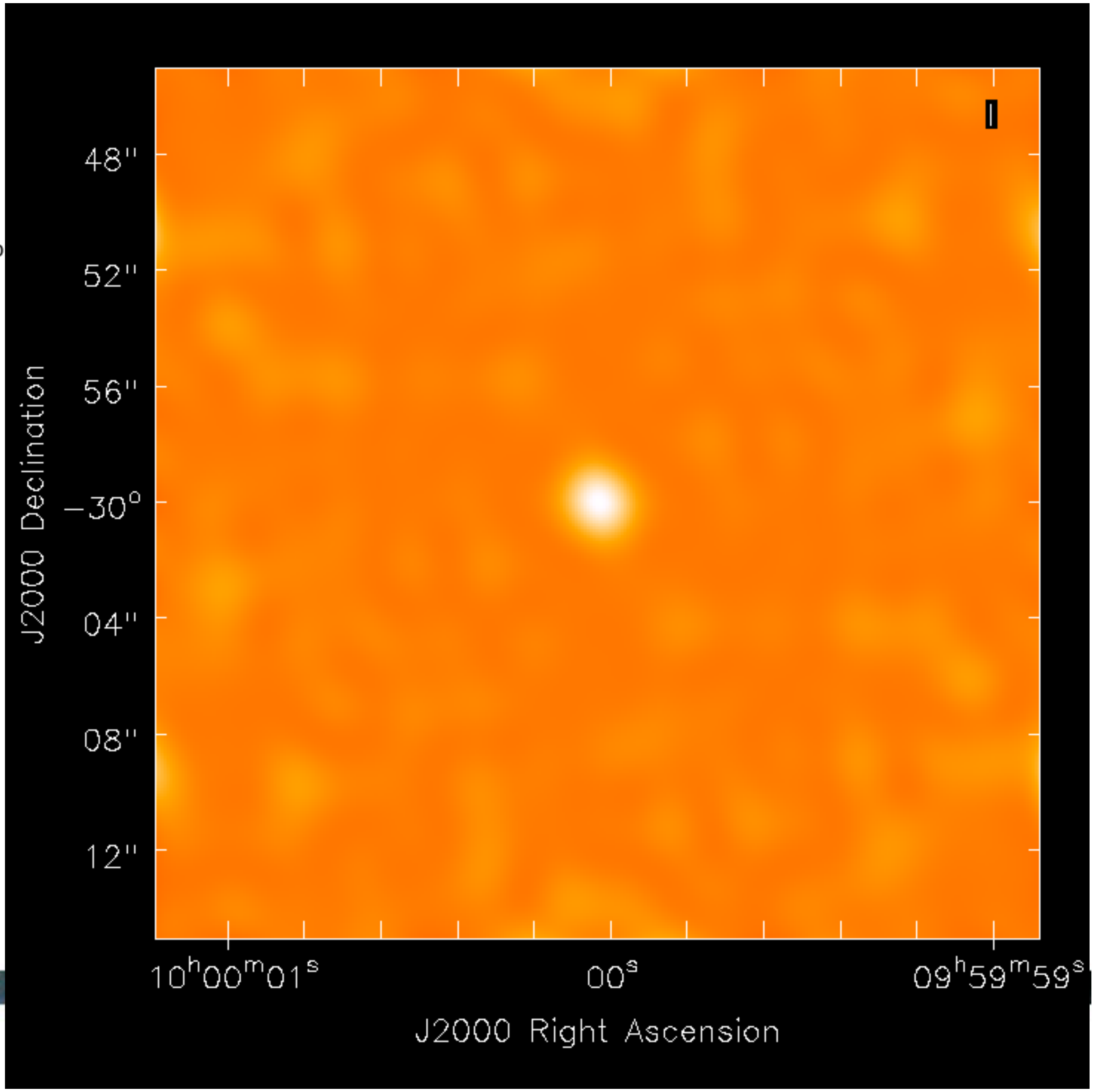




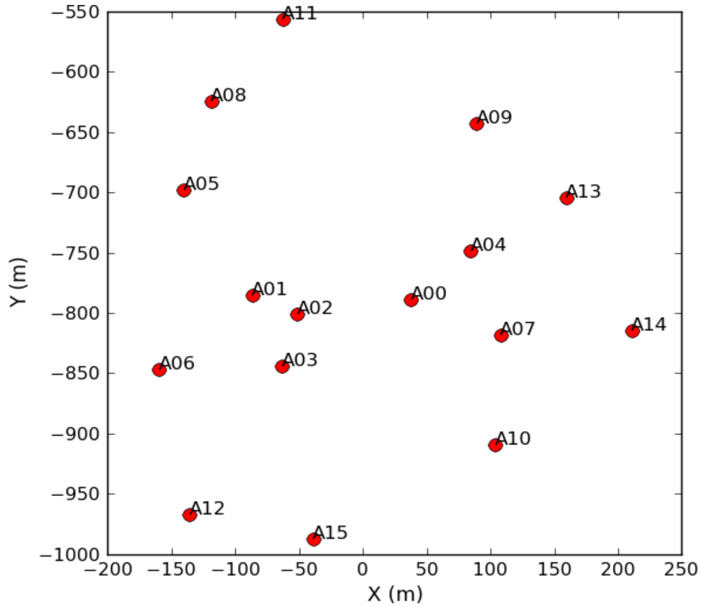
16 Antennas – Compact Configuration

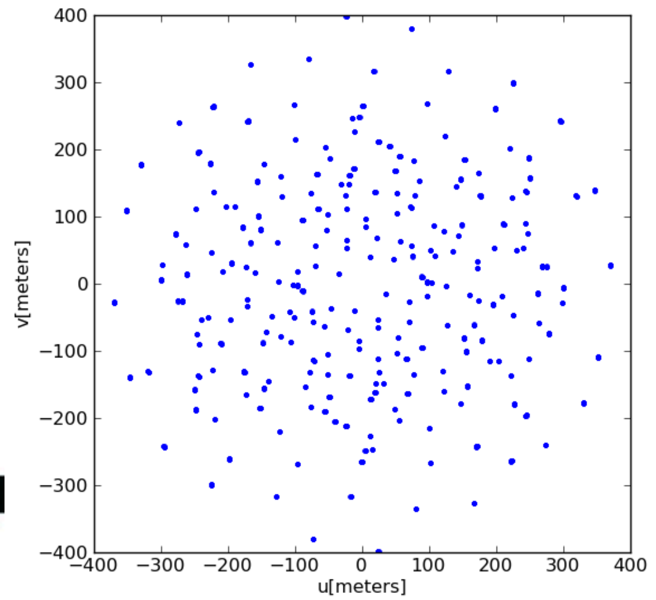


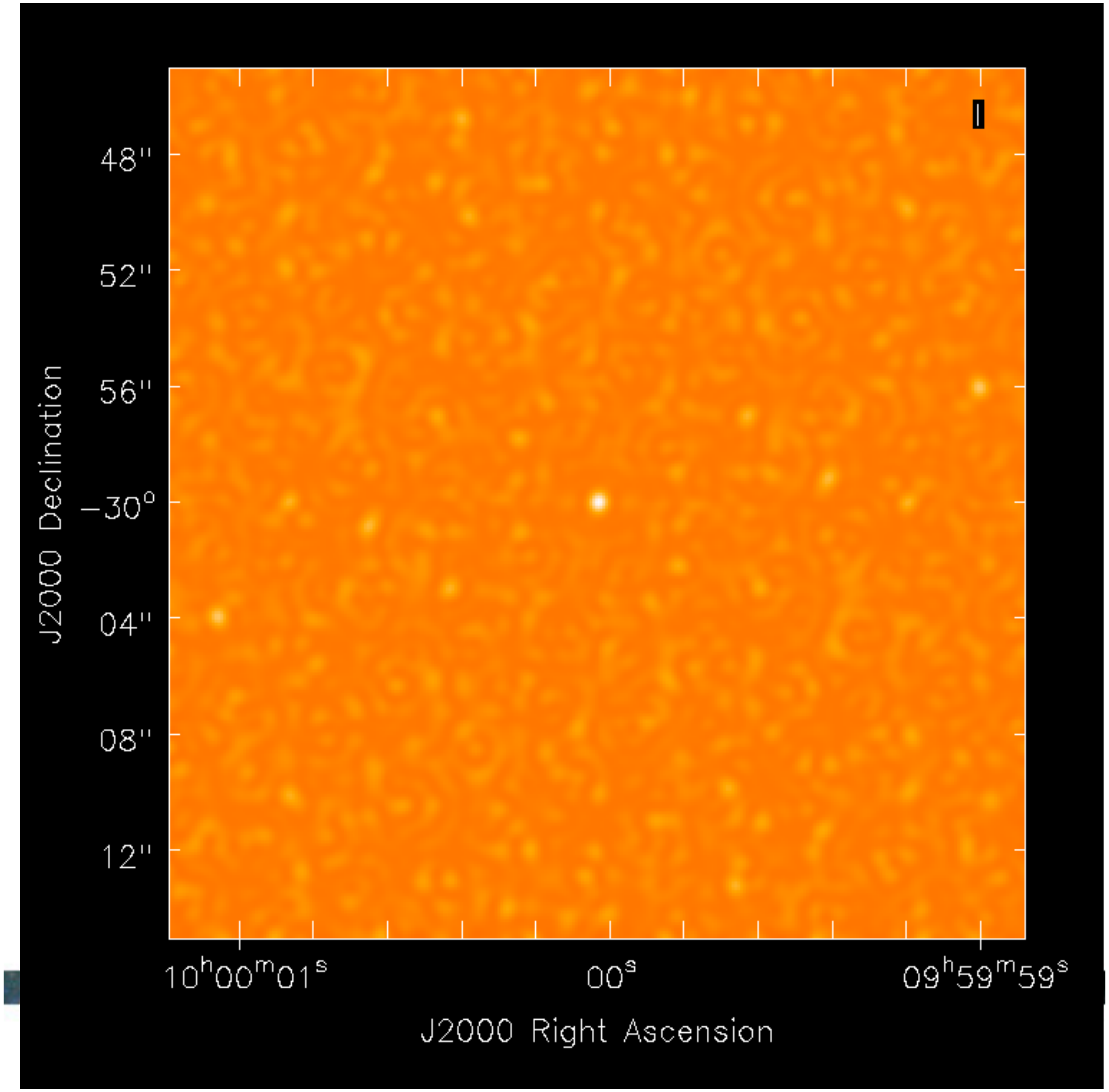




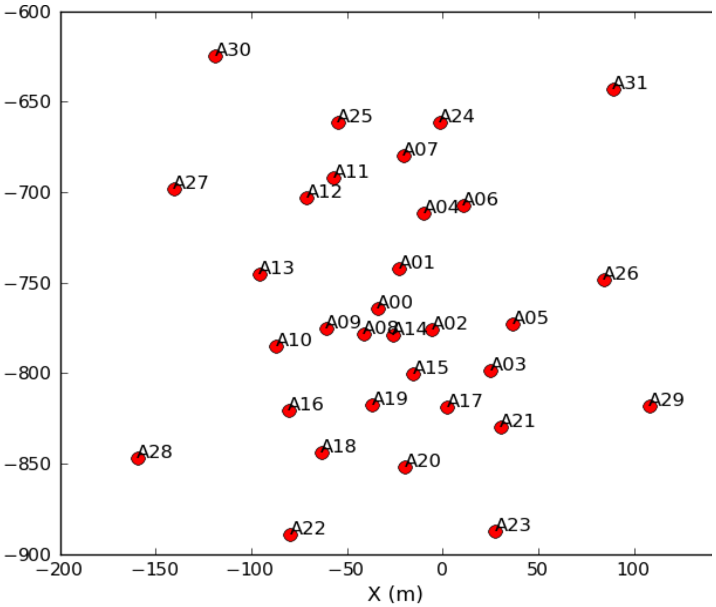
16 Antennas – Extended Configuration

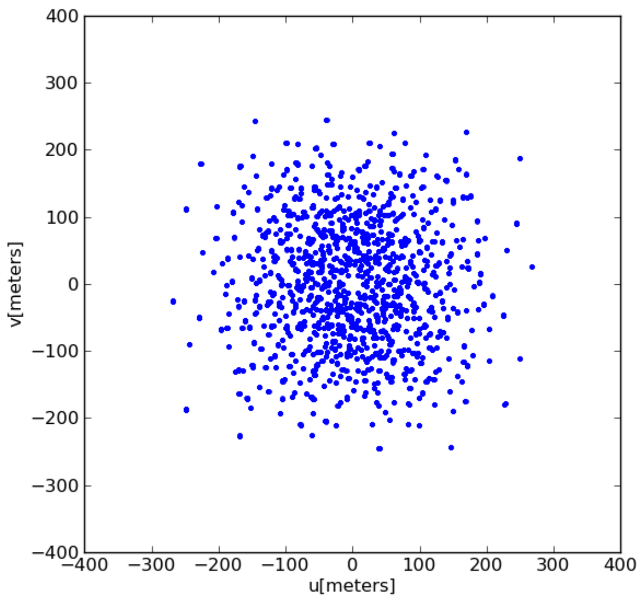


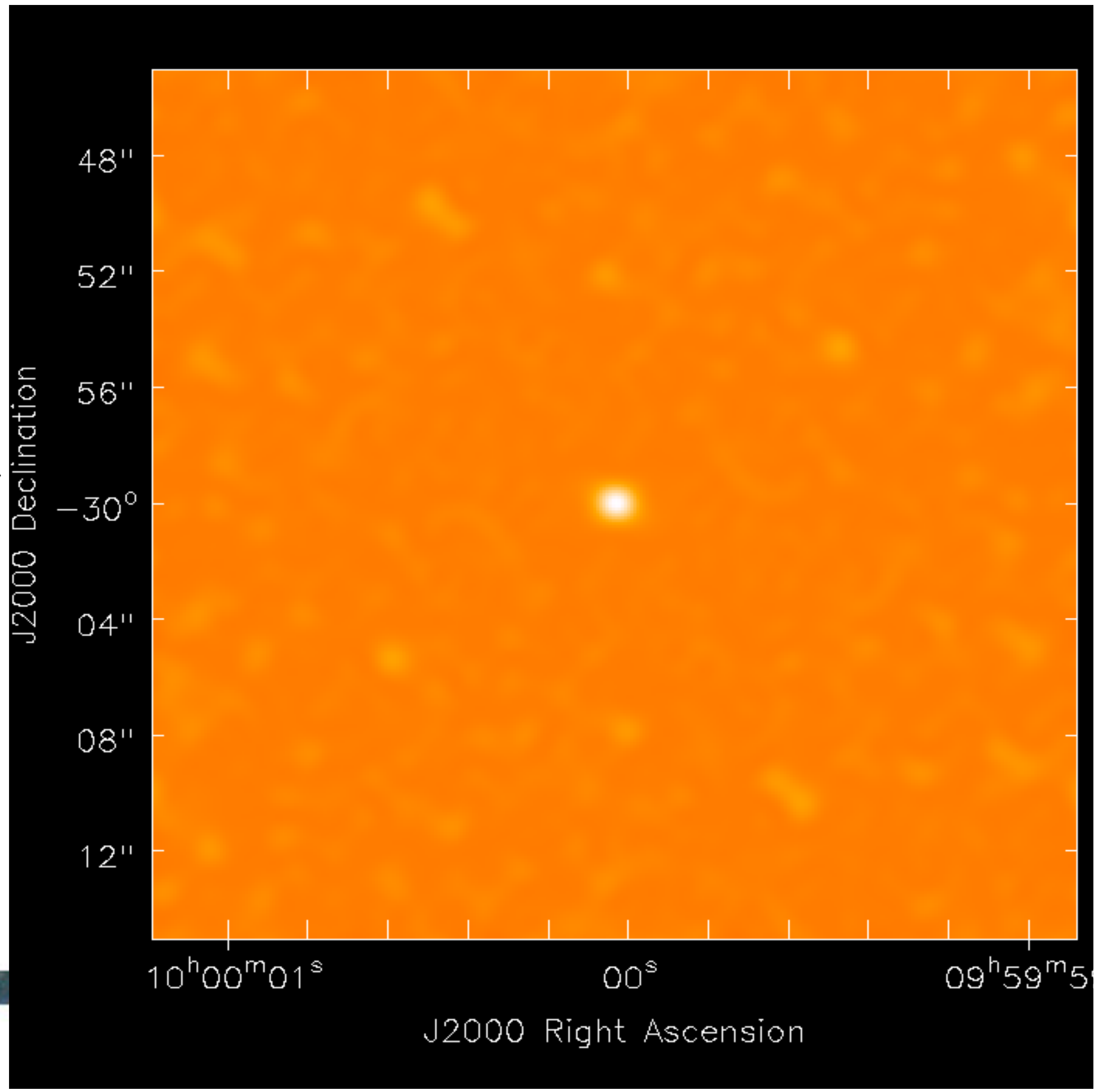




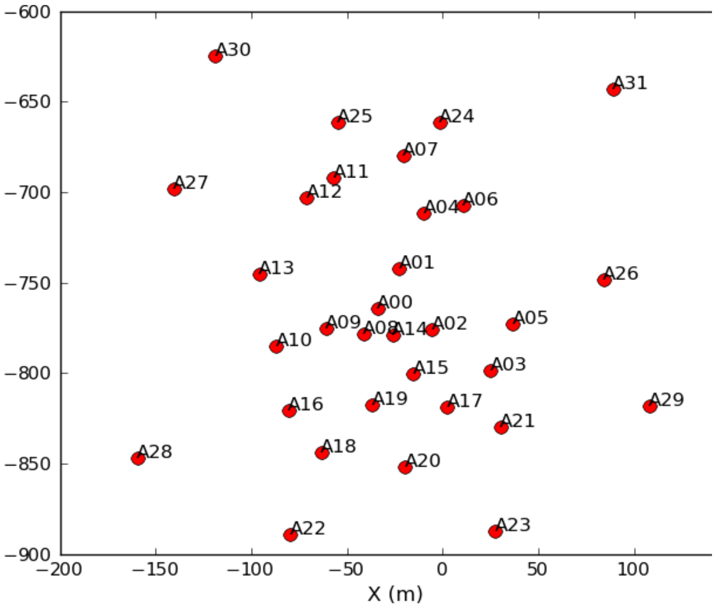
32 Antennas – Instantaneous

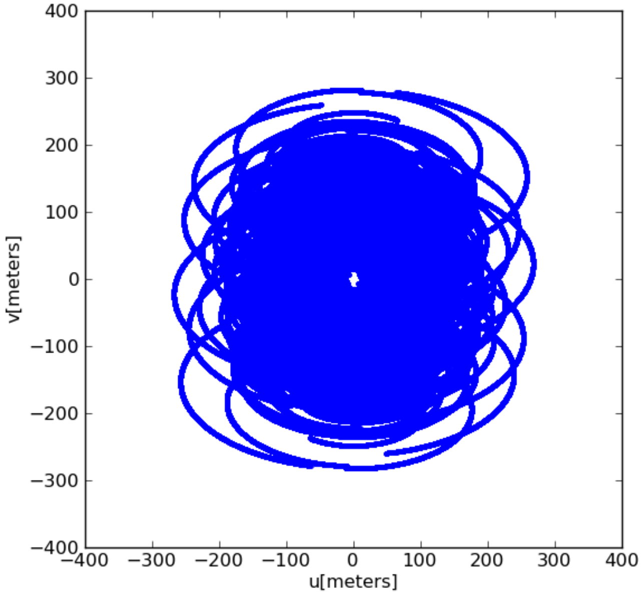


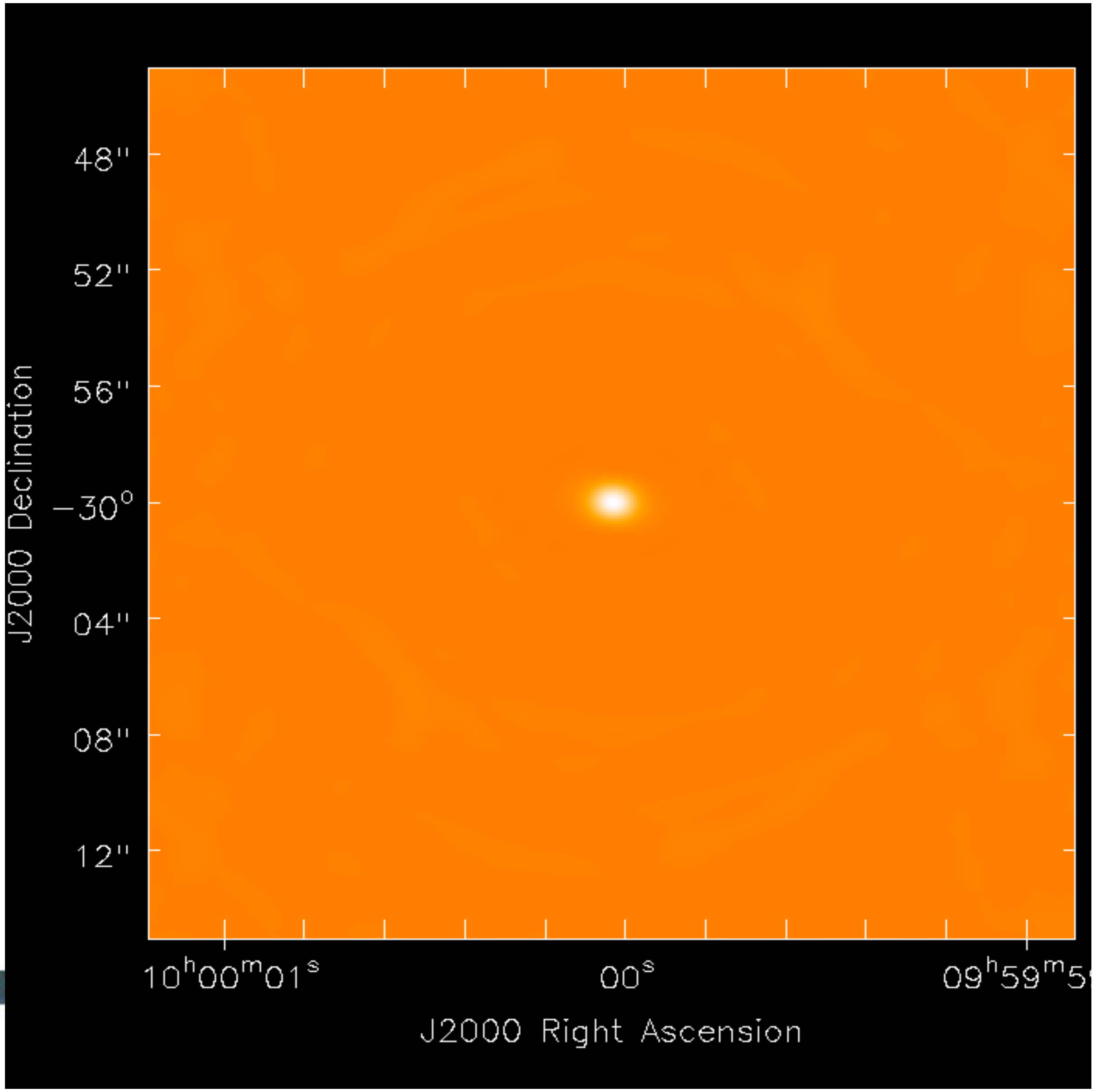




32 Antennas – 8 hours

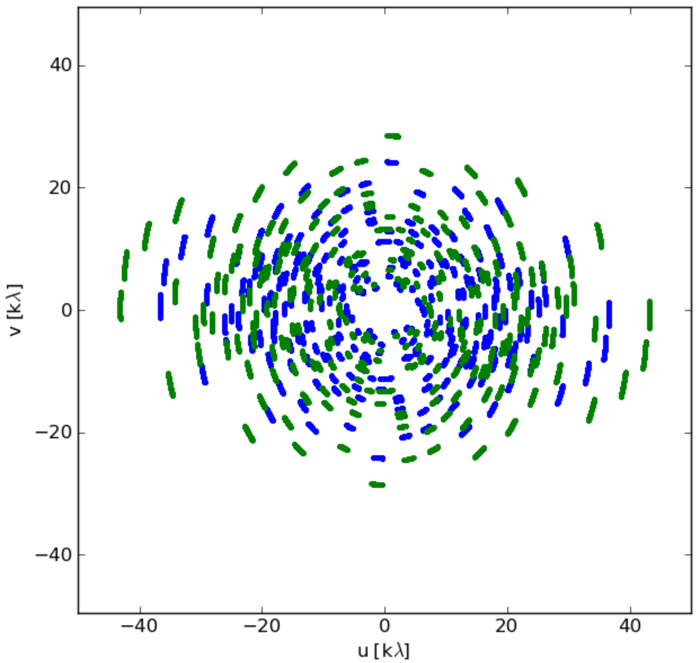


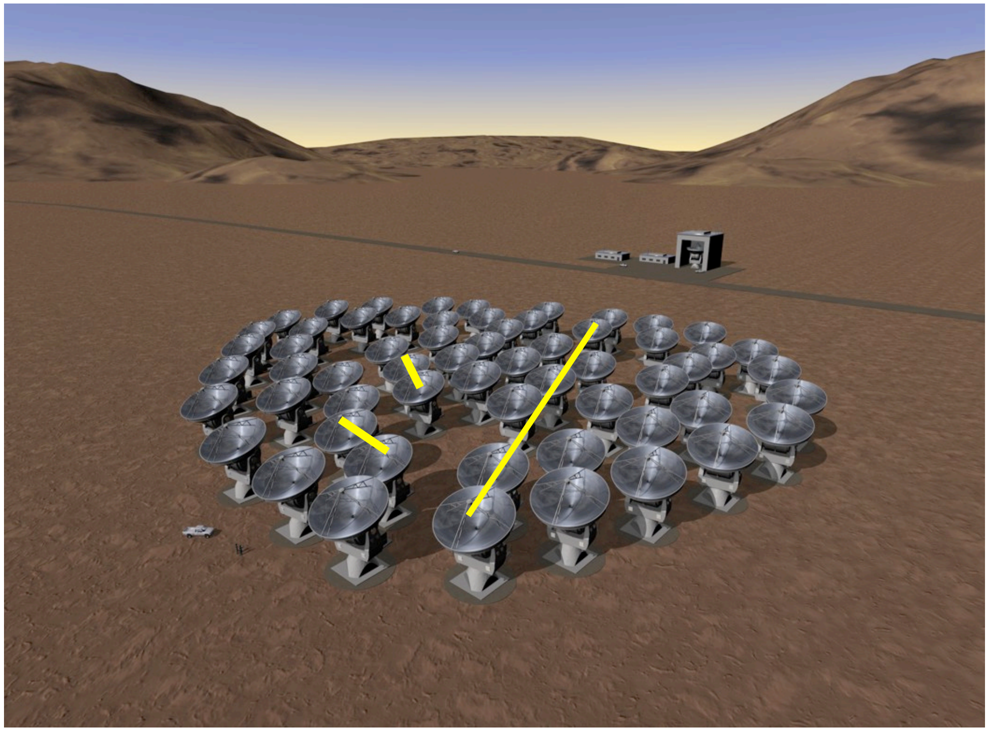




Sampling Function

Interferometers cannot see the entire Fourier/uv domain. But each antenna pair samples one spot: ➔ **imperfect image**

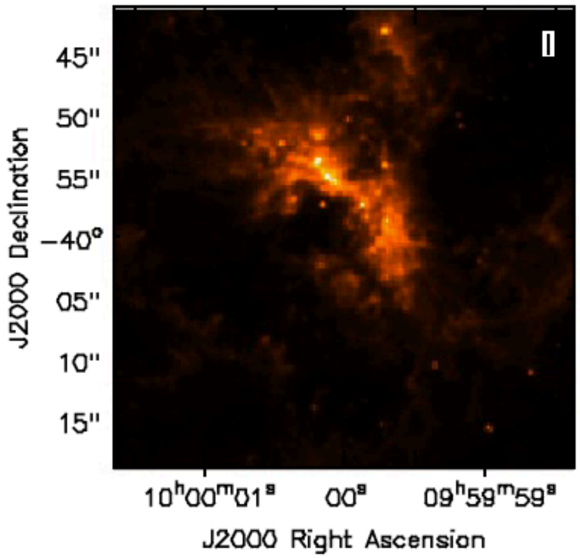




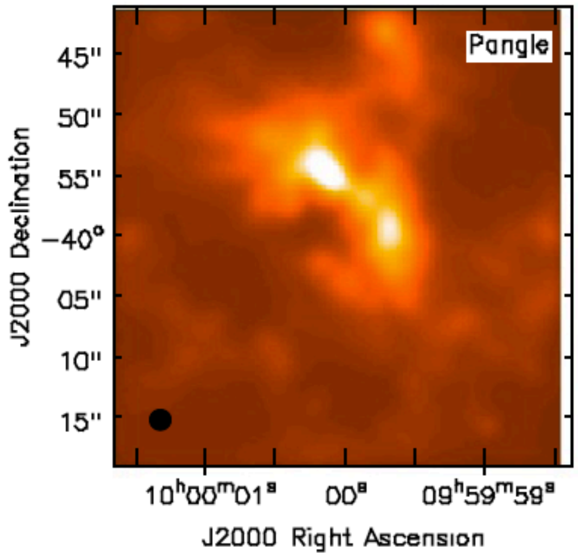
Small uv-distance: short baselines (measure extended emission)
Long uv-distance: long baselines (measure small scale emission)
Orientation of baseline also determines orientation in the uv-plane

Model: Complicated image

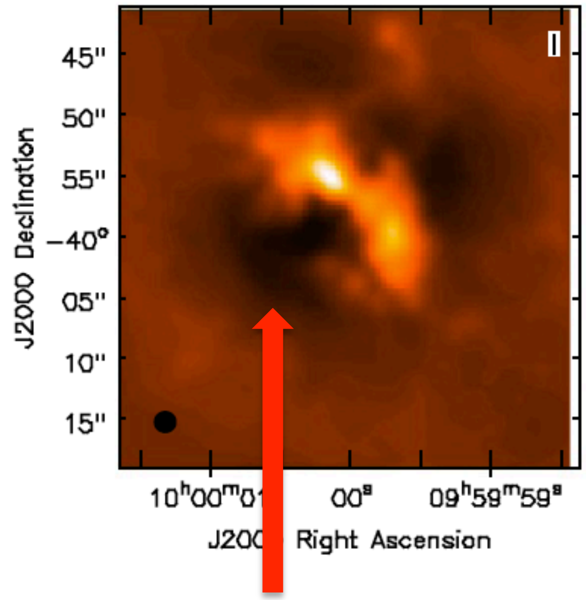
Model Image



Convolved Model



"Observed" Image

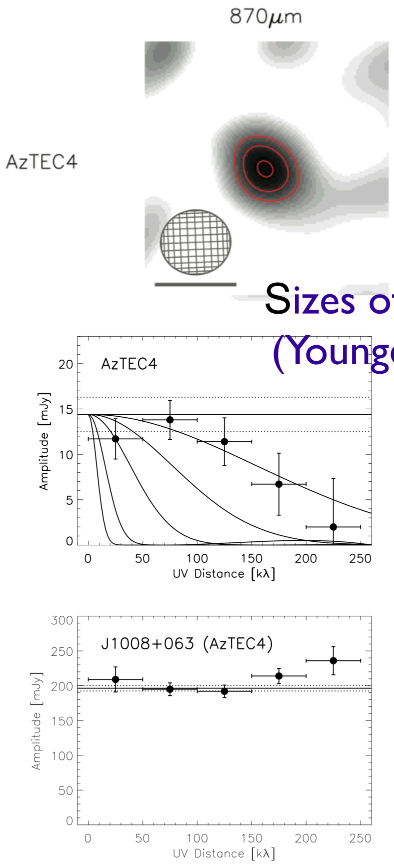


2 hour observation with
32 antennas

Large scale emission: Fill in with shorter baselines

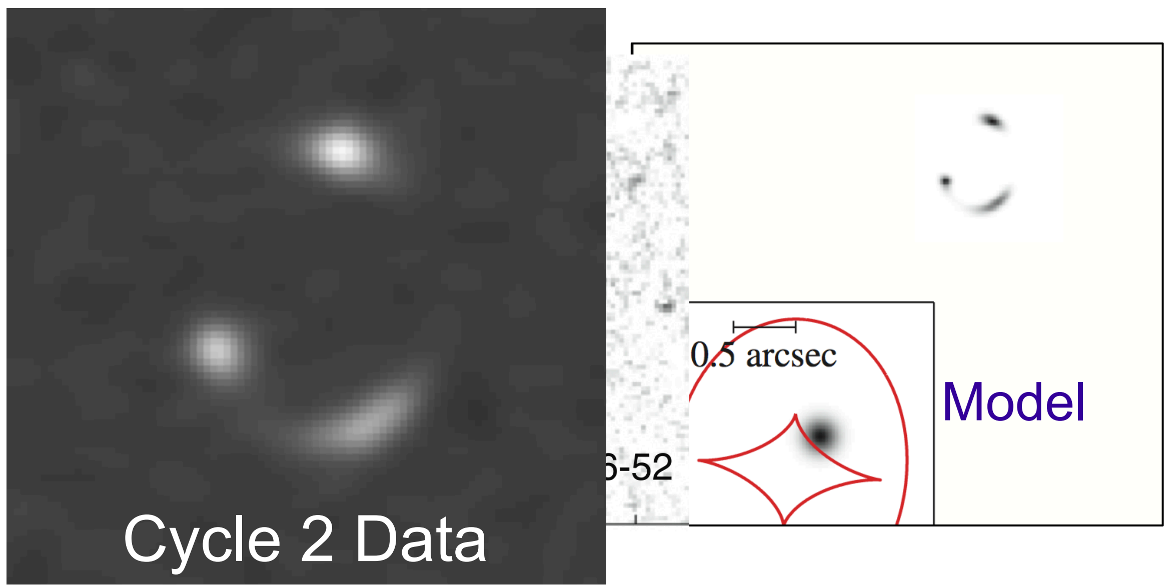
Model: Fourier Modeling

When possible, comparing models to visibilities is more robust than using images

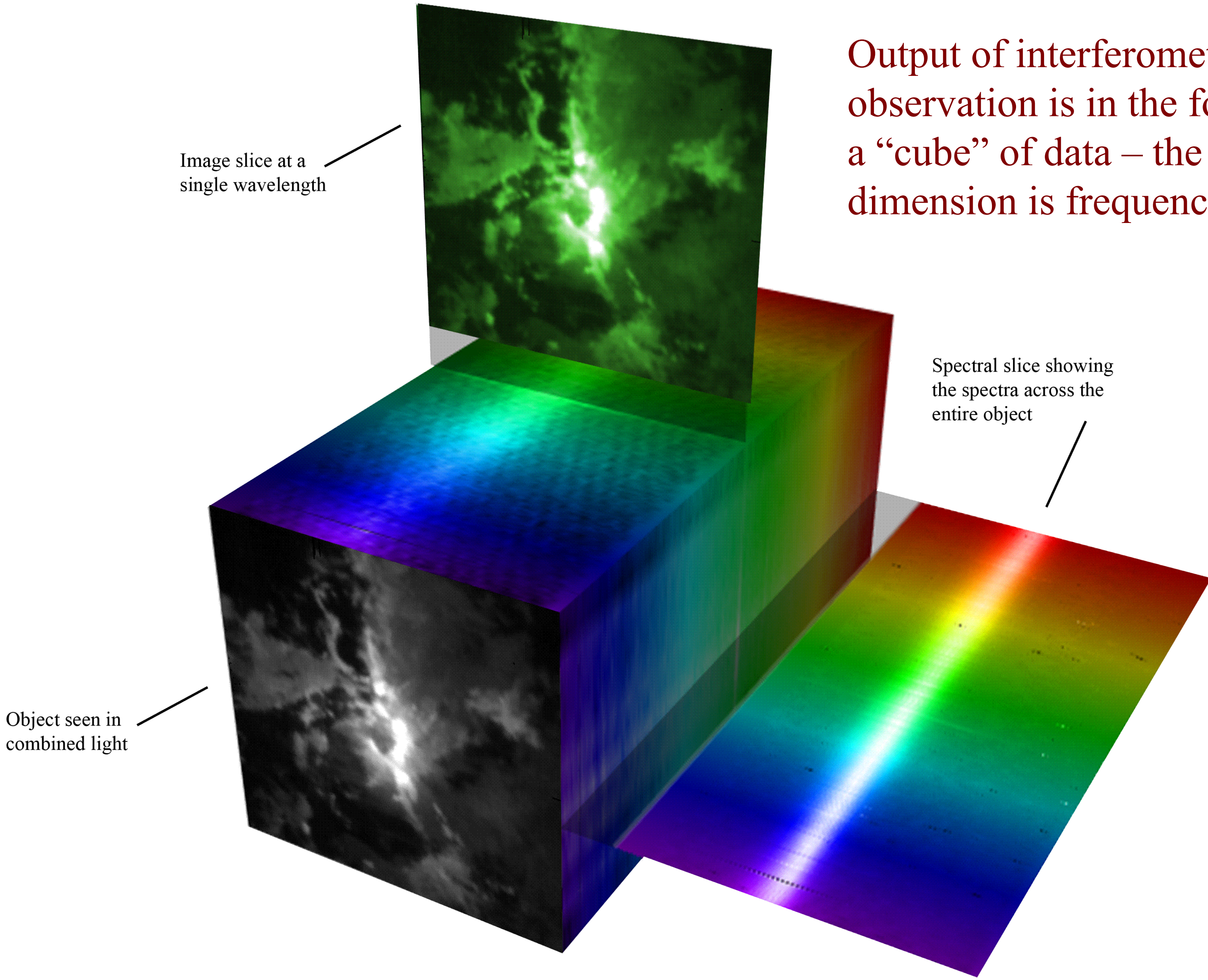


Sizes of SMGs (Younger+10)

Gravitational Lens Modeling with ALMA (Hezaveh, Marrone+13)

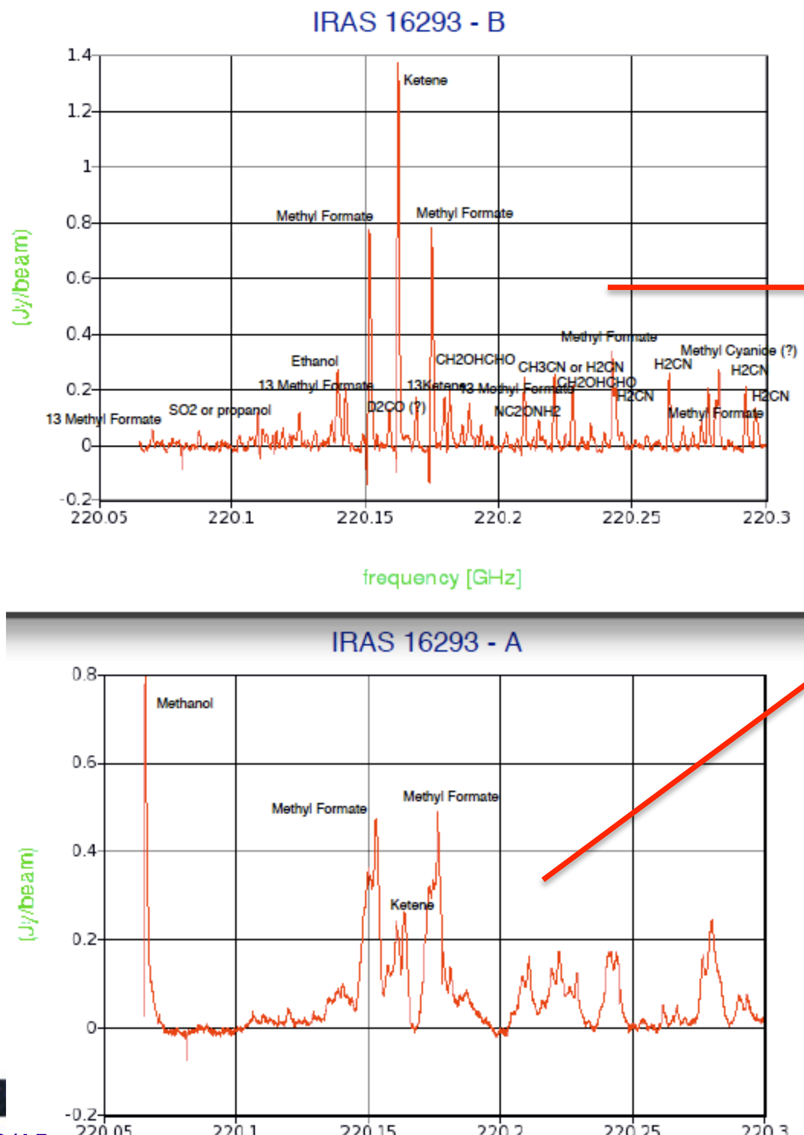


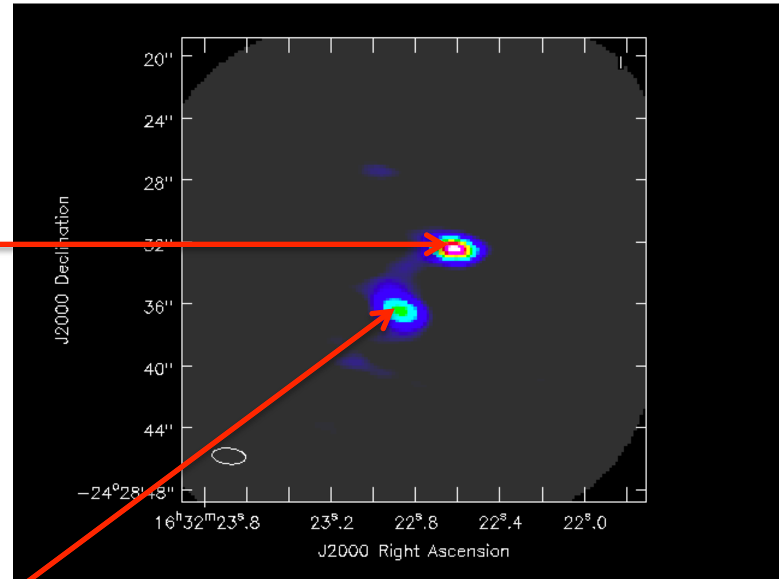
Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.



Interesting result not always an image

Band 6



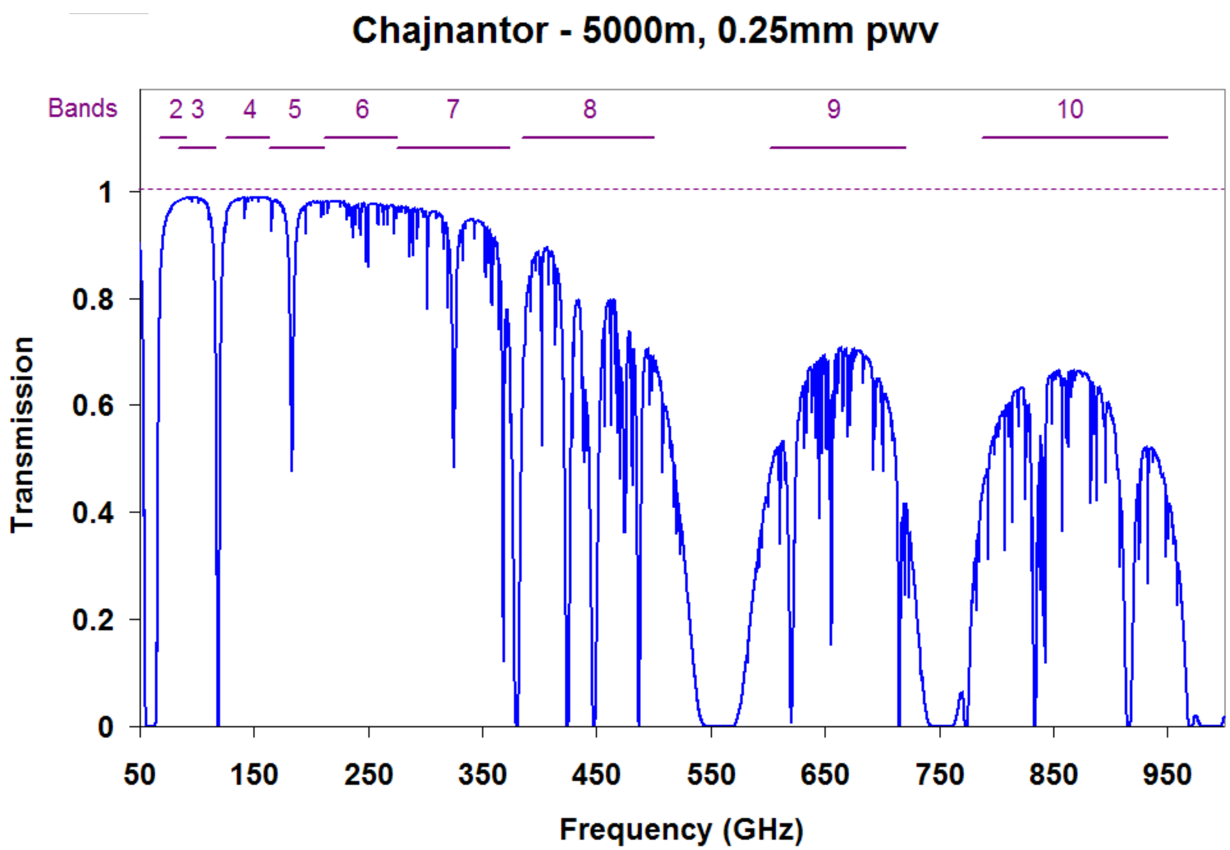


J. Turner & ALMA CSV team

Young Low Mass Stars: IRAS16293

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

Atmospheric Transmission in the mm/submm wavelength range



Earth's atmospheric lines block access to some spectral regions except at Earth's highest driest site. ALMA's spectral reach enables study of the Universe in all mm/submm windows for which transmission is better than 50%

Observing Strategy

Choose your array by largest angular scale of target

- Interferometer acts as spatial filter, shorter baselines are sensitive to larger targets:

  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 to solve for atmospheric and instrumental variations with time: Reasonably bright quasar **near** science target
- Bandpass calibrator to solve for instrumental effects and variations with frequency
  - Usually bright quasar
- Absolute flux calibrator to scale amplitudes
  - Solar system object or quasar

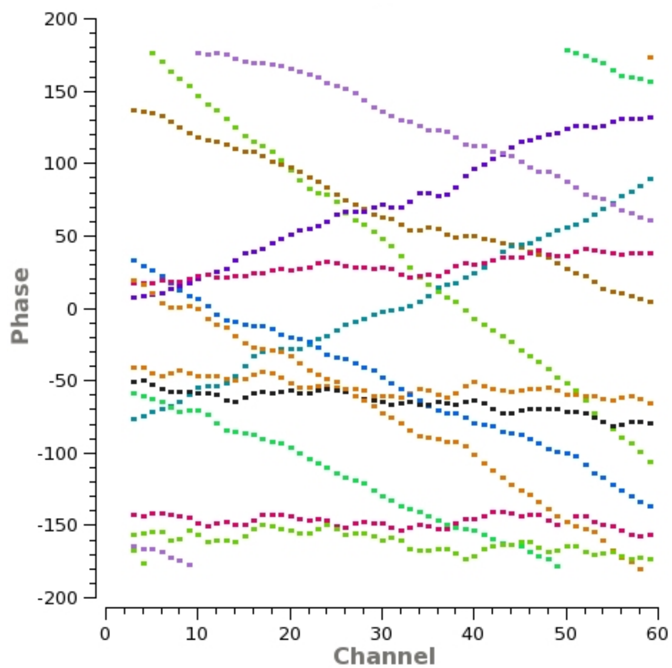
Calibration Process

- Correct frequency-dependent telescope response (Bandpass cal)
- Remove affects of atmospheric water vapor (Phase cal)
- Correct time-varying phases and amplitudes (Phase/gain cal)
- Set absolute flux scale (Flux cal)
- Remove problematic data (flagging)

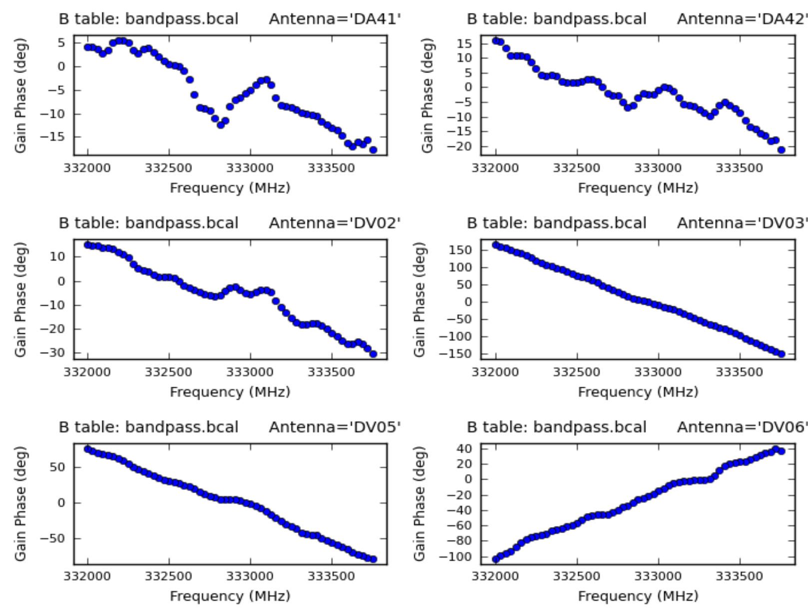
Bandpass Calibration: Phase

“Flat fielding” for the antennas
Typically, baseline responses are inverted to antenna-based correction

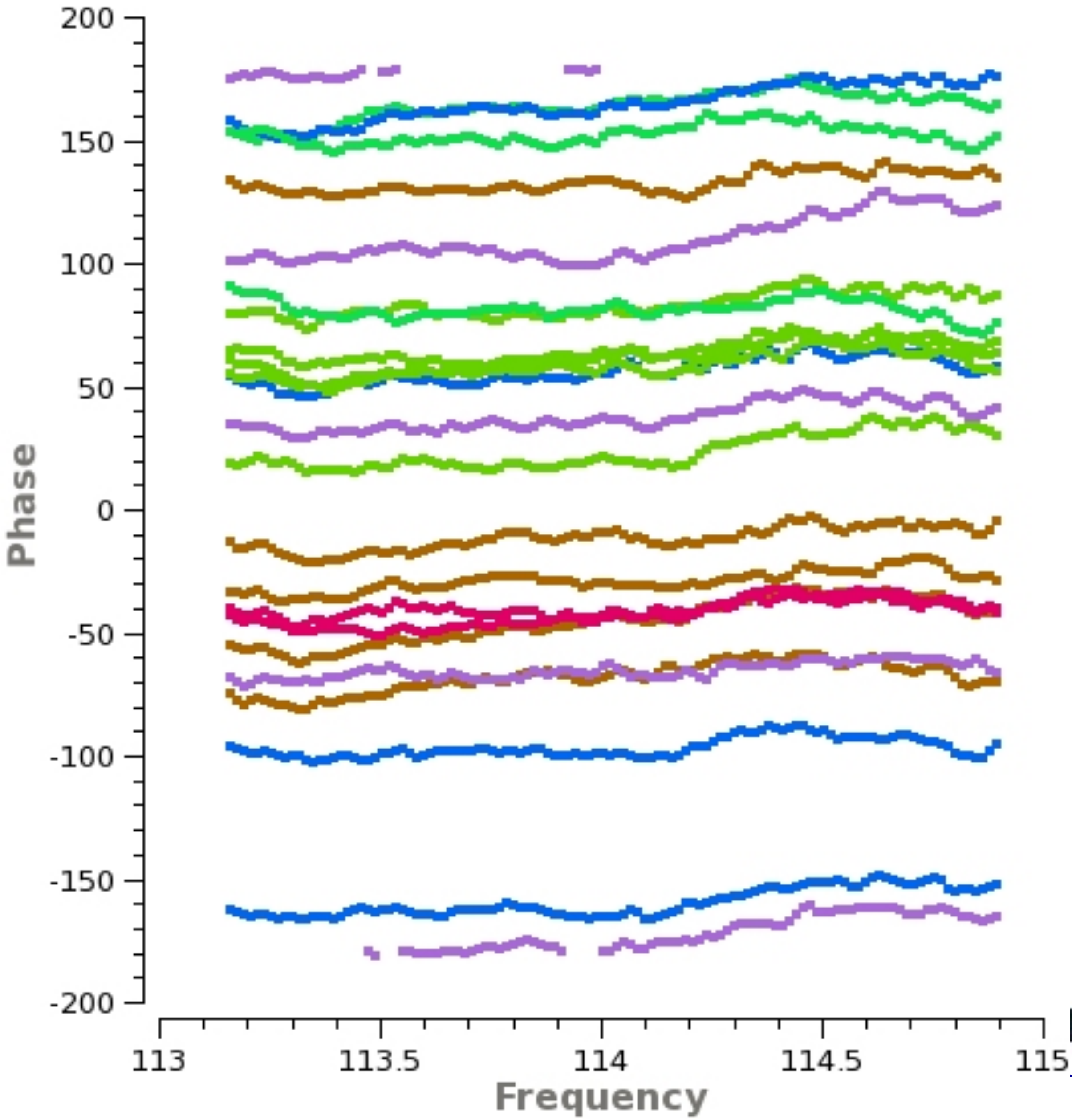
Baselines to one antenna



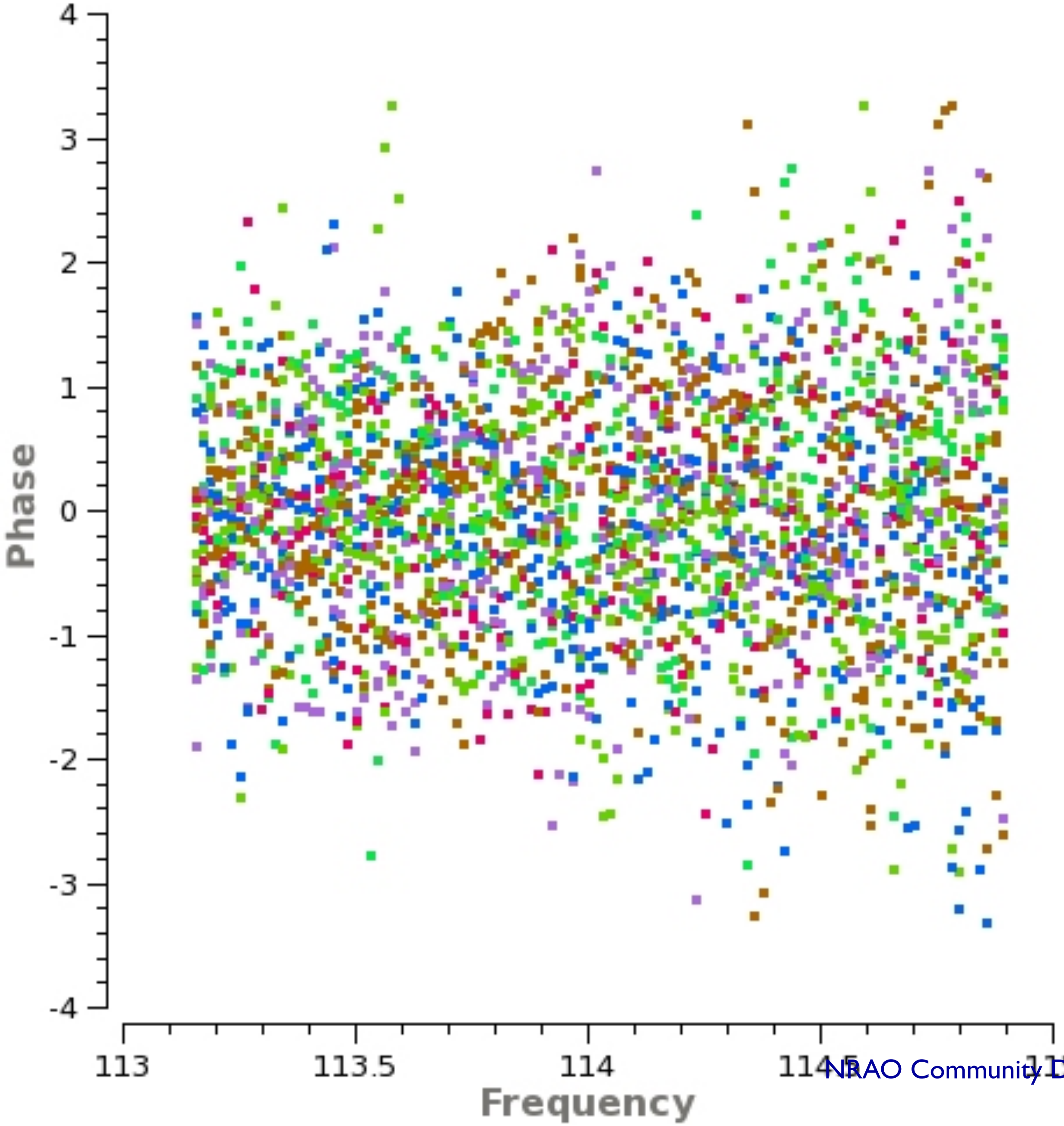
Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)

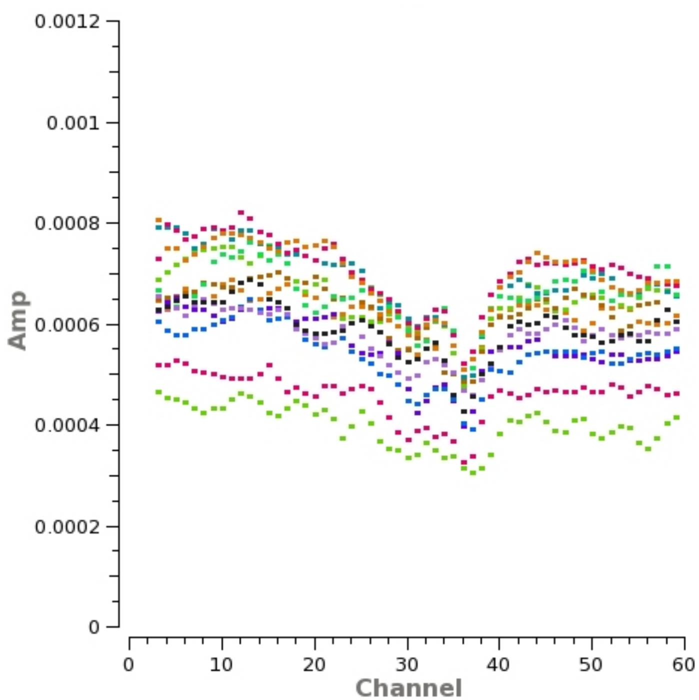


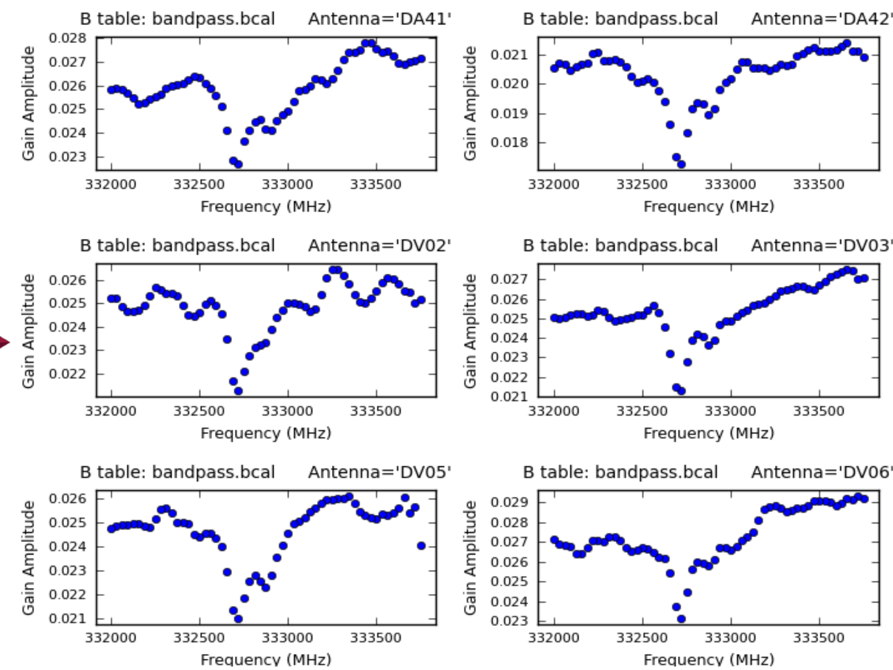
Bandpass Phase vs. Frequency (After)



Bandpass Calibration: Amplitude

Baselines to one antenna





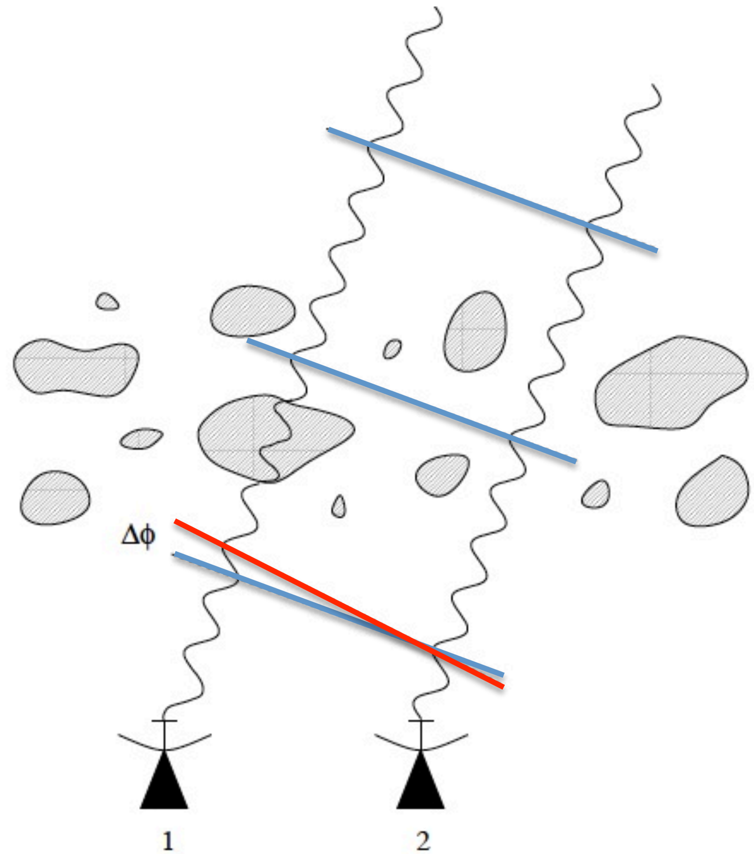
Amplitude Before Bandpass Calibration

Antenna-based Bandpass Solution

Atmospheric Phase Correction

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations and result in
  - Low coherence (loss of sensitivity)
  - Radio "seeing", typically 1″ at 1 mm
  - 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.

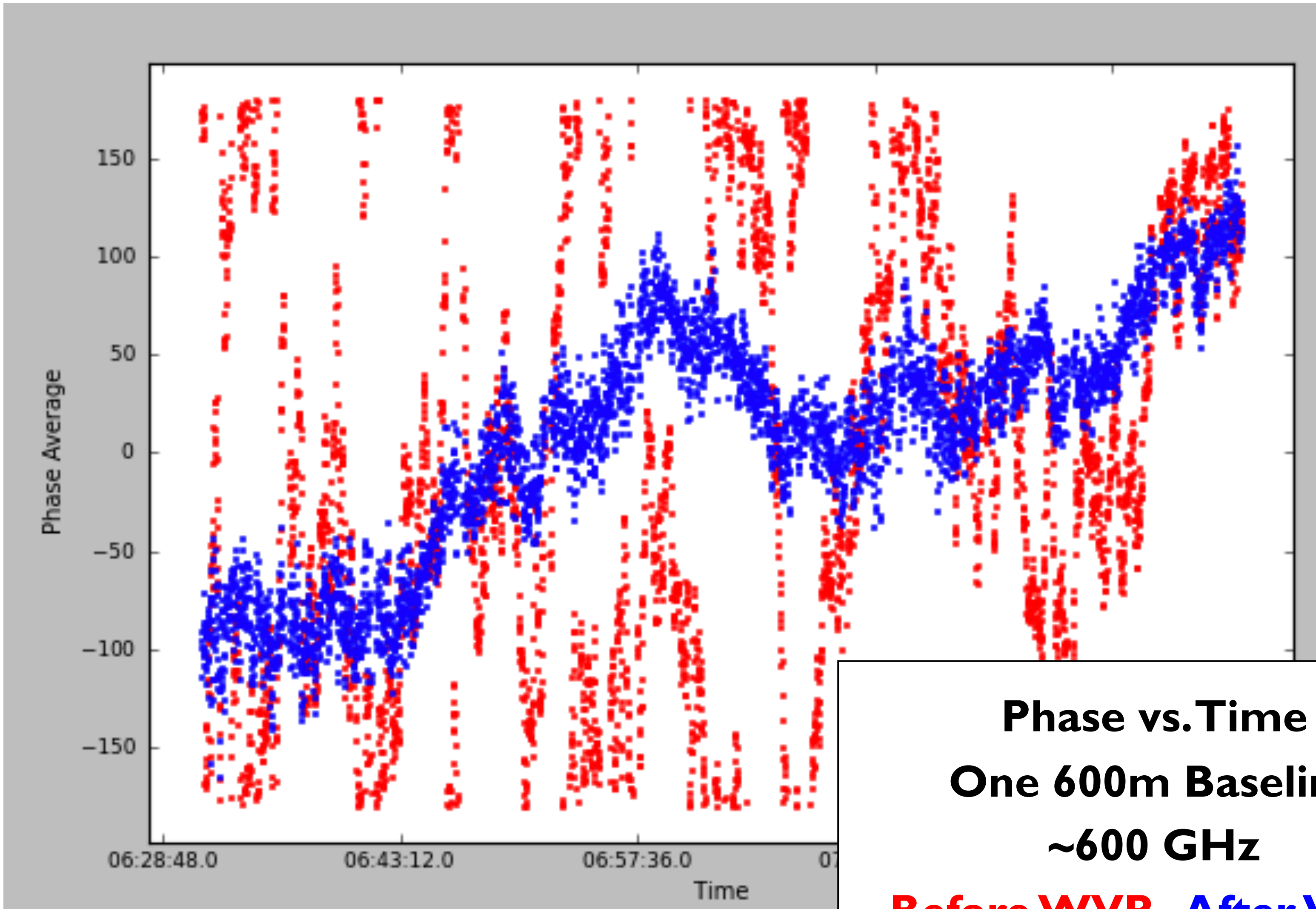


Gain (or Phase) Calibration

Determine the variations of phase and amplitude with time

- First pass atmospheric correction from Water Vapor Radiometers
- Final correction from gain calibrator (point source near to target)

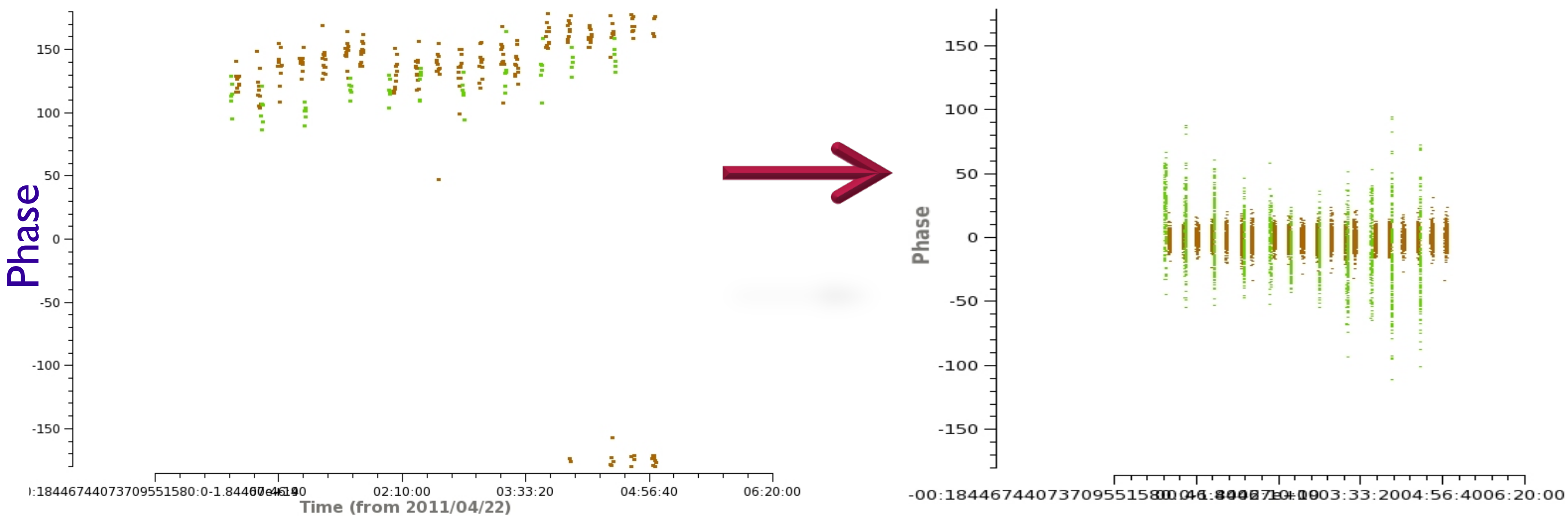
Water Vapor Correction on ALMA



Phase vs. Time
One 600m Baseline
~600 GHz
Before WVR, After WVR

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.



Time

Corrected using point source model

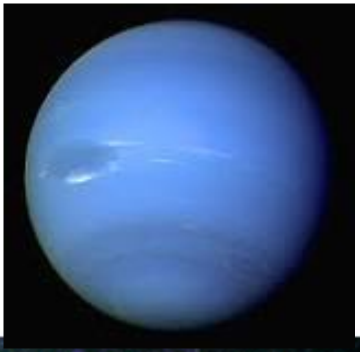
Flux (or Amplitude) Calibration

Two Steps:

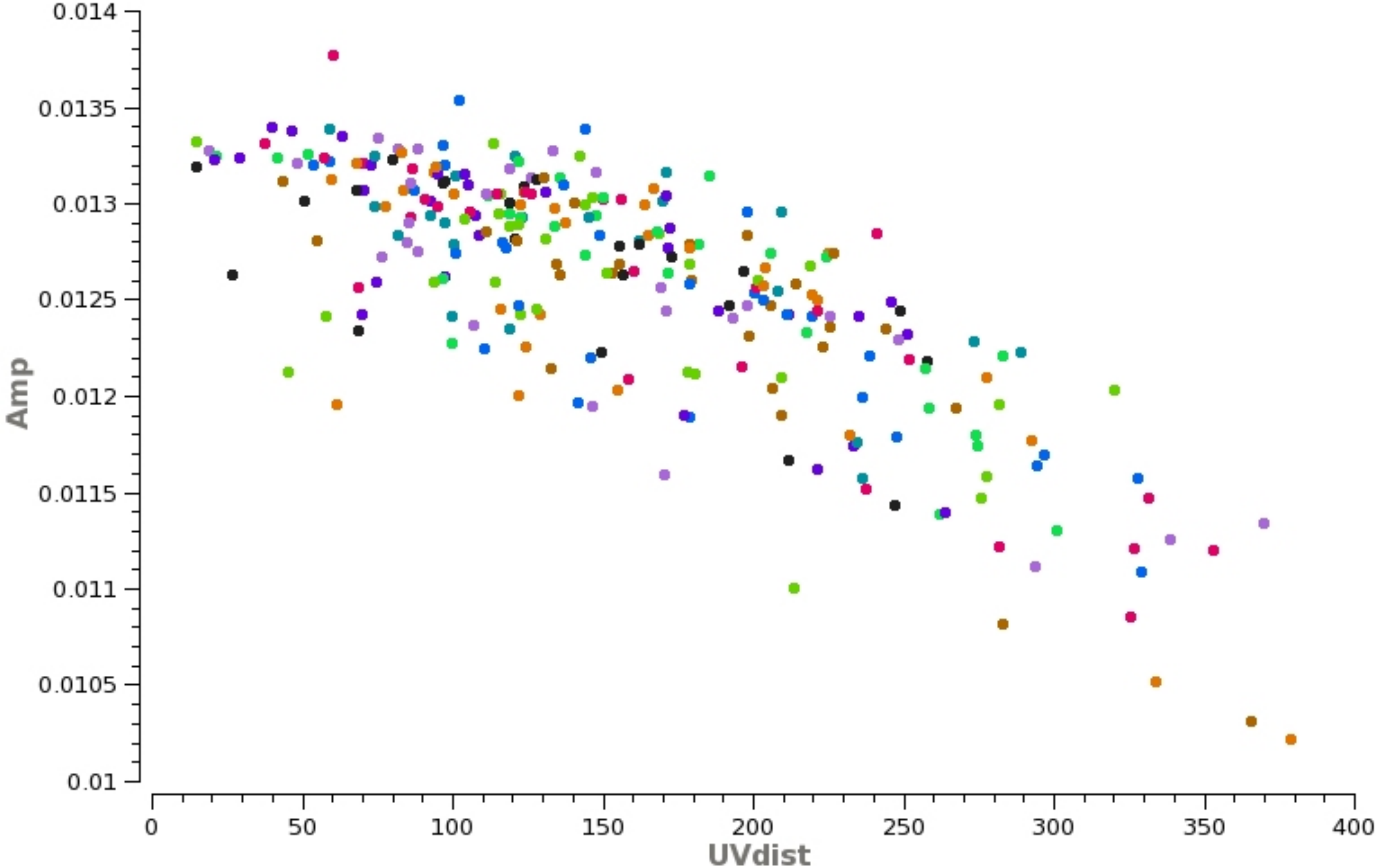
- Use calibration devices of known temperature (hotload and ambient load) to measure System Temperature frequently.

- Use a source of known flux to convert the signal measured at the antenna to common unit (Janskys). If the source is resolved, or has spectral lines, it must be very well modeled.

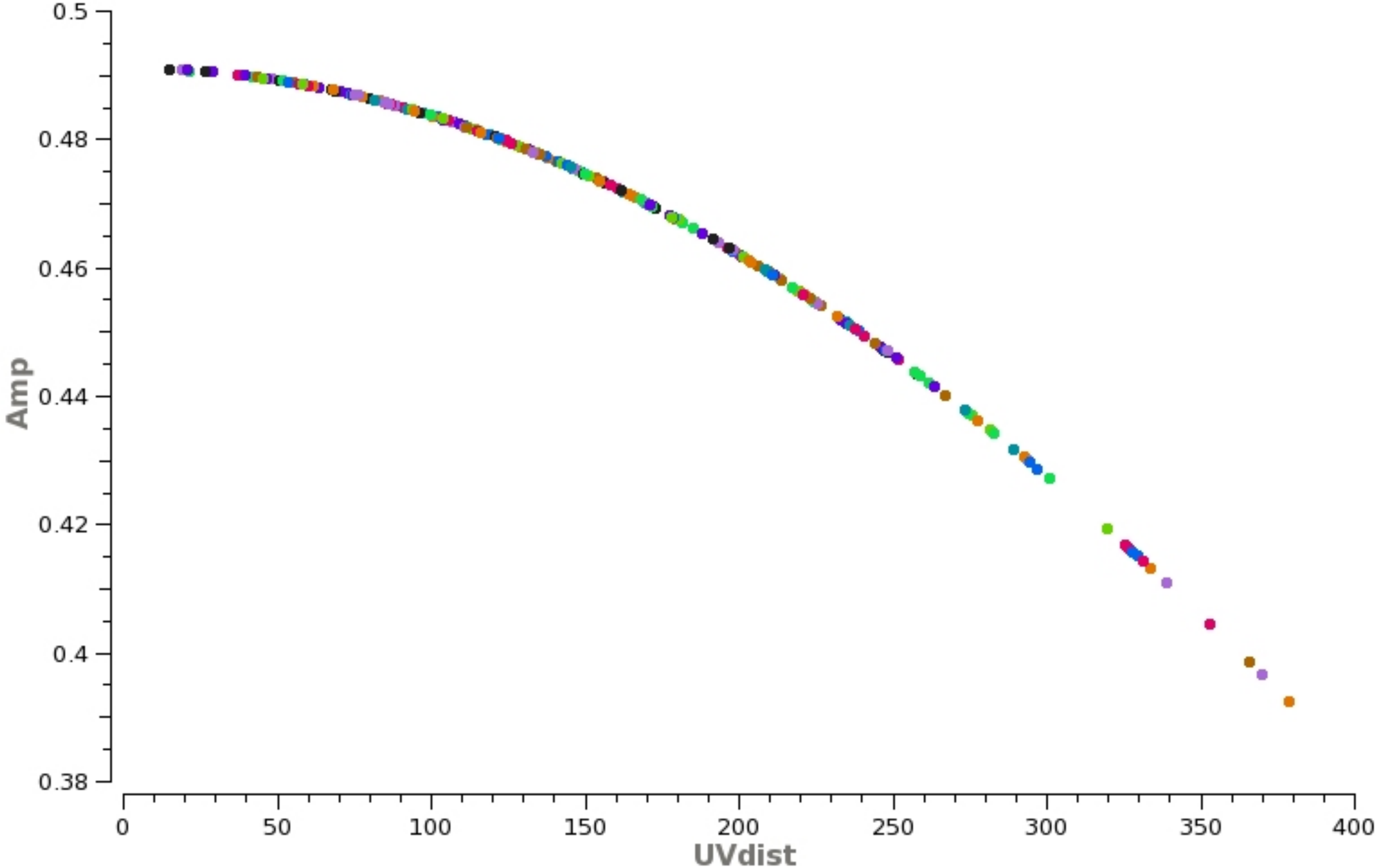
- The derived amplitude vs. time corrections for the flux calibrator are applied to the science target.



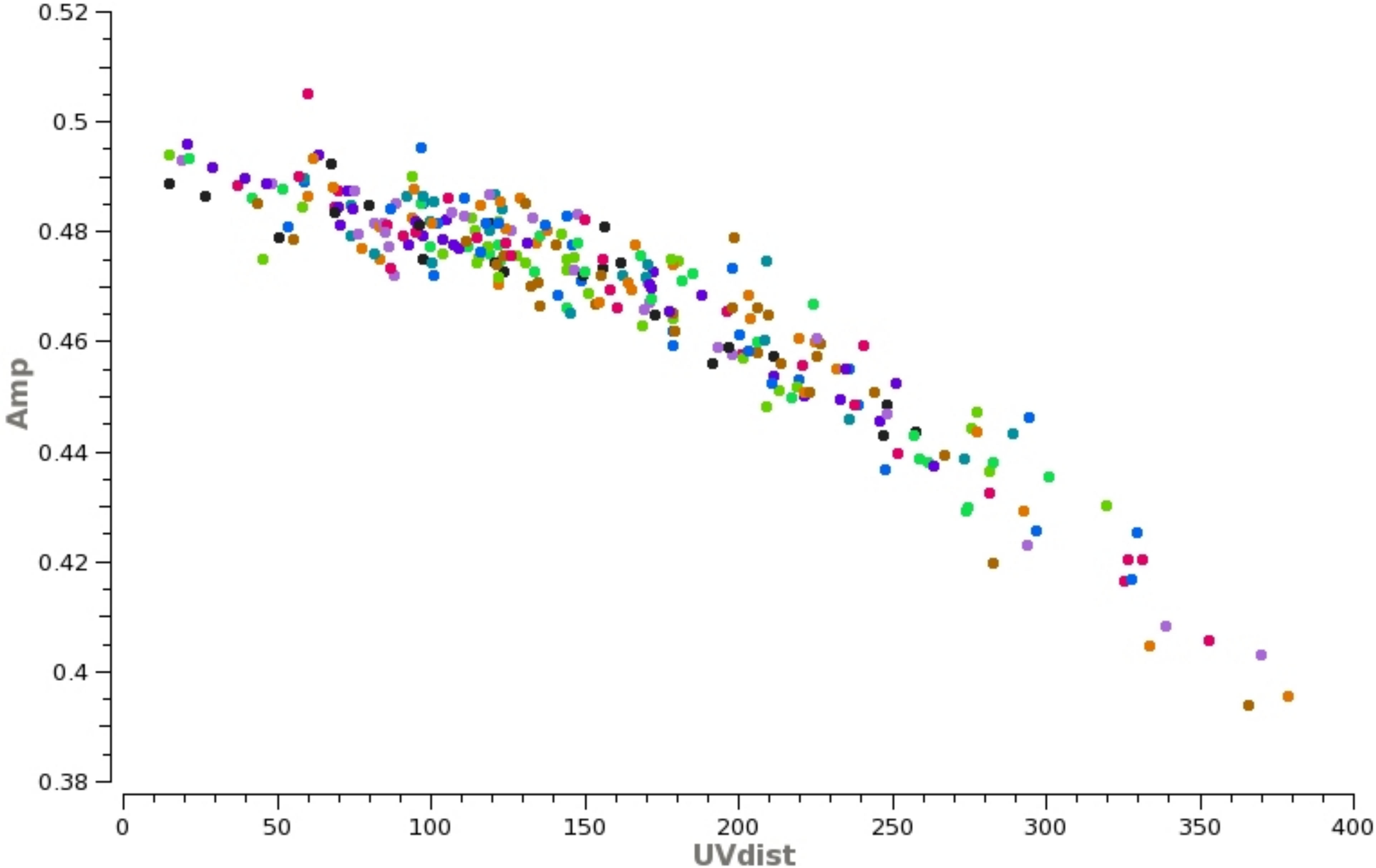
Ampcal Amplitude vs. uv-distance (Before)



Ampcal Amplitude vs. uv-distance (Model)



Ampcal Amplitude vs. uv-distance (After)



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

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.