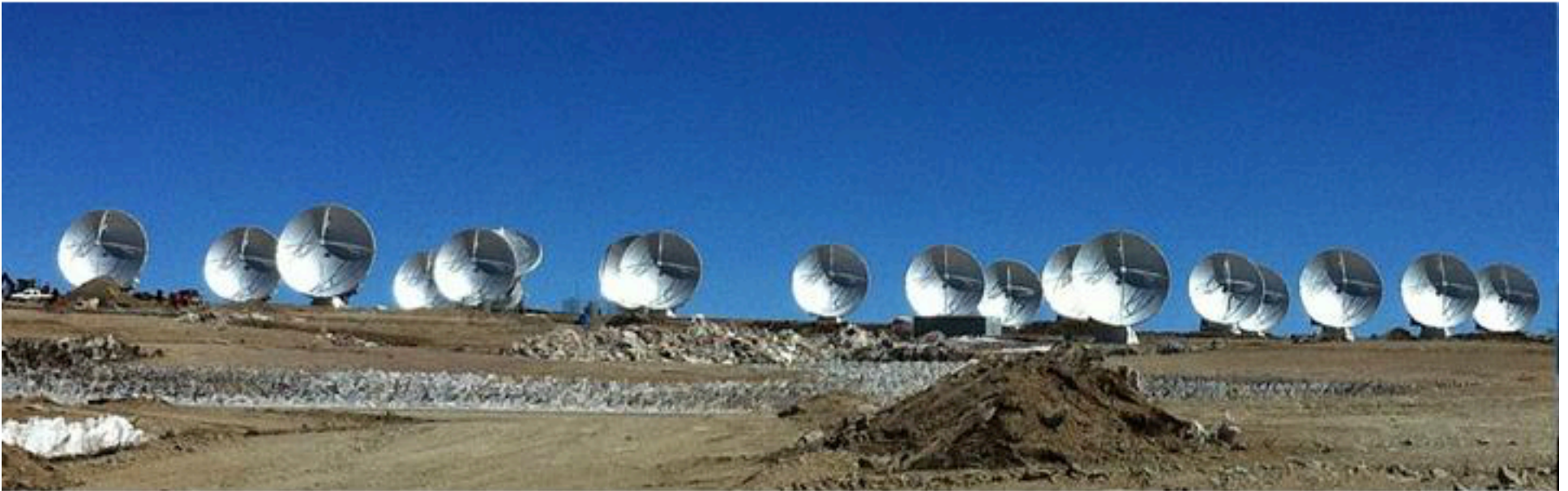


Introduction to Radio Interferometry



Sabrina Stierwalt

Alison Peck, Jim Braatz, Ashley Bemis

Atacama Large Millimeter/submillimeter Array

Expanded Very Large Array

Robert C. Byrd Green Bank Telescope

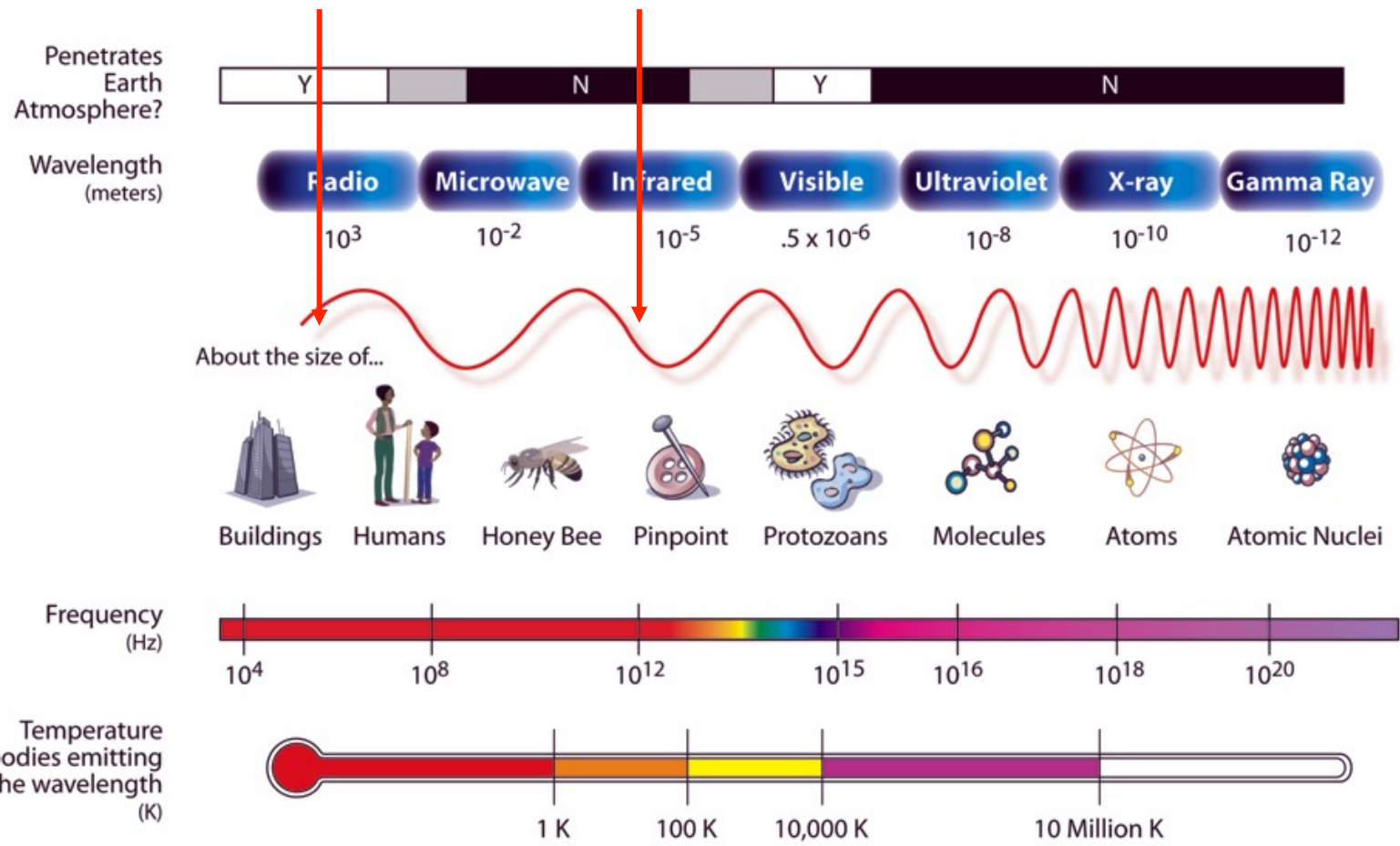
Very Long Baseline Array



Radio Astronomy

Now used to refer to most telescopes using heterodyne technology

THE ELECTROMAGNETIC SPECTRUM



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.

**Synoptic diagram of heterodyne receivers
(basic building blocks)**

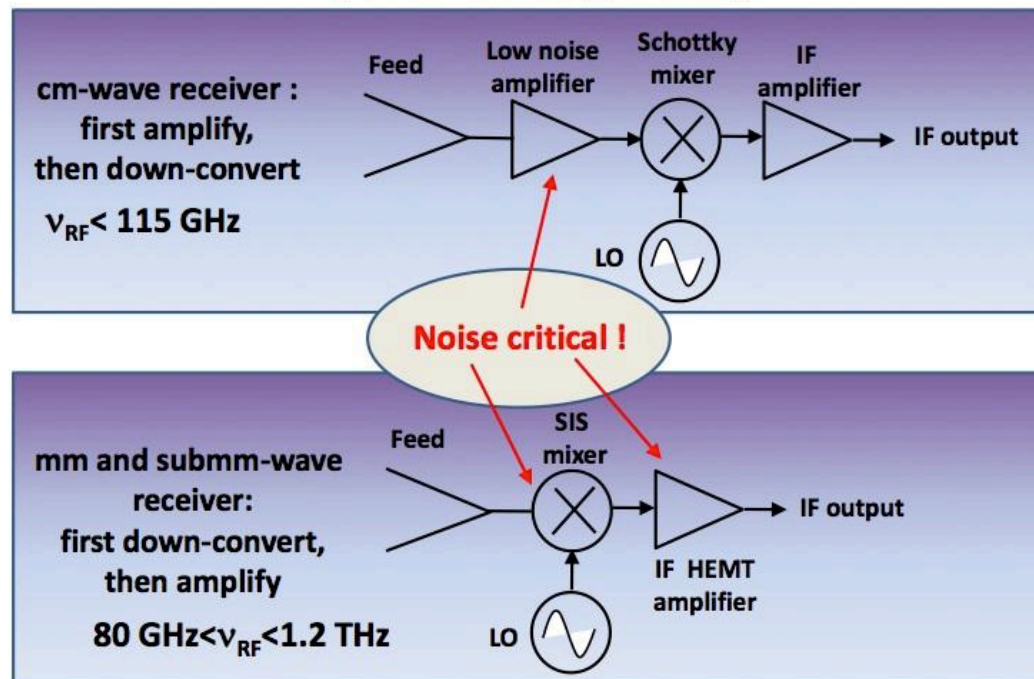


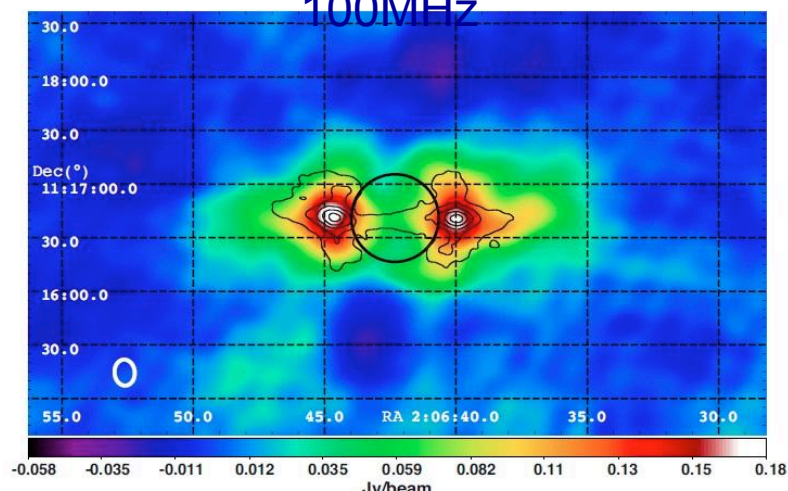
Image from
Alessandro Navarrini
(IRAM)

Long wavelength means no glass

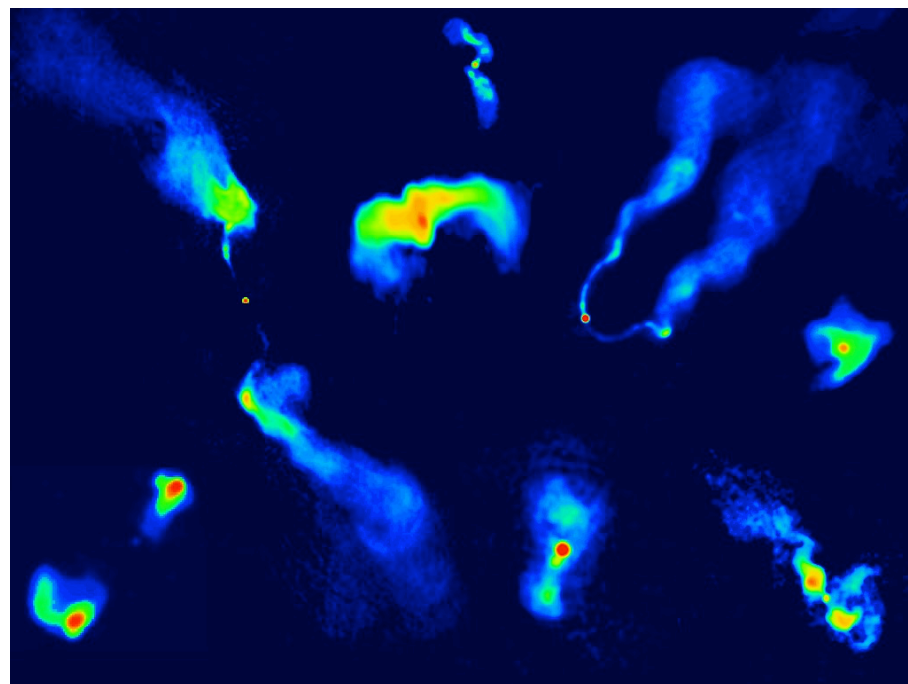
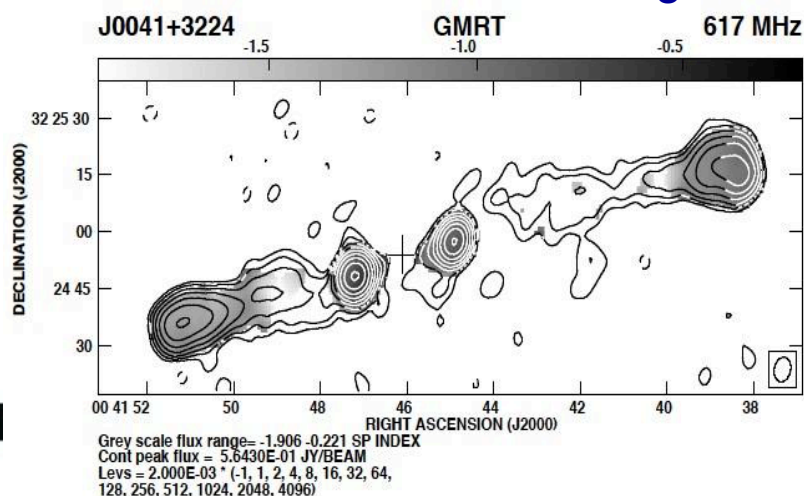


What can we observe? (MHz-GHz range)

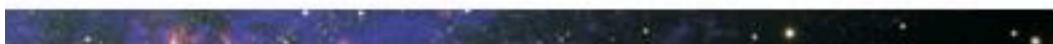
Jupiter's radiation belt at 100MHz



Relic emission from old radio galaxies



Synchrotron emission from extended radio galaxies (5 GHz)

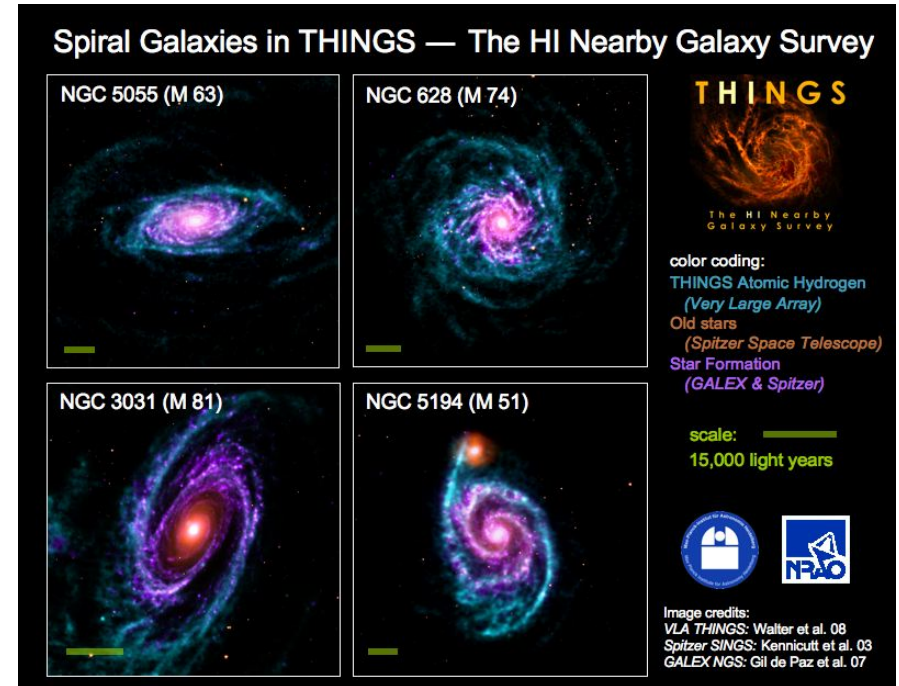
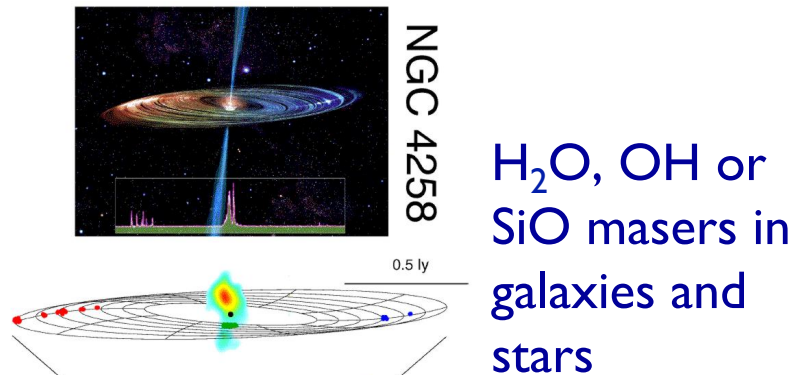


Images from NRAO Image Gallery: <http://images.nrao.edu/>

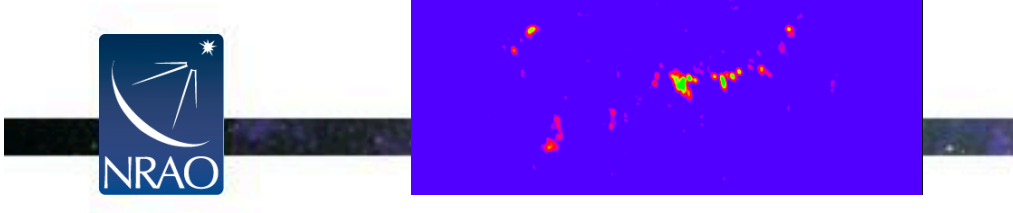
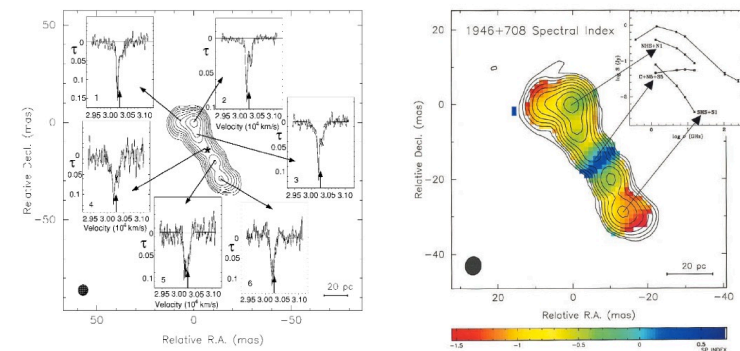
- Images from NRAO Image Gallery
<http://images.nrao.edu/>

What should we observe?

At low frequencies (MHz-GHz):

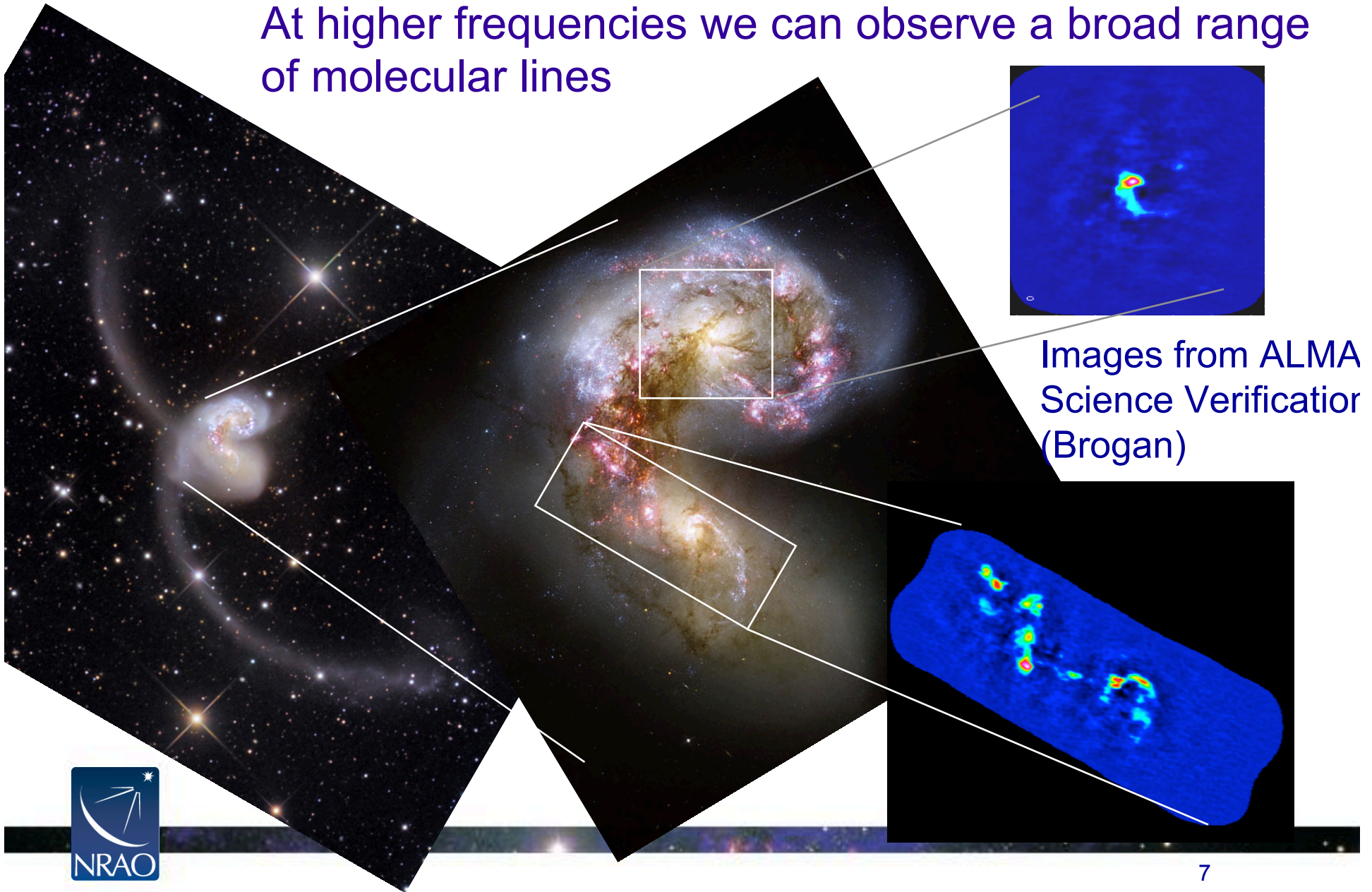


HI emission and absorption, free-free absorption in galaxies



What can we observe?

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



Resolution of Observations

Angular resolution for most telescopes is $\sim \lambda/D$

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

For example, Hubble Space Telescope:

- $\lambda \sim 1\mu\text{m}$ / D of 2.4m = resolution $\sim 0.13''$

To reach that resolution for a $\lambda \sim 1\text{mm}$ observation, one would need a 2 km-diameter dish!

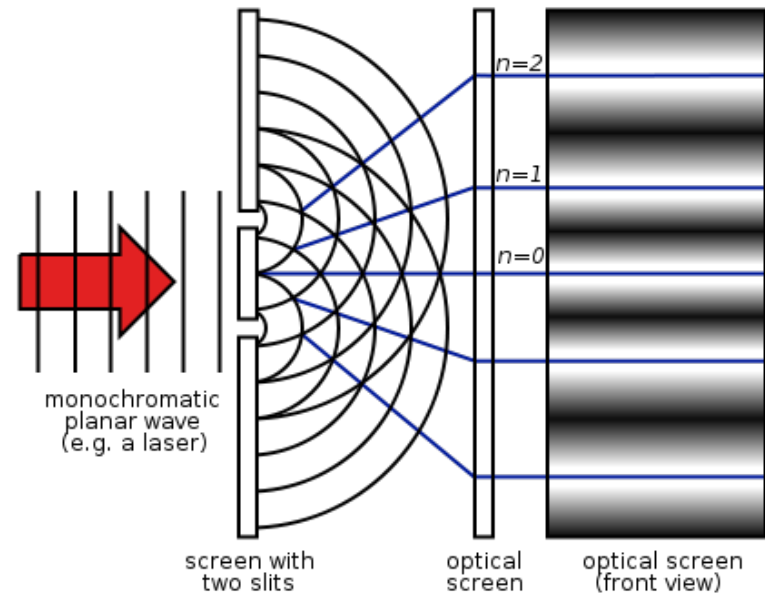
Instead, we use arrays of smaller dishes to achieve the same high angular resolution at radio frequencies

This is interferometry



What is an interferometer?

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



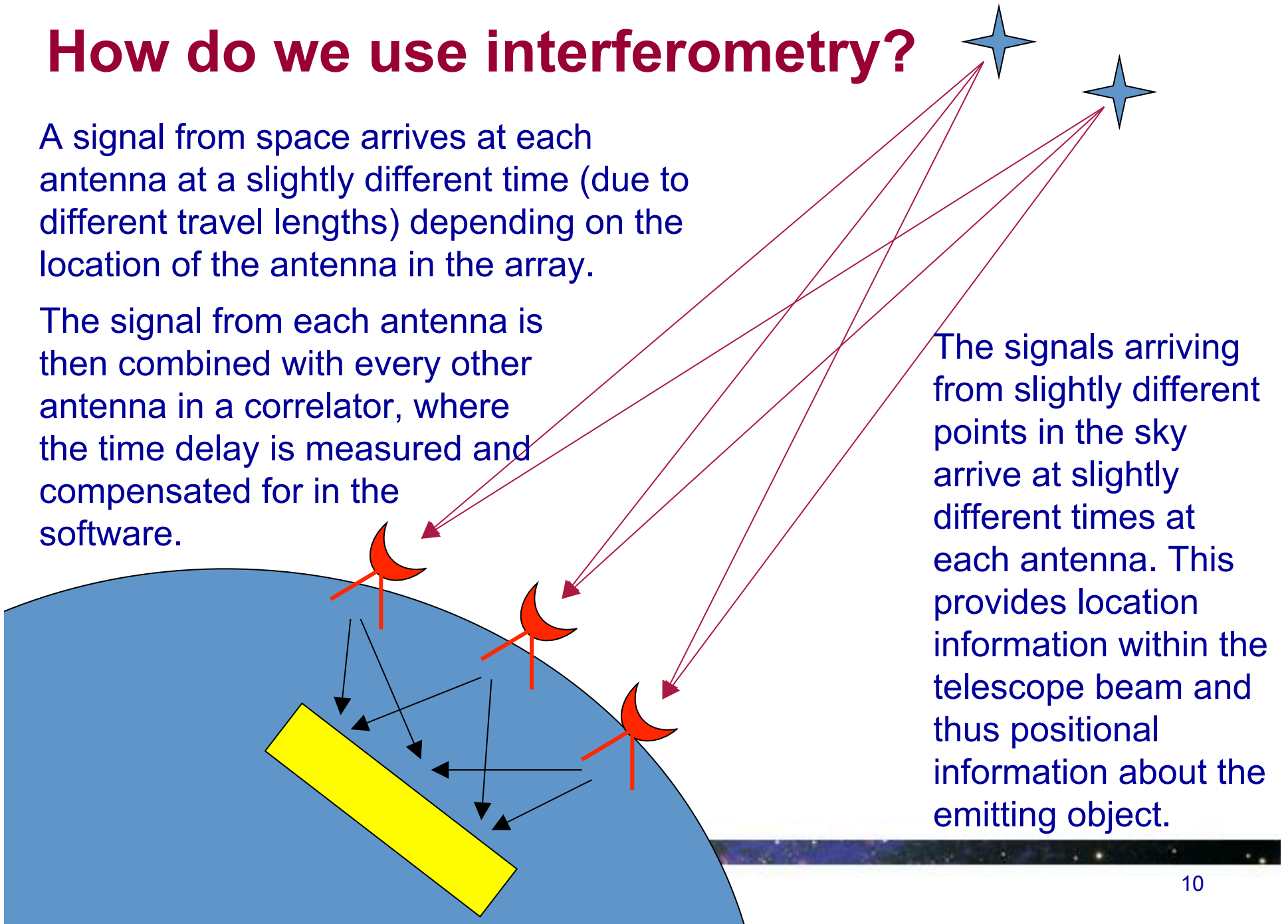
*However, the interference patterns measured by radio telescopes are produced by **multiplying** - not adding - the wave signals measured at the different telescopes (i.e. apertures)

How do we use interferometry?

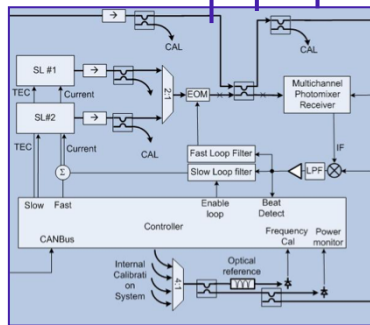
A signal from space arrives at each antenna at a slightly different time (due to different travel lengths) depending on the location of the antenna in the array.

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.



Some instrument details...

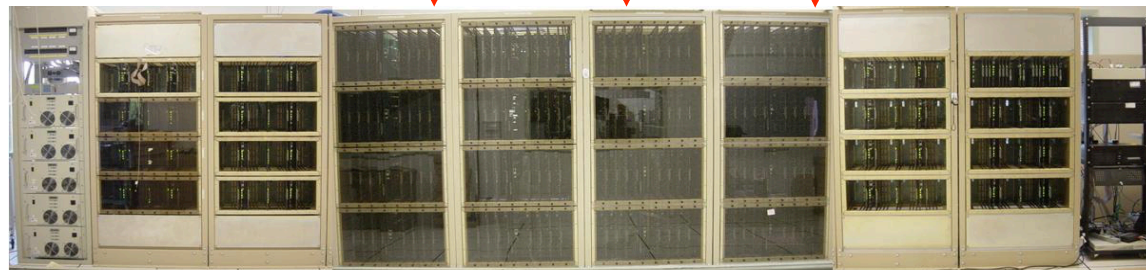
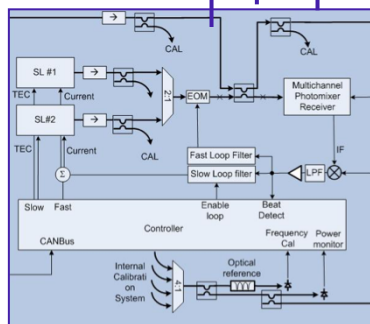


To precisely measure arrival times we need very accurate clocks

- At Band 10 one wavelength error = 1 picosecond (!!)
- We need $\ll 1$ wavelength timing precision so each antenna has an on-board clock with high sampling rates

Once determined, the reference time is distributed to all antennas

Some instrument details...

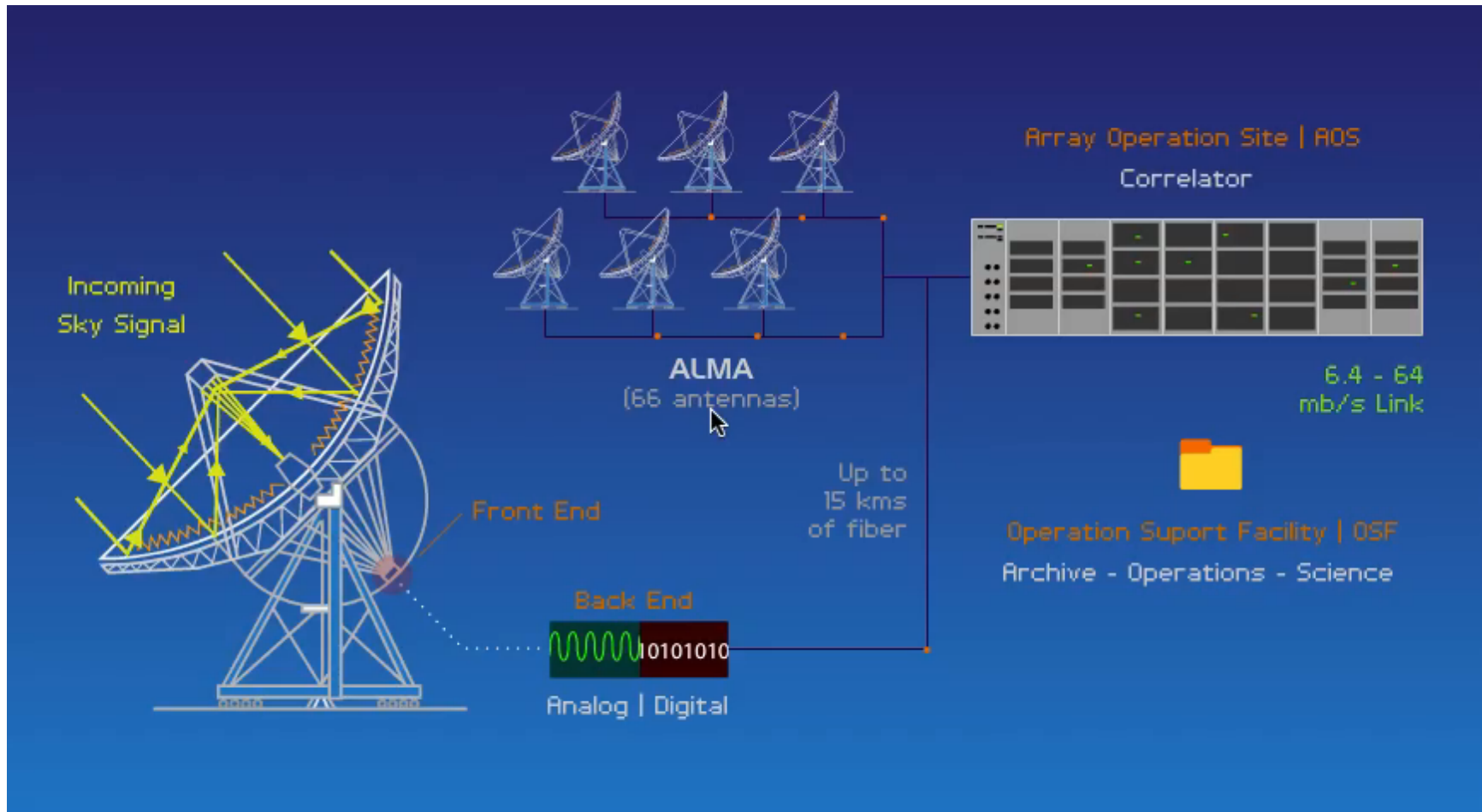


Signal from each antenna are digitized and sent to the correlator for multiplication & averaging.

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

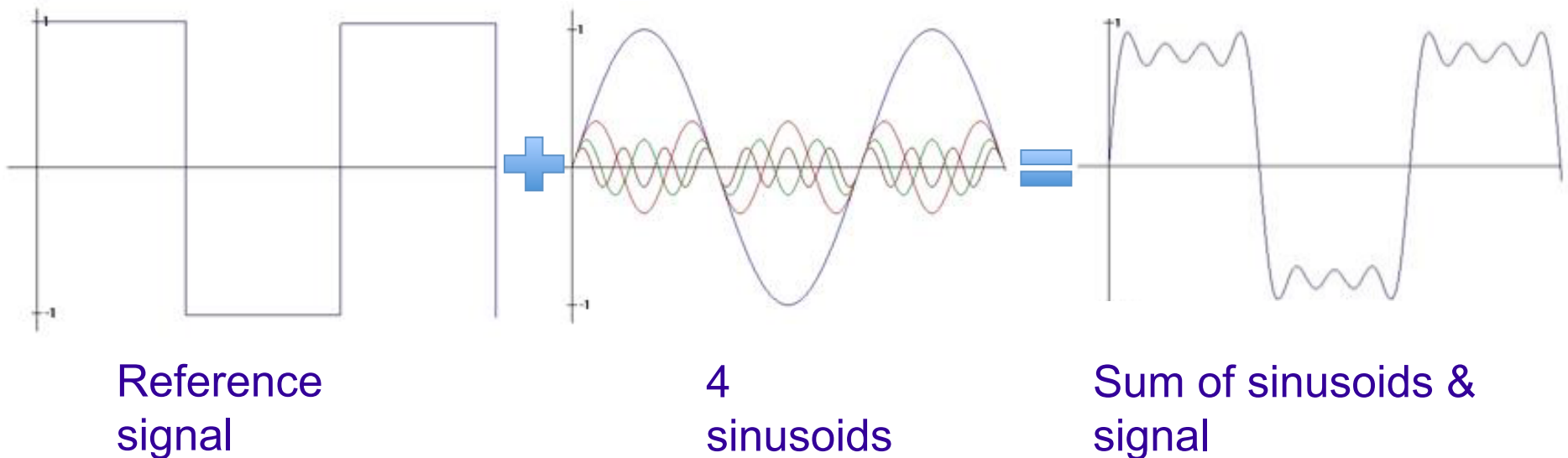


An interferometer in action



The Fourier Transform

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



- 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 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

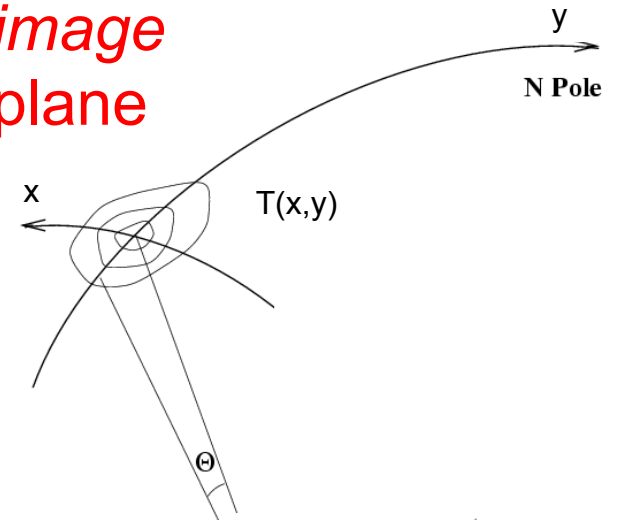
Fourier space/

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

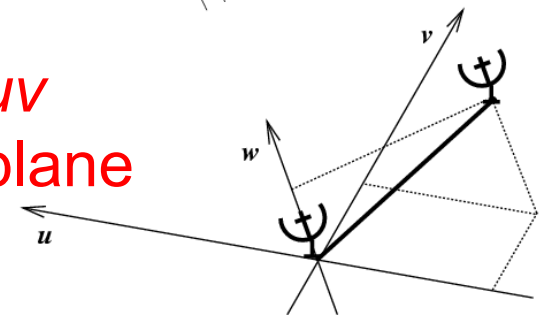
Image space/

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

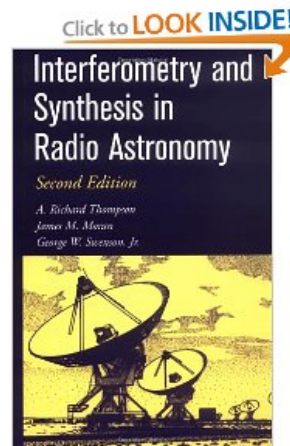
image
plane



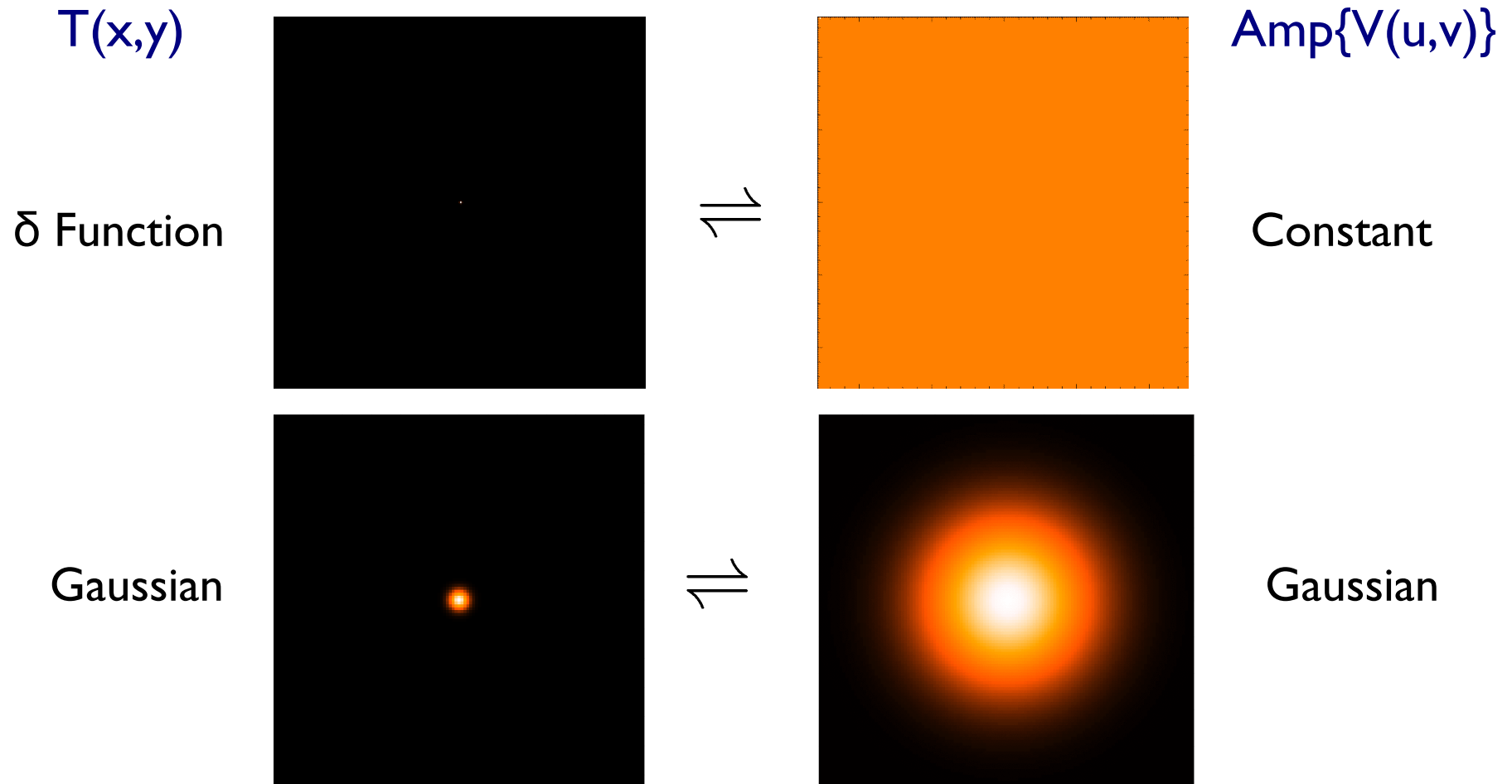
uv
plane



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



Some 2D Fourier Transform Pairs

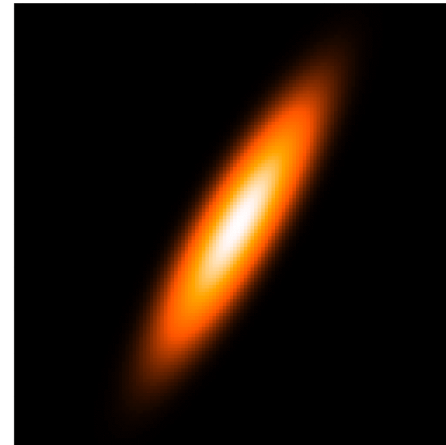
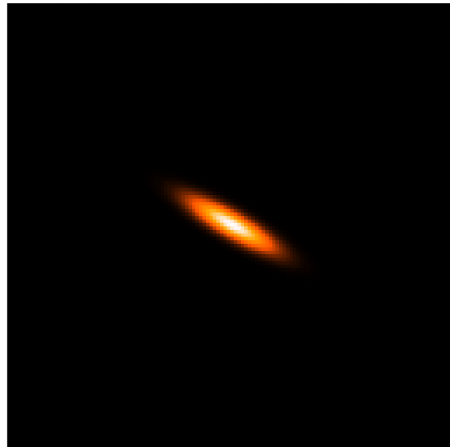


narrow features transform to wide features (and vice-versa)

2D Fourier Transform Pairs

$T(x,y)$

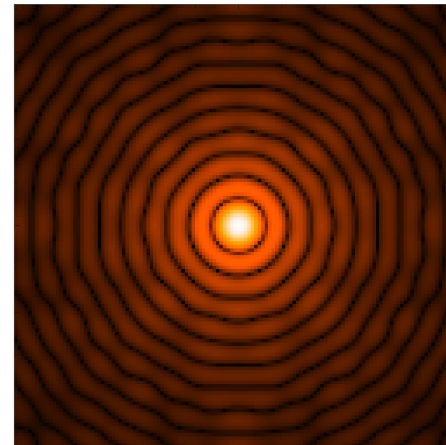
elliptical
Gaussian



$\text{Amp}\{V(u,v)\}$

elliptical
Gaussian

Disk



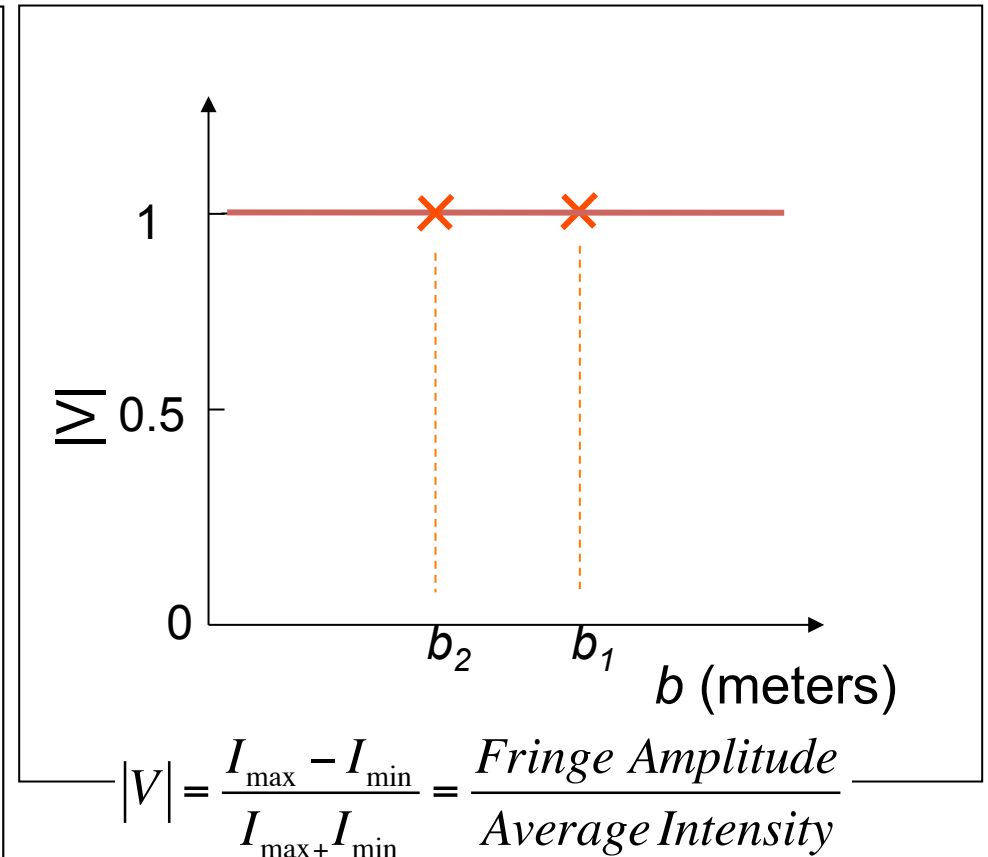
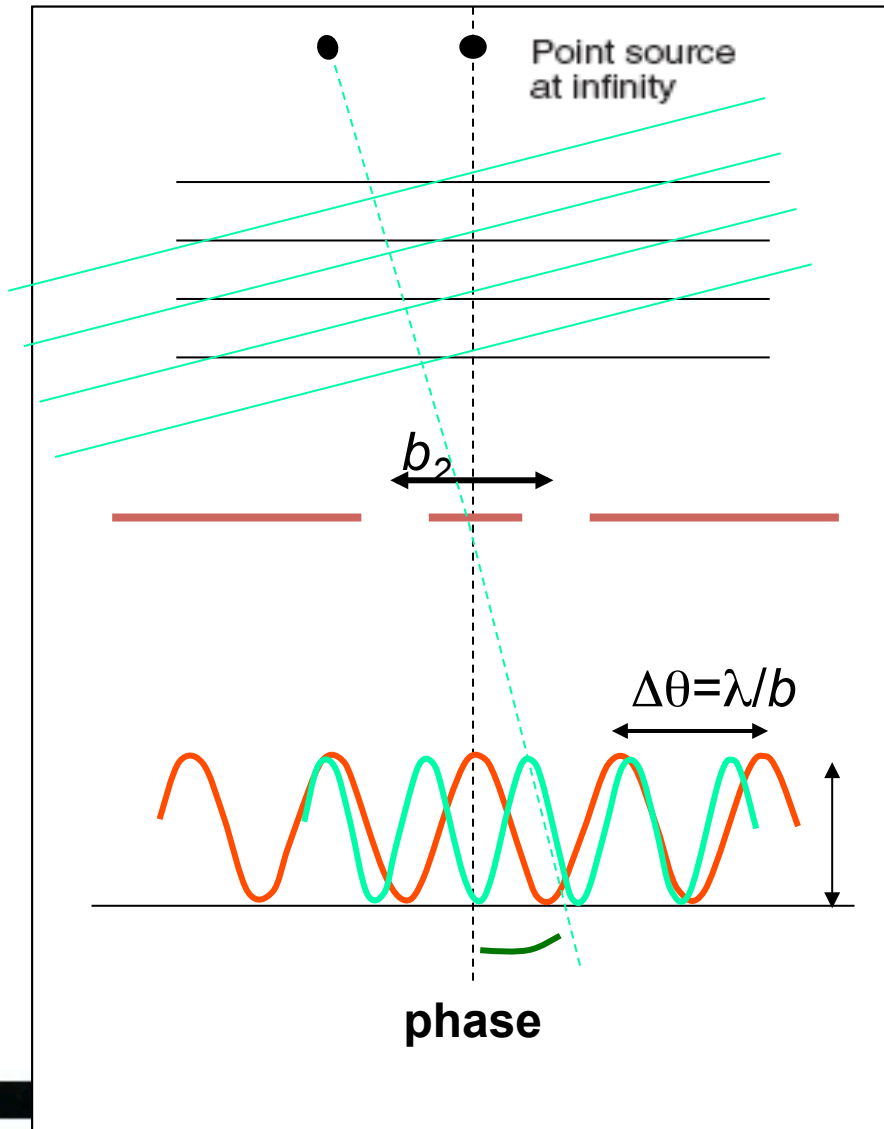
Bessel



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

Visibility and Sky Brightness

Graphic courtesy Andrea Isella

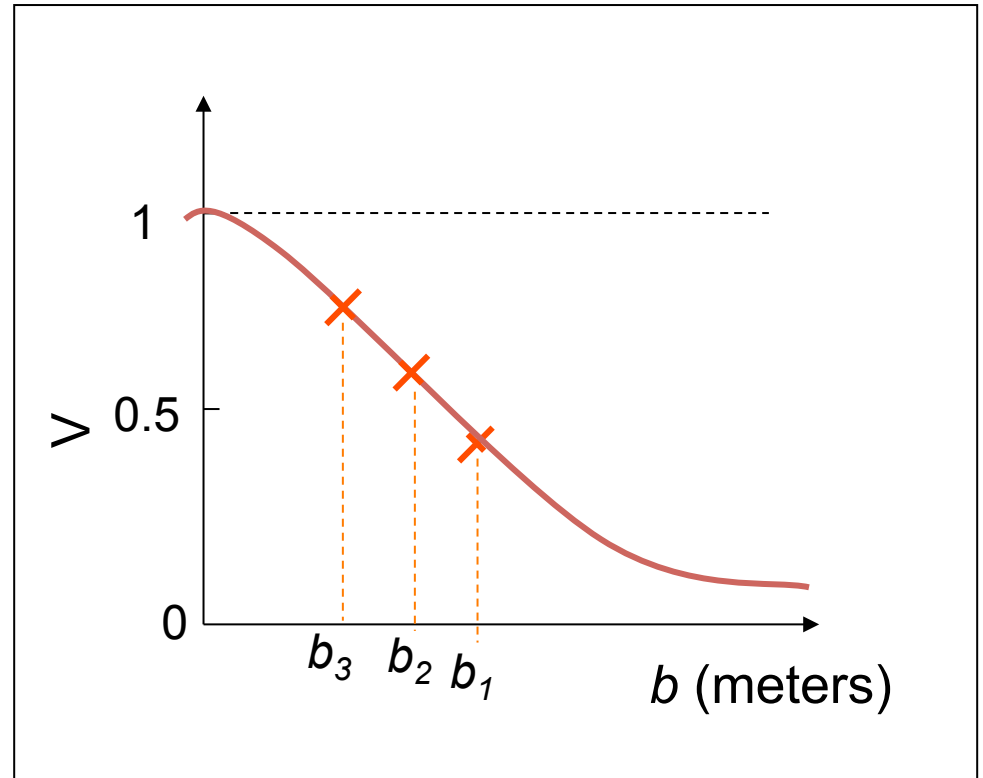
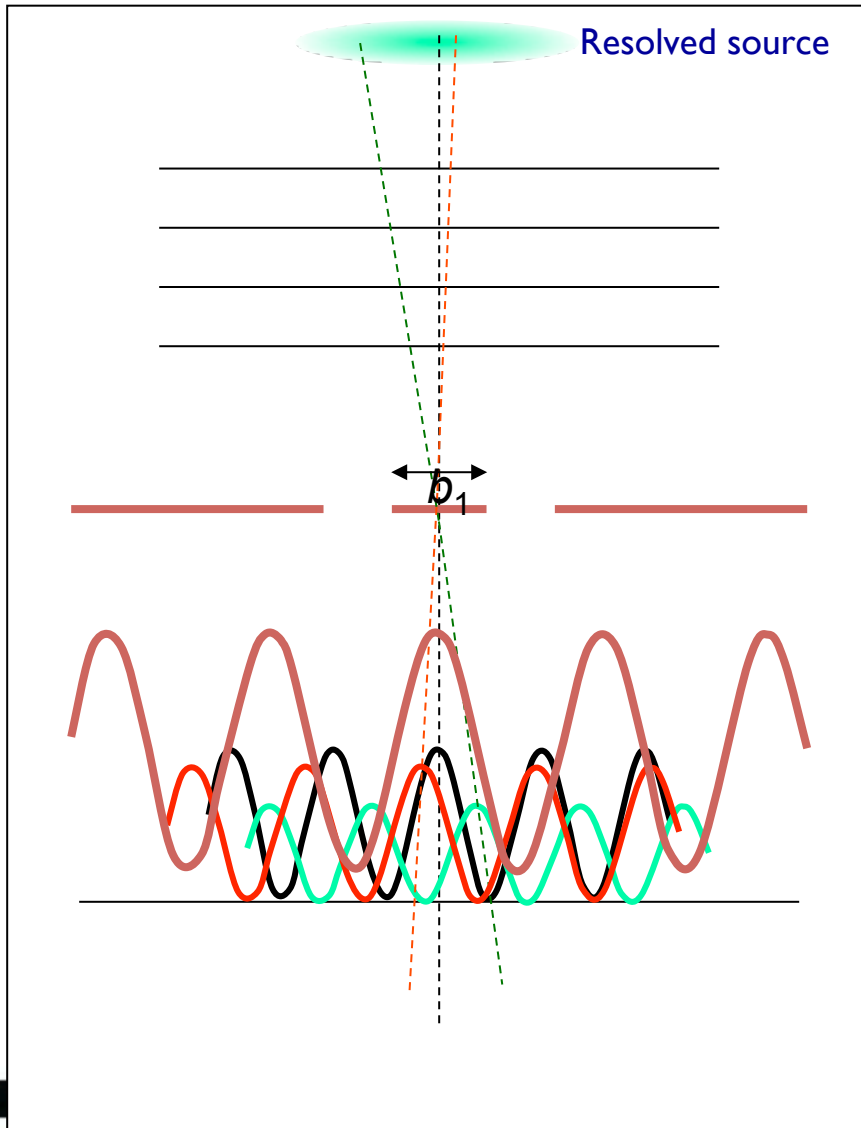


The visibility is a **complex** quantity:

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

Visibility and Sky Brightness

Graphic courtesy Andrea Isella



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

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.

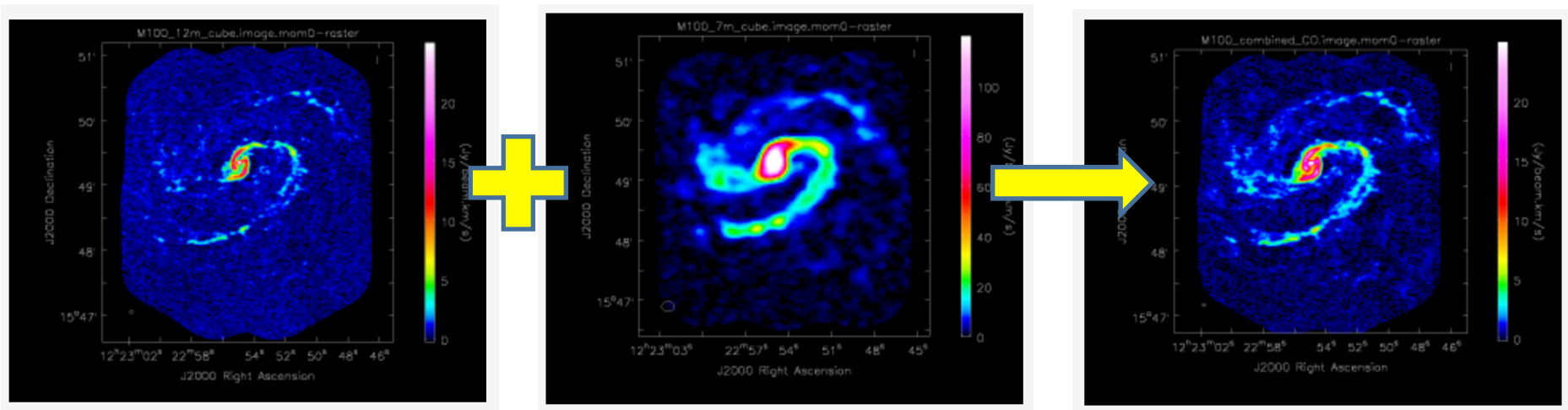
An interferometer is sensitive to a range of angular sizes

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

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



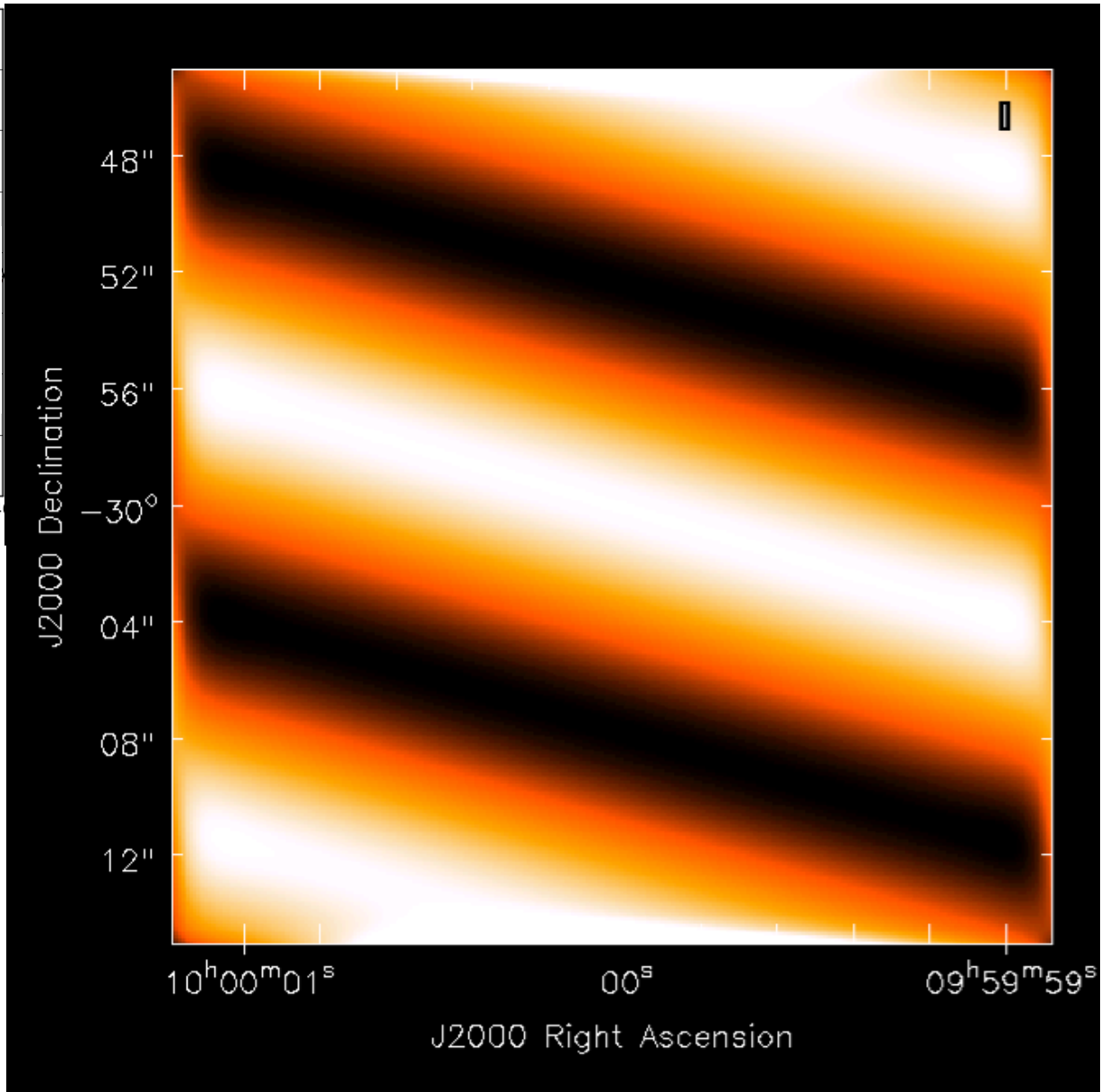
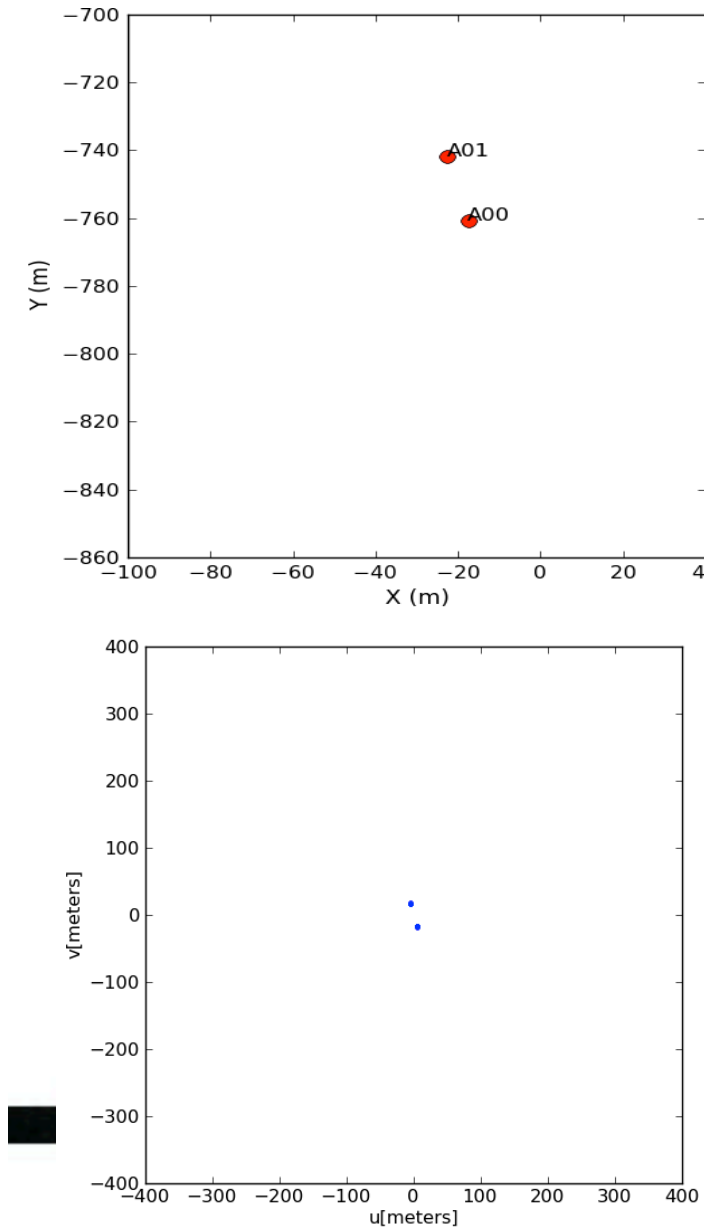
- 12m data reveals information on smaller spatial scales (denser, clumpier emission)
- 7m data reveals information on larger spatial scales (diffuse, extended emission)
- To get both: you need a combined image

Interferometry: Spatial Scales

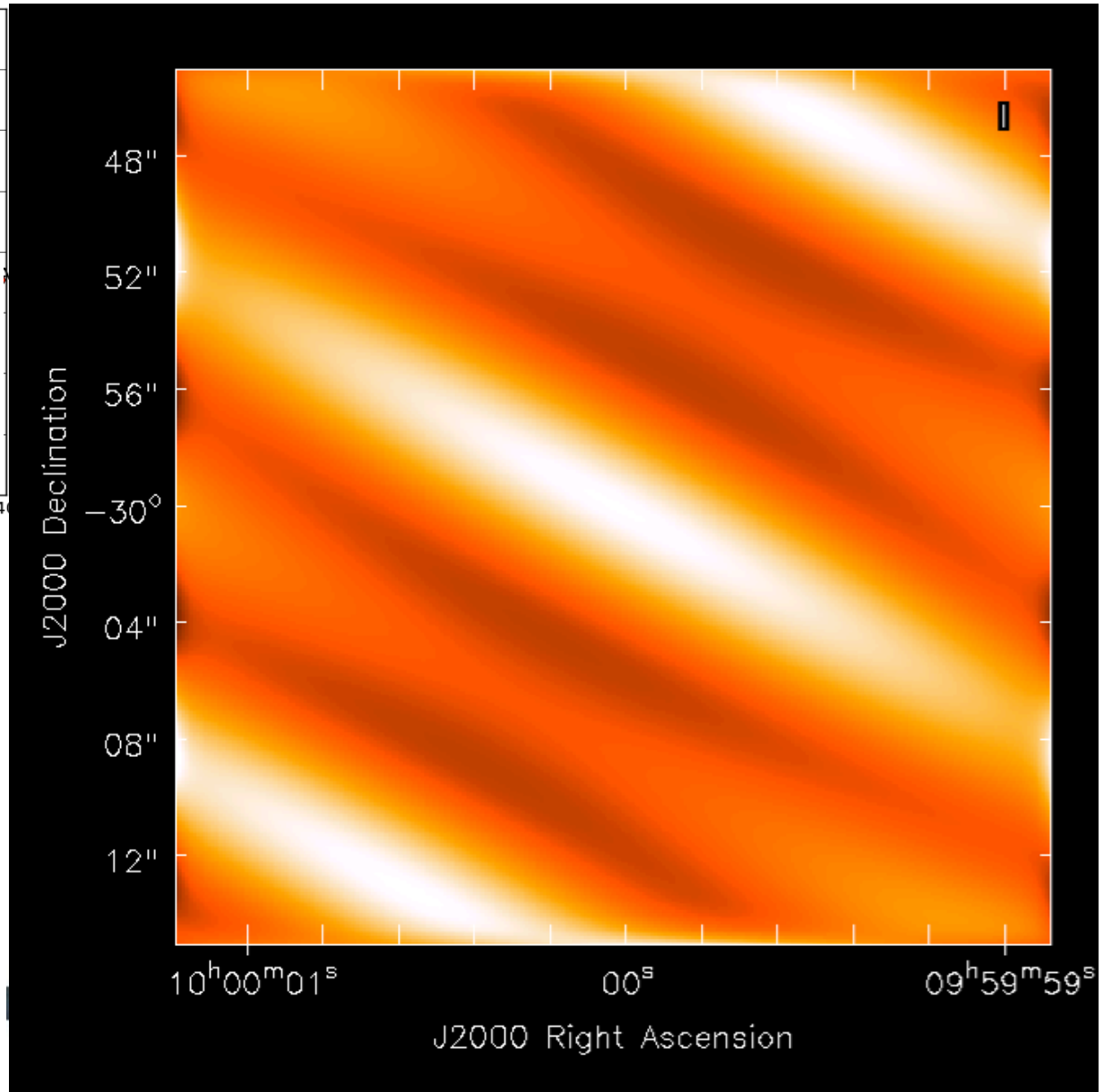
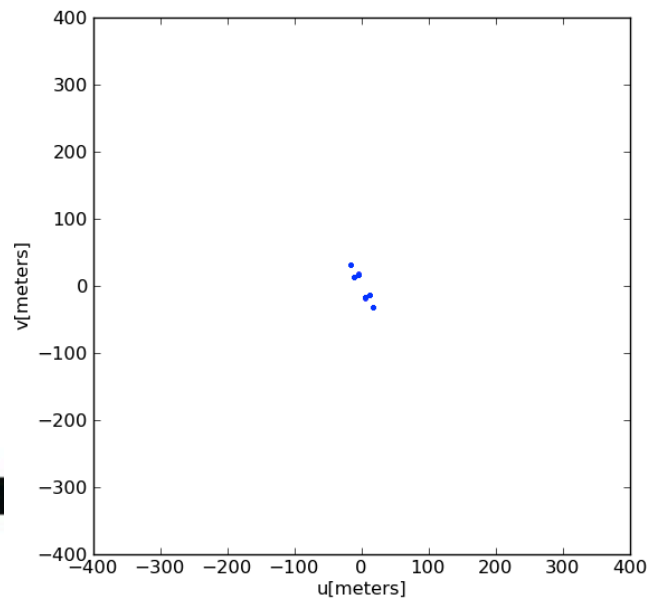
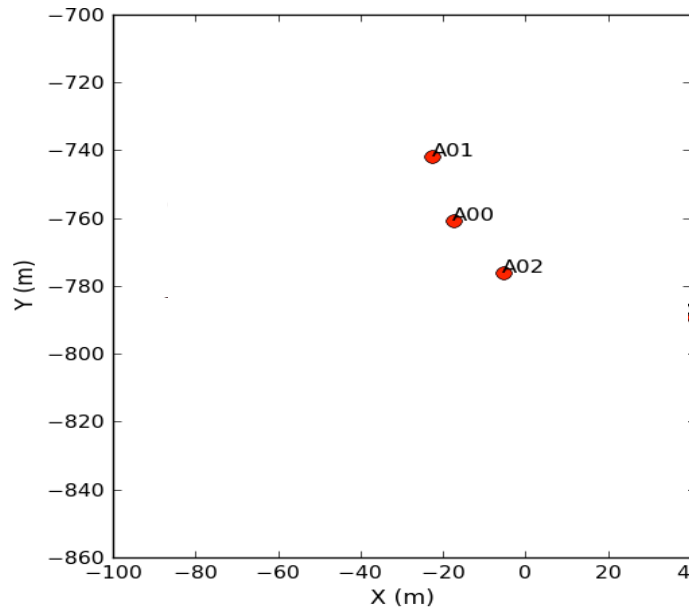
- The **sensitivity** is given by the number of antennas times their area
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam)
- The **resolution** is given by the largest distance between antennas (called the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



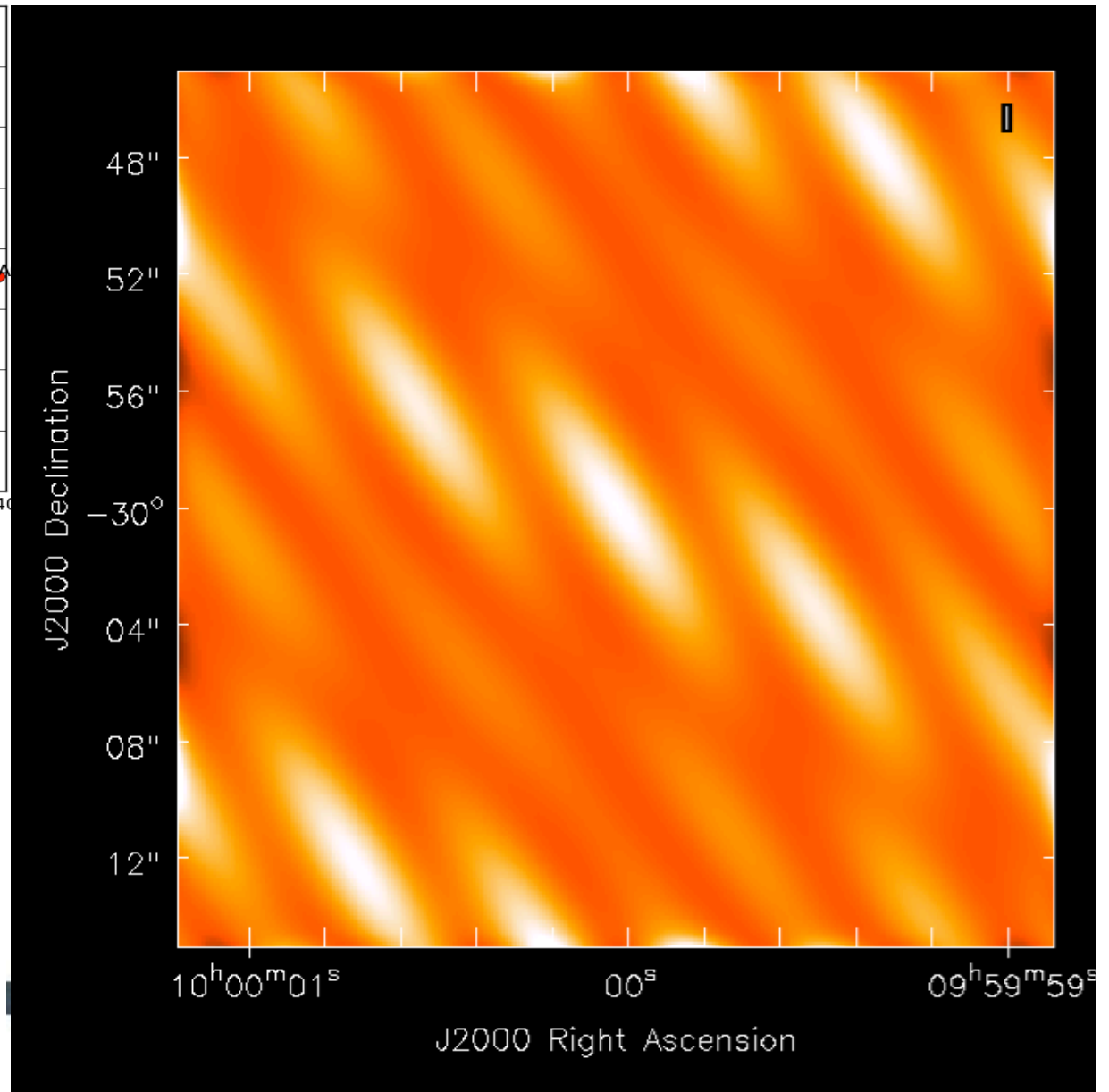
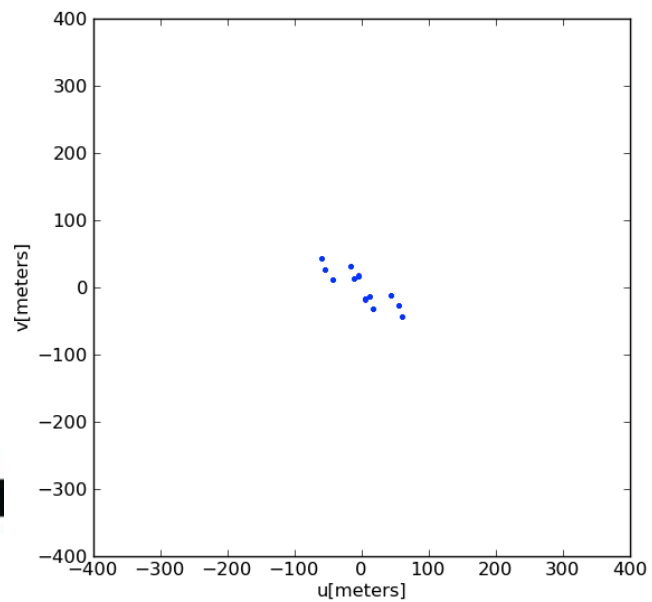
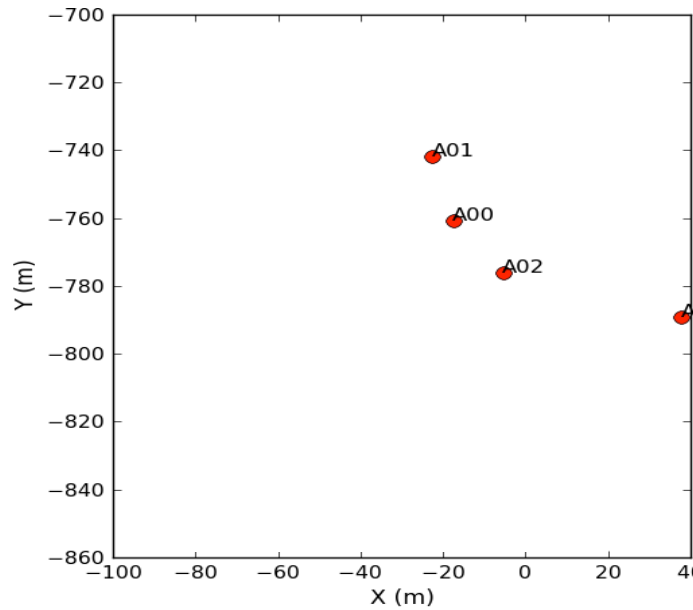
Example: Fringe pattern with 2 Antennas



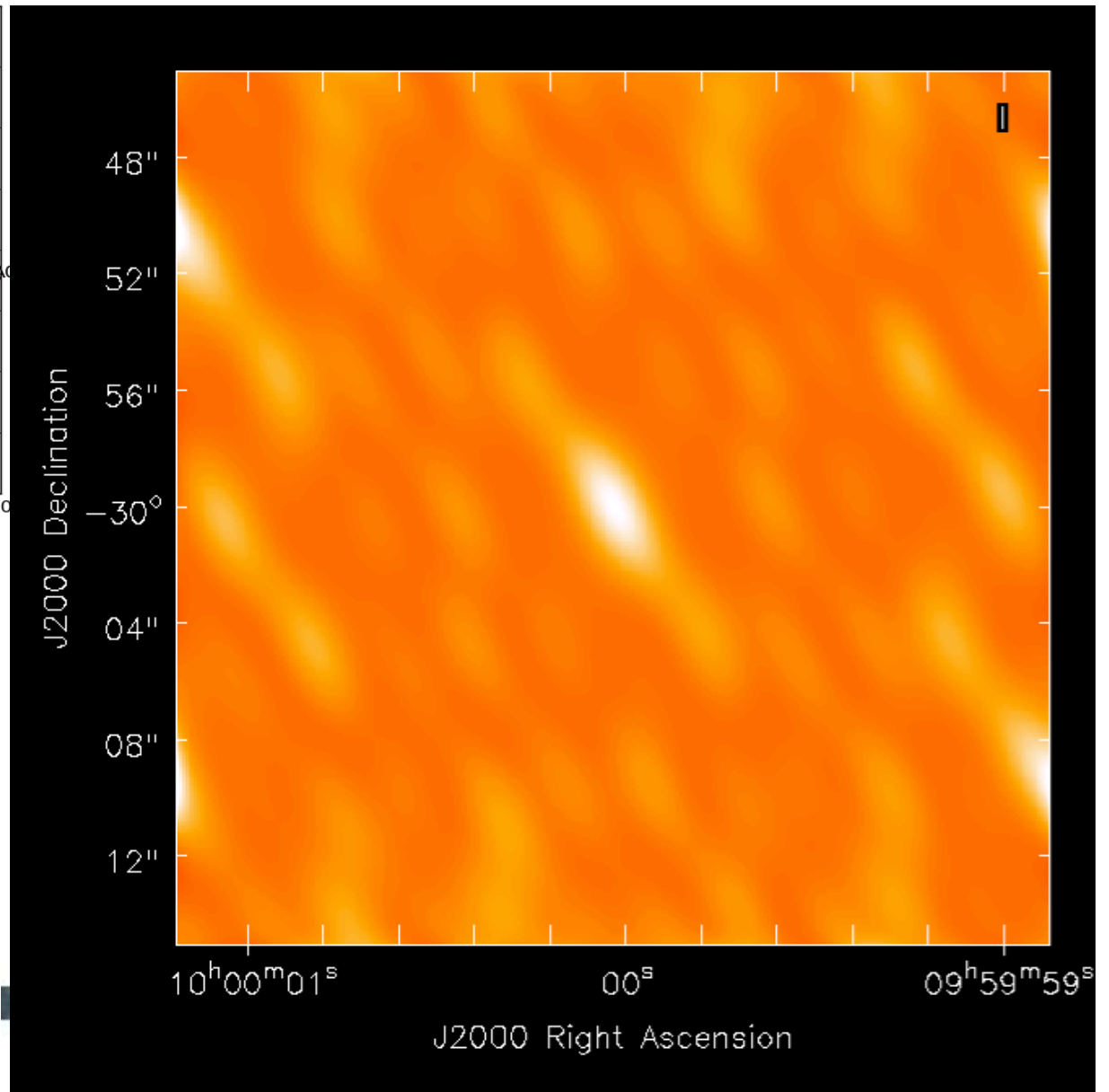
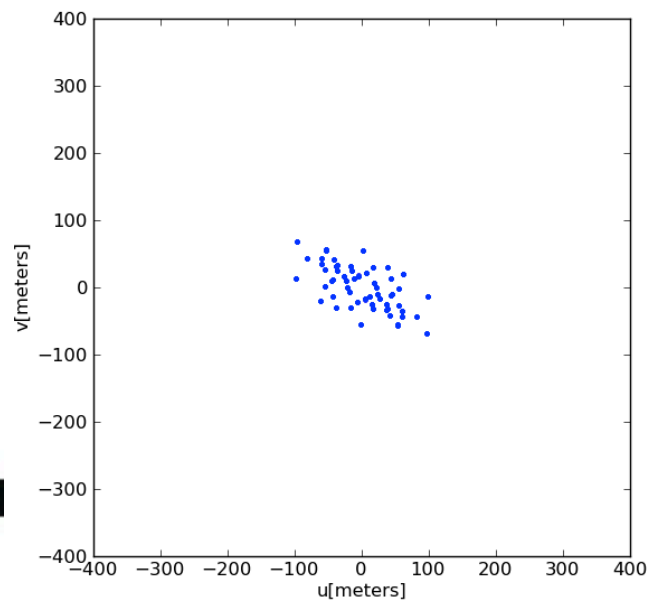
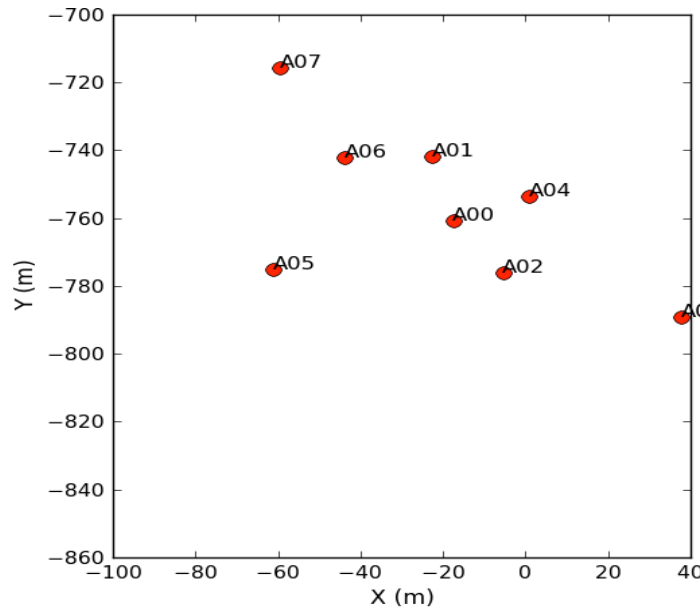
Example: Fringe pattern with 3 Antennas



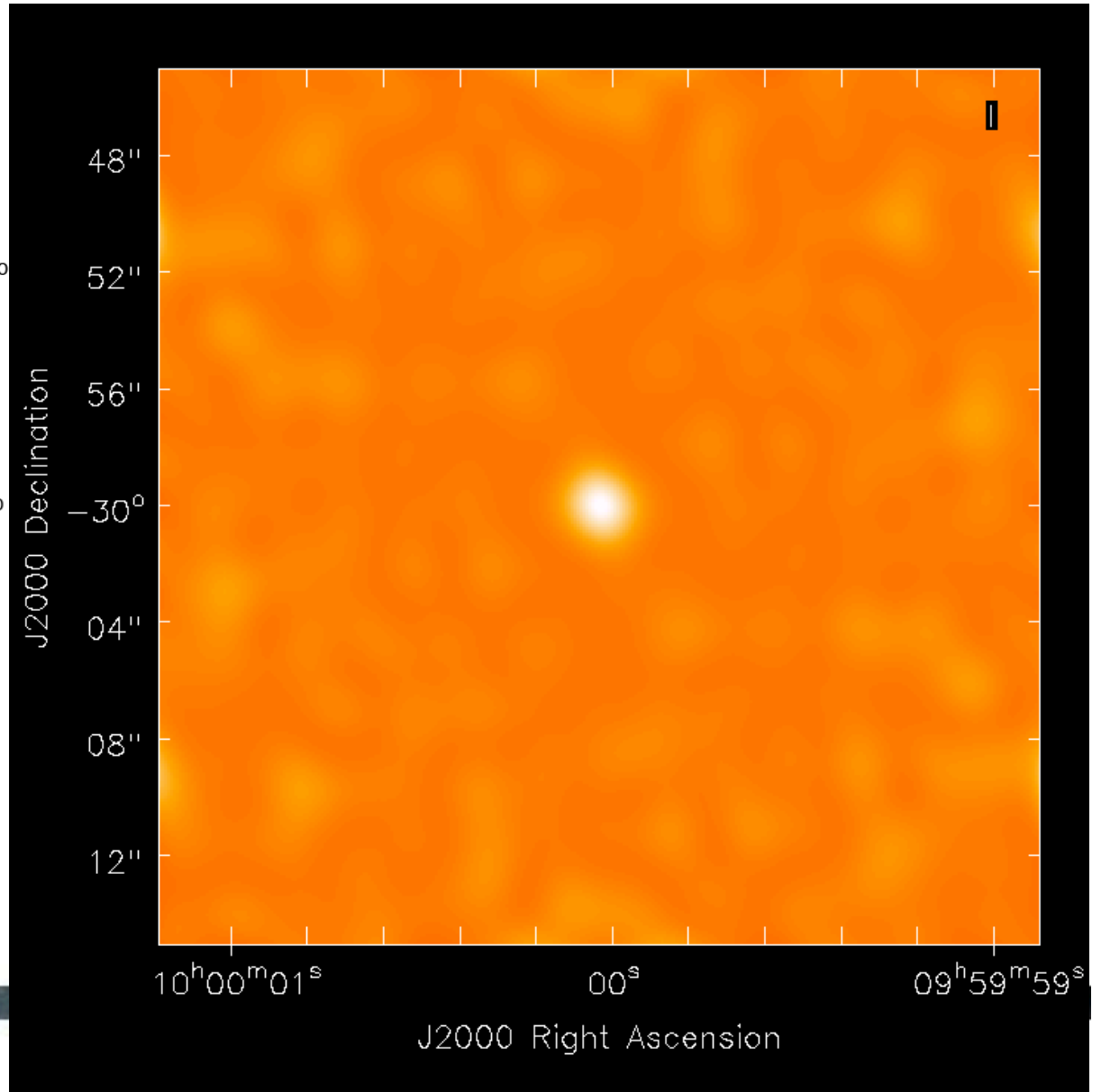
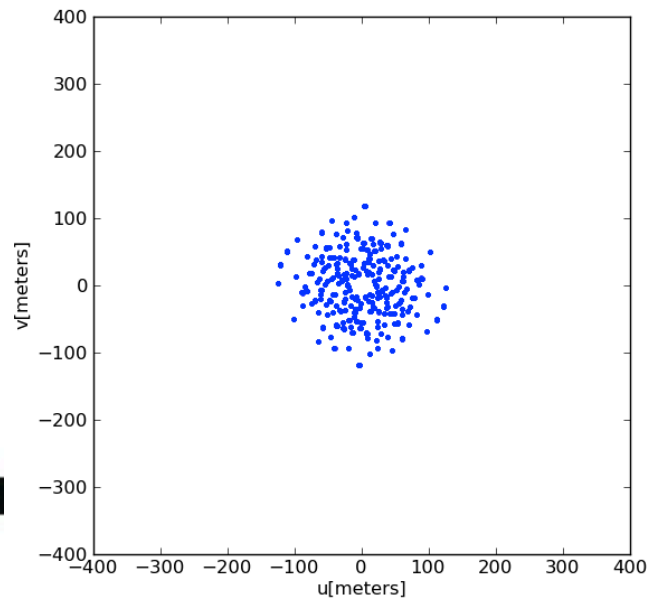
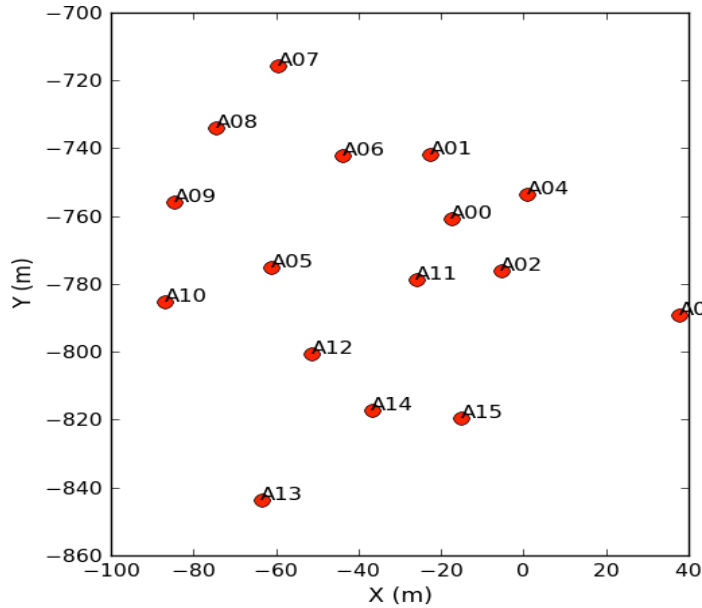
Example: Fringe pattern with 4 Antennas



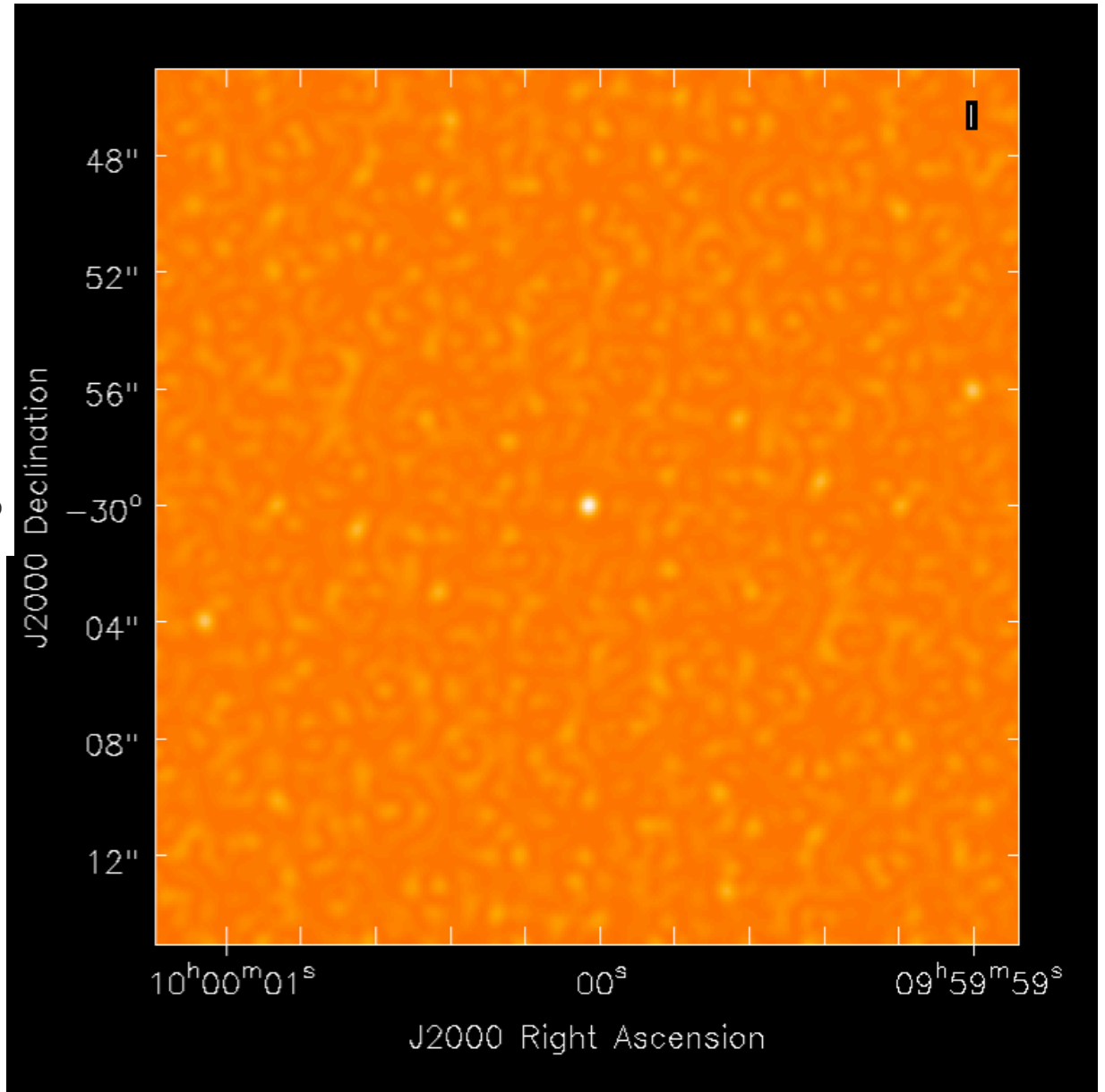
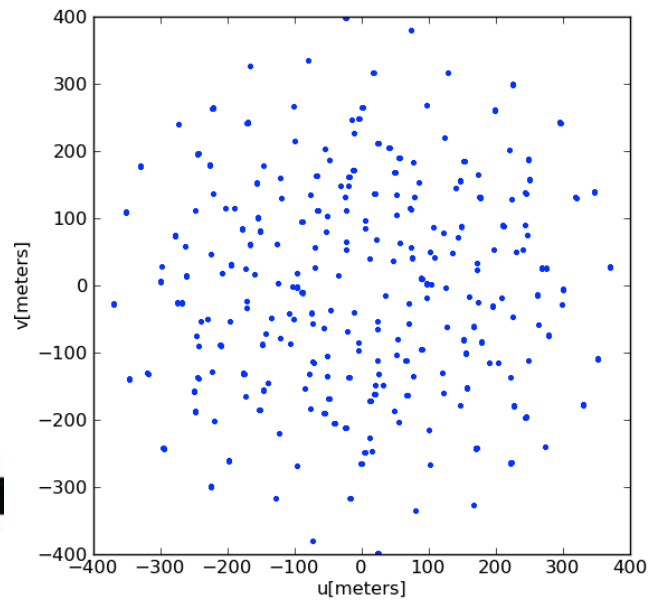
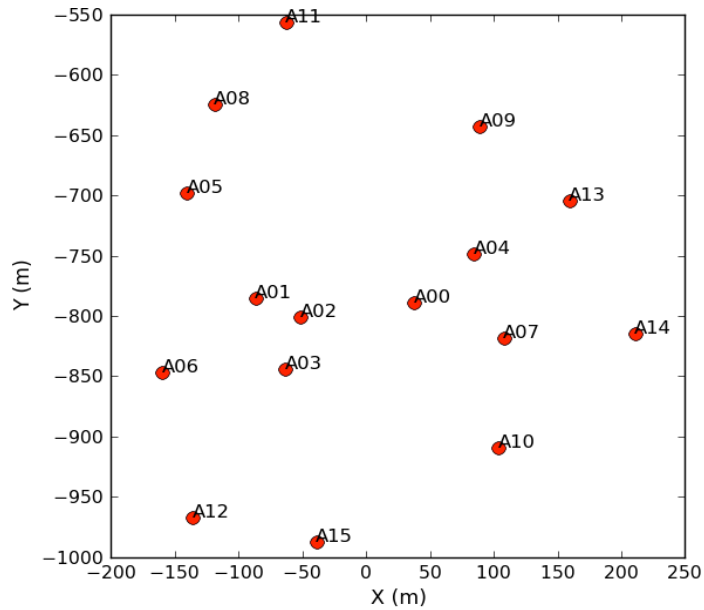
Example: Fringe pattern with 8 Antennas



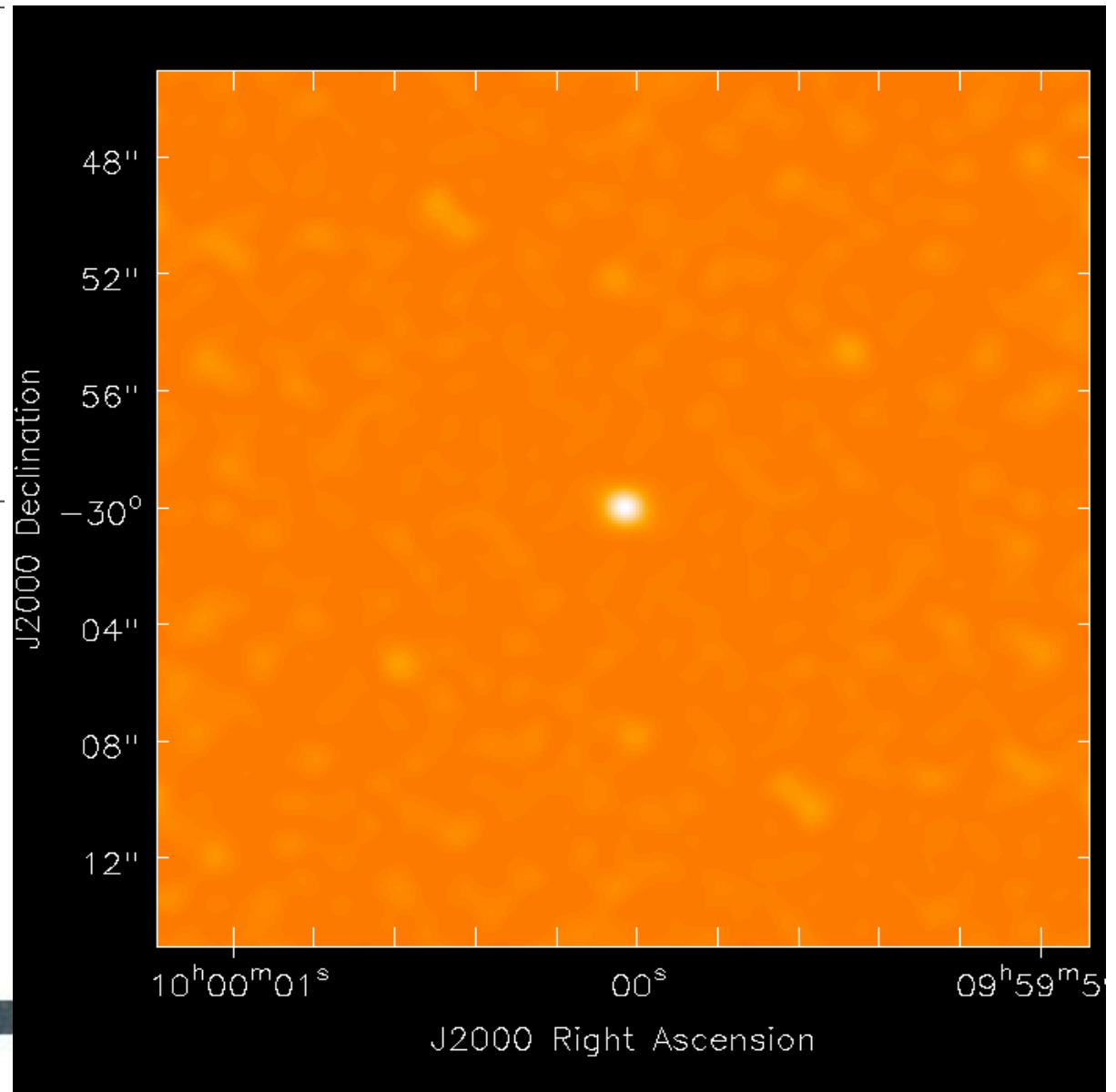
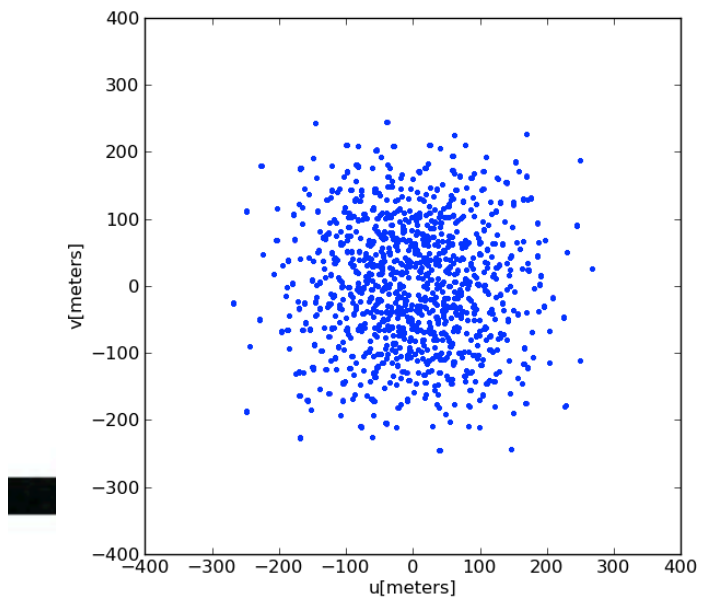
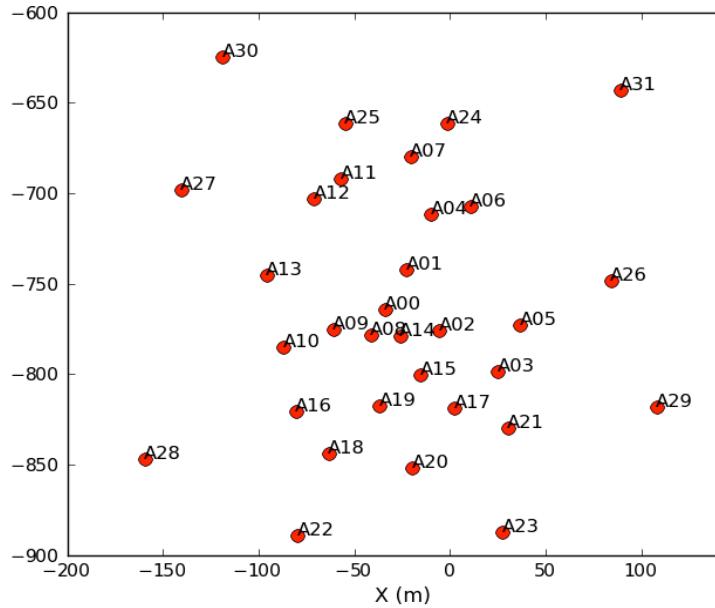
16 Antennas – Compact Configuration



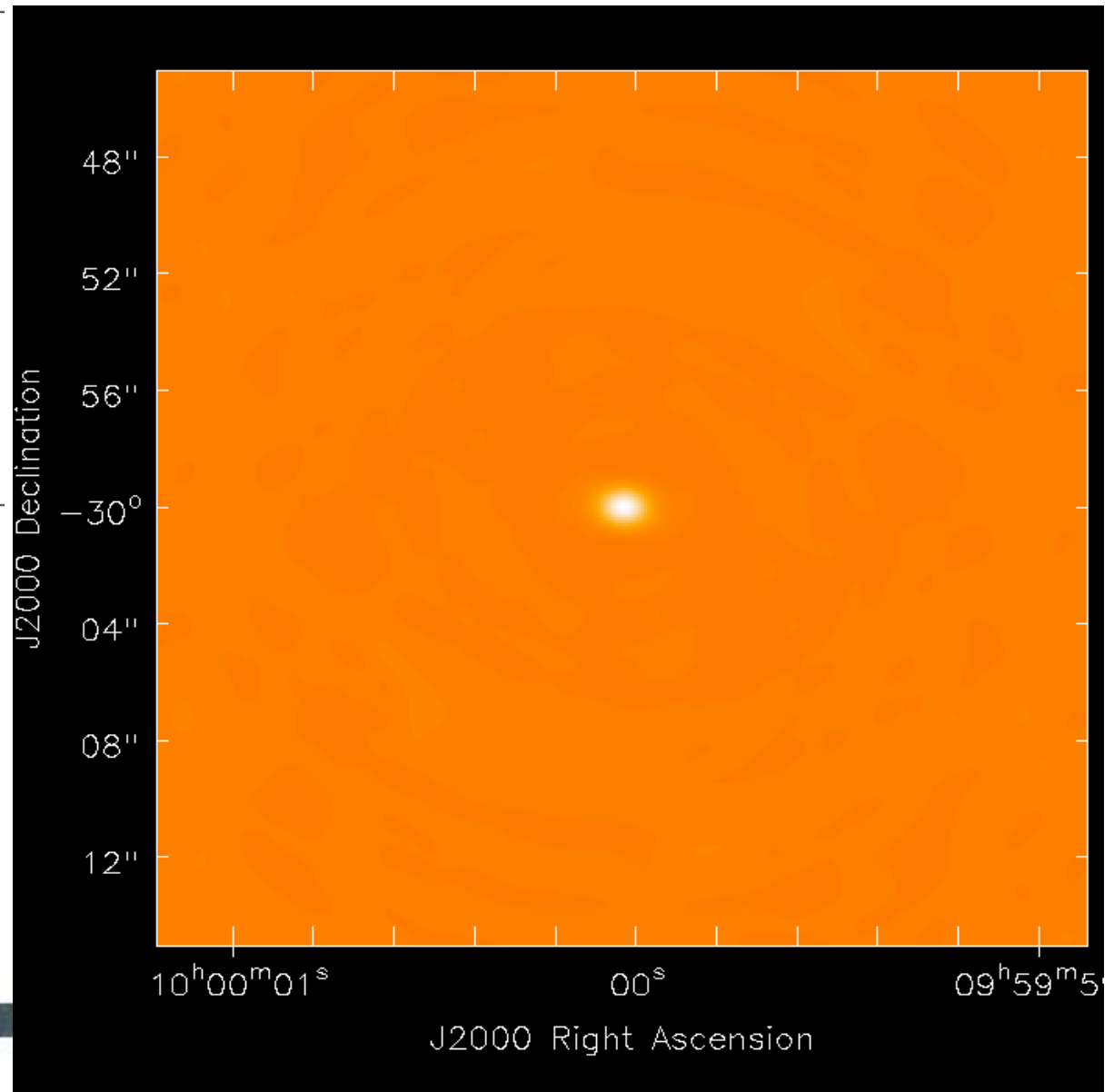
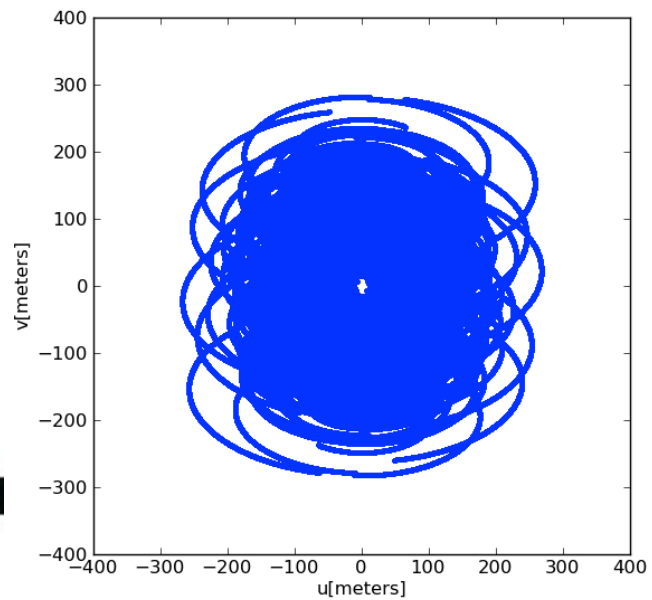
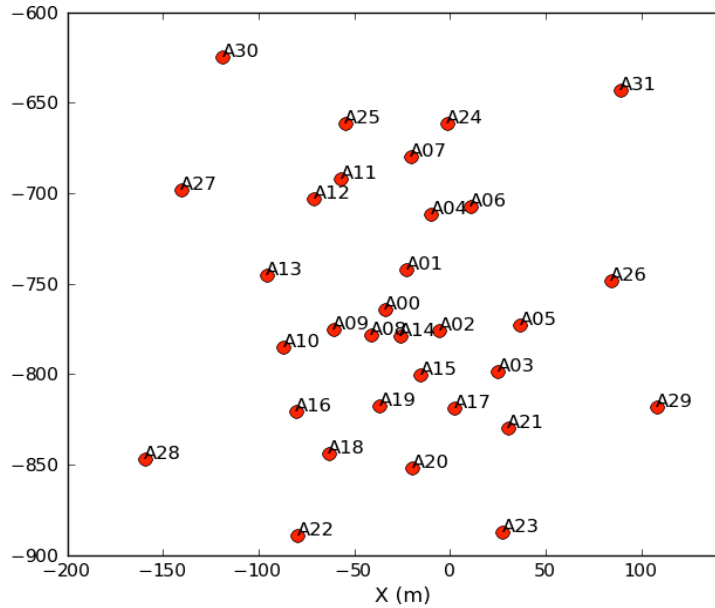
16 Antennas – Extended Configuration



32 Antennas – Instantaneous

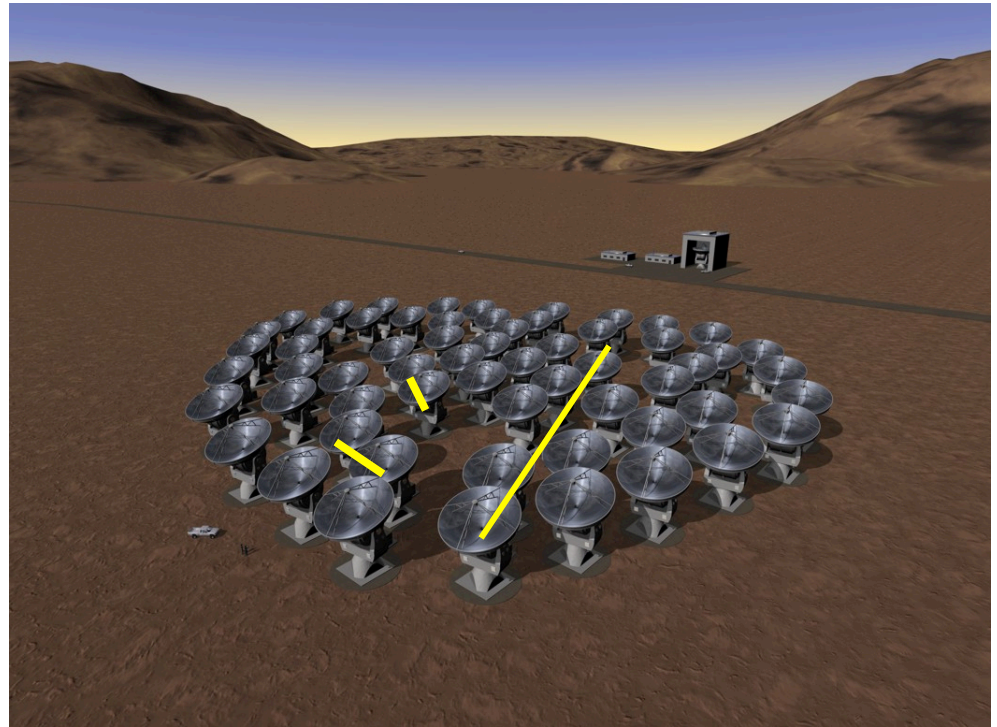
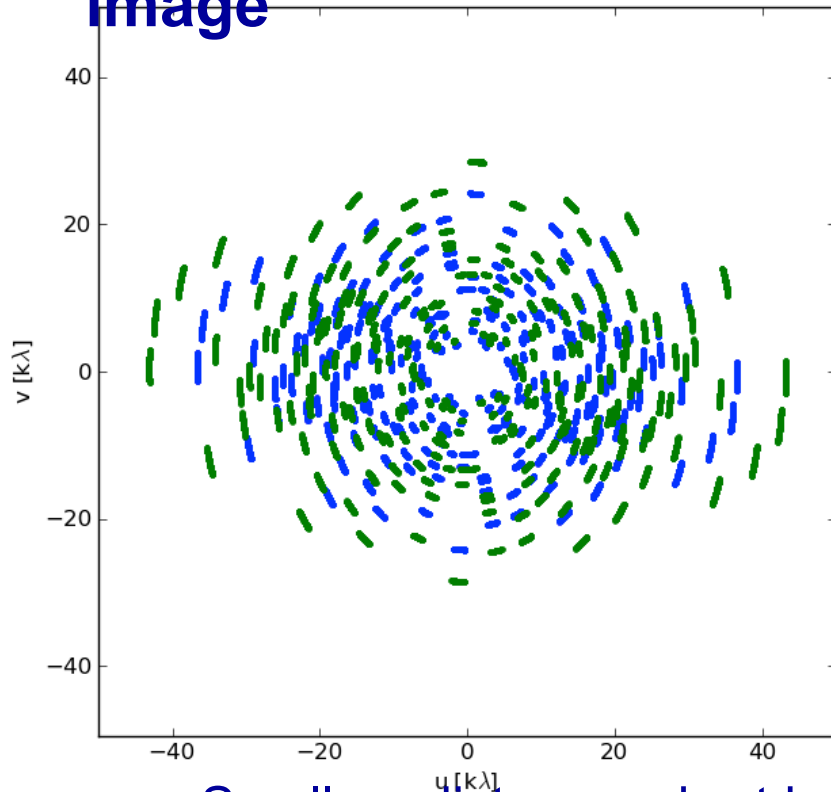


32 Antennas – 8 hours



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)

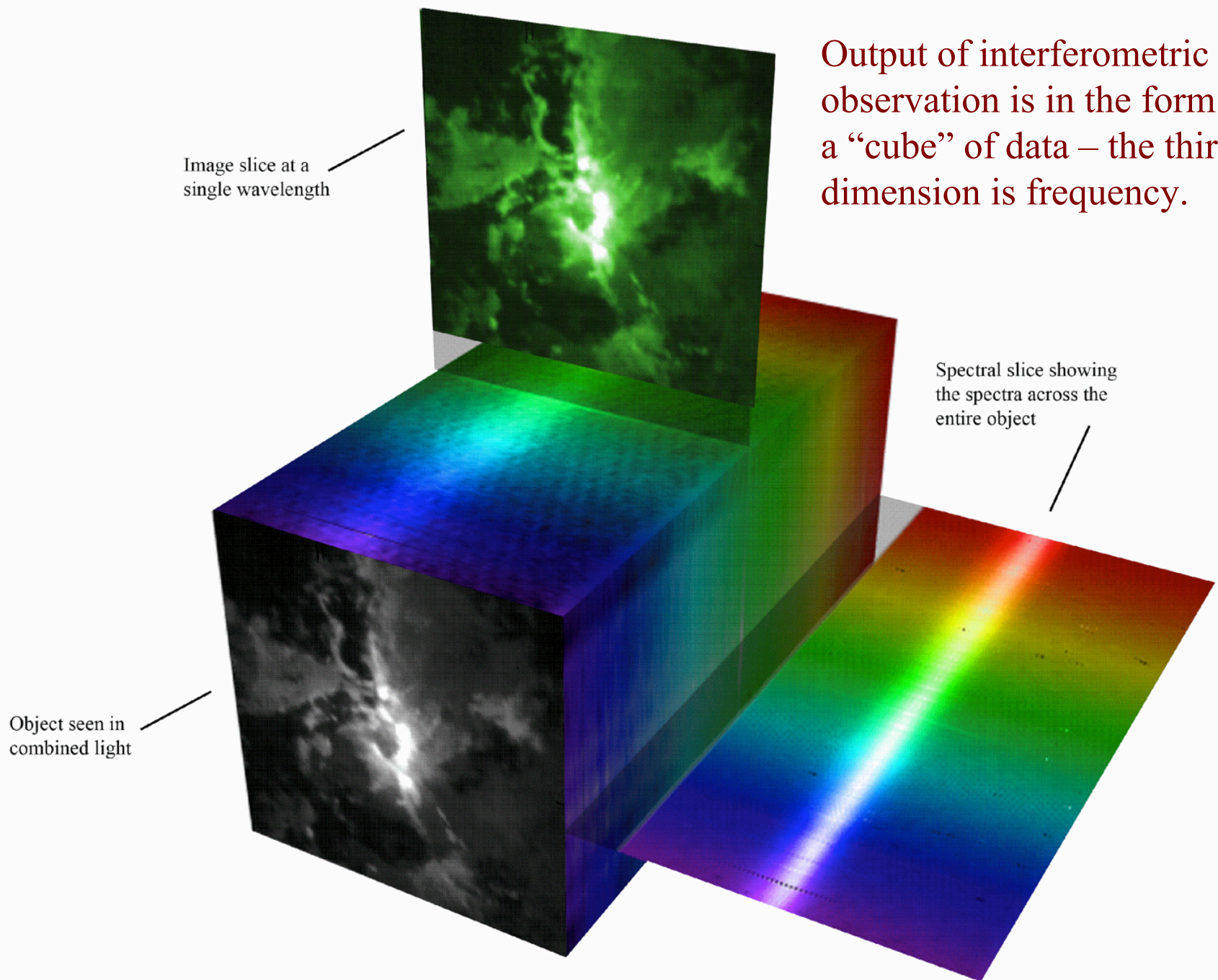
Orientation of baseline also determines orientation in the uv-plane

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 (more on this tomorrow!) or we can fill in the information with 7m observations or ultimately single dish data.

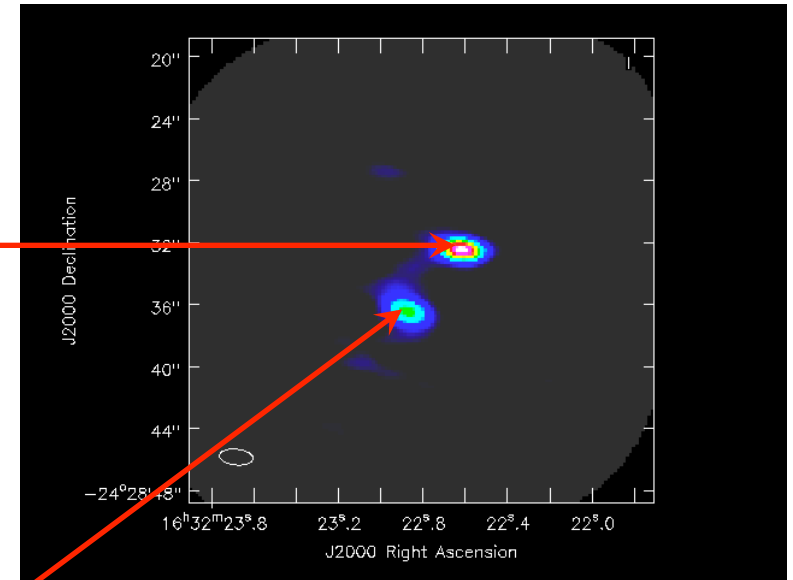
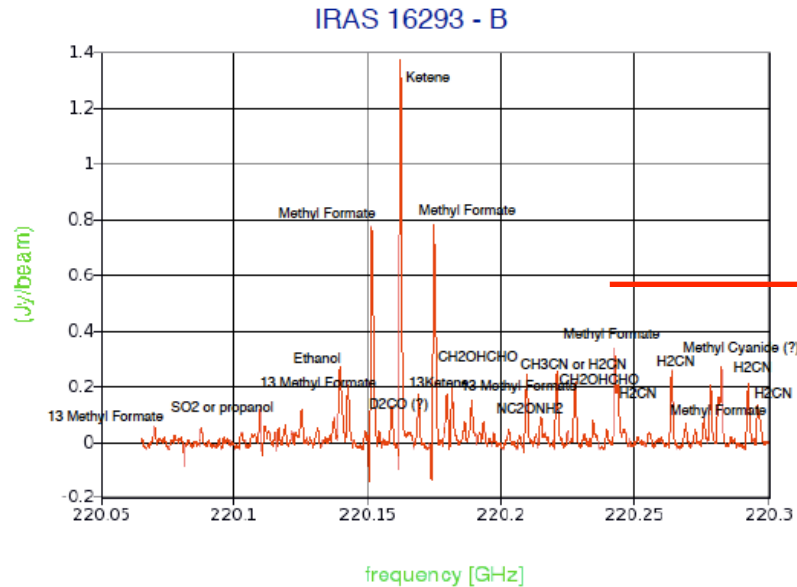


Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.



Sometimes the most interesting science lies in the third dimension

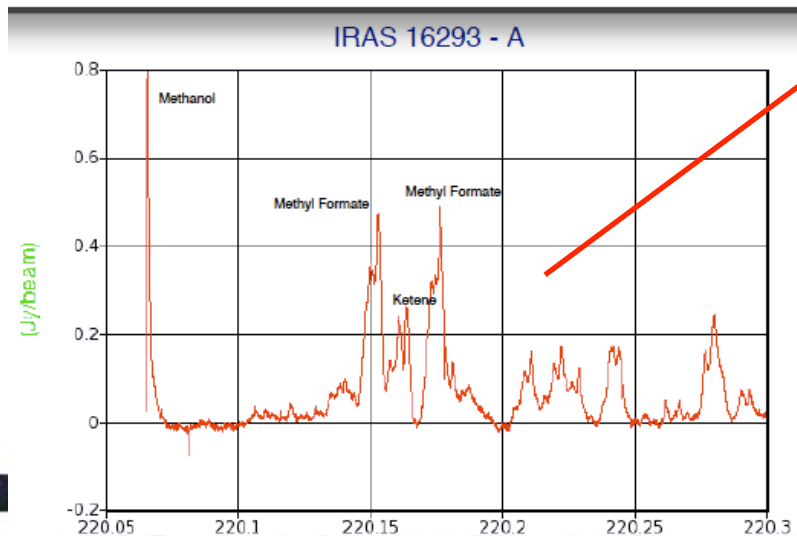
Band 6



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.



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



Calibration Process

Calibration is the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations.

Steps in calibrating interferometric data:

(Note: You don't have to worry about these in your observational set up!)

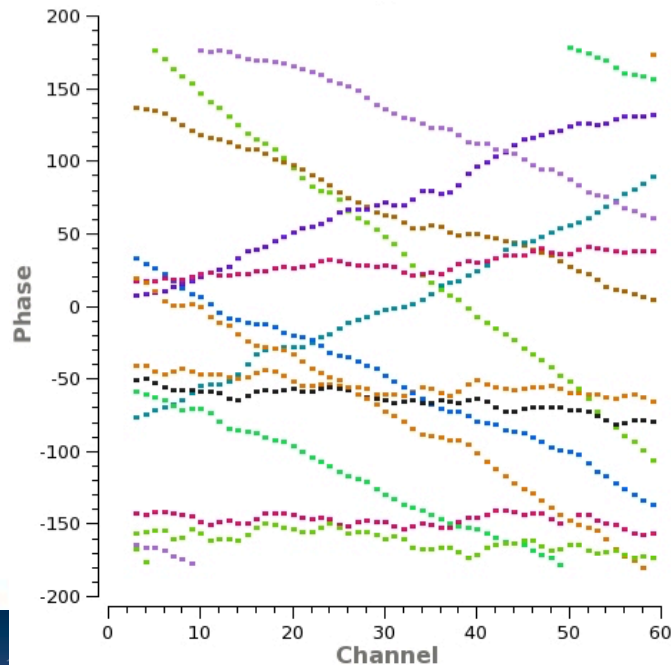
- Bandpass calibration (correct frequency-dependent telescope response)
- Phase and amplitude gain calibration (remove effects of atmospheric water vapor and correct time-varying phases/amplitudes)
- Set absolute flux scale



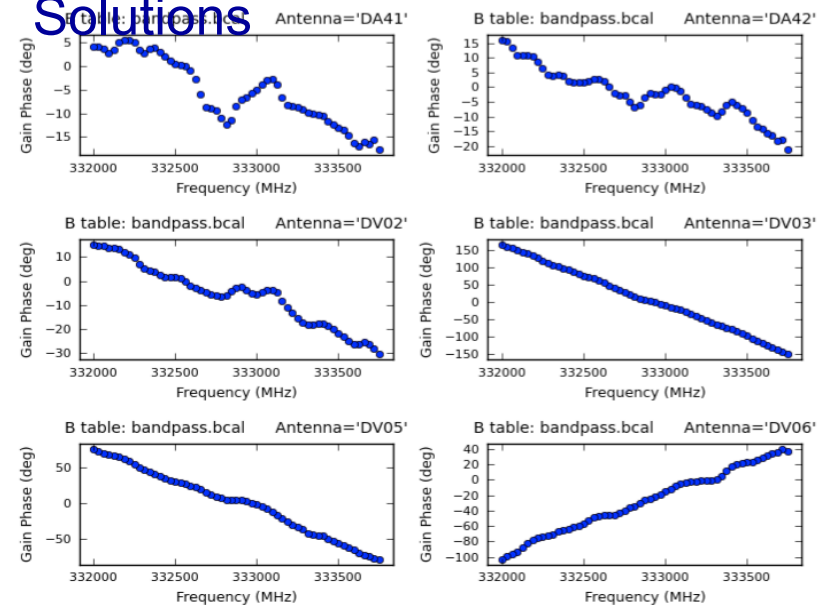
Bandpass Calibration: Phase

- * Analogous to optical “flat fielding” + bias subtraction for each antenna.
- * Primarily correcting for frequency dependent telescope response (i.e. in the correlator/spectral windows)
- * Done once in an SB, uses bright point sources like quasars
- * Typically, baseline responses are inverted to antenna-based correction

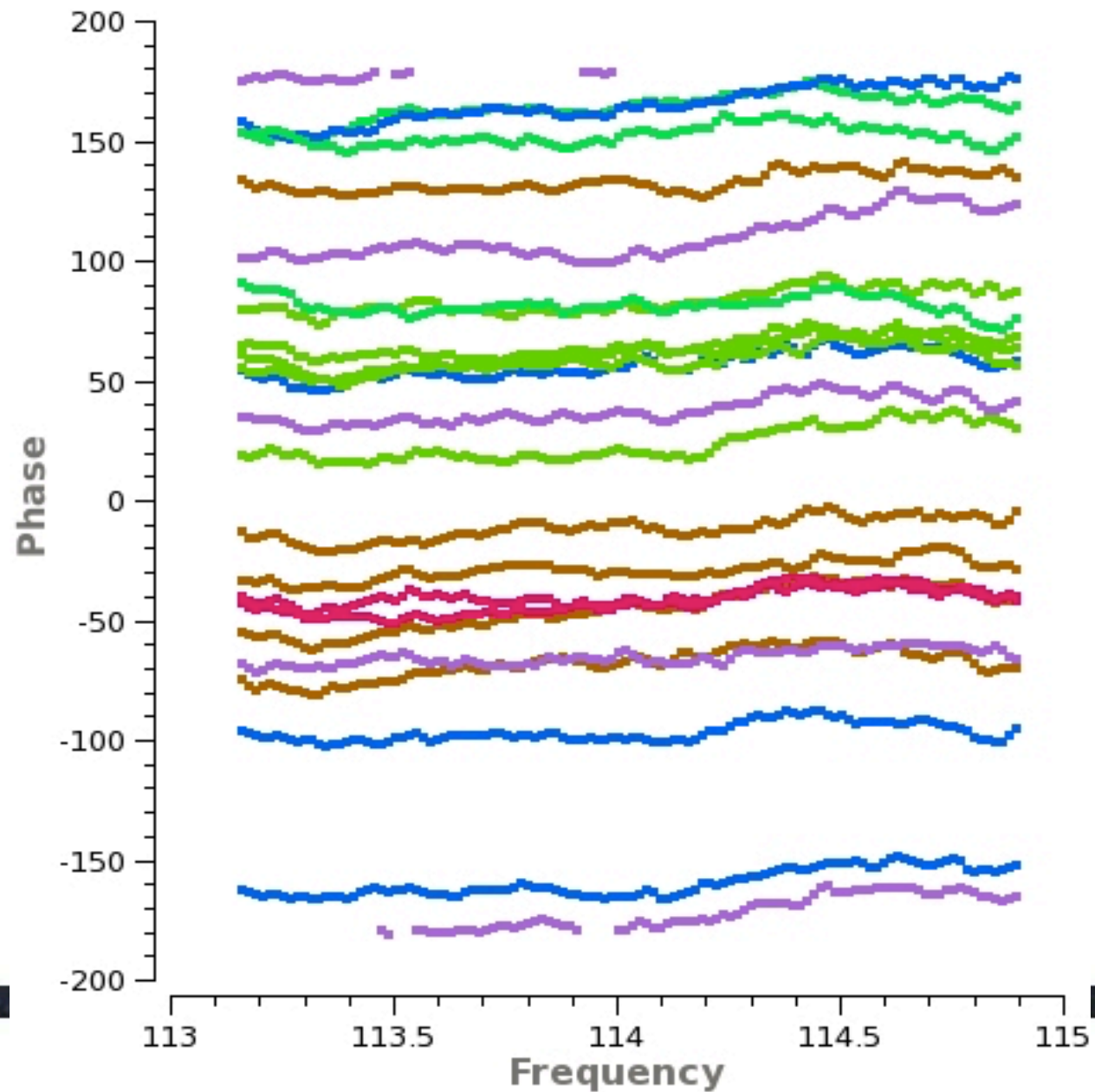
Baselines to one antenna



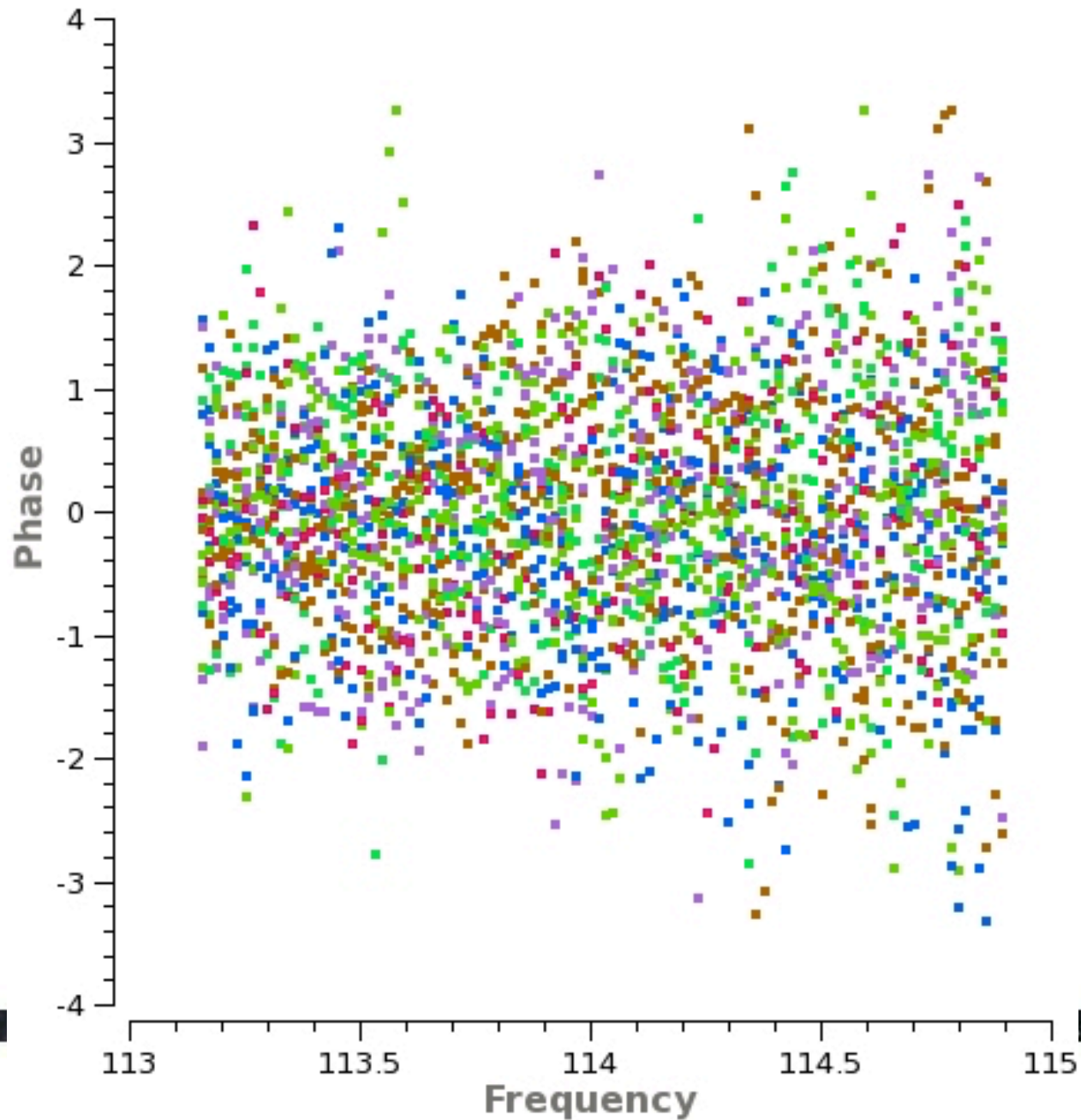
Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)

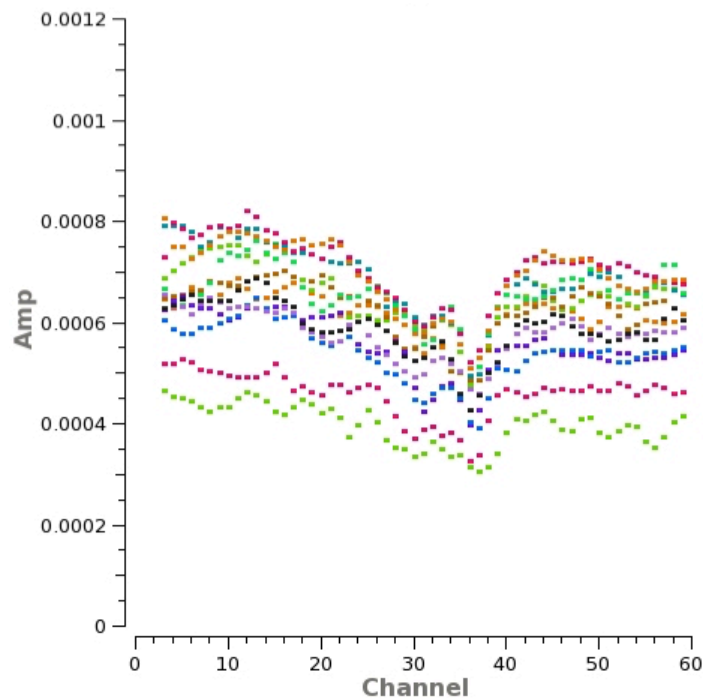


Bandpass Phase vs. Frequency (After)

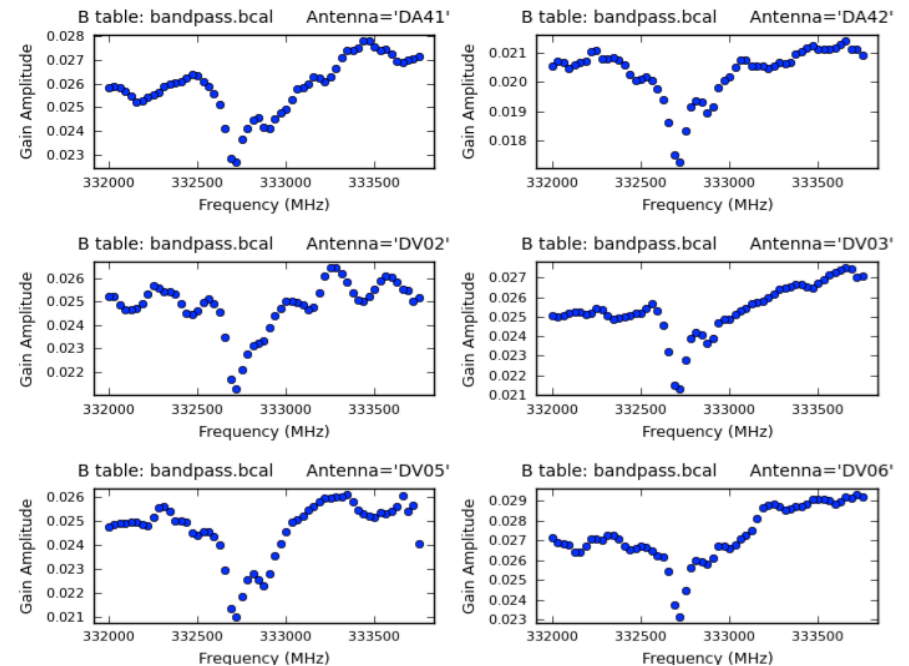


Bandpass Calibration: Amplitude

Baselines to one antenna



Amplitude Before Bandpass Calibration



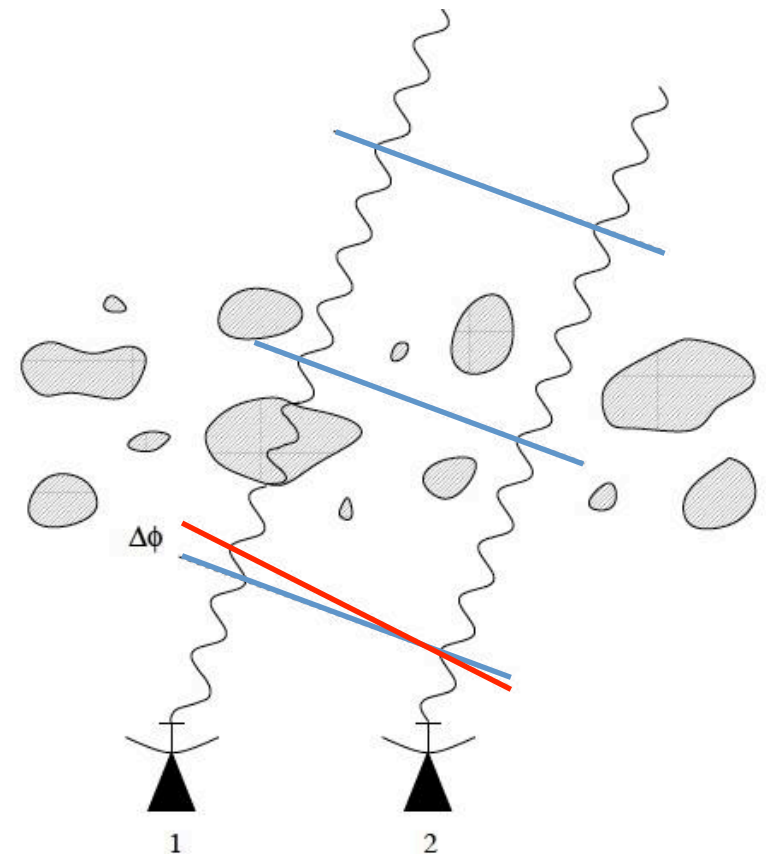
Bandpass solutions for individual antennas



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.

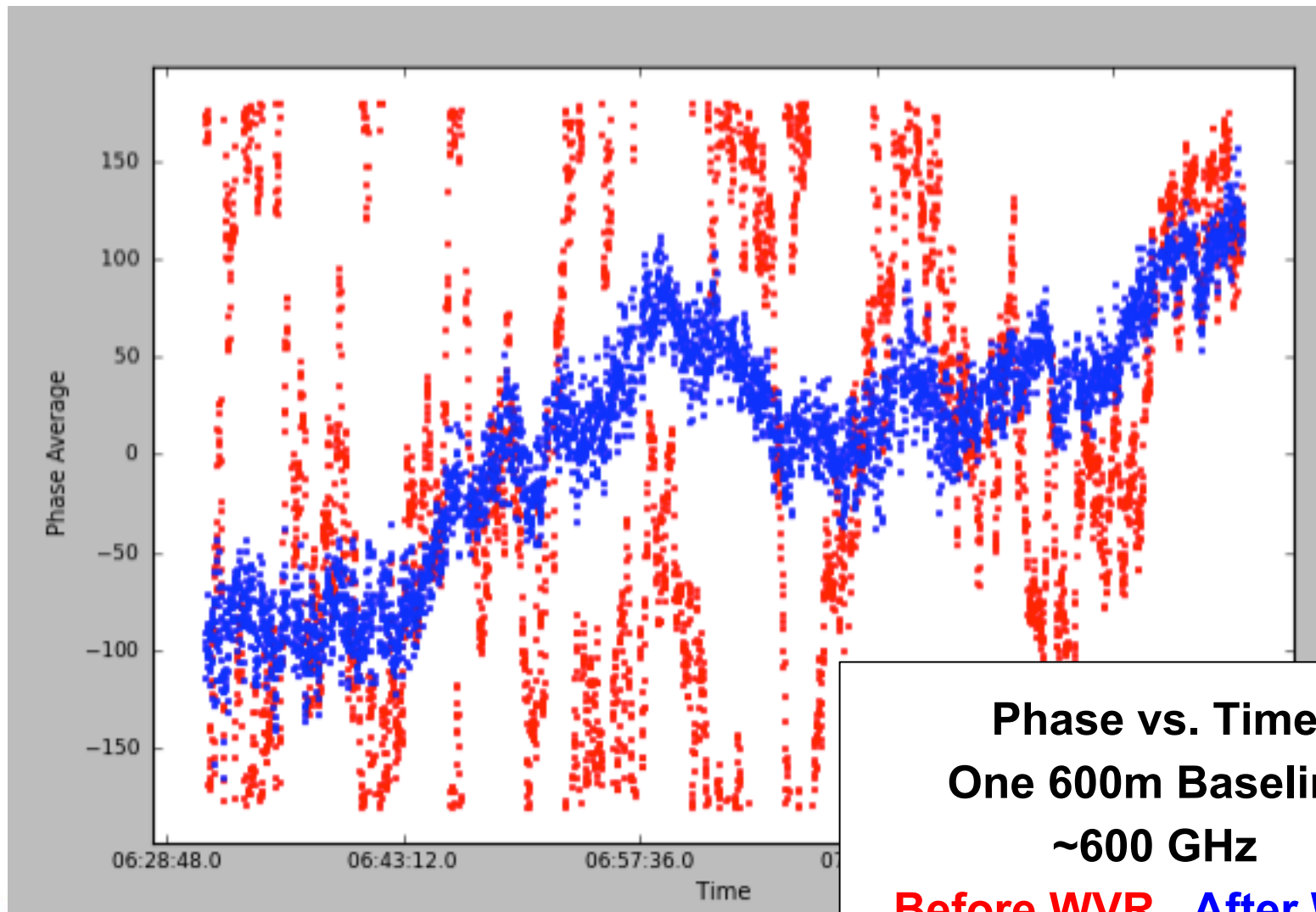


Phase & Amplitude Gain Calibration

Determines the variations of phase and amplitude over time

- First pass is atmospheric correction from Water Vapor Radiometers readings
- Final correction from gain calibrator (point source near to target) that is observed every few minutes throughout the observation (analogous to repeat trips to a standard star)

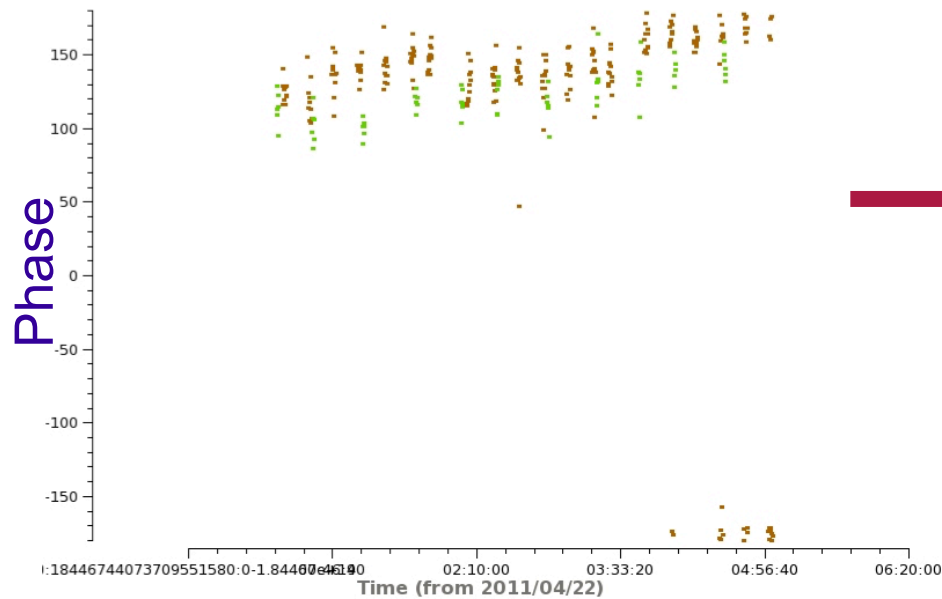
Water Vapor Correction on ALMA



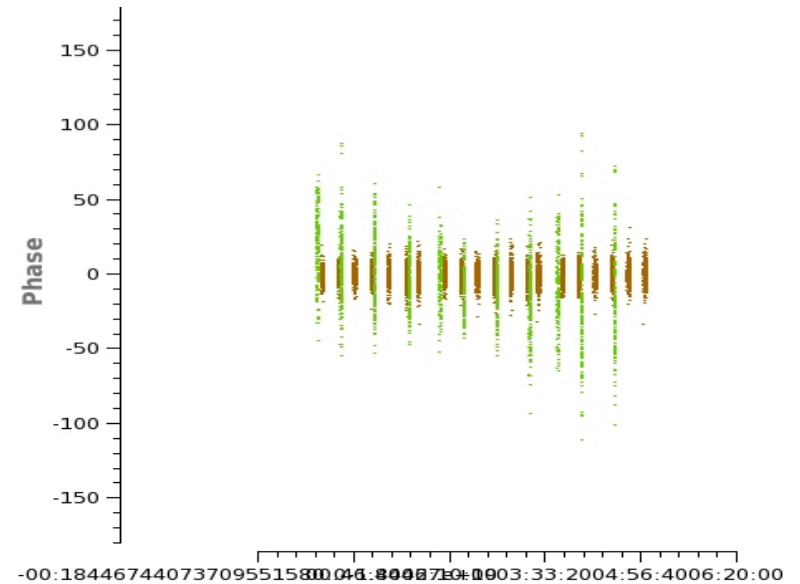
Phase vs. Time
One 600m Baseline
~600 GHz
Before WVR, After WVR

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

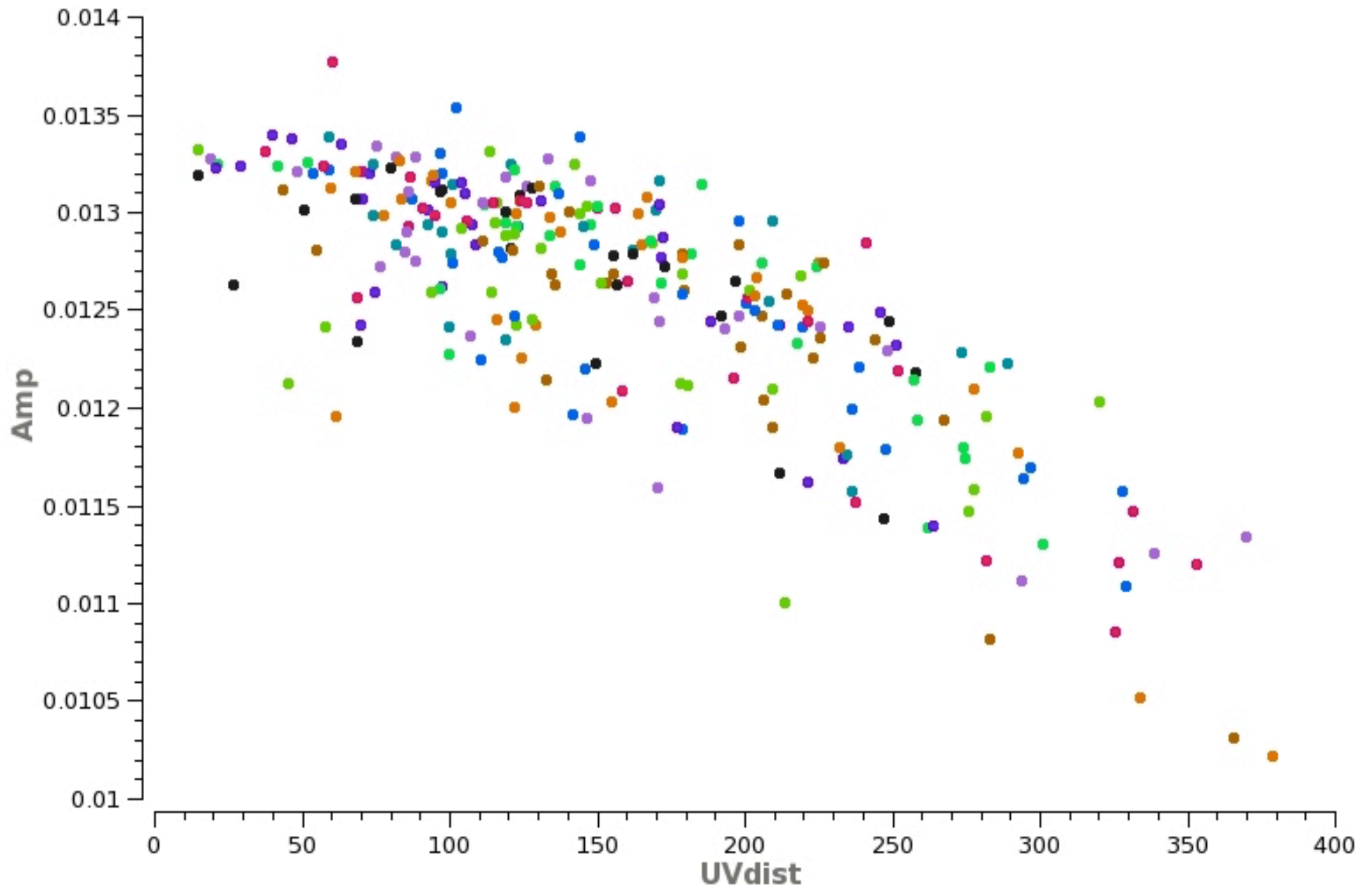
Two Steps:

1. Use calibration devices with known temperatures (hotload and ambient load) to measure System Temperature frequently.
2. 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 modeled very well.

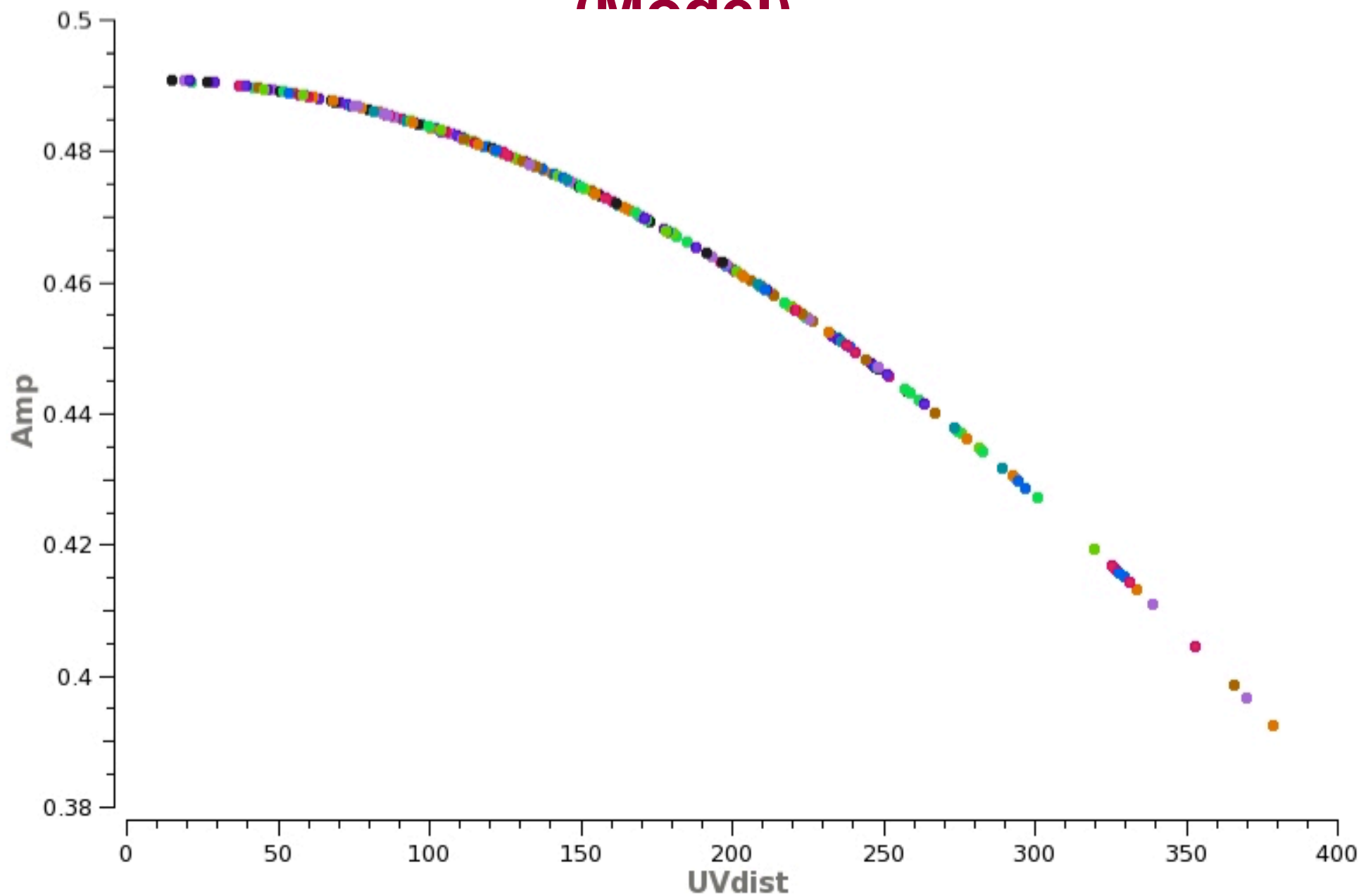
The derived amplitude vs. time corrections for the calibrator are then applied to the science target.



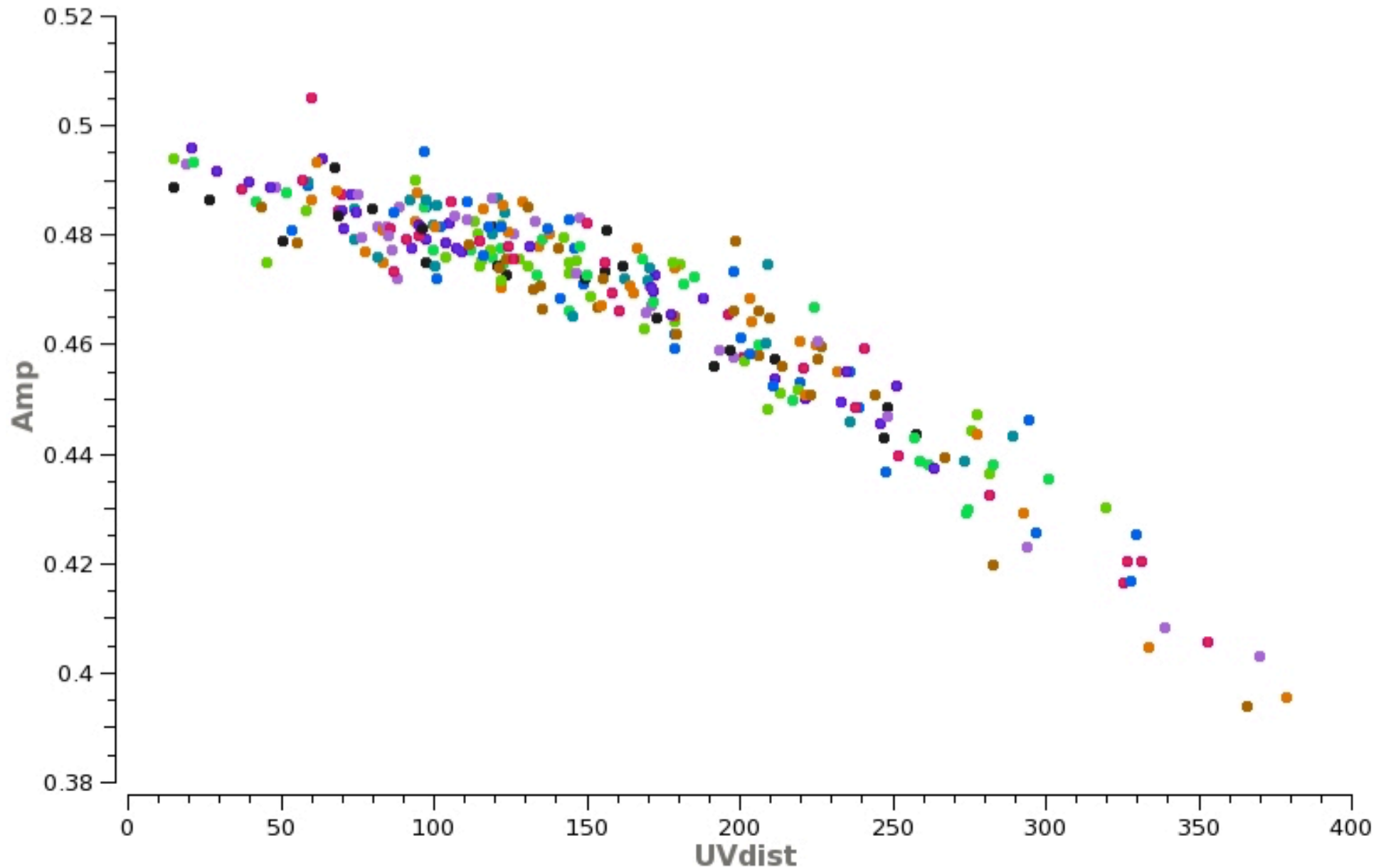
Amp-Calibrators Amp vs. uv-distance (Before)



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



Amp-Calibrators Amp 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>

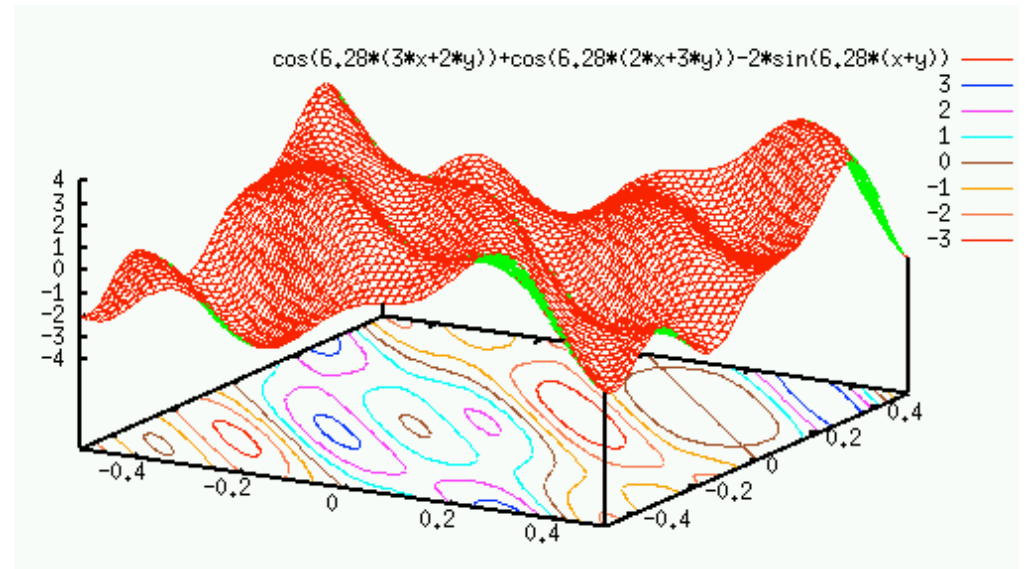
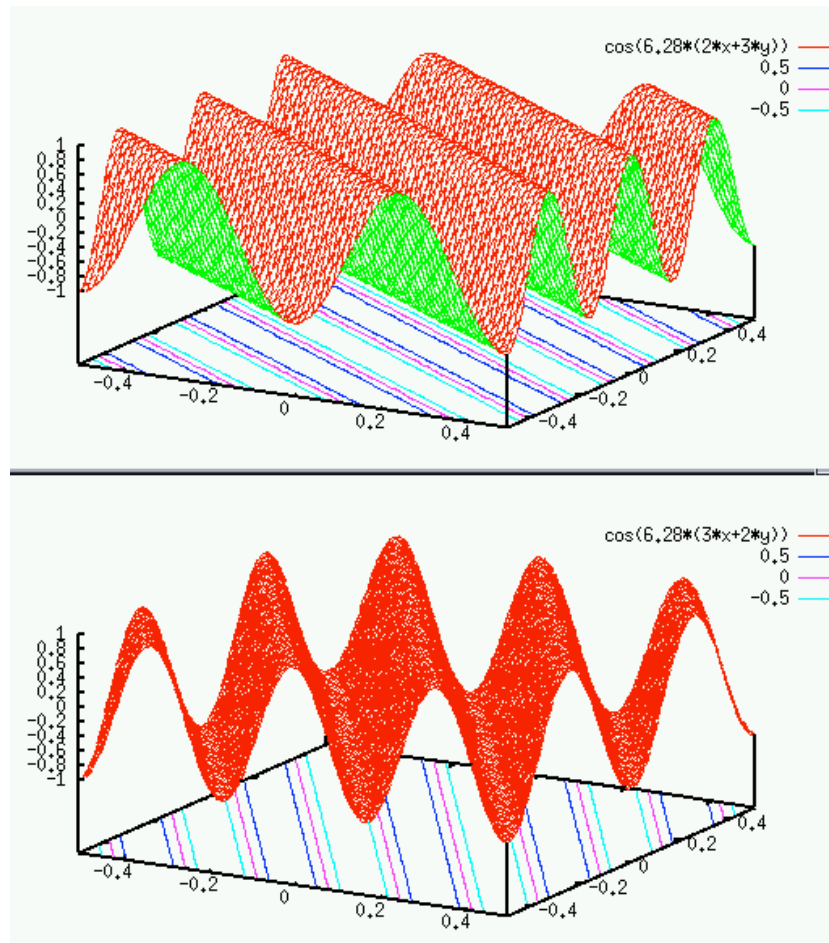
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The Fourier Transform



Example: 2D Fringe pattern



Some 1D Fourier Transform Pairs

