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

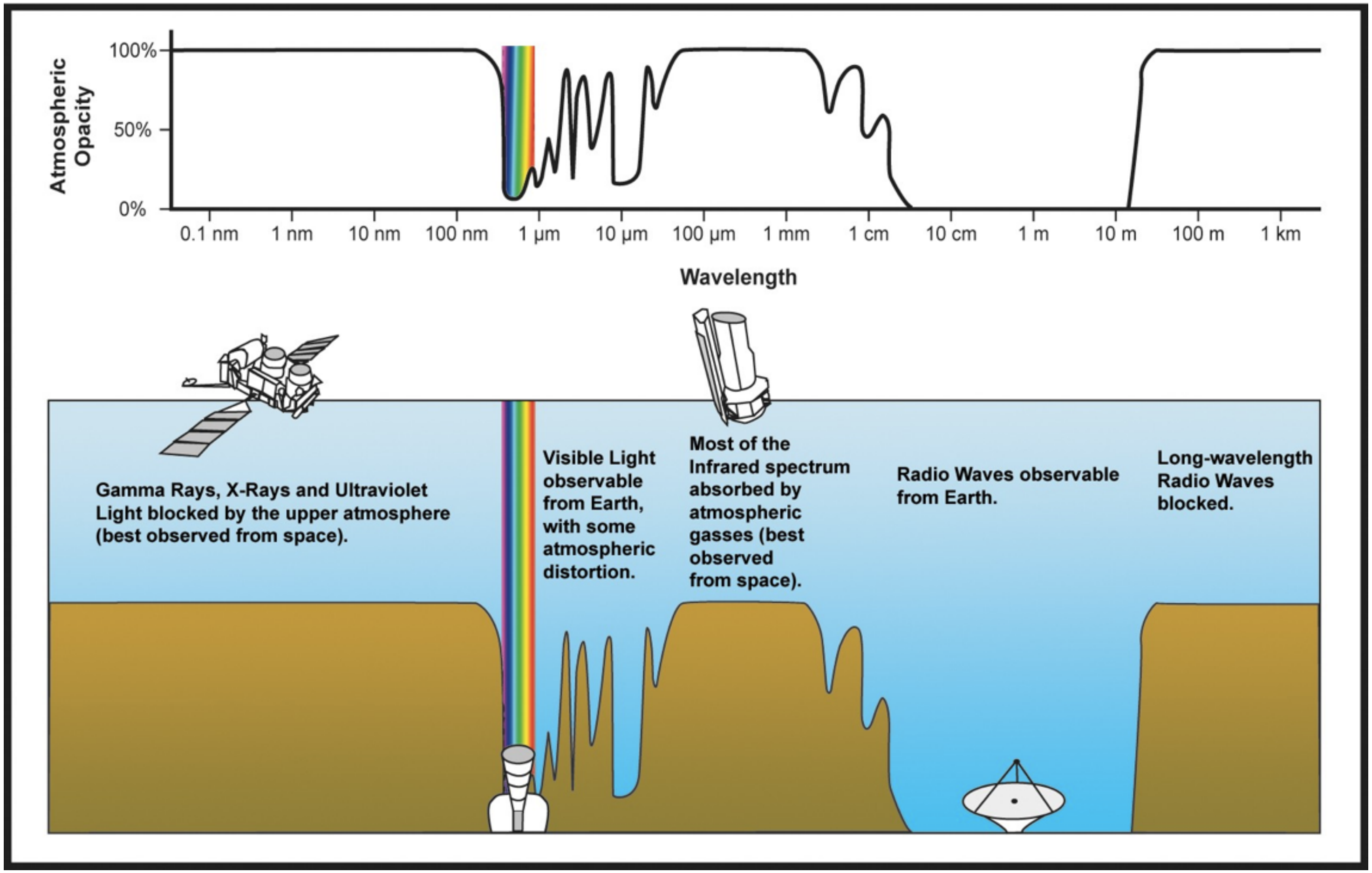


Image from IRAC Cool Cosmos

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.

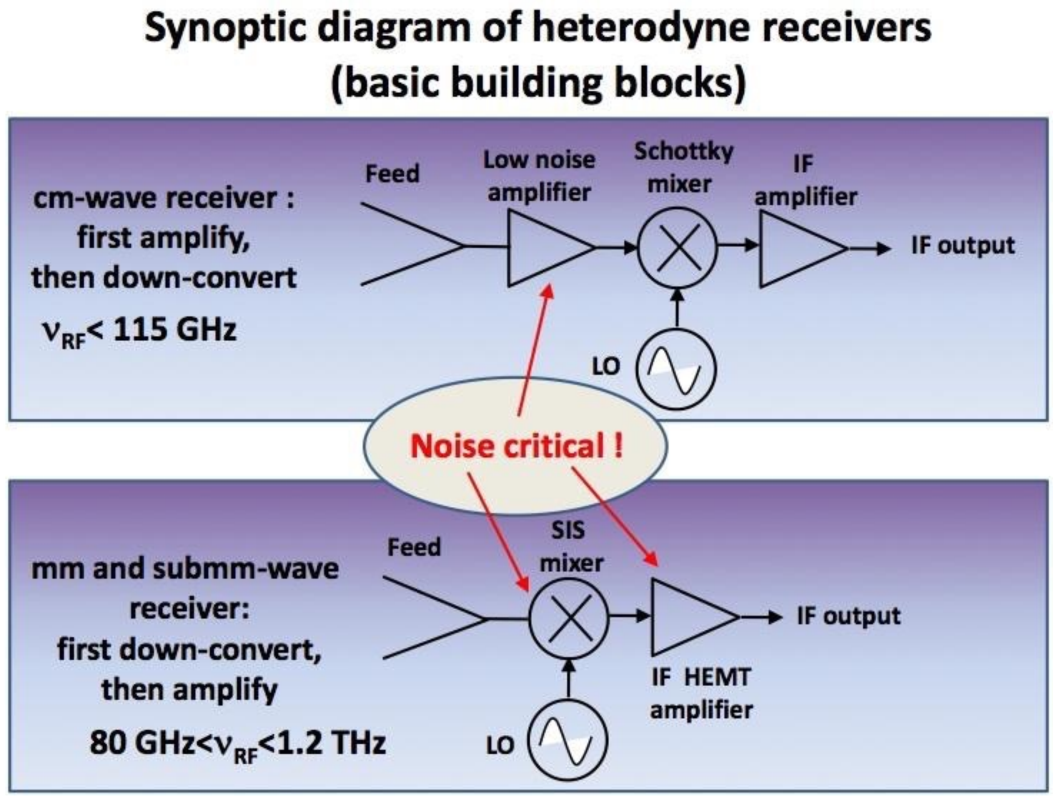
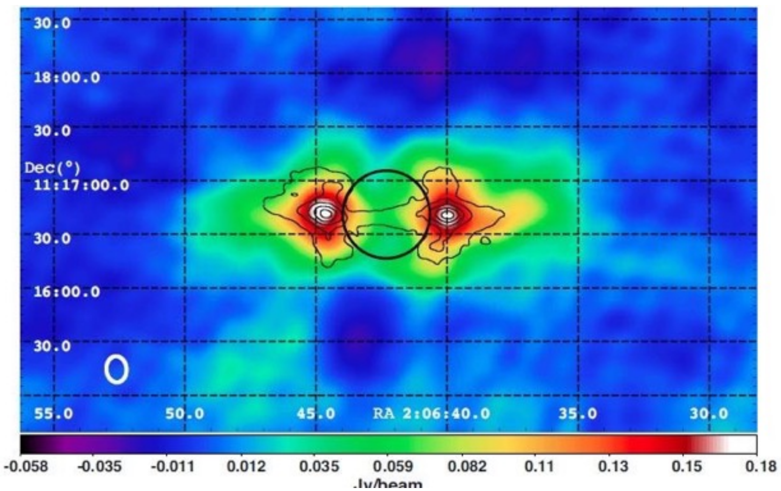


Image from Alessandro Navarrini (IRAM)

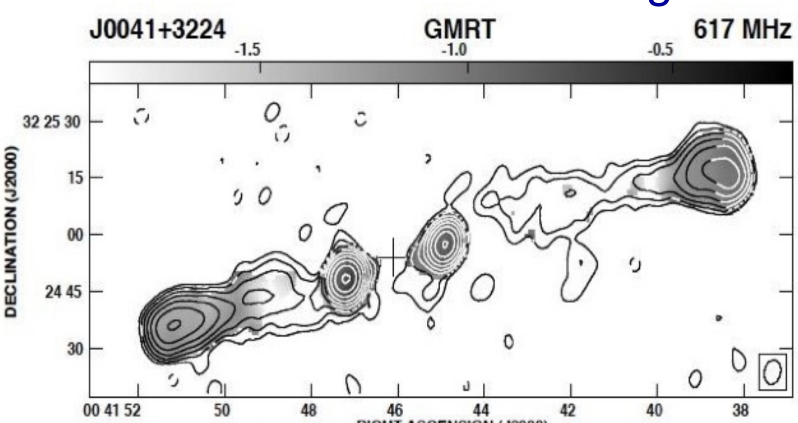
Long wavelength means no glass mirrors

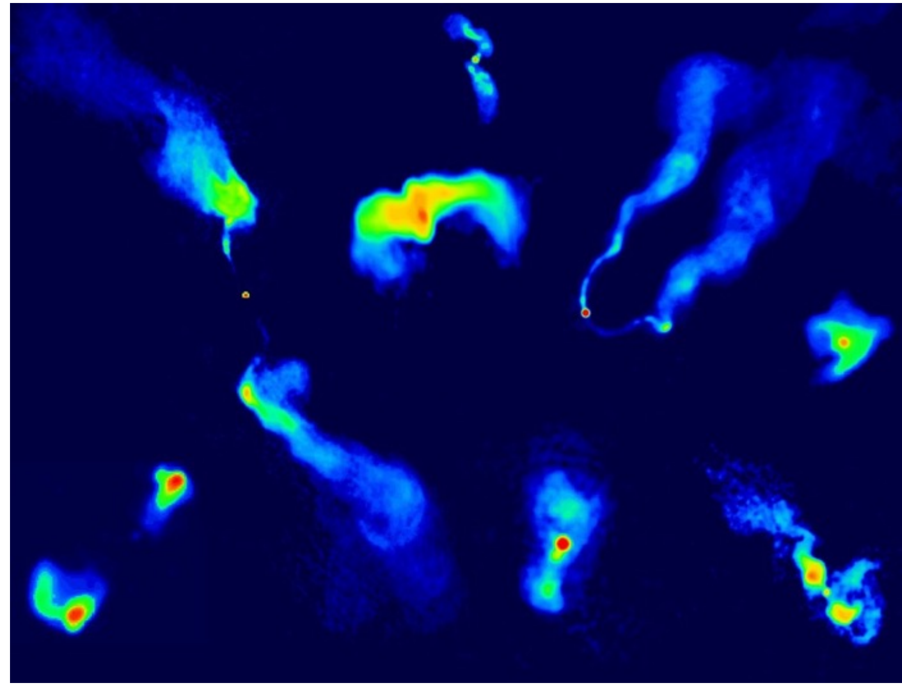
What can we observe? (100 MHz- 50 GHz range)

Jupiter's radiation belt at 100MHz



Relic emission from old radio galaxies



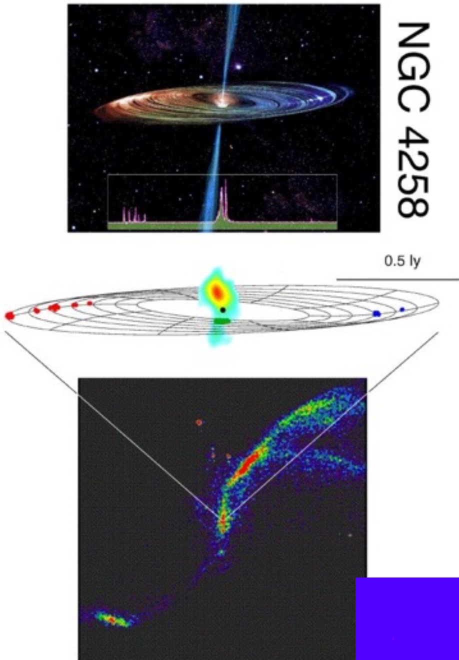


Synchrotron emission from extended radio galaxies (5 GHz)

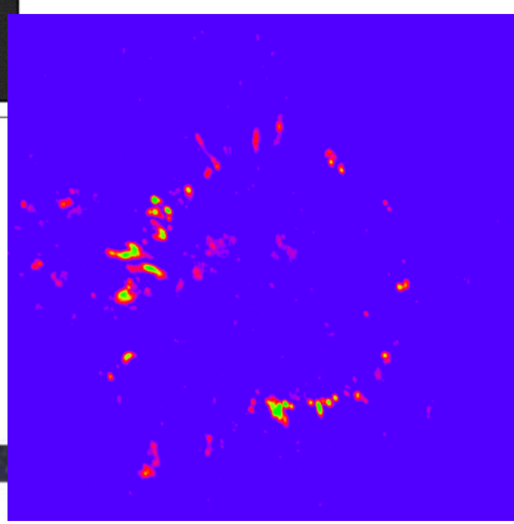
Images from NRAO Image Gallery: http://images.nrao.edu/

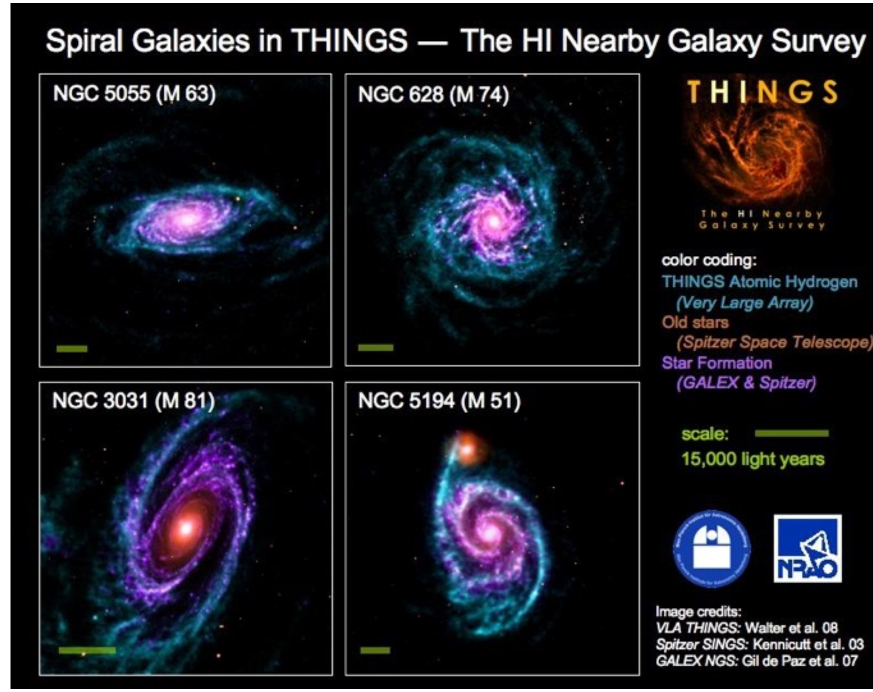
Images from NRAO Image Gallery
http://images.nrao.edu/

What else can we observe?
(100 MHz- 50 GHz range)

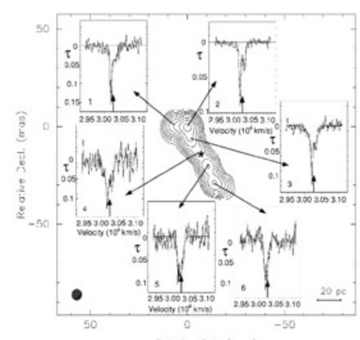


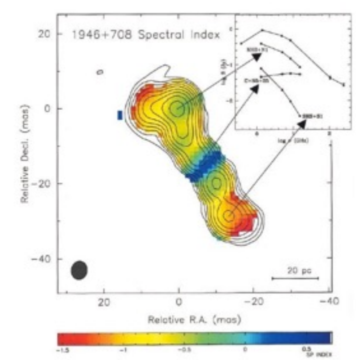
H_2O, OH or SiO masers in galaxies and stars





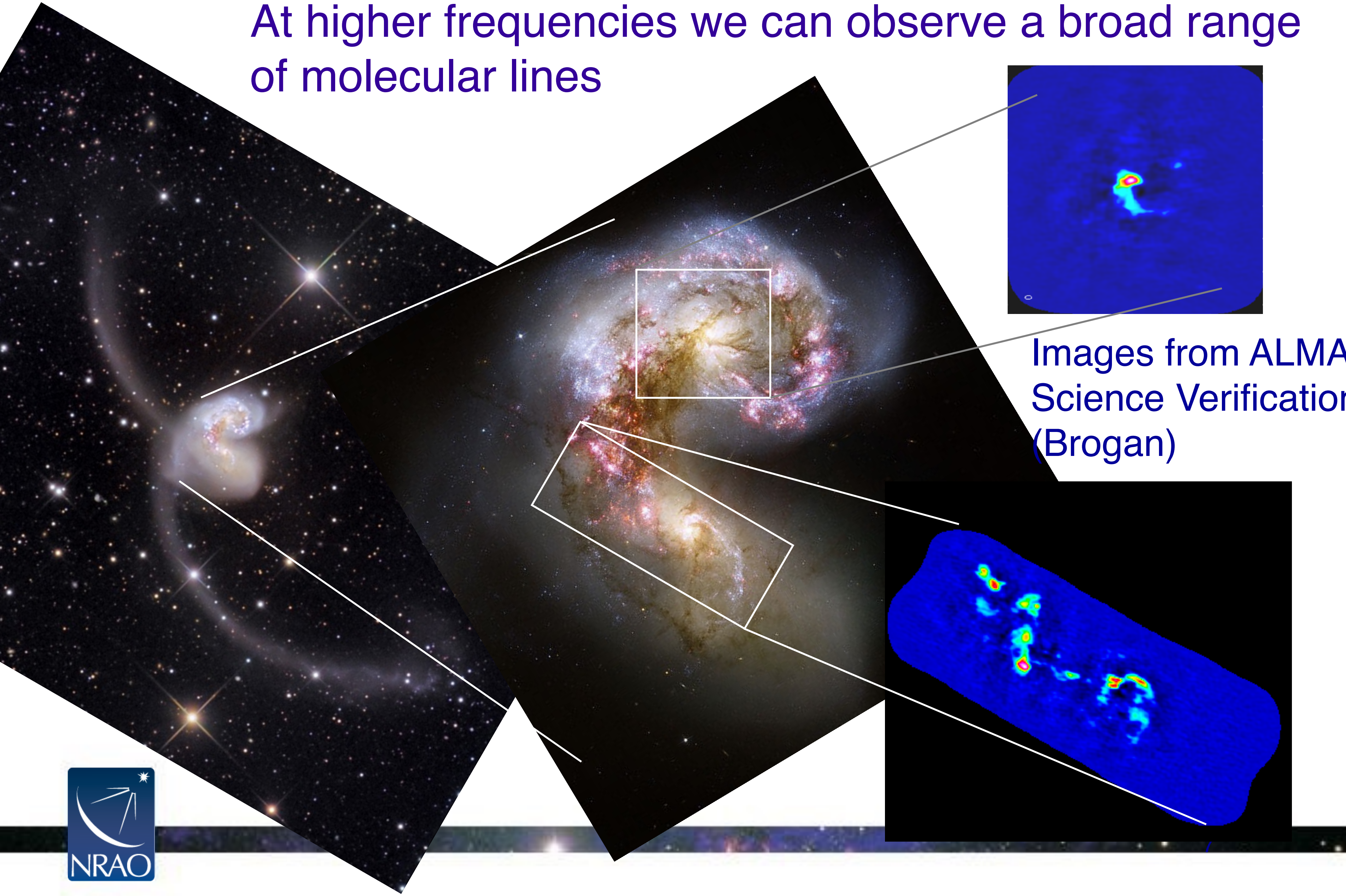
HI emission and absorption, free-free absorption in galaxies





What can we observe? (90 GHz- 700 GHz range)

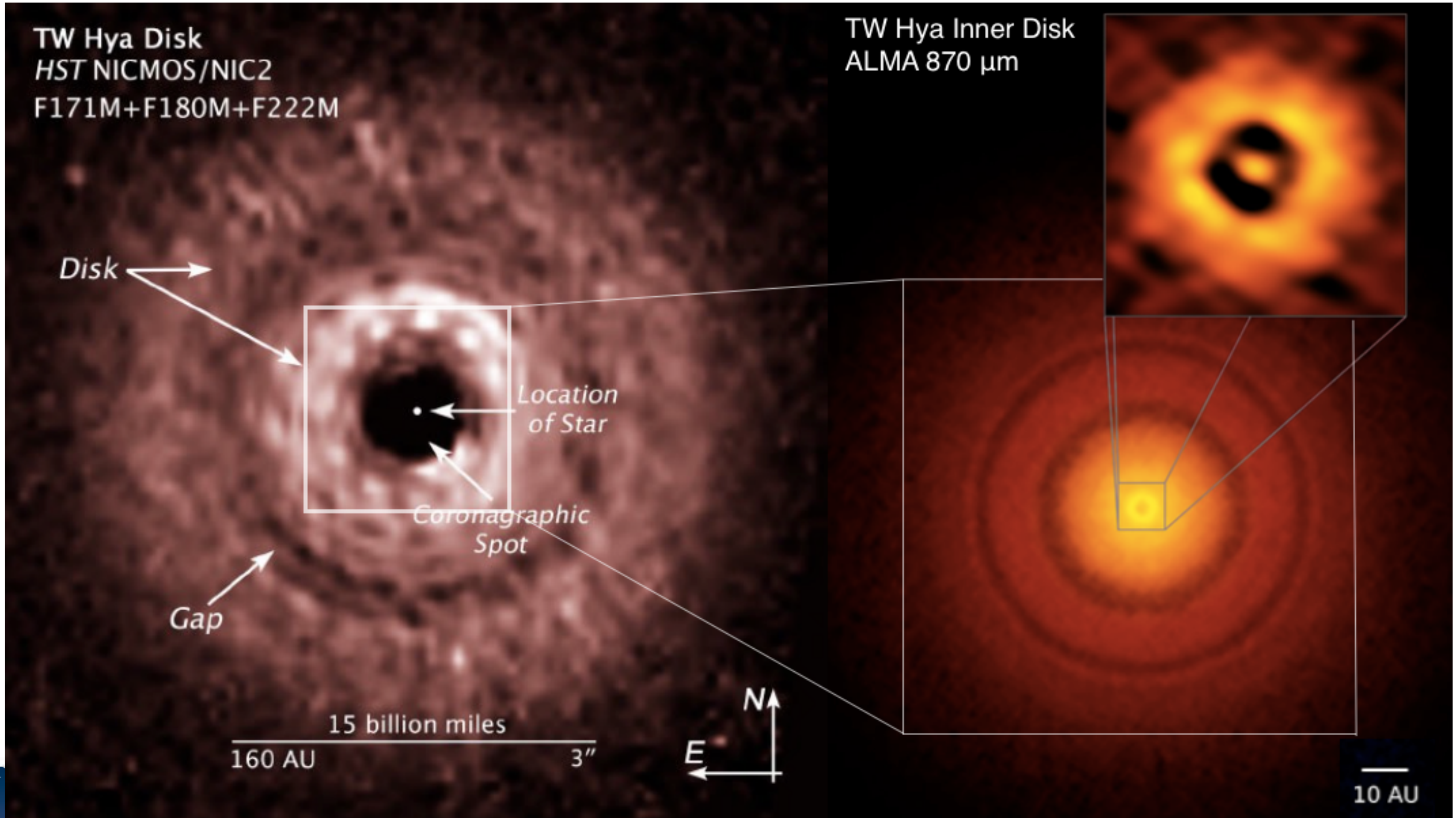
At higher frequencies we can observe a broad range of molecular lines



Images from ALMA Science Verification (Brogan)

What can we observe? (90 GHz- 700 GHz range)

At higher frequencies we can observe sensitive dust continuum… WAY better than Hubble



(NASA / ESA / J. Debes, STScI / H. Jang-Condell, University of Wyoming / A. Weinberger, Carnegie Institution of Washington / A. Roberge, Goddard Space Flight Center / G. Schneider, University of Arizona, Steward Observatory / A. Feild, STScI, AURA)

S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)

Resolution of Observations

Angular resolution for most telescopes is ~ λ/D

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

For example, Hubble Space Telescope:

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

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

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

This is interferometry

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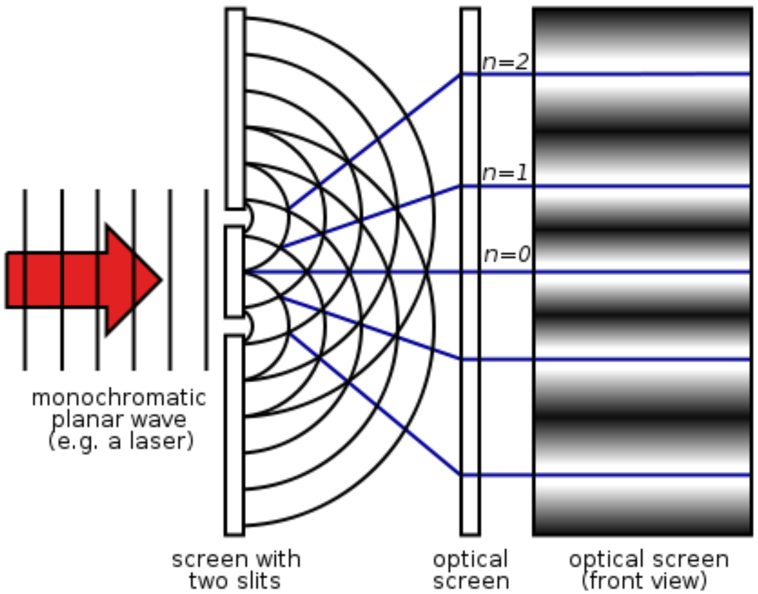
What is an interferometer?

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

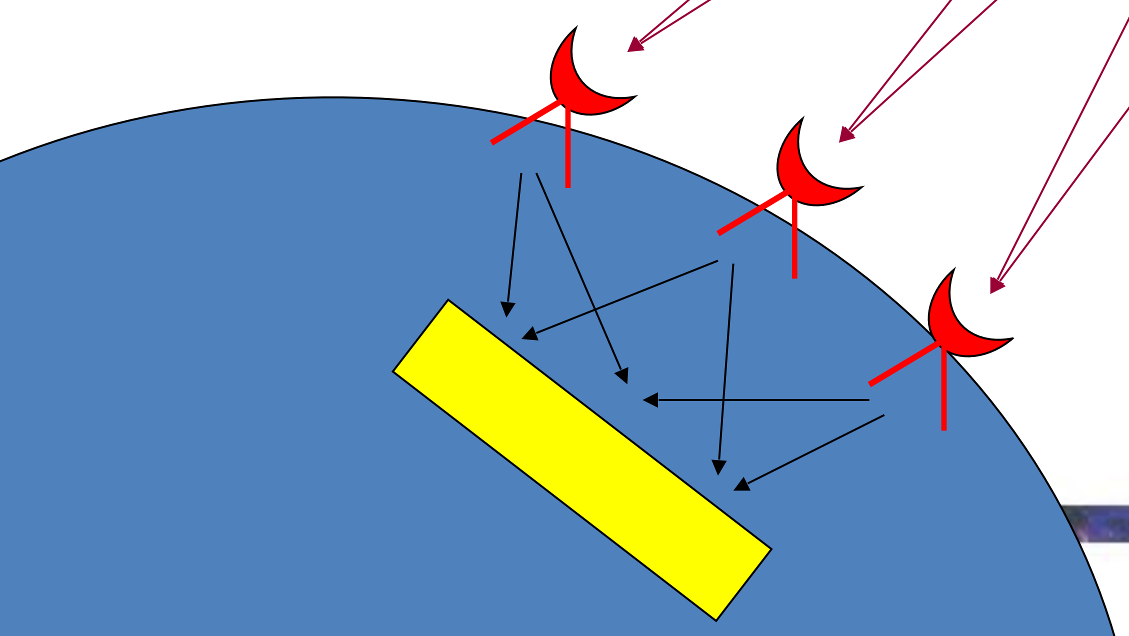


*However, the interference patterns measured by radio telescopes are produced by **multiplying** - not adding - the wave signals measured at the different telescopes (i.e. apertures)

How do we use interferometry?

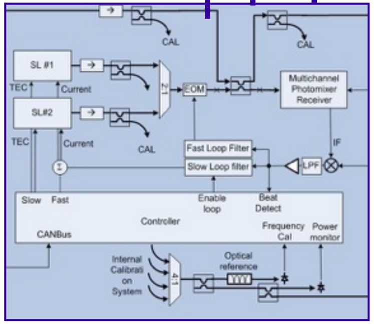
A signal from space arrives at each antenna at a slightly different time (due to different travel lengths) depending on the location of the antenna in the array.

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…

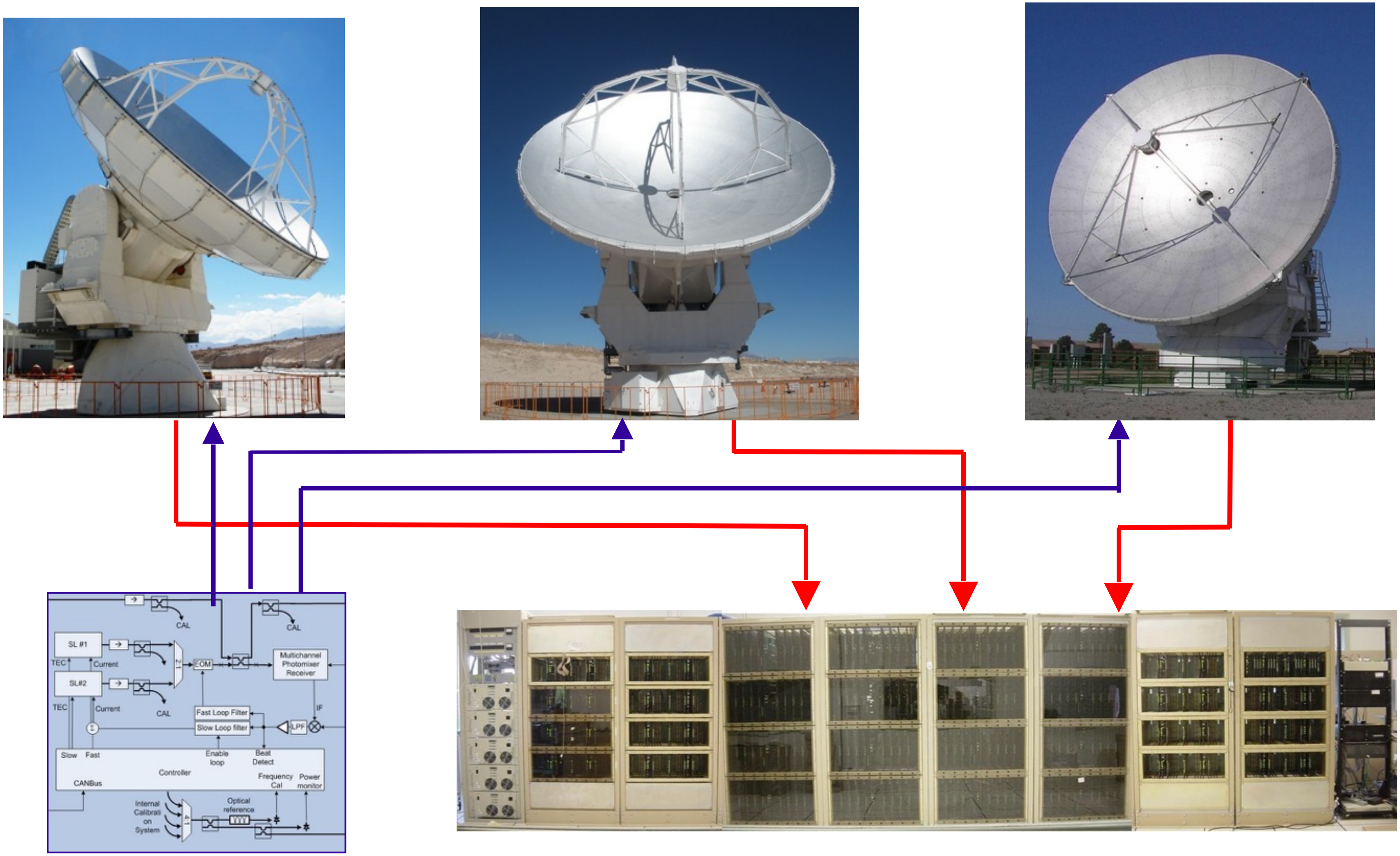


To precisely measure arrival times we need very accurate clocks

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

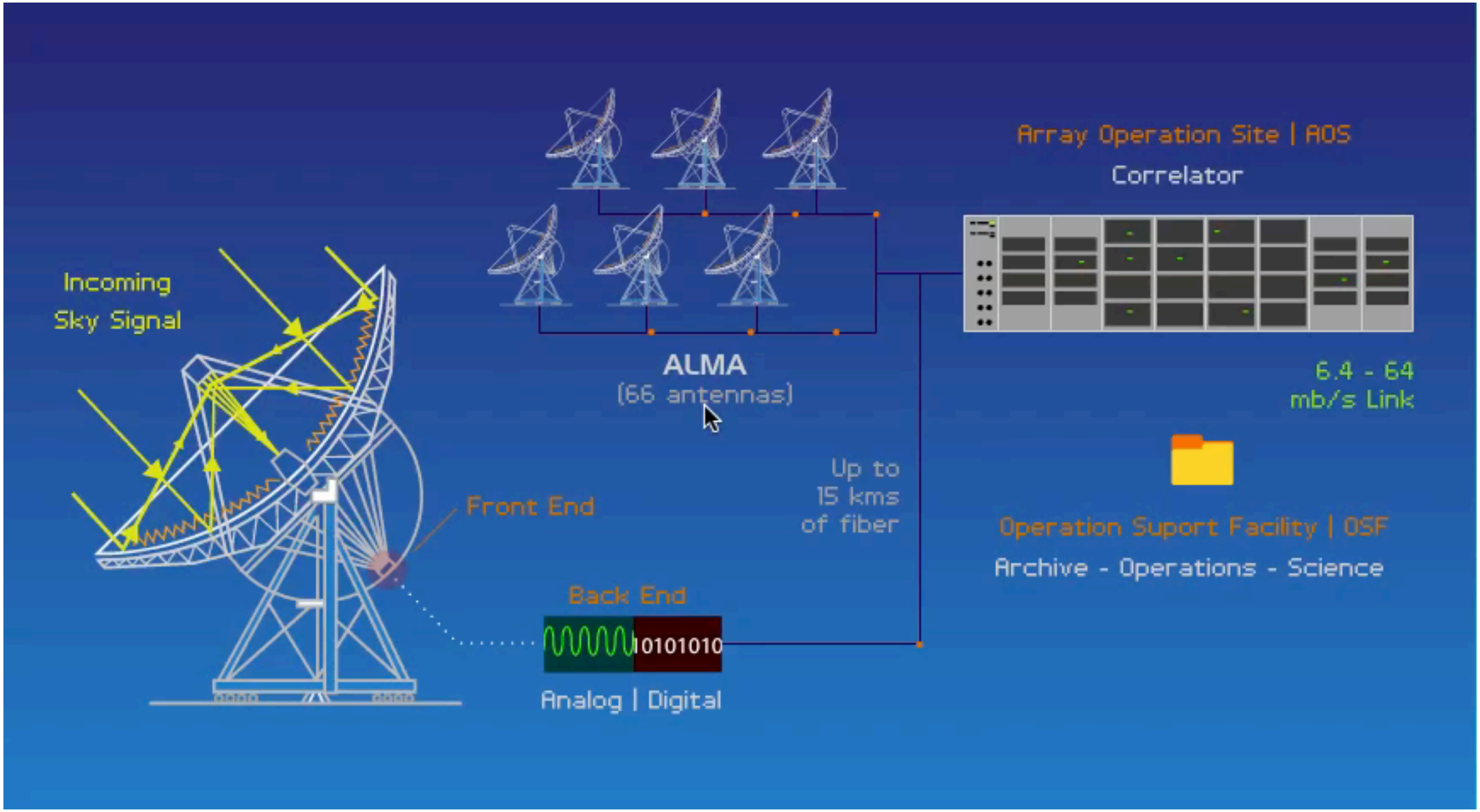
Once determined, the reference time is distributed to all antennas

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



Interferometry: Spatial Scales

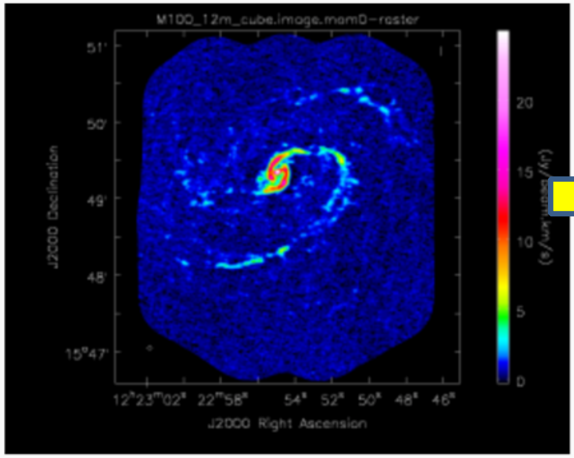
- The **sensitivity** is given by the number of antennas times their area

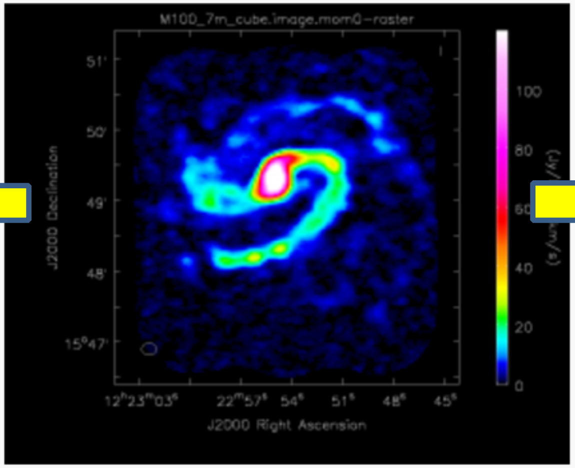
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam)

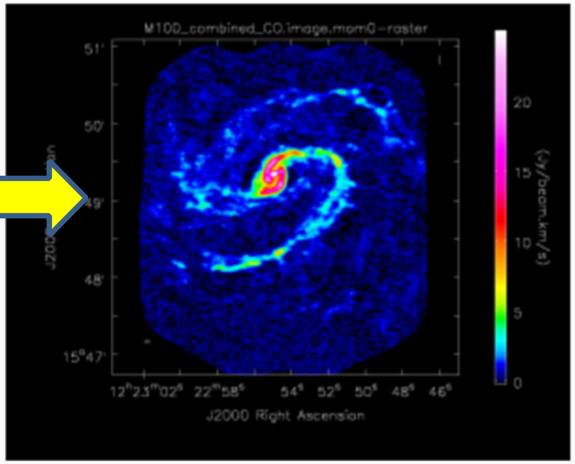
- The **resolution** is given by the largest distance between antennas (called the synthesized beam)

- The **largest angular scale** that can be imaged is given by the shortest distance between antennas

Characteristic Angular Scales: M100



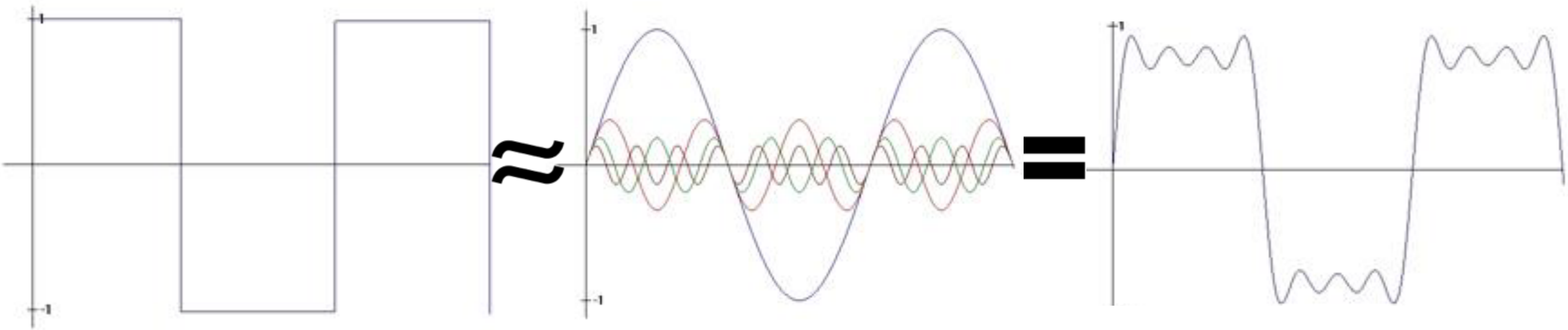




- 12m data reveals information on smaller spatial scales (denser, clumpier emission)
- 7m data reveals information on larger spatial scales (diffuse, extended emission)
- To get both: you need a combined image

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

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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)

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

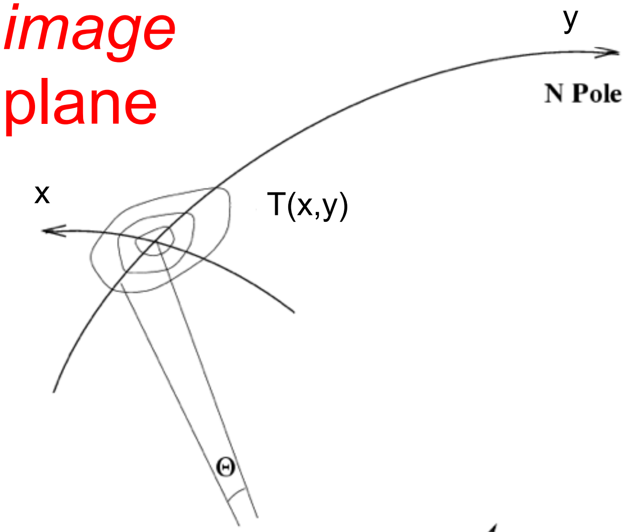
Fourier space/

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

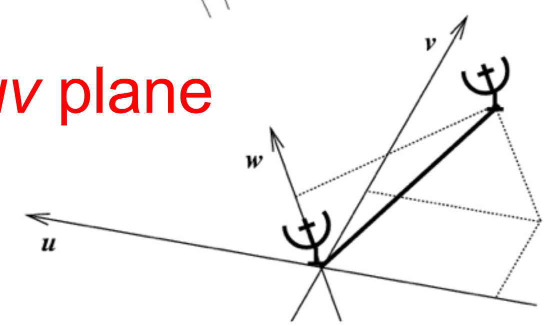
Image space/

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

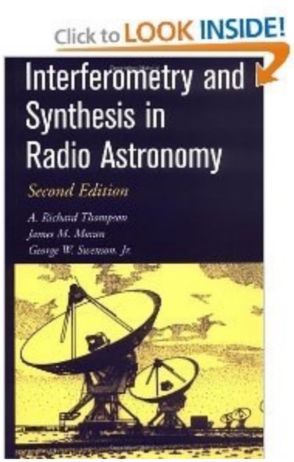
image plane



uv plane



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



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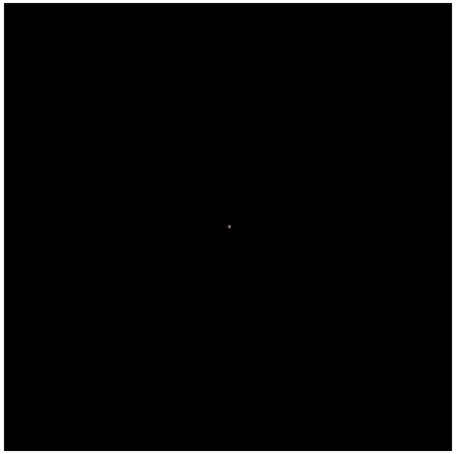
Some 2D Fourier Transform Pairs

T(x,y)

Amp{V(u,v)}

δ Function



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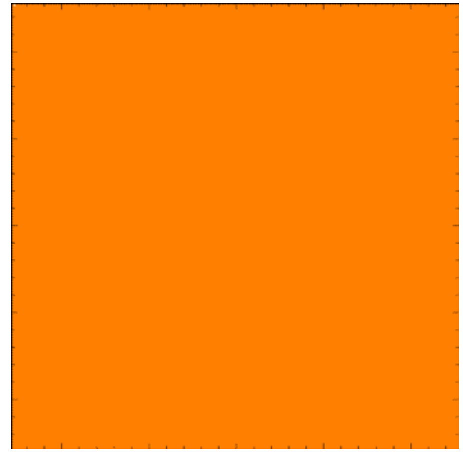
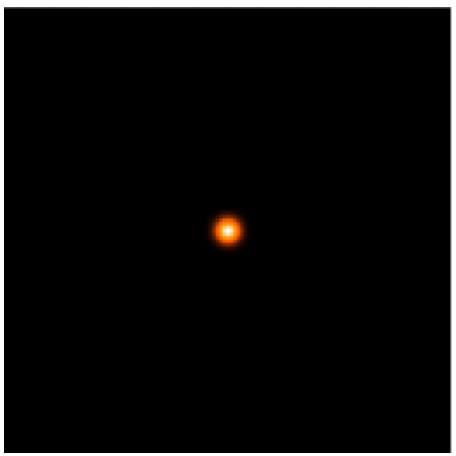


Constant

Gaussian



⇌

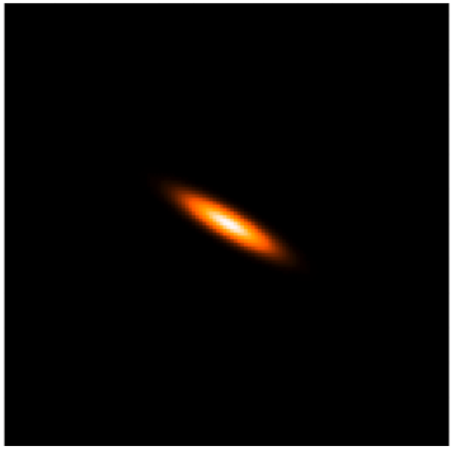
Gaussian

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

2D Fourier Transform Pairs

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

elliptical Gaussian

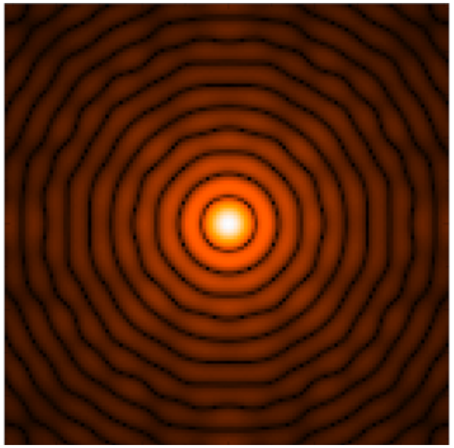


⇌

elliptical Gaussian

Disk

⇌



Bessel
(sinc function, "ringing", Gibbs phenomenon)

sharp edges result in many high spatial frequencies

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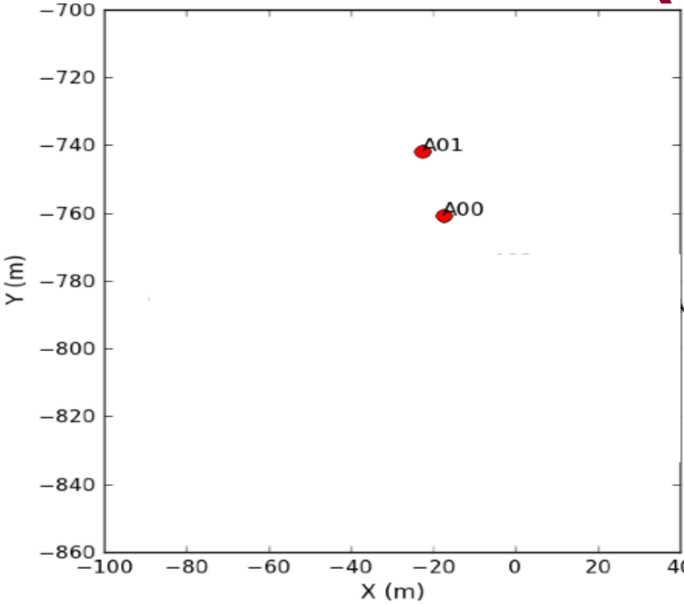
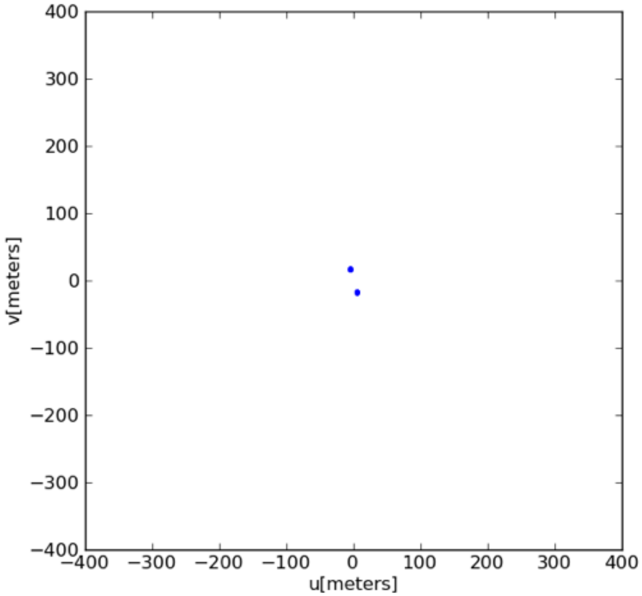
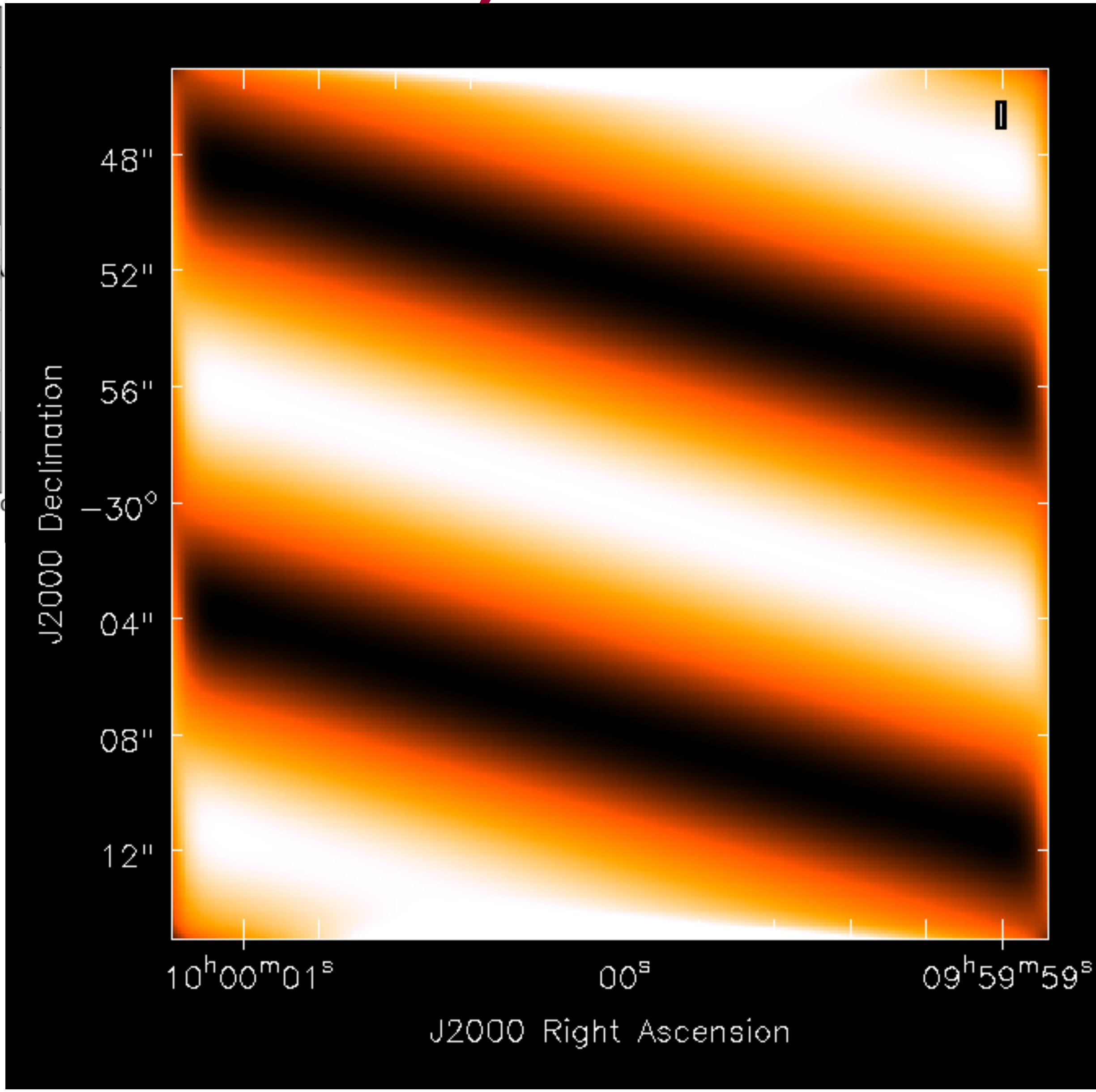
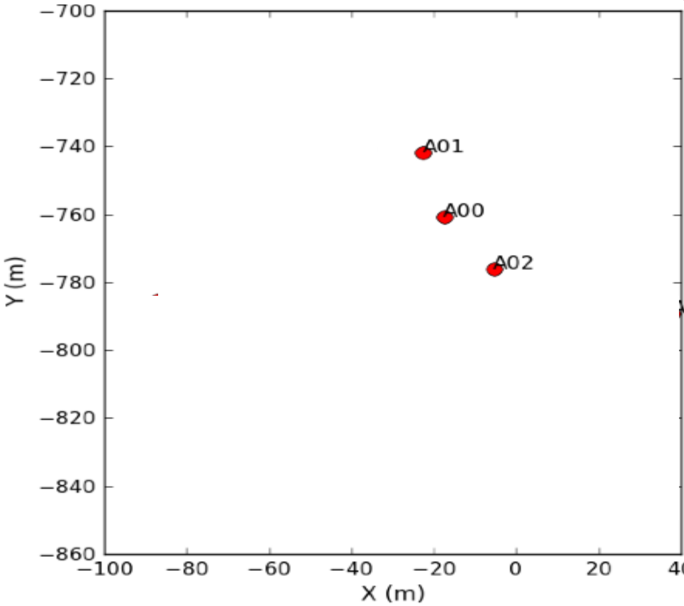
Example: Fringe pattern with 2 Antennas (one baseline)

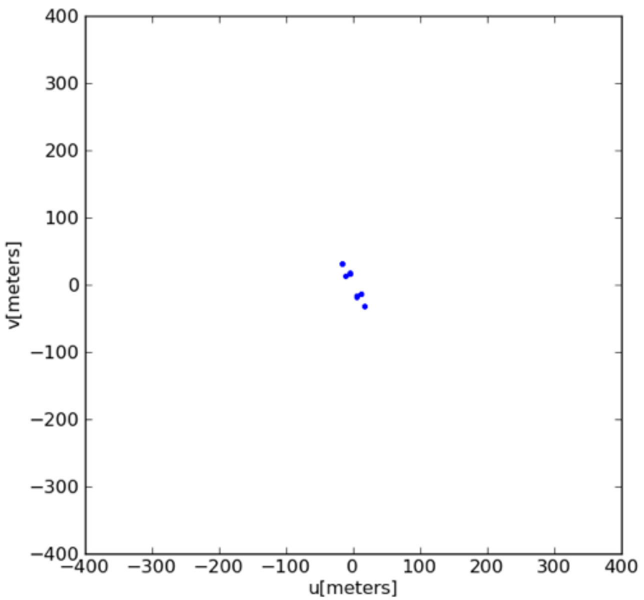


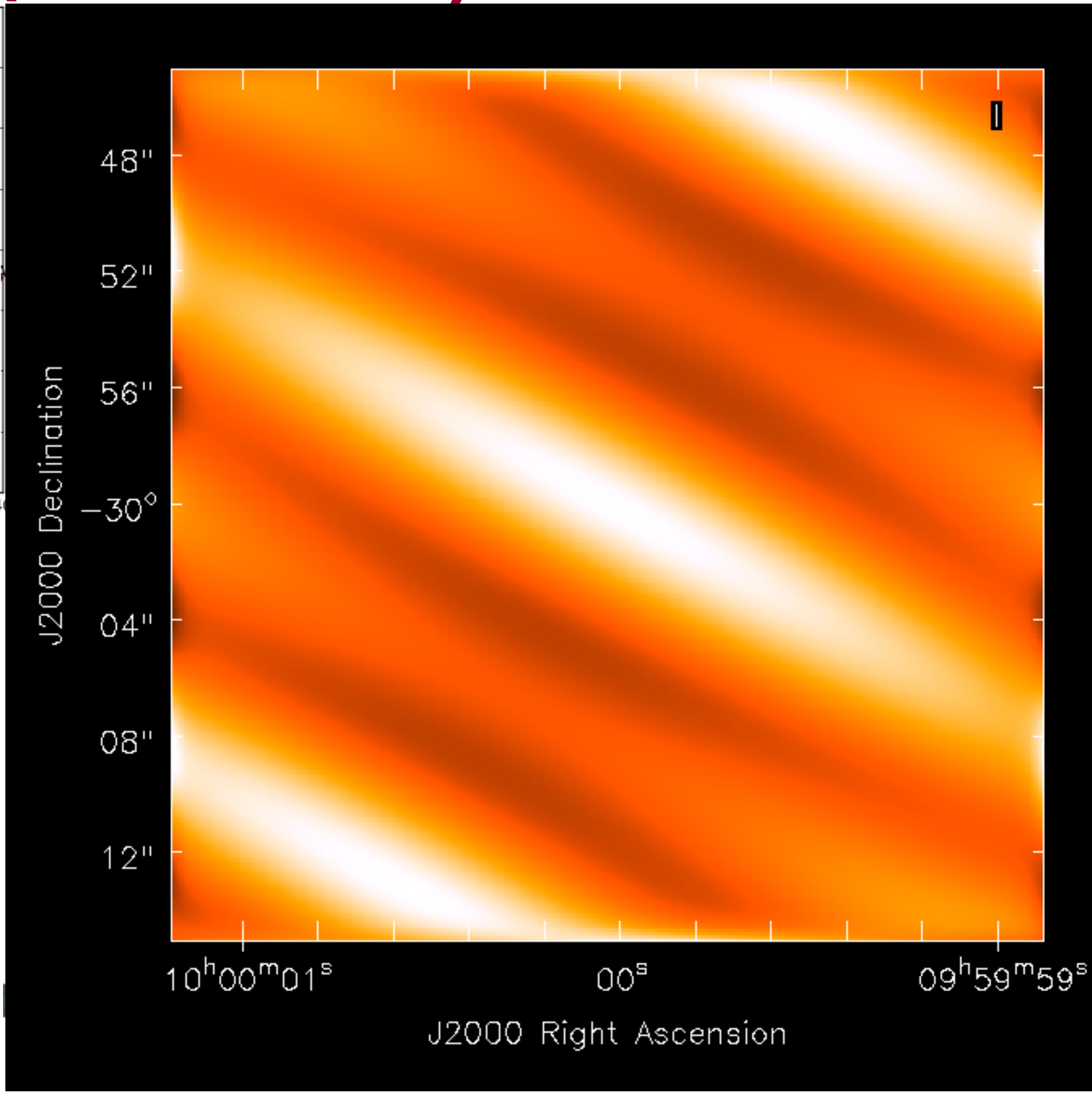




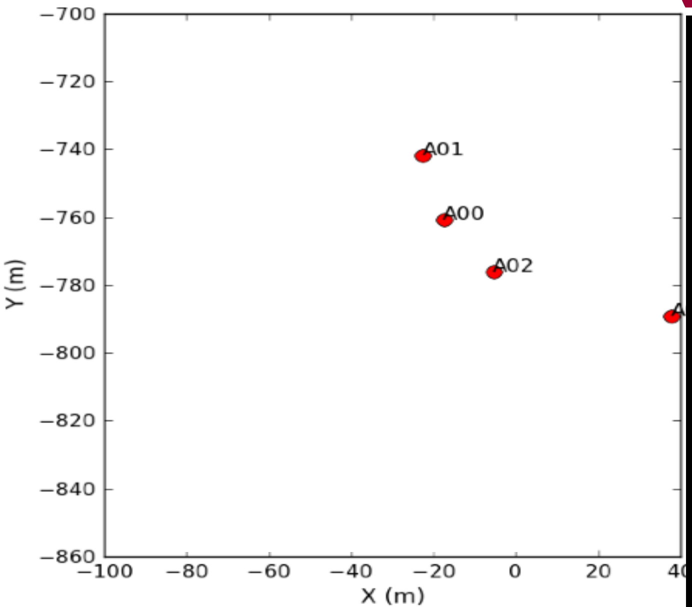
Example: Fringe pattern with 3 Antennas (3 baselines)

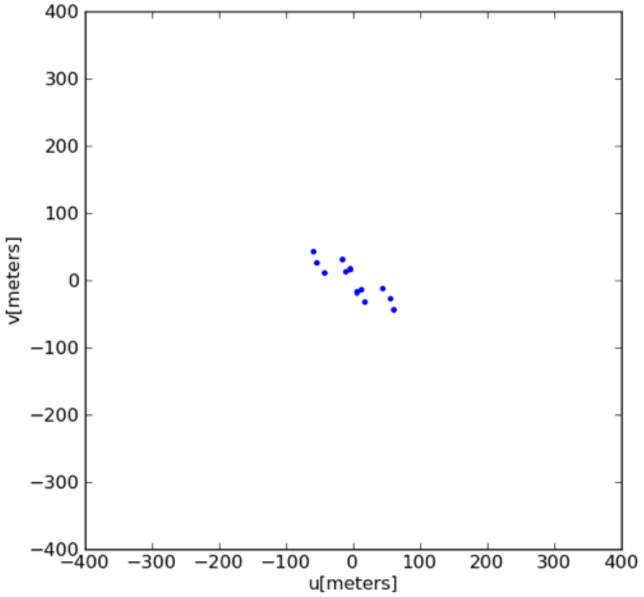


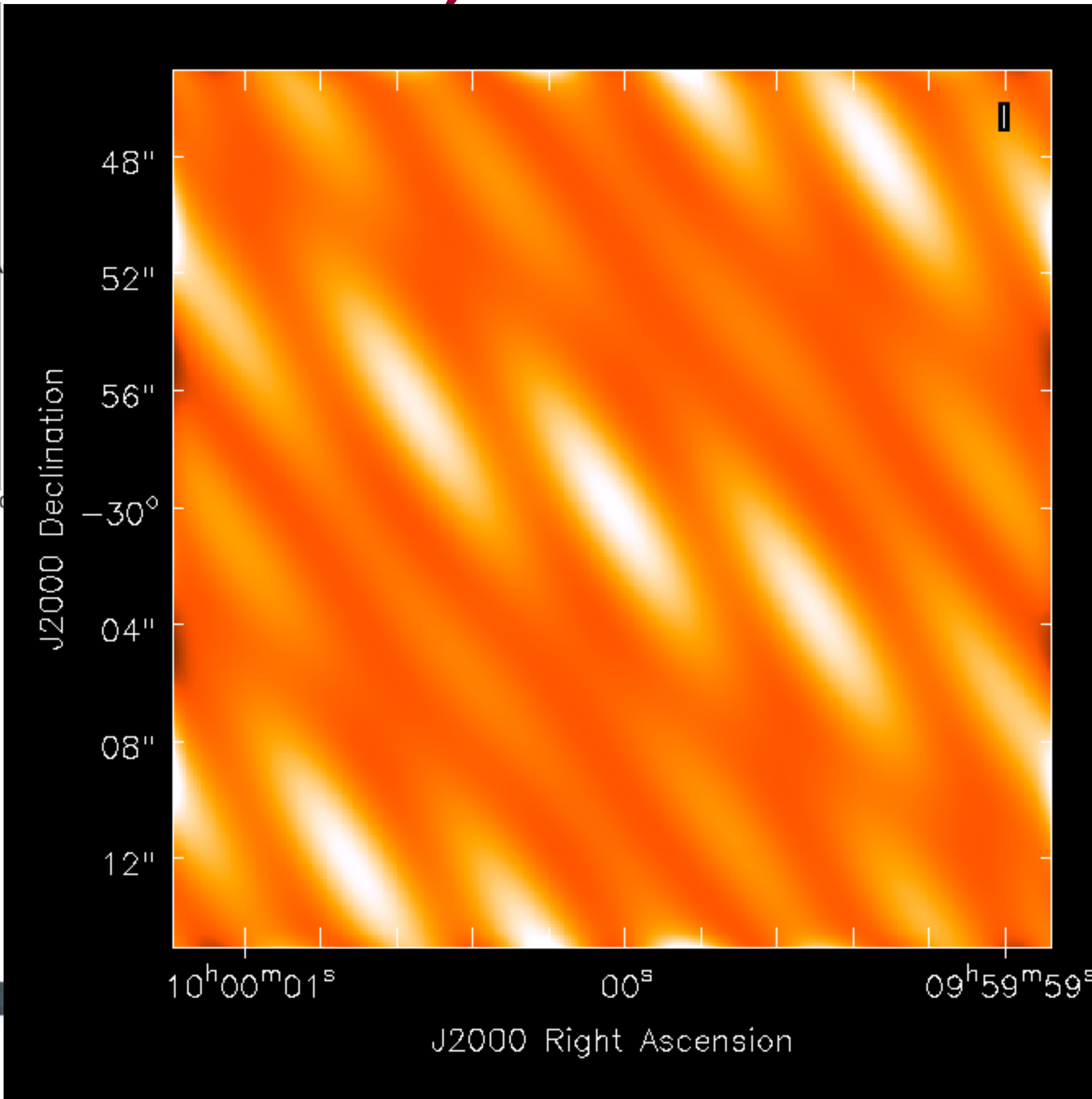




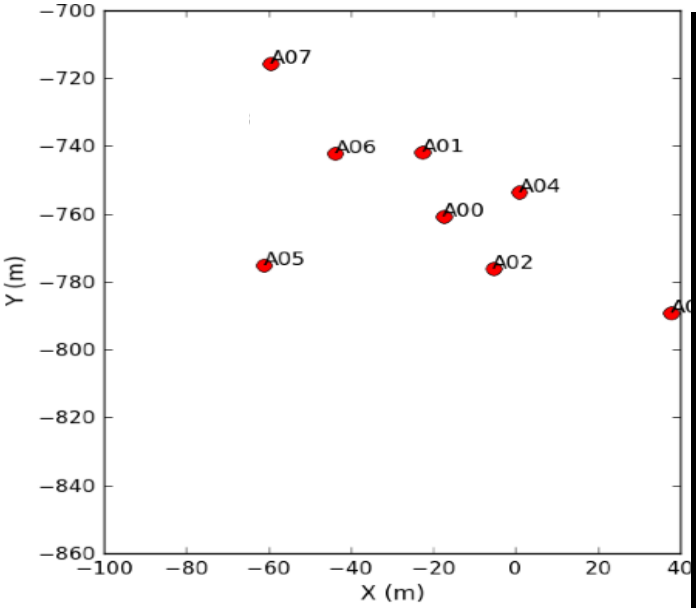
Example: Fringe pattern with 4 Antennas (6 baselines)

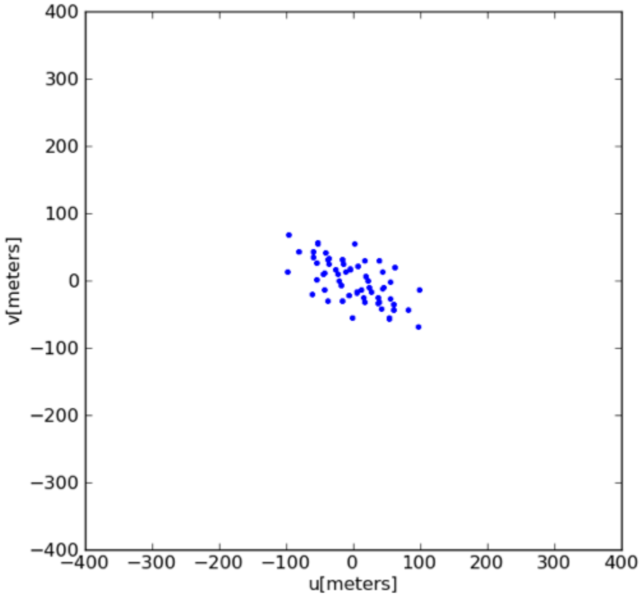


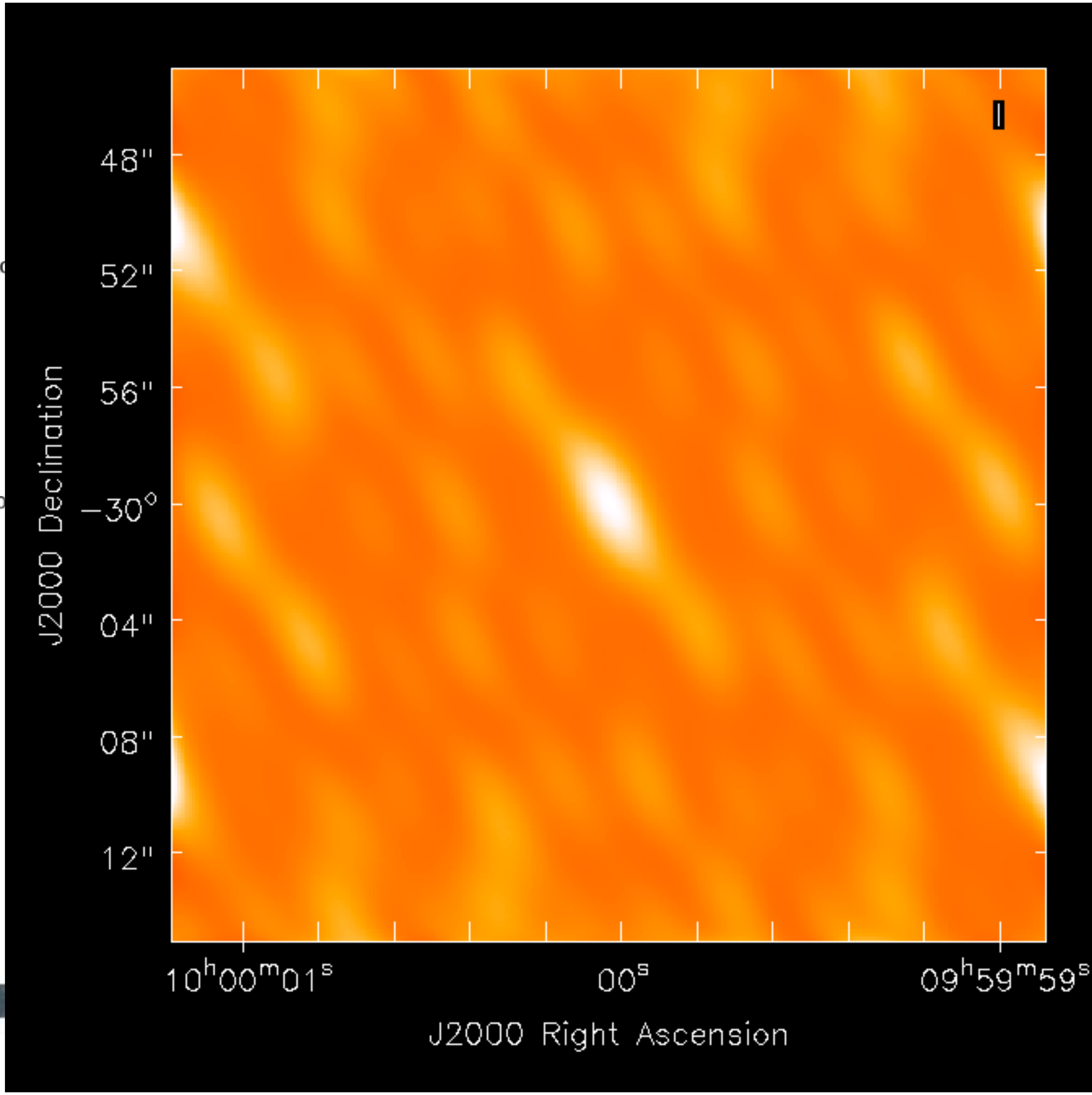




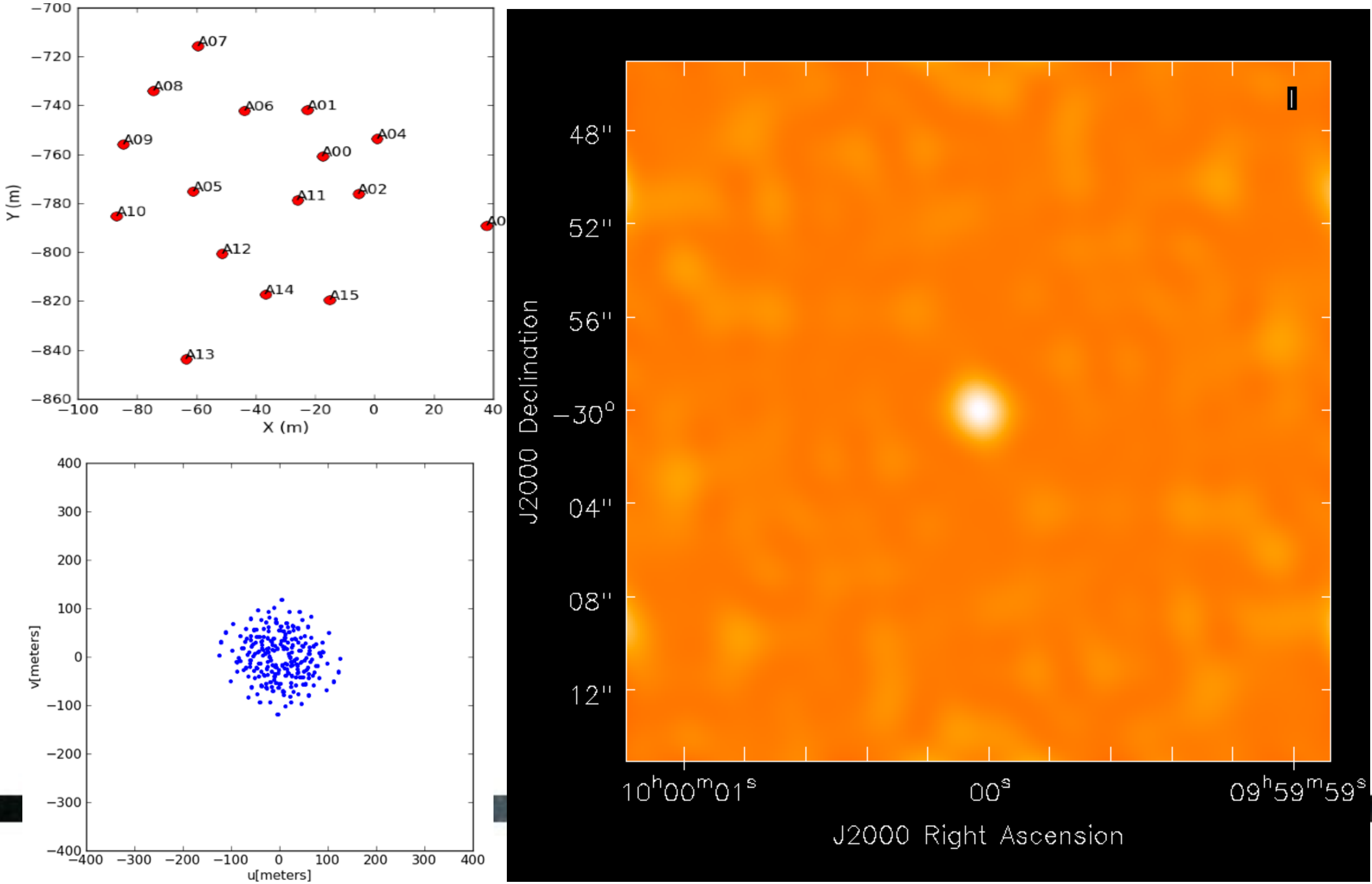
Example: Fringe pattern with 8 Antennas (28 baselines)



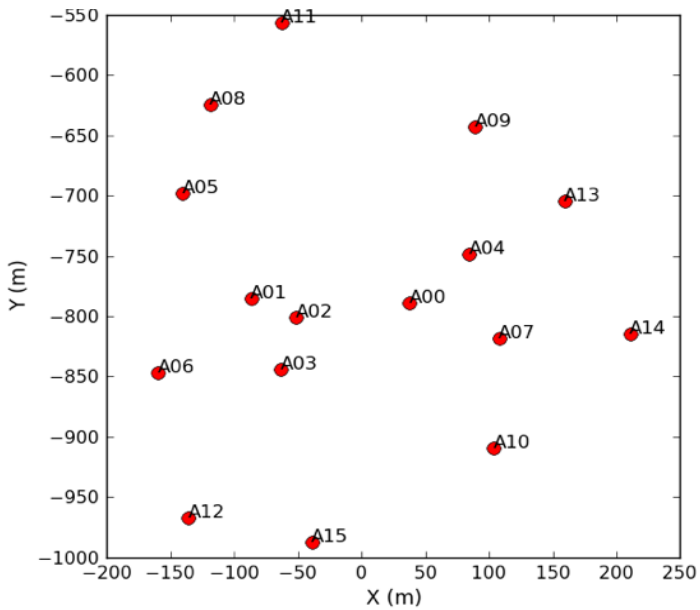


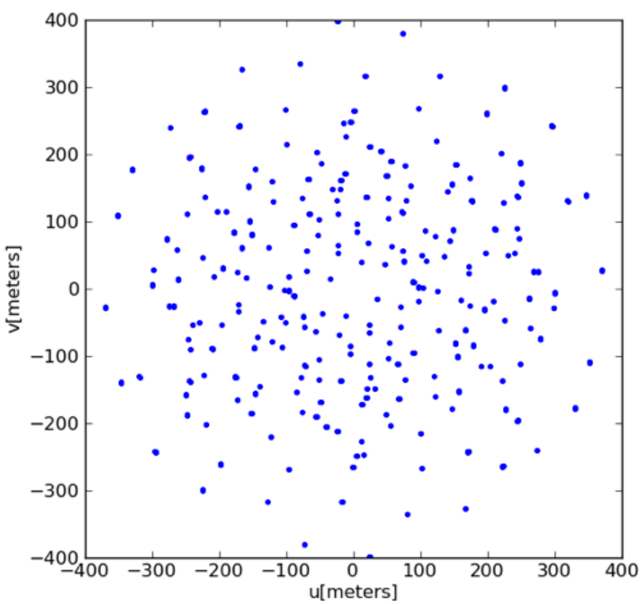


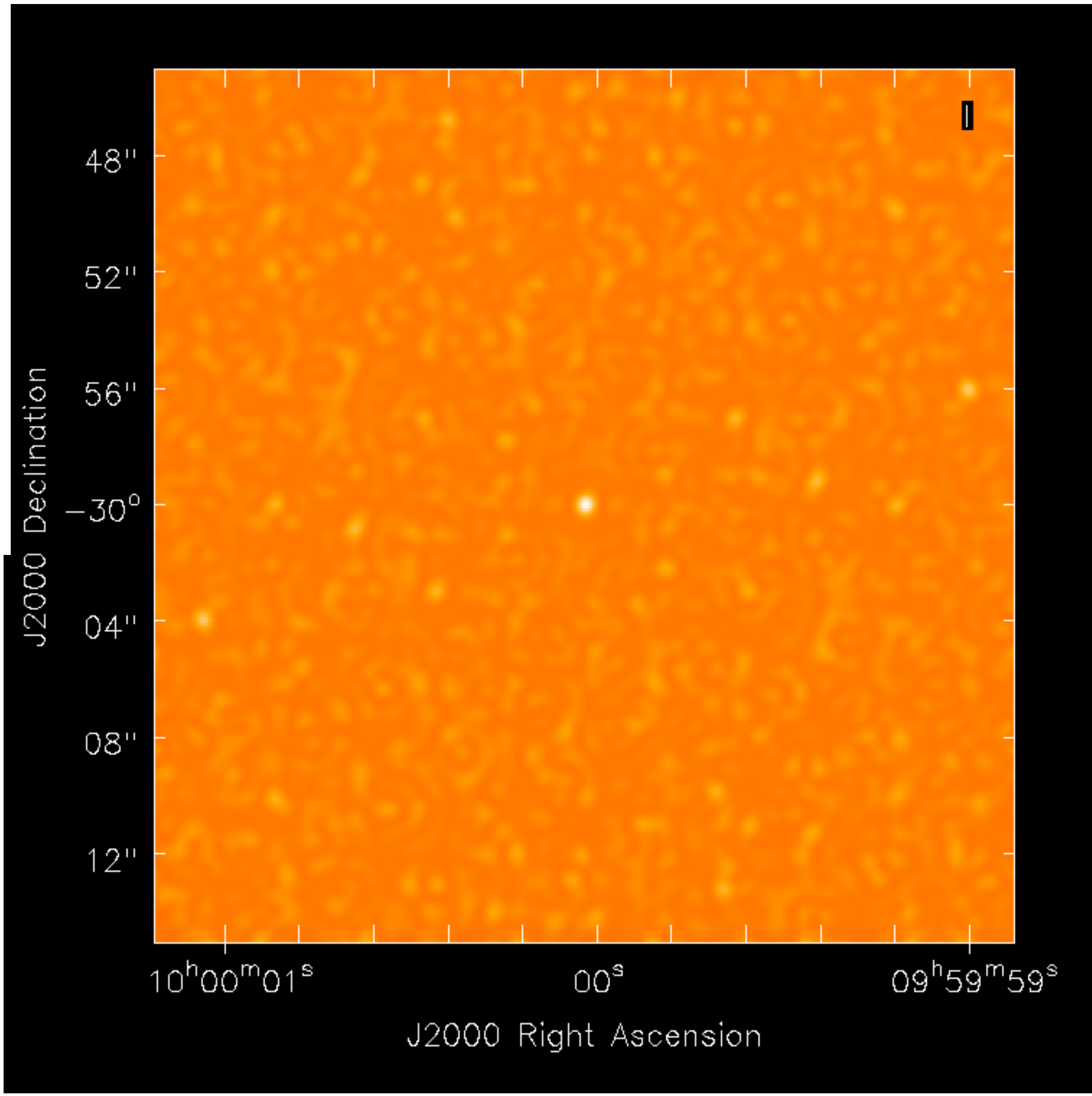
16 Antennas – Compact Configuration



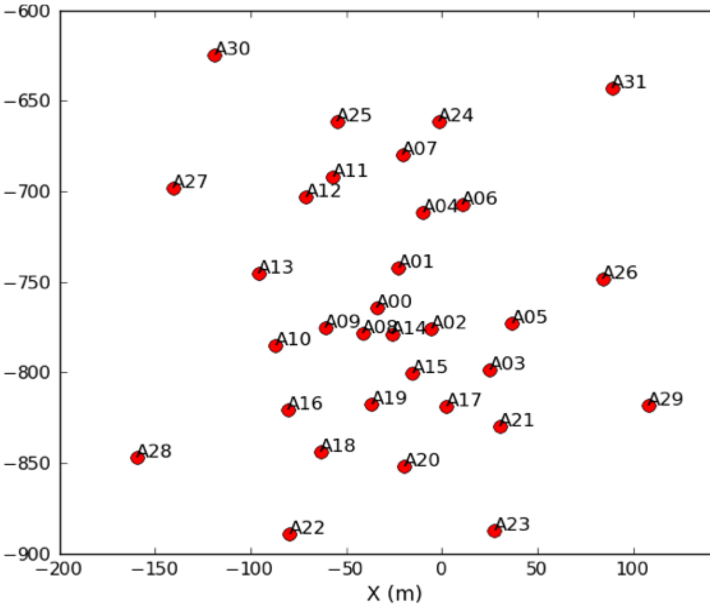
16 Antennas – Extended Configuration

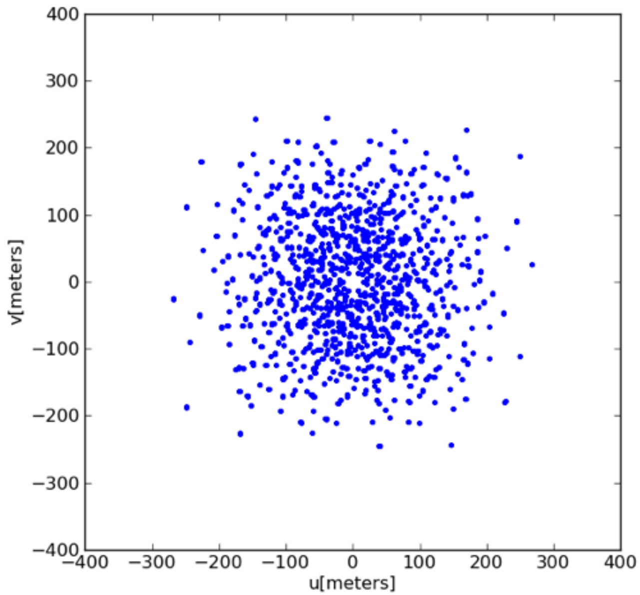


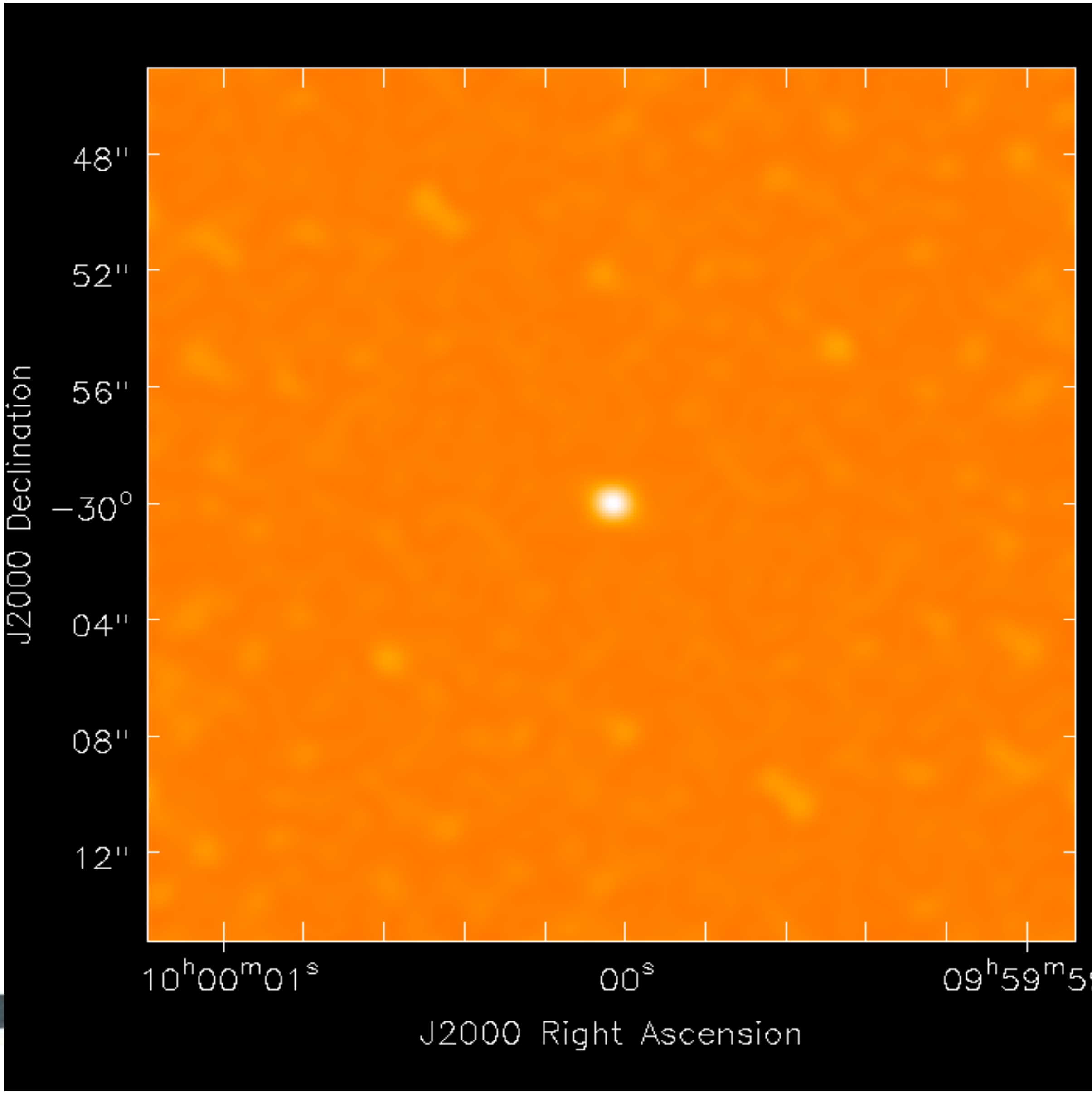




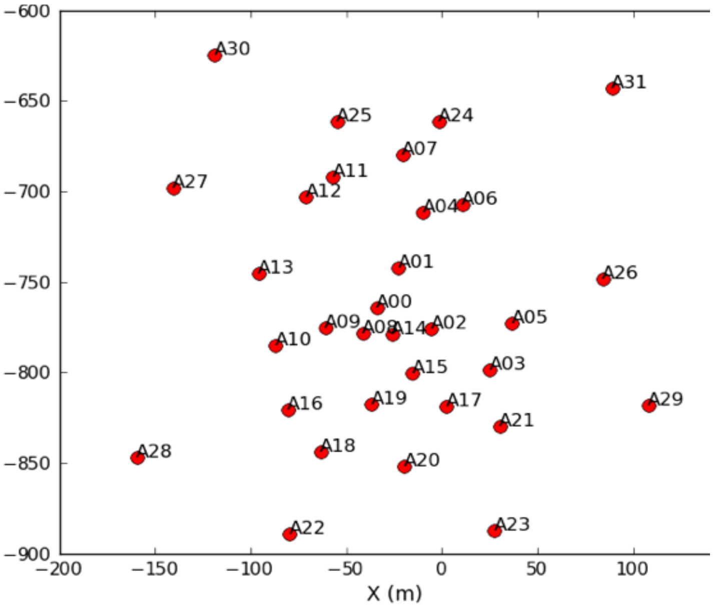
32 Antennas – Instantaneous

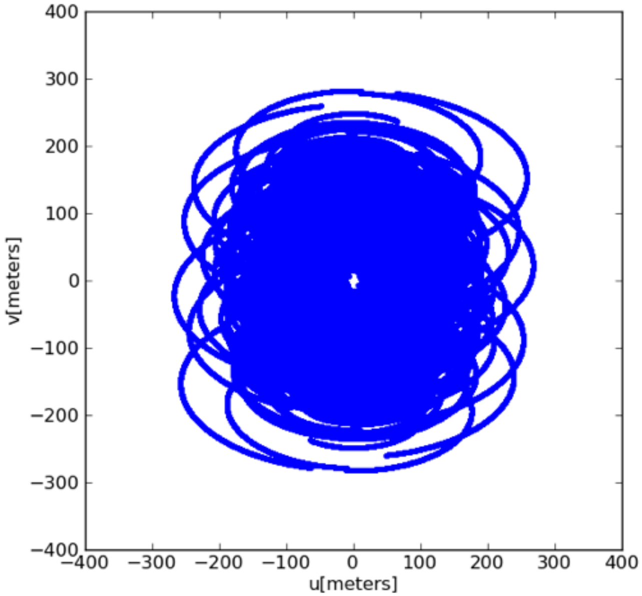


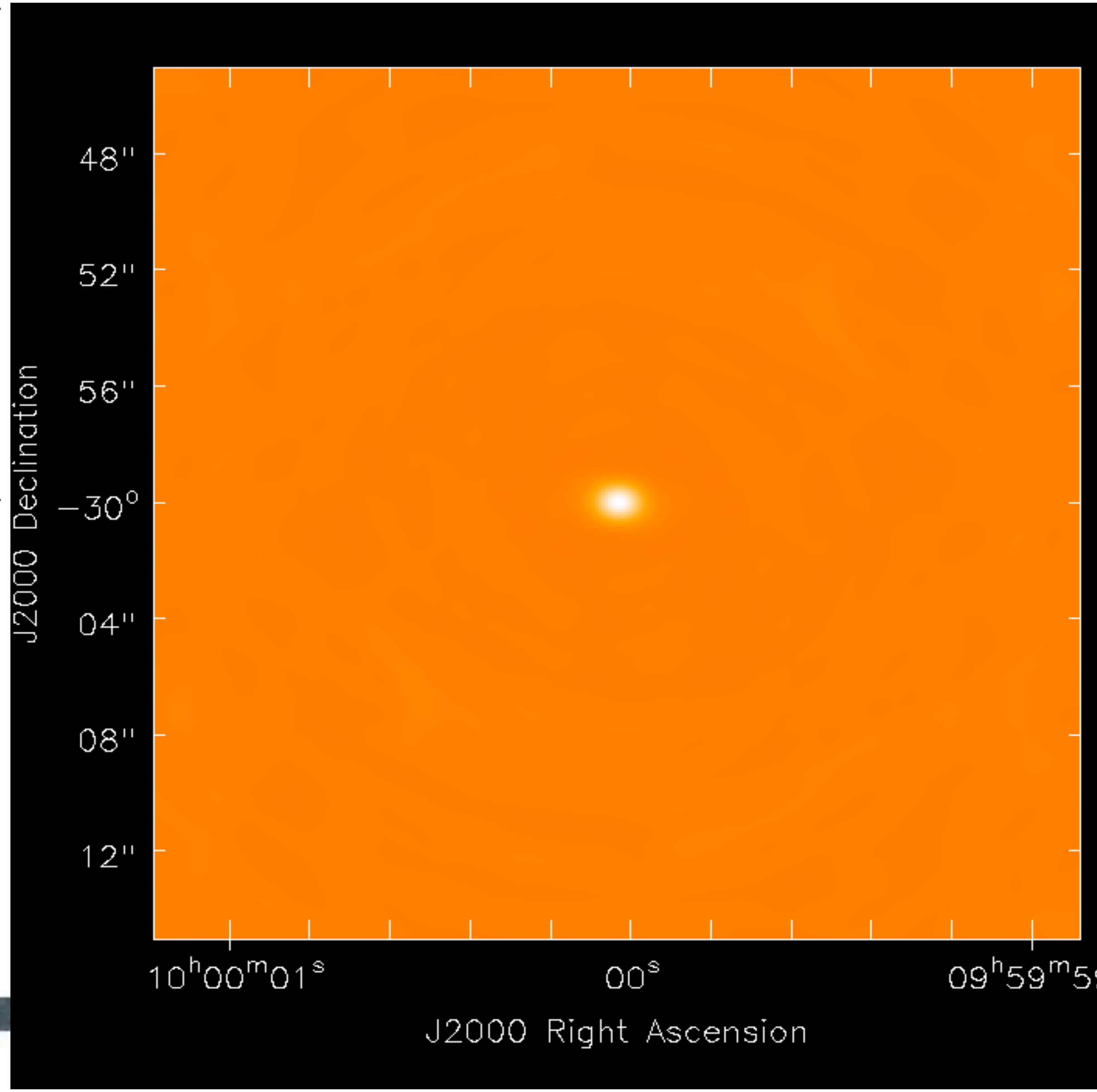




32 Antennas – 8 hours

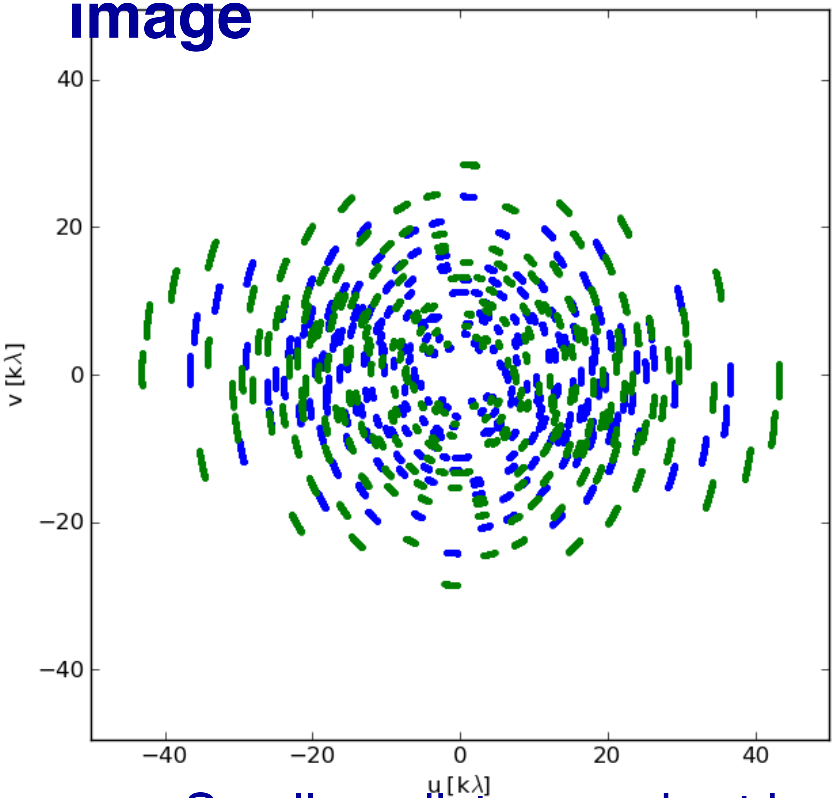


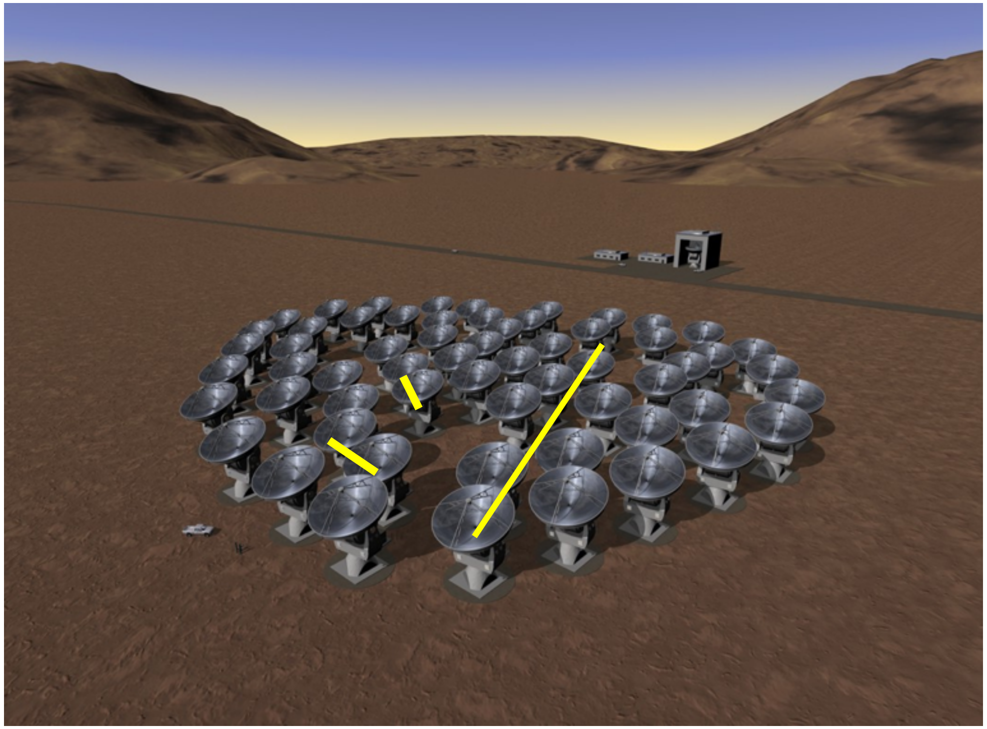




Sampling Function

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



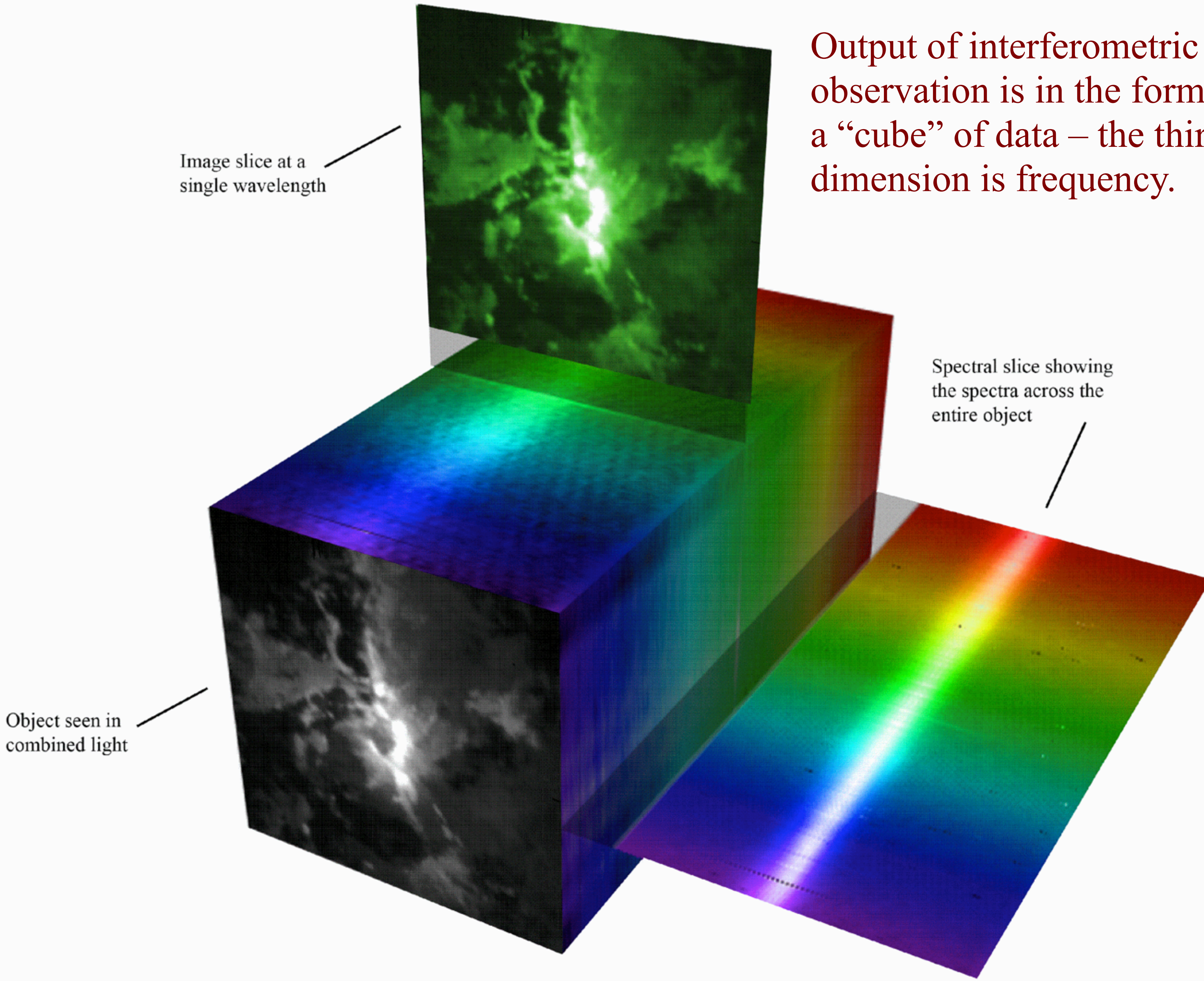


Small uv-distance: short baselines (measure extended emission)
Long uv-distance: long baselines (measure small scale emission)
Orientation of baseline also determines orientation in the uv-plane

uv coverage: why the central hole?

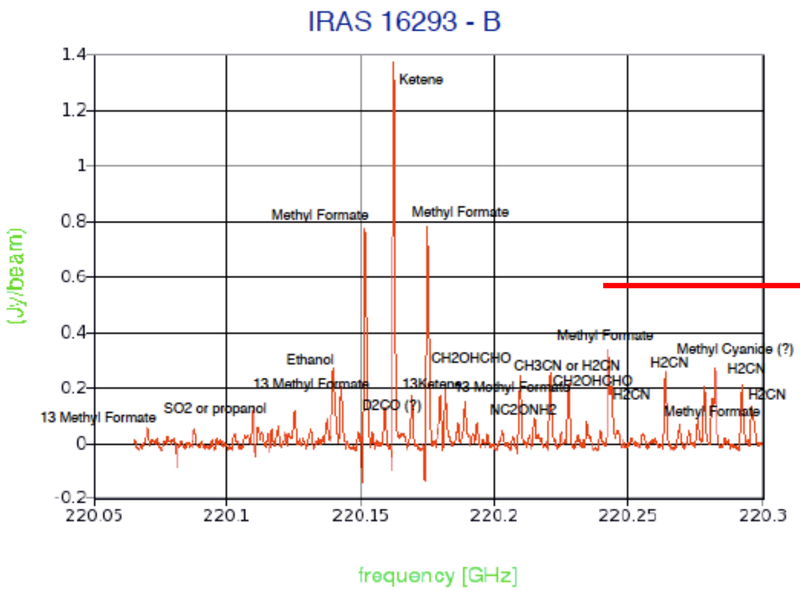
- The central hole in the sampling of the uv plane arises due to **short baselines**
- The largest angular scale that an interferometer is sensitive to is given by the shortest distance between 2 antennas.
- The field of view is given by the beam of a single antenna.
- A single antenna diameter will 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.

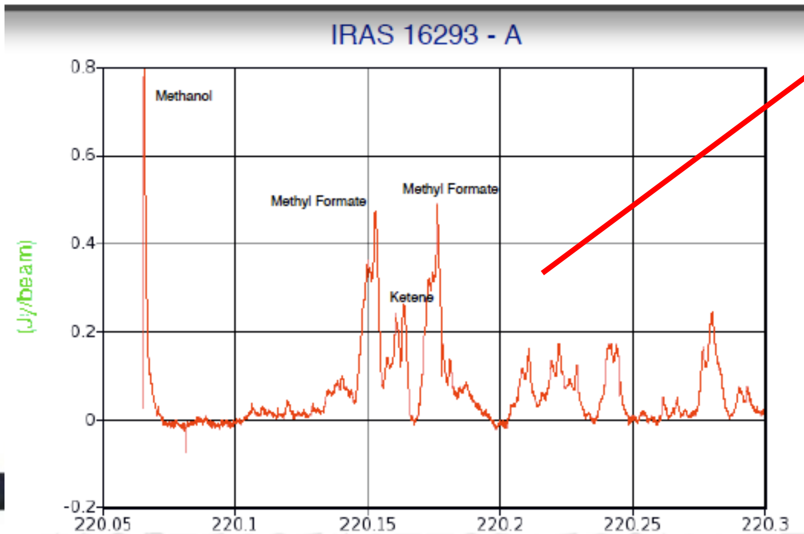
Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.

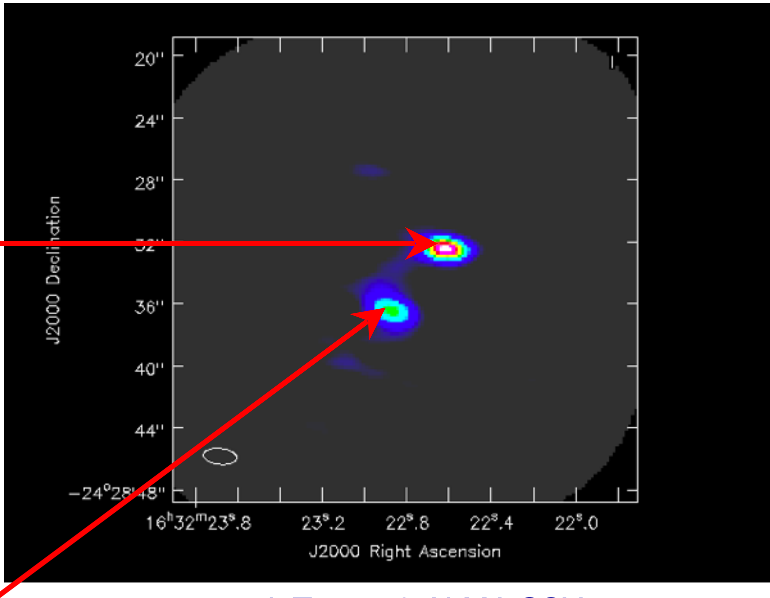


Sometimes the most interesting science lies in the third dimension

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.

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

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Calibration Process

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

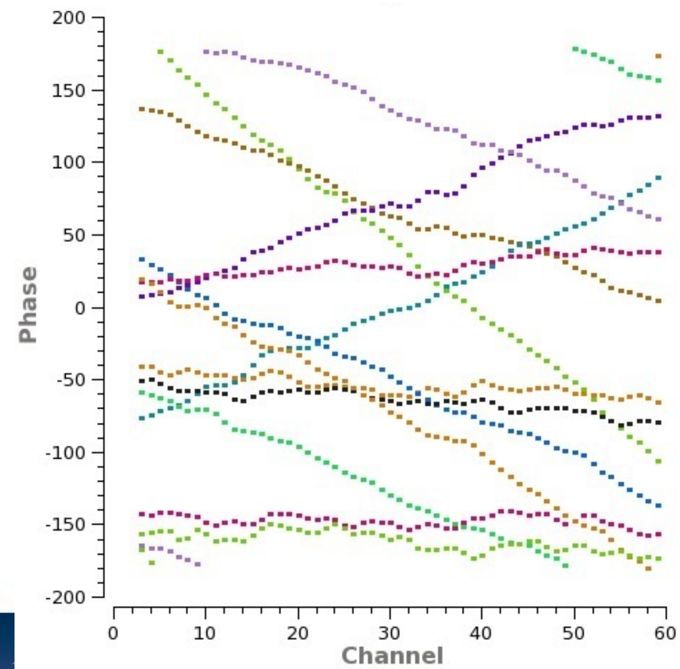
Steps in calibrating interferometric data:
(Note: You don't have to worry about these in your observational set up!)

- 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

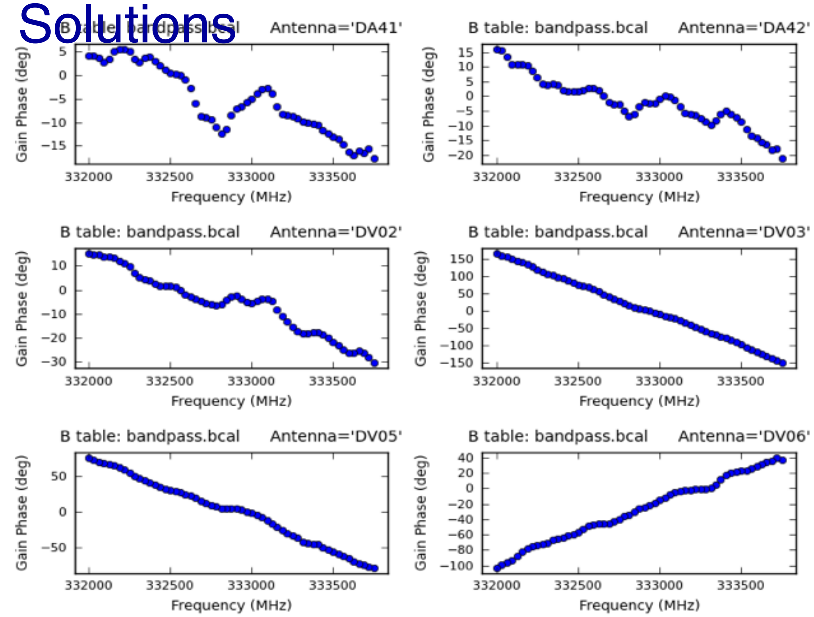
Bandpass Calibration: Phase

* 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

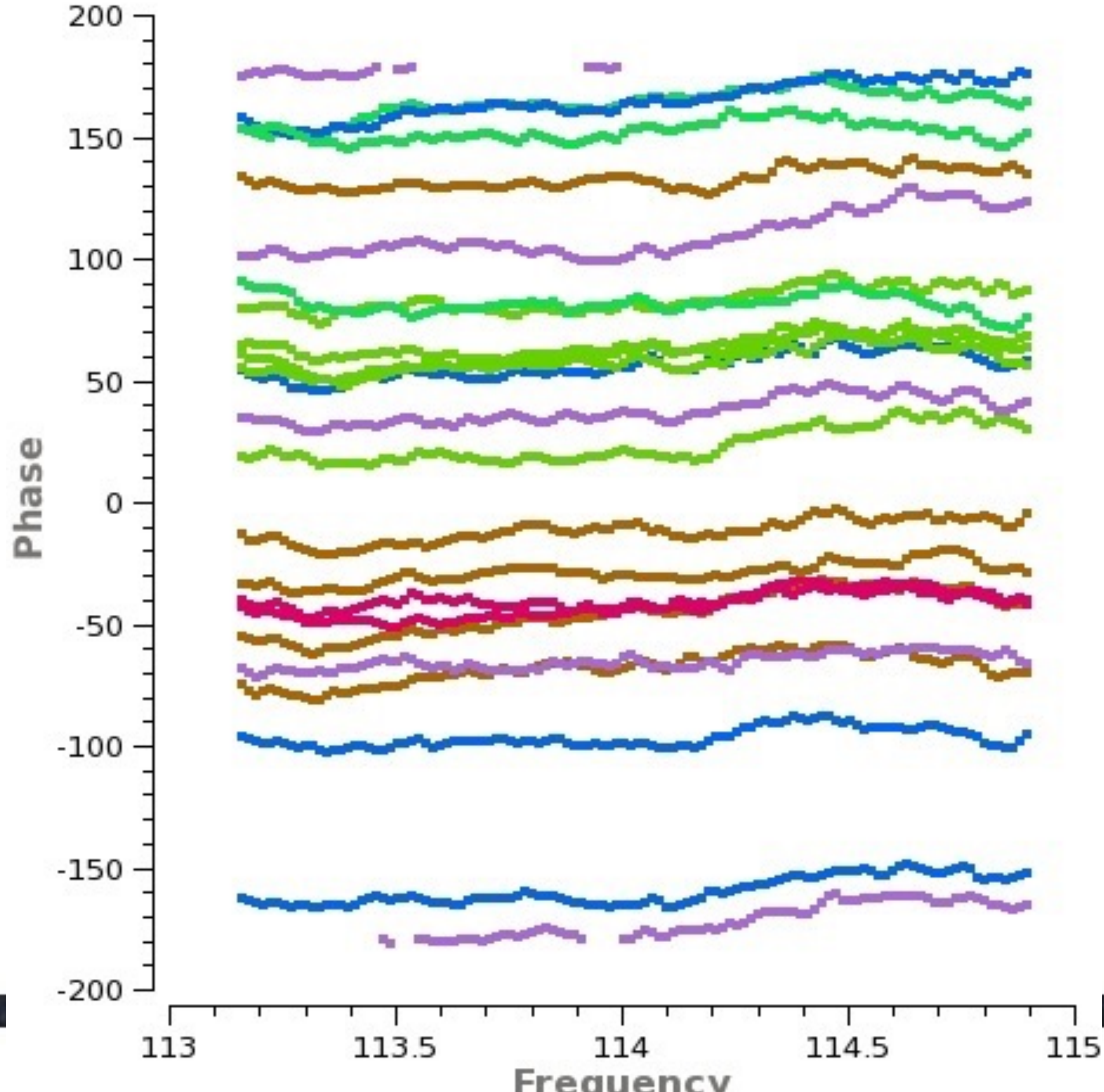
Baselines to one antenna



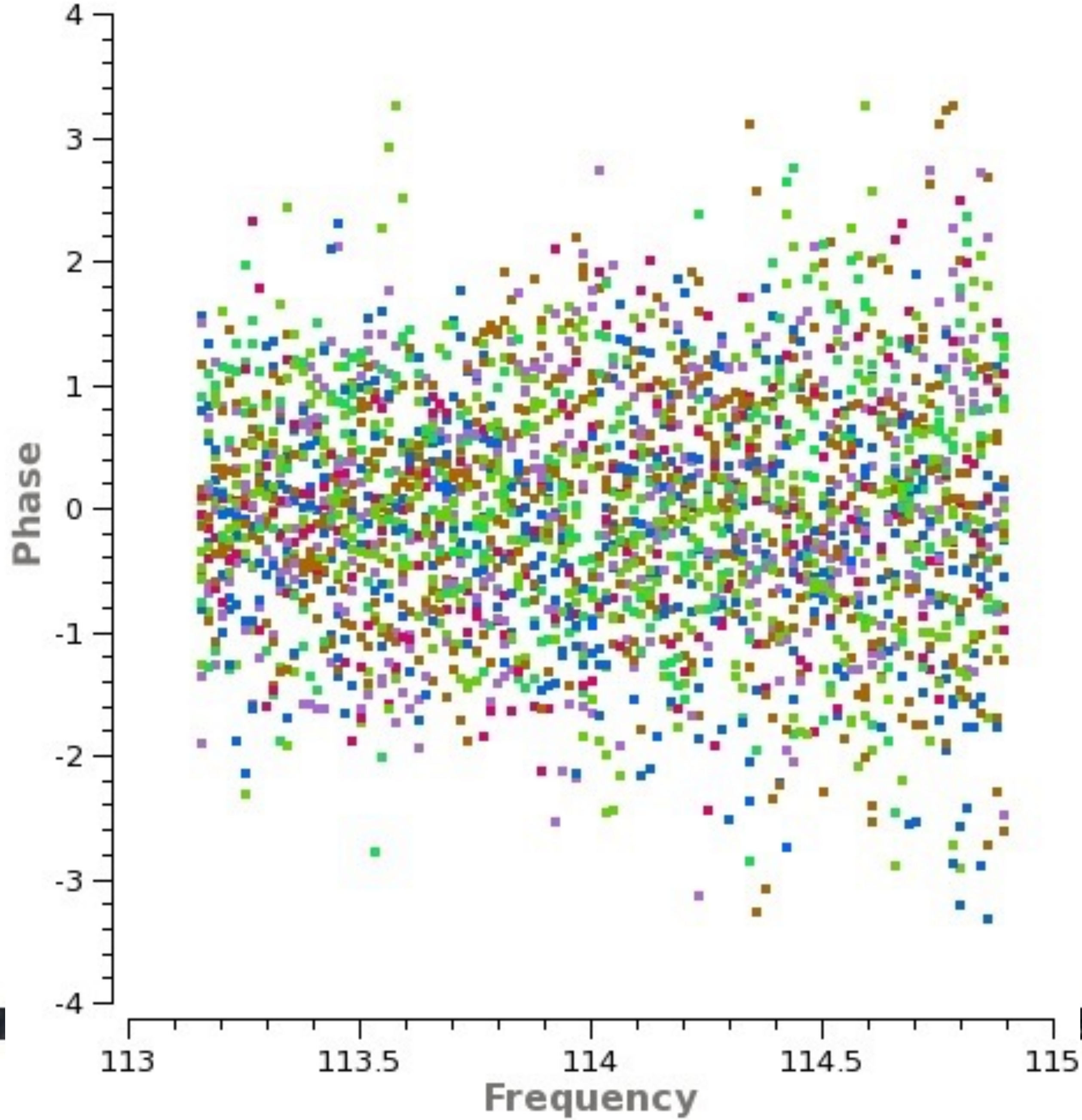
Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)



Bandpass Phase vs. Frequency (After)



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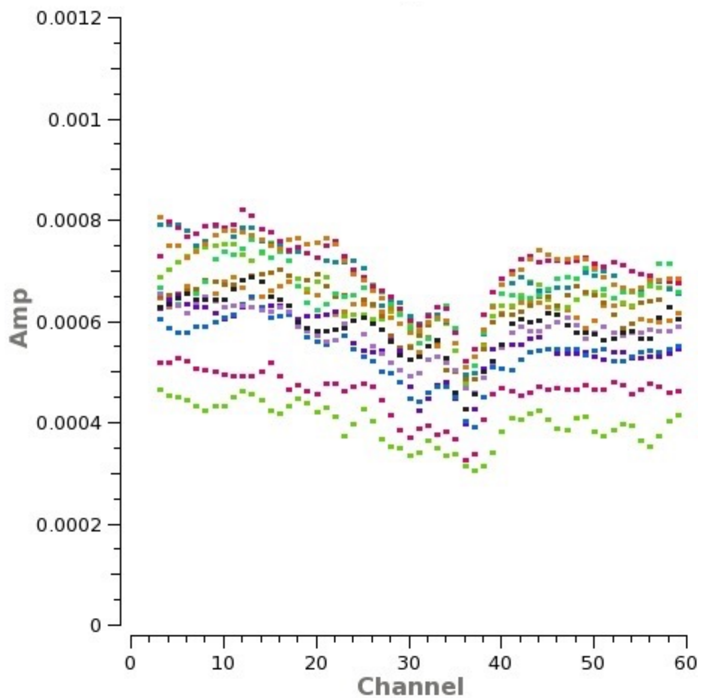
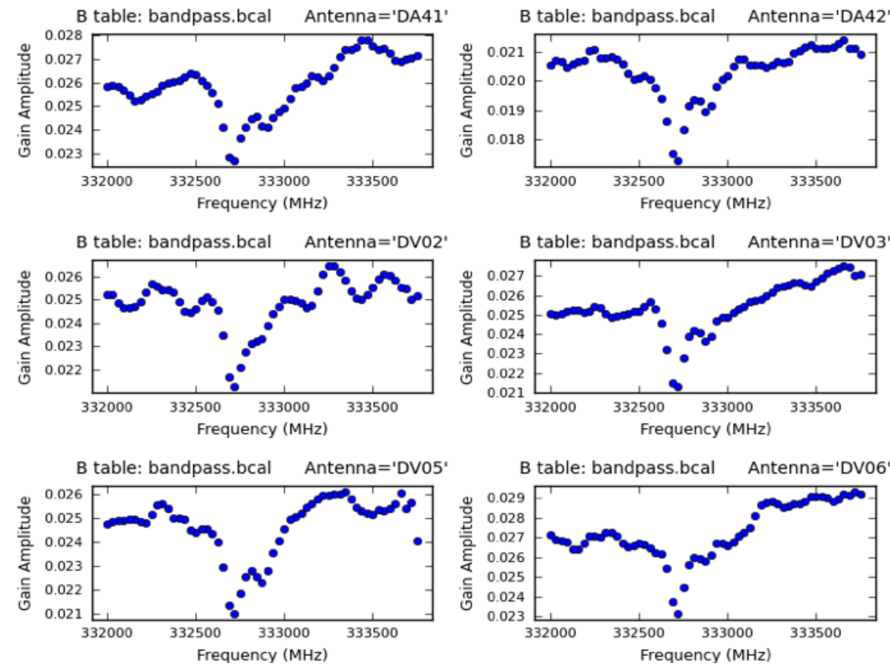
Bandpass Calibration: Amplitude

Baselines to one antenna





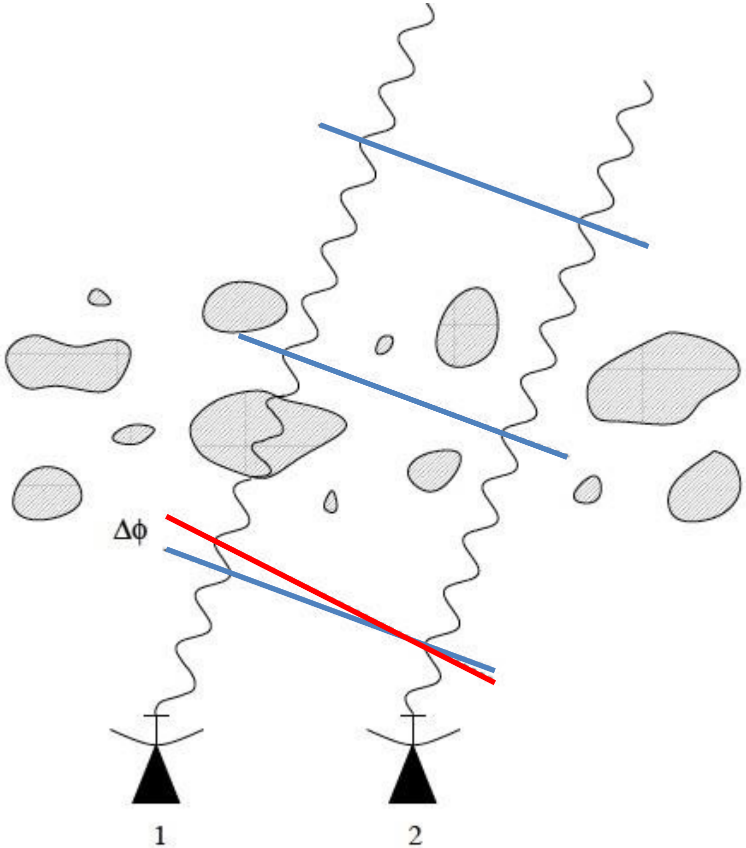
Amplitude Before Bandpass Calibration

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.

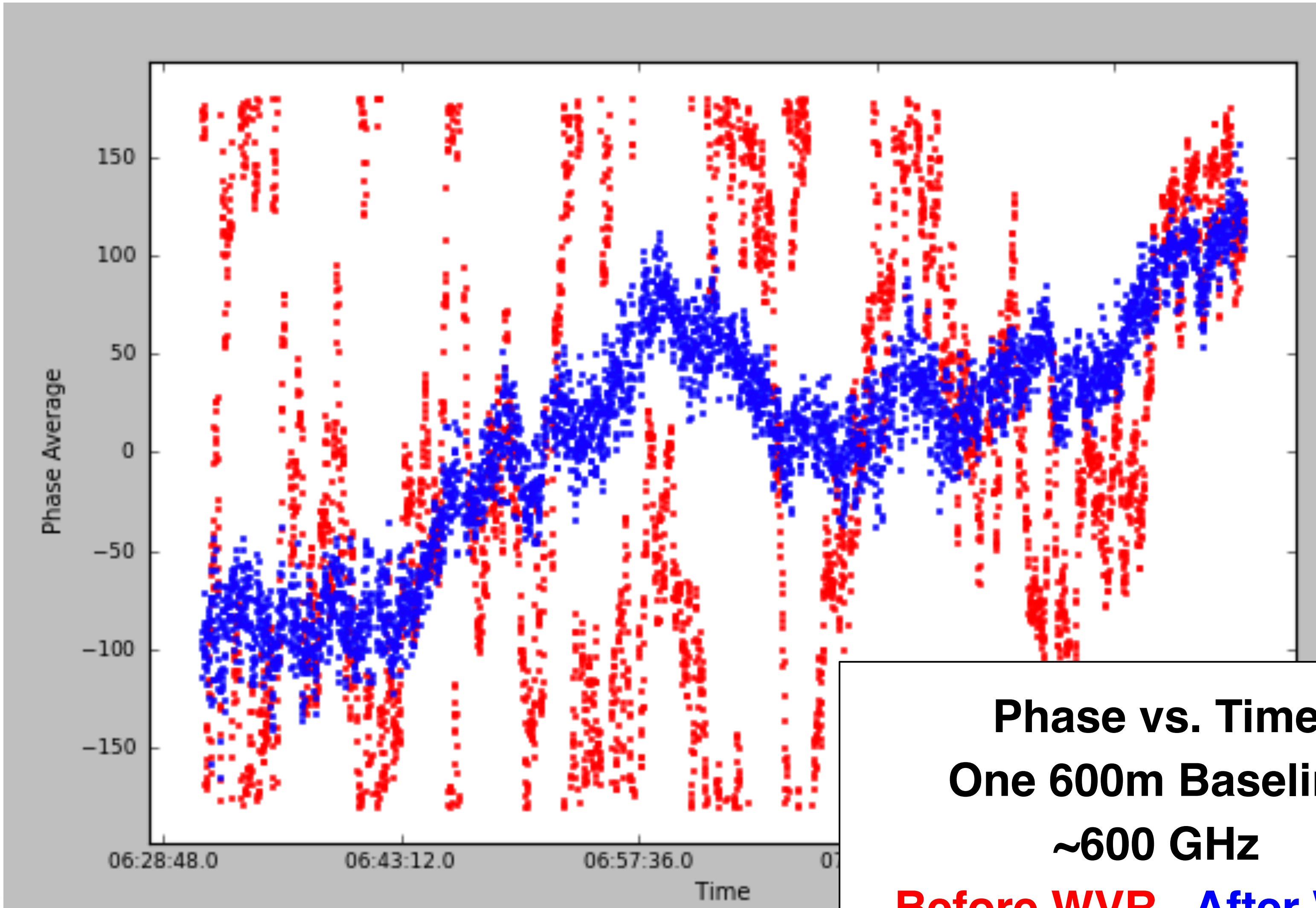


Phase & Amplitude Gain Calibration

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

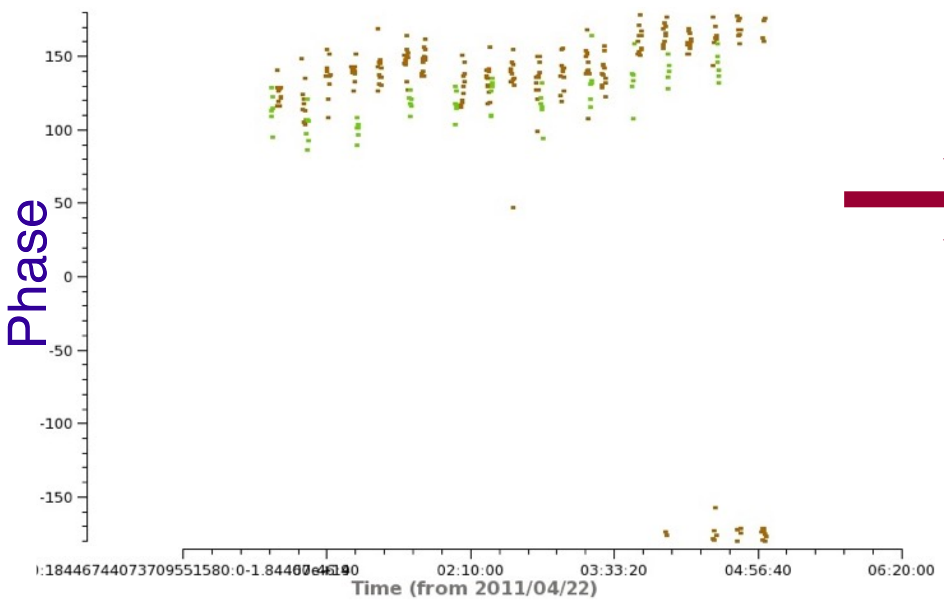
One 600m Baseline

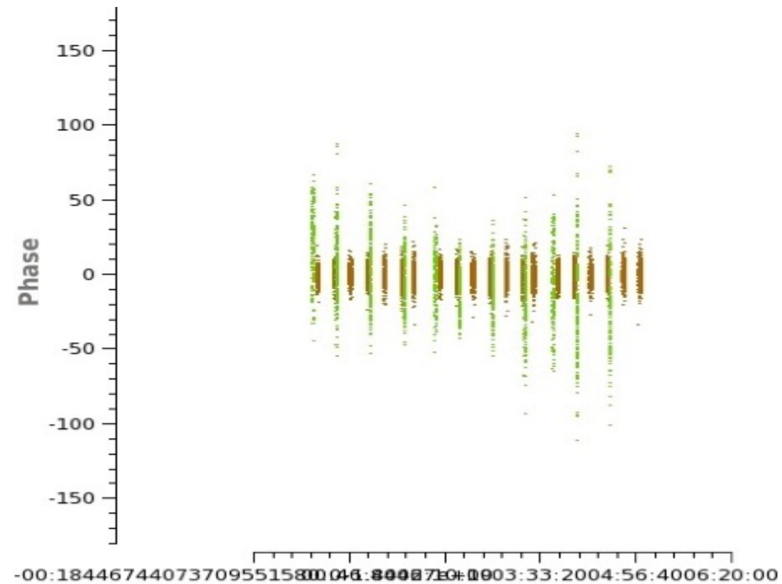
~600 GHz

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 mode

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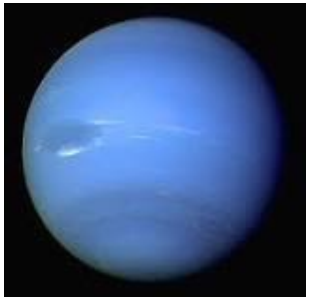
Flux (or Amplitude) Calibration

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 flux calibrator are then applied to the science target.



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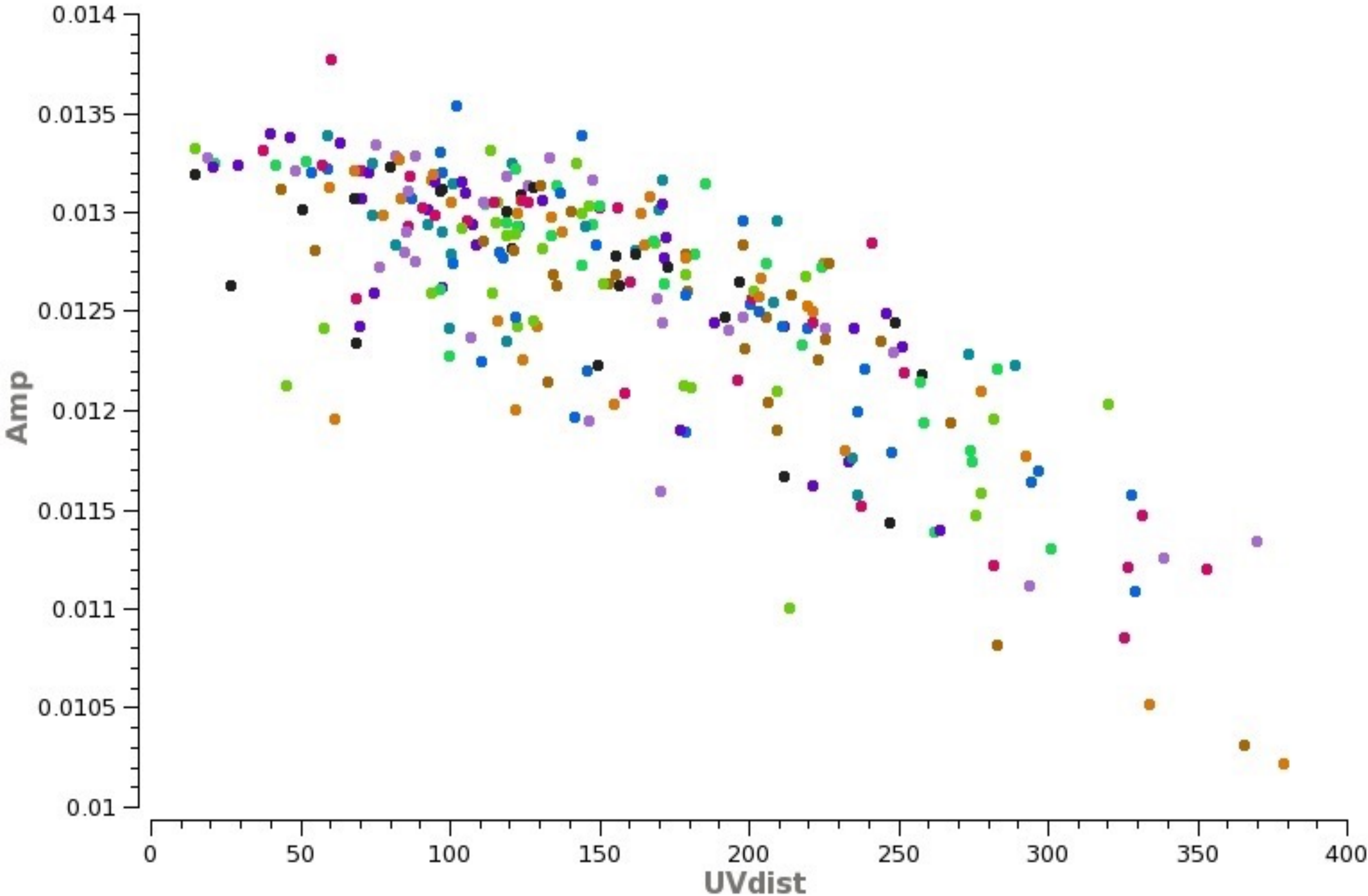
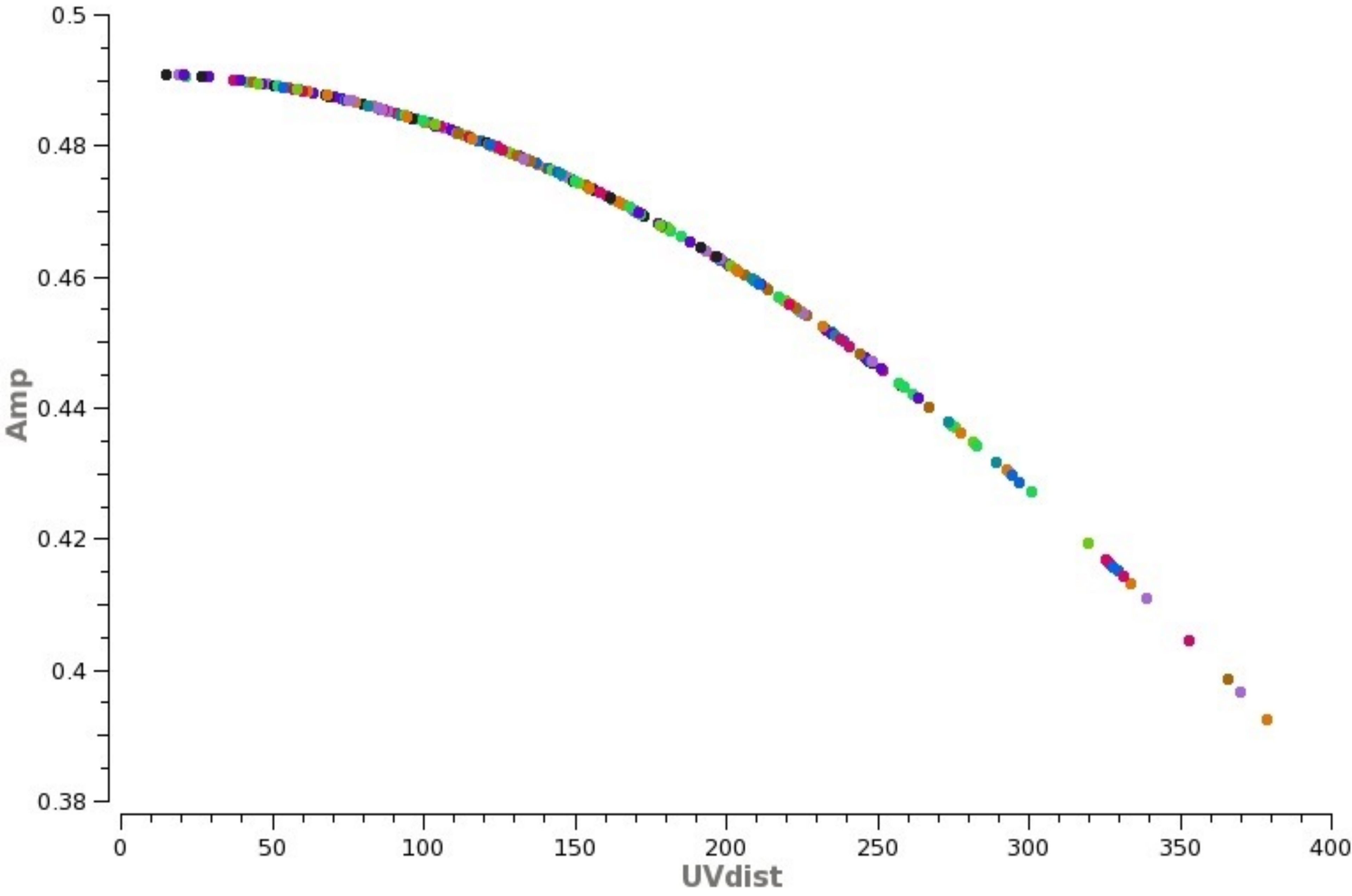
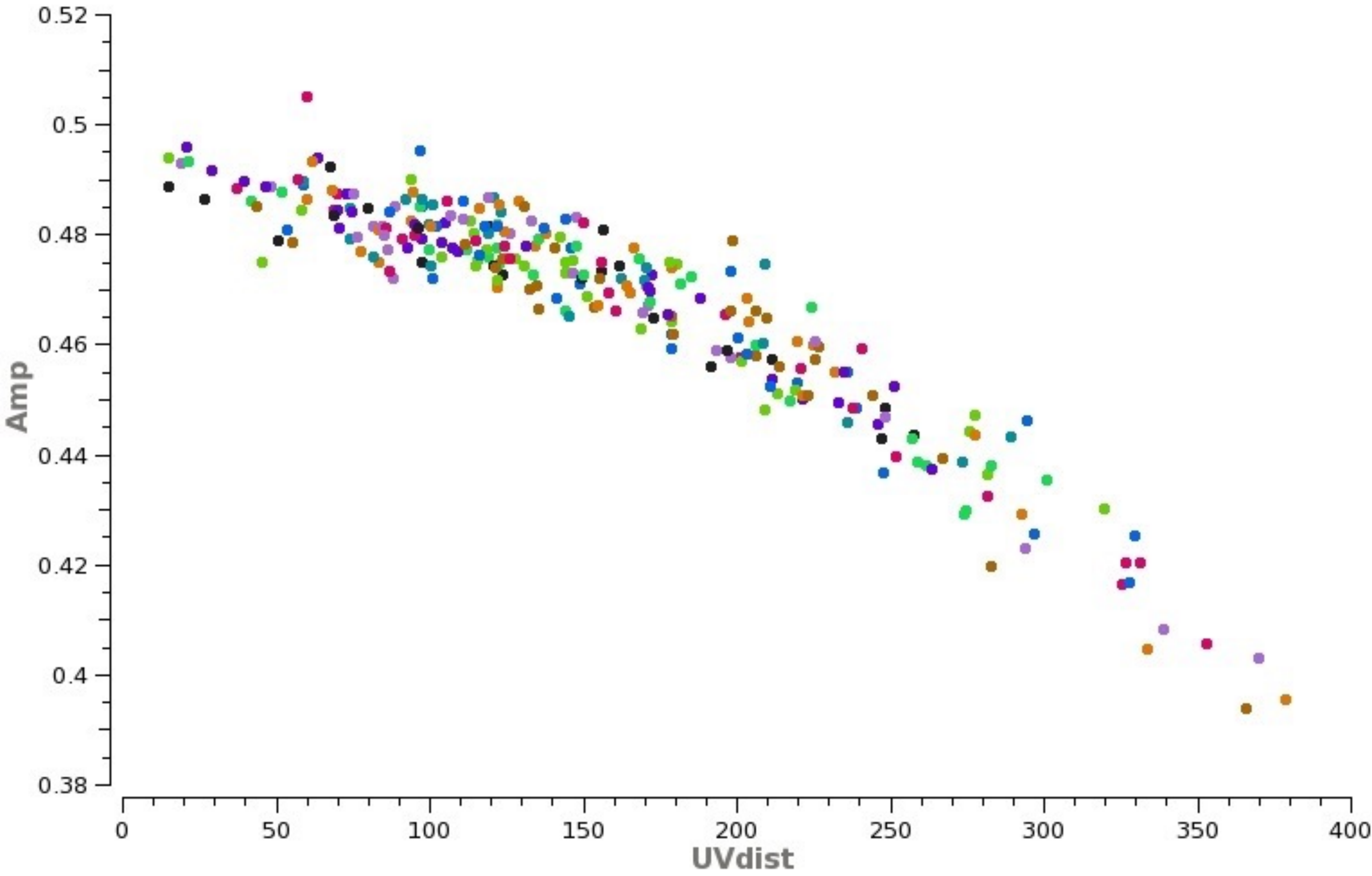
Amp-Calibrators Amp vs. uv-distance (Before)



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

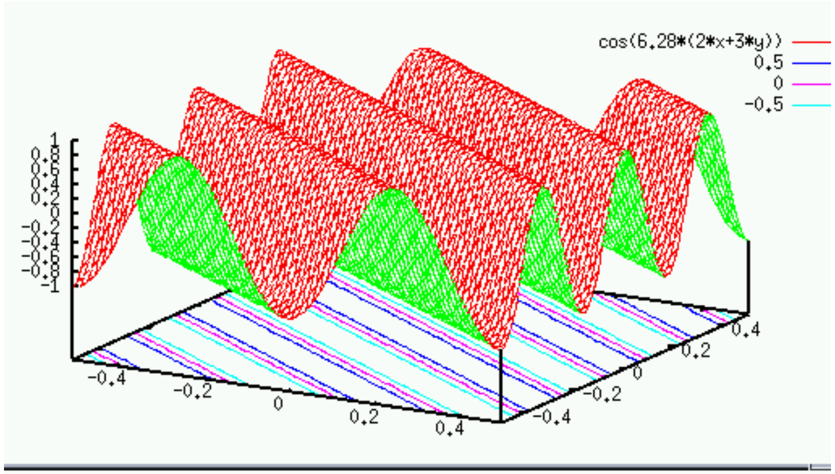
For more info:

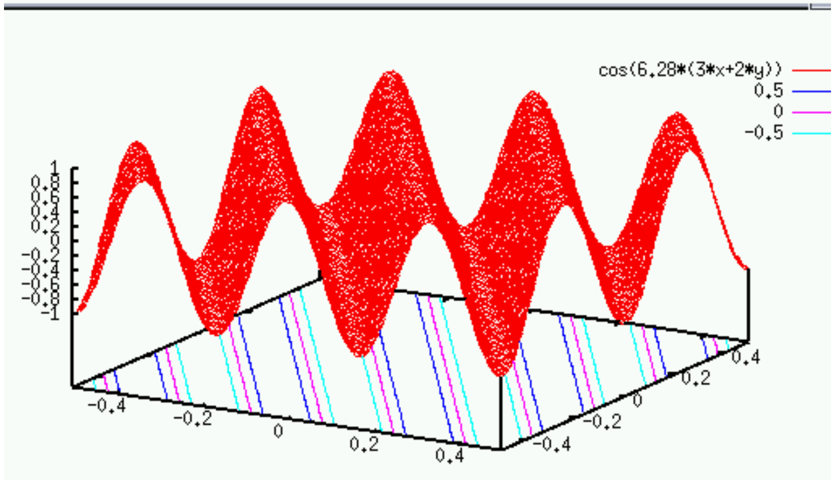
http://www.almaobservatory.org

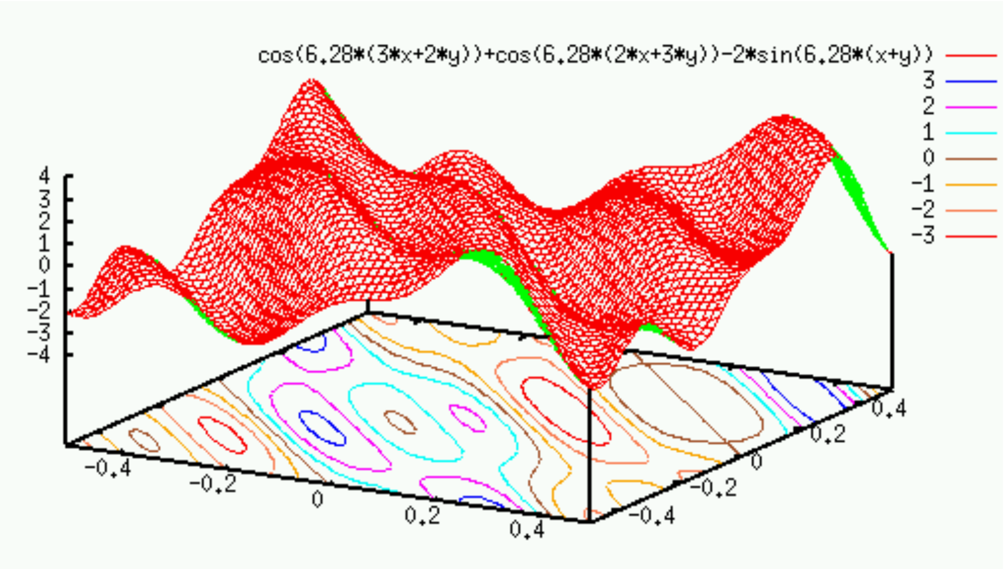
The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of 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.

The Fourier Transform

Example: 2D Fringe pattern







Some 1D Fourier Transform Pairs