Introduction to Radio Interferometry

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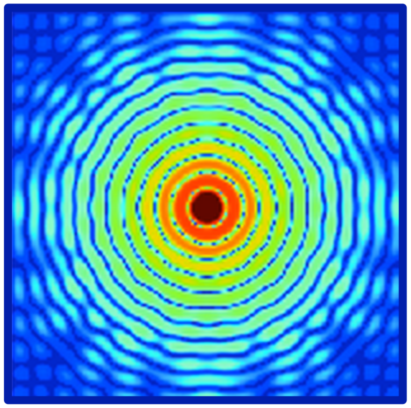
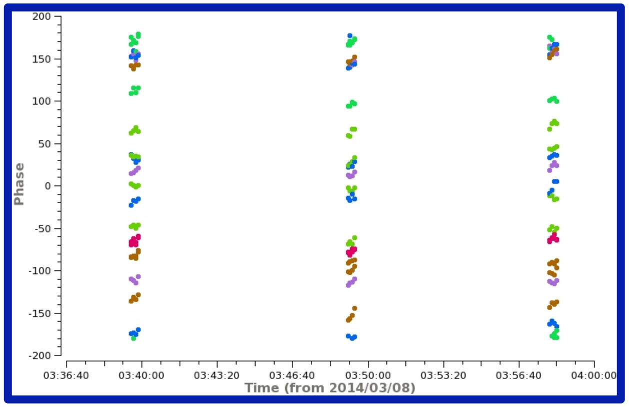
NRAO

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

NRAO



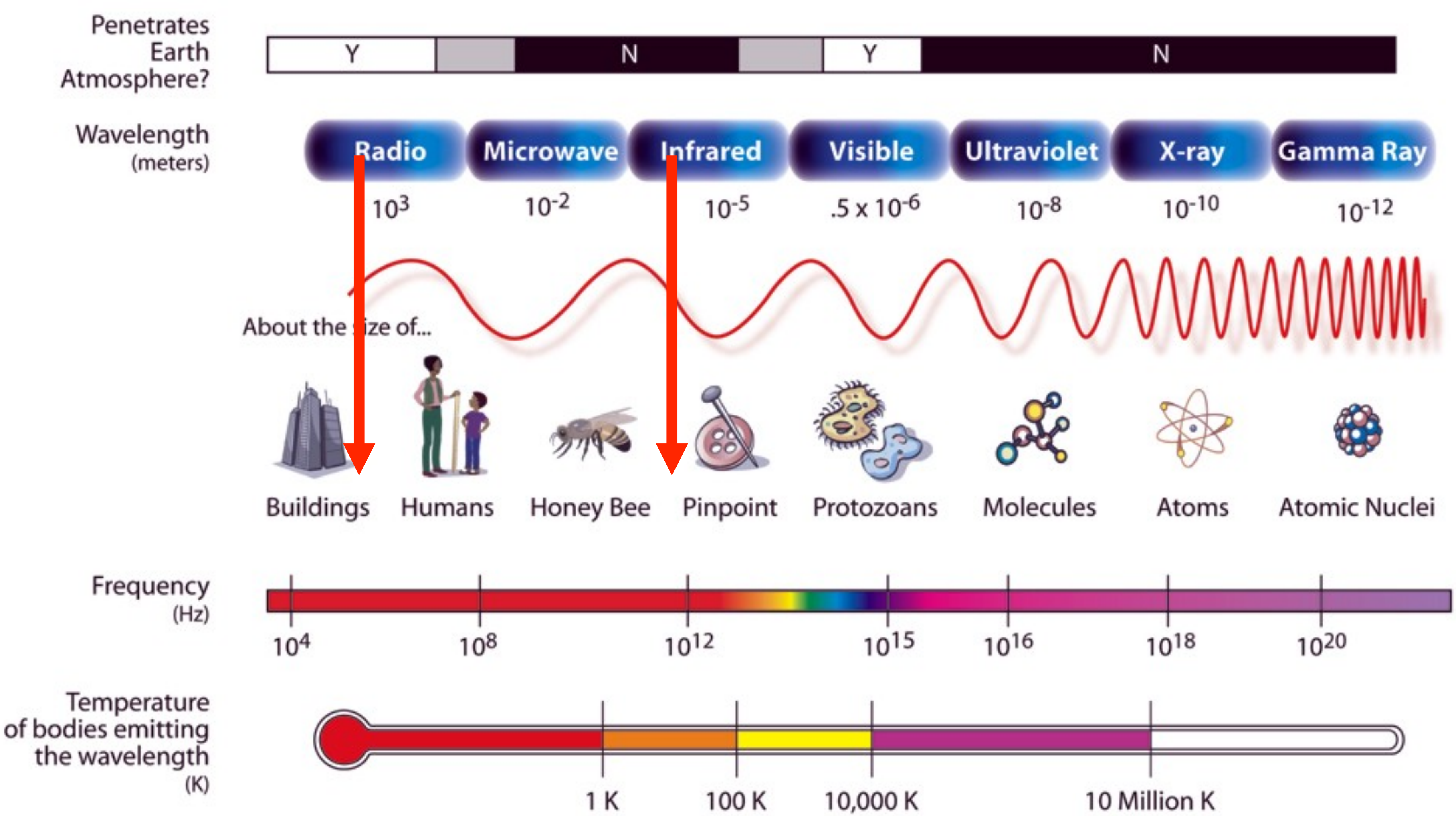


Define what we mean by radio interferometry

Discuss what interferometers measure

Present an overview of data calibration

THE ELECTROMAGNETIC SPECTRUM



Radio astronomy is roughly defined as the regime that uses heterodyne technology.

The heterodyne technique was invented in Canada in early 1900's whereby 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.

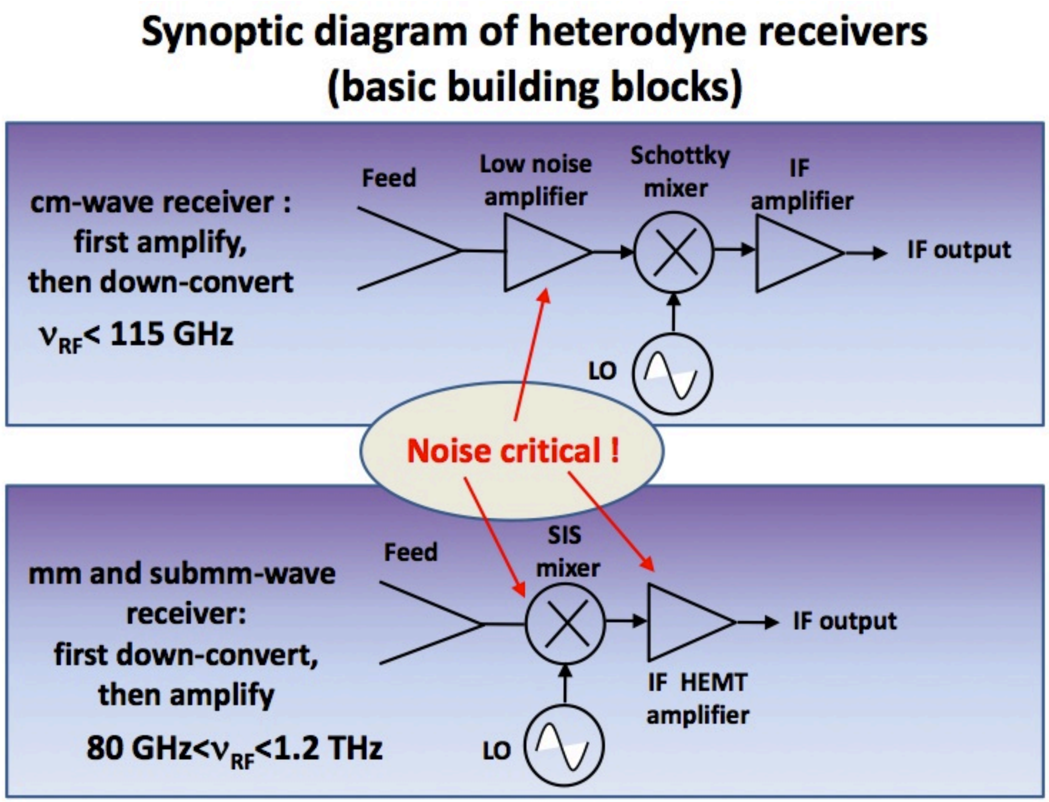


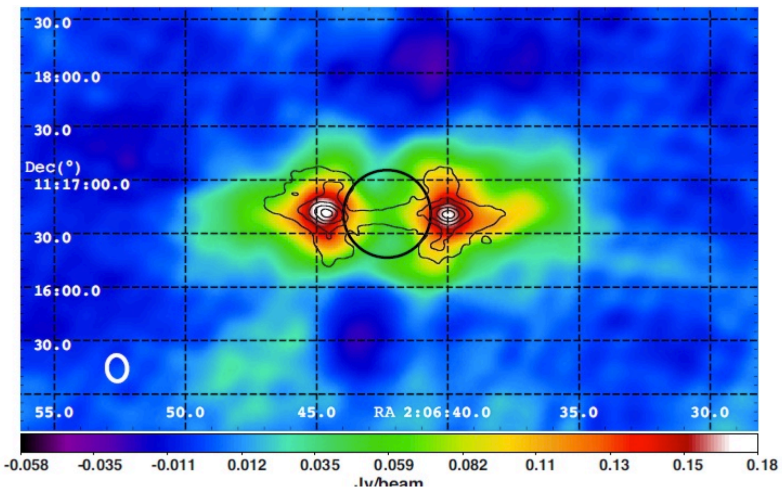
Image from Alessandro Navarrini (IRAM)

Long wavelength means no glass mirrors

NRAO

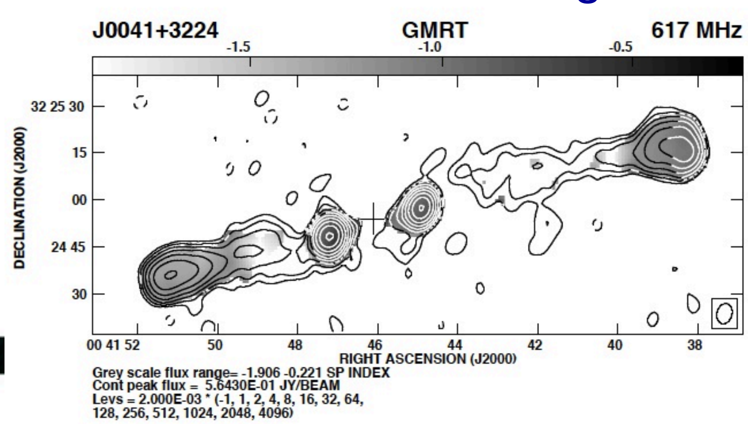
What should we observe?

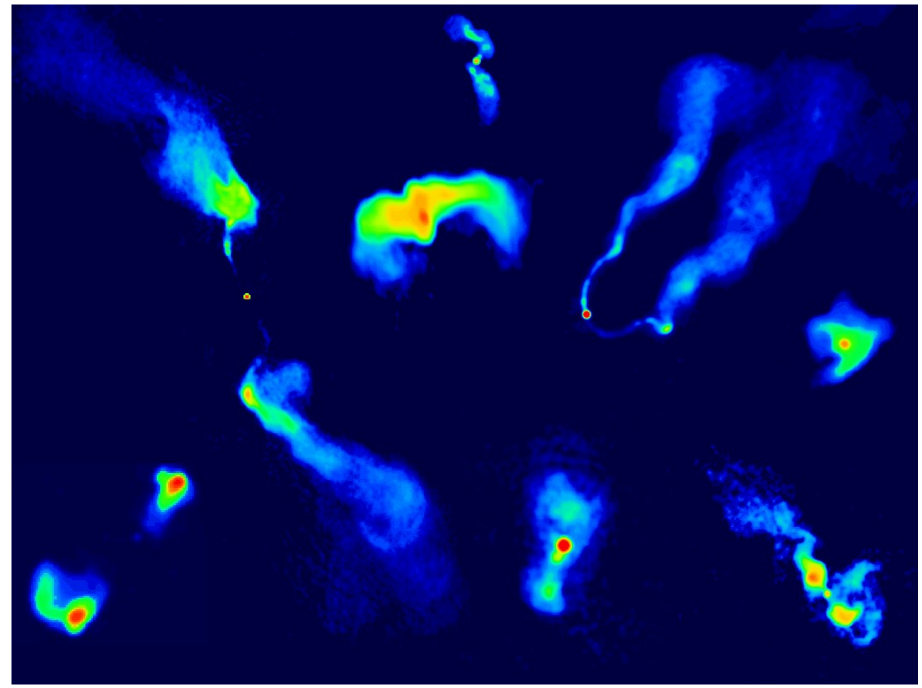
At low frequencies (MHz-GHz):



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/

What should we observe?

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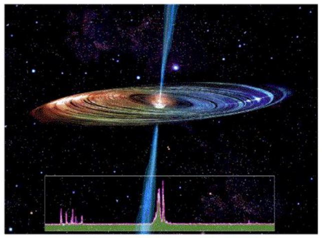
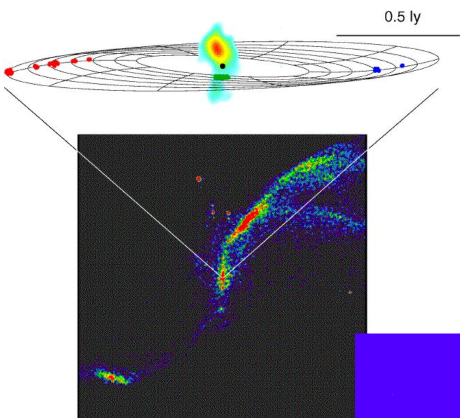
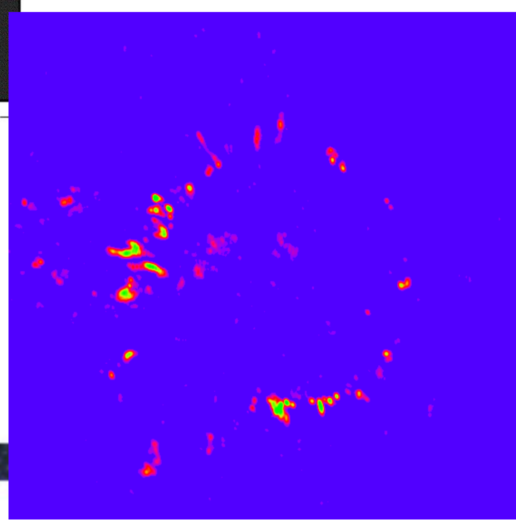
At low frequencies (MHz-GHz):

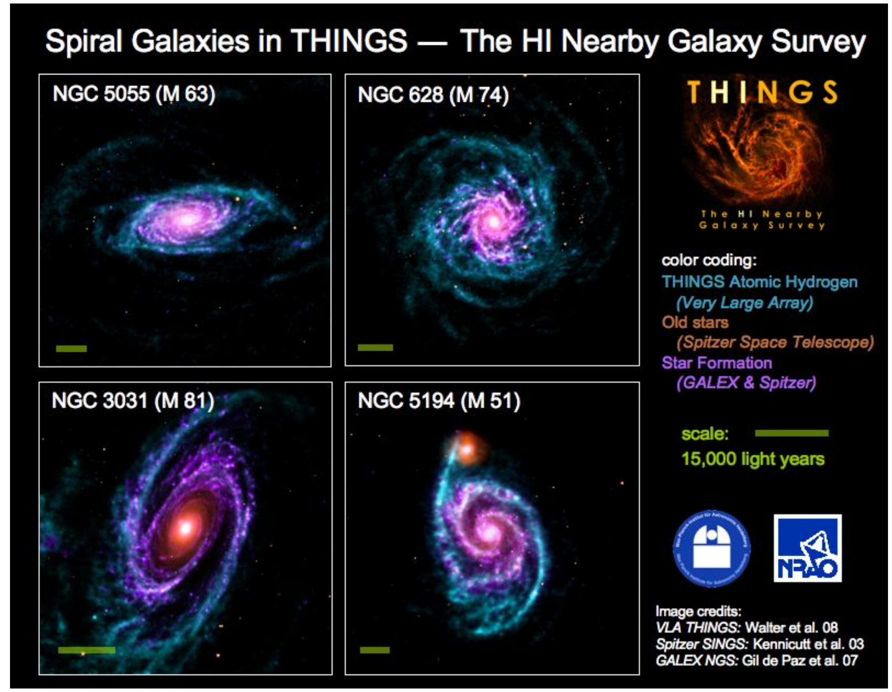


NGC 4258

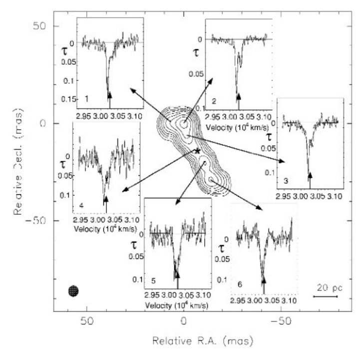


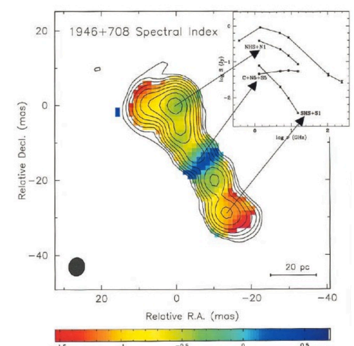
H_2O, OH or SiO masers in galaxies and stars





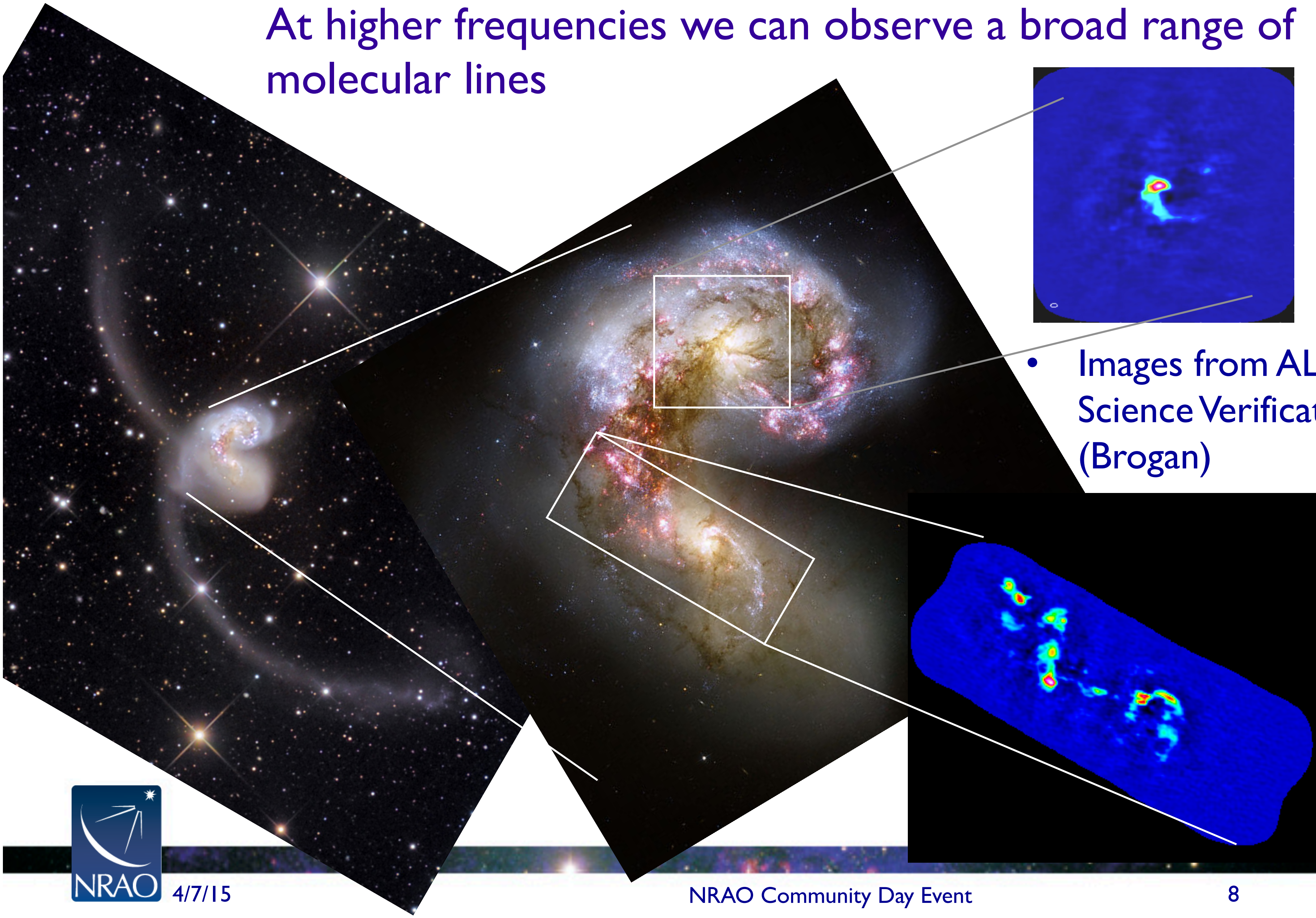
HI emission and absorption, free-free absorption in galaxies





What should we observe?

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

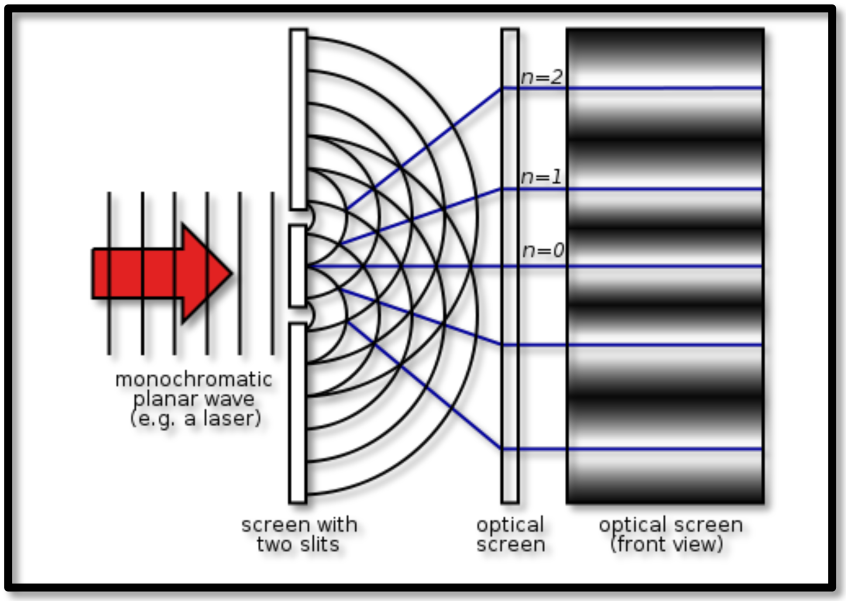


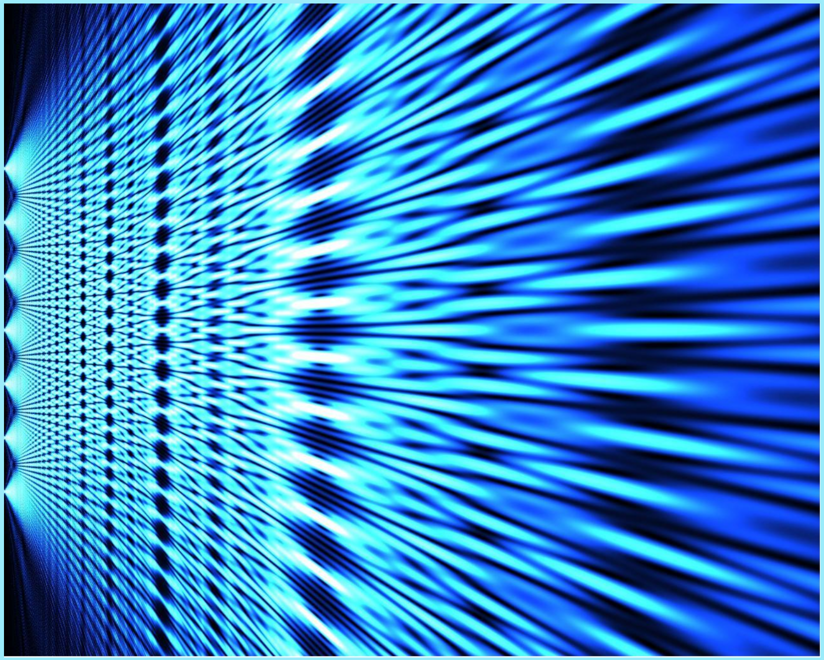
- Images from ALMA Science Verification (Brogan)

Interferometers are used to get higher resolution.

- Angular resolution for most telescopes ~ λ/D
  - D is the diameter of the telescope, λ is wavelength of observation
- Hubble Space Telescope resolution ~ 0.05”
  - D = 2.4m, λ ~ 500nm
- For mm wavelength observations, one would need a 5km diameter antenna to reach this resolution
- Instead, we use arrays of smaller telescopes to achieve high angular resolution in radio astronomy

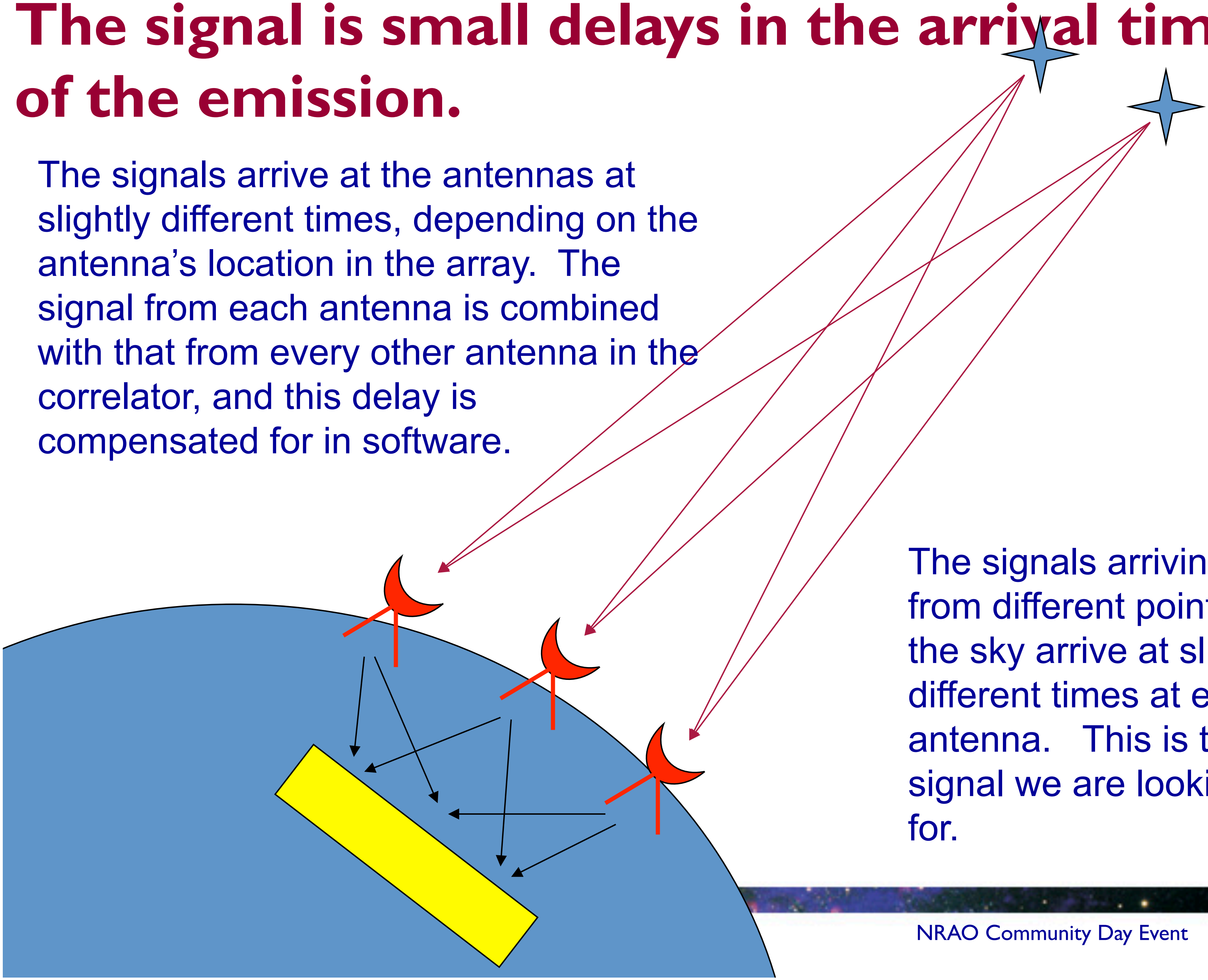
An interferometer measures interference patterns.





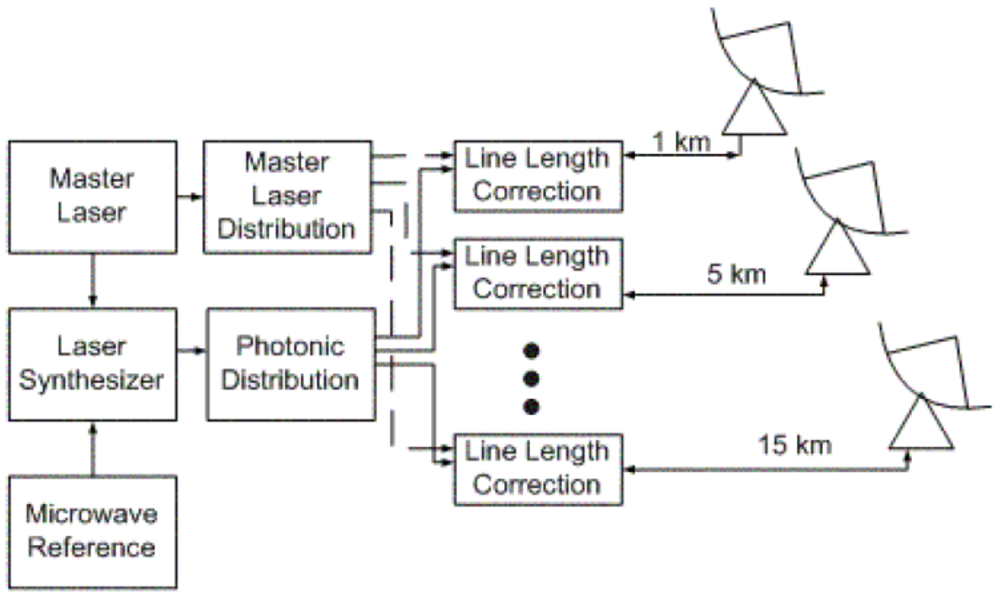
The signal is small delays in the arrival time of the emission.

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.



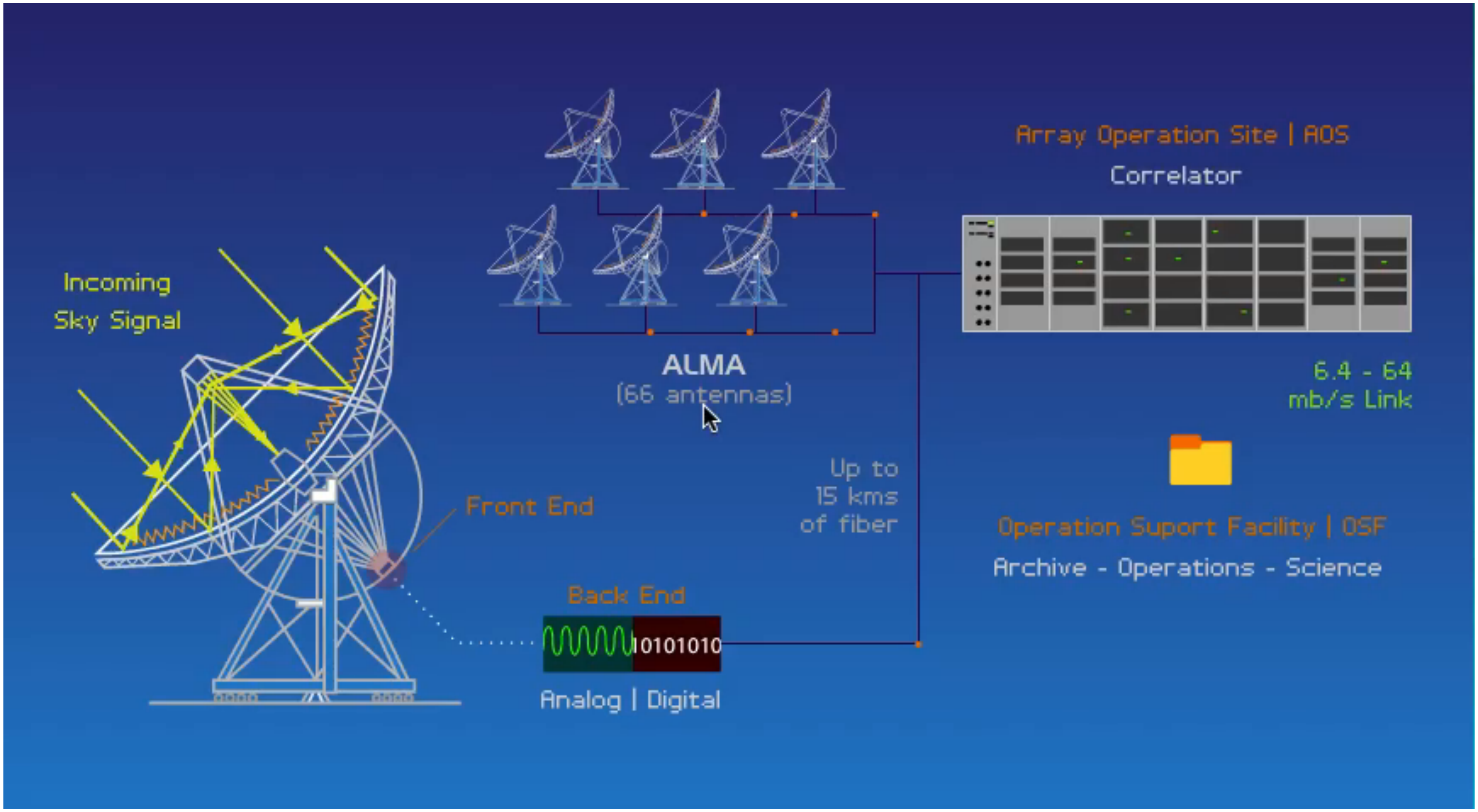
The signals arriving from different points in the sky arrive at slightly different times at each antenna. This is the signal we are looking for.

Precise Timing Required
to synchronize signals

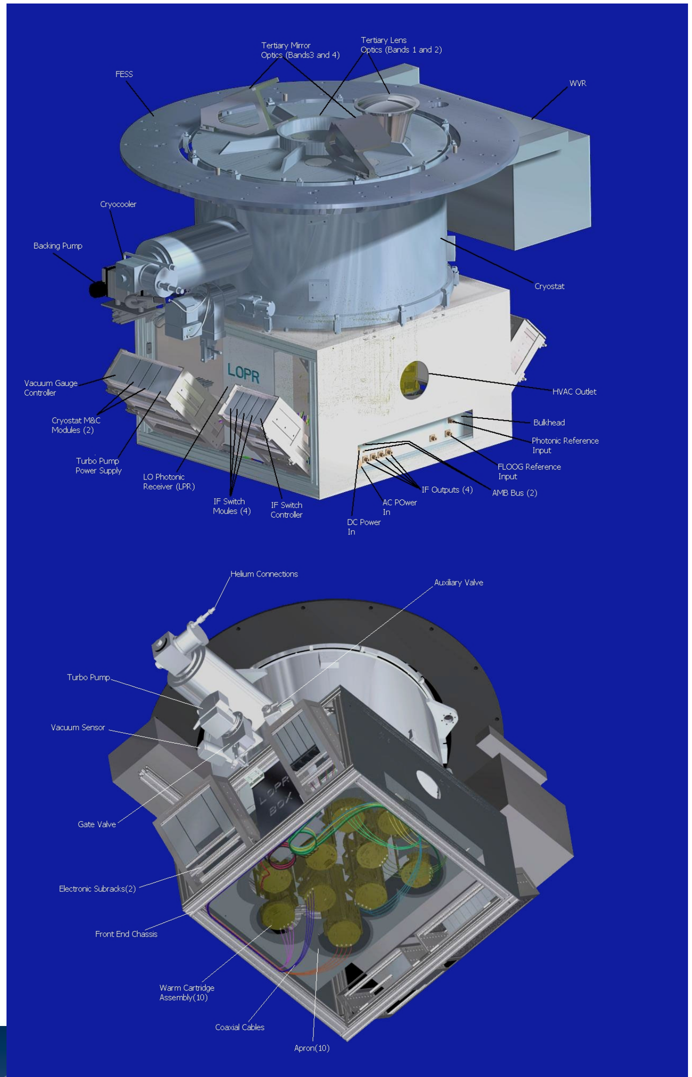


Reference signal can be generated at radio frequencies, but ALMA makes extensive use of photonics to stabilize the fiber between antennas and to synchronize the receivers which has to be done at the ~25 femto-second level.

An interferometer in action

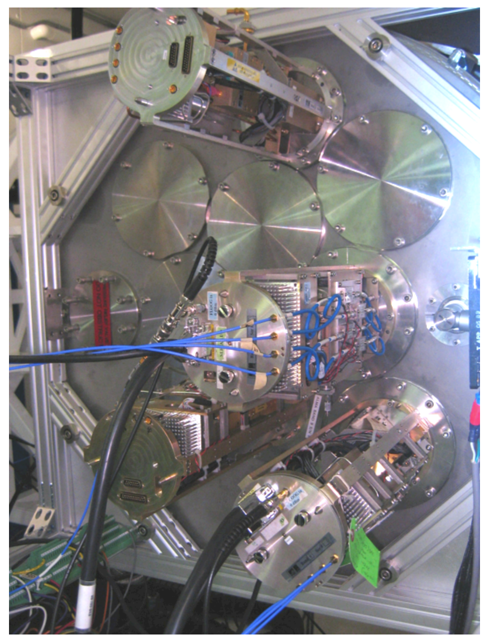


The Front End houses the receivers



ALMA

Band 3



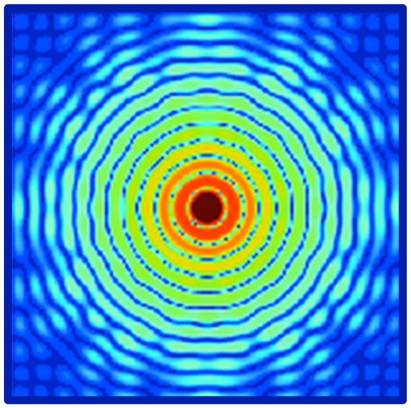
Band 7

Band 6

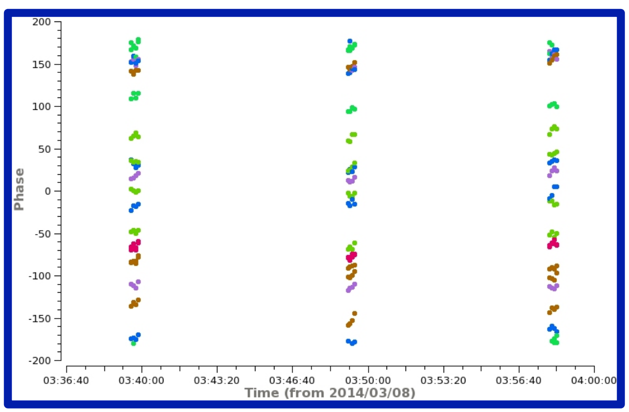
Band 9

For frequencies higher than 100 GHz, we require SIS mixers for good sensitivity, so these must be cooled to 4K. At lower frequencies, feeds are much larger, requiring more space, but easier and cheaper to build and maintain

Define what we mean by radio interferomety



Discuss what interferometers measure



Present an overview of data calibration

Interferometers measure the interference pattern produced by pairs of apertures.

The complex amplitude and phase for a particular pair of antennas is referred to as a **visibility**.

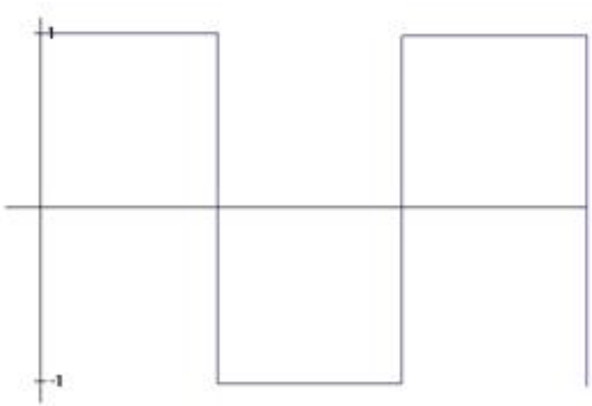
The interference pattern is directly related to the source brightness.

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)

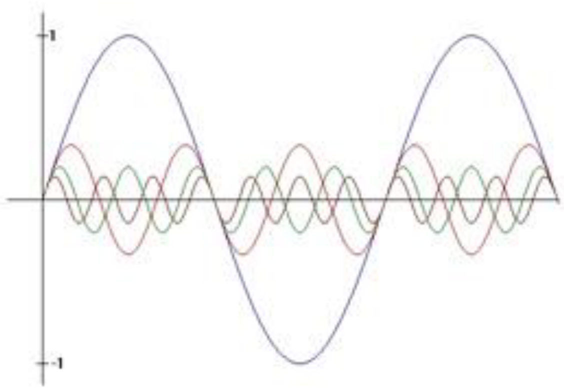
(van Cittert-Zernike theorem)

The Fourier Transform

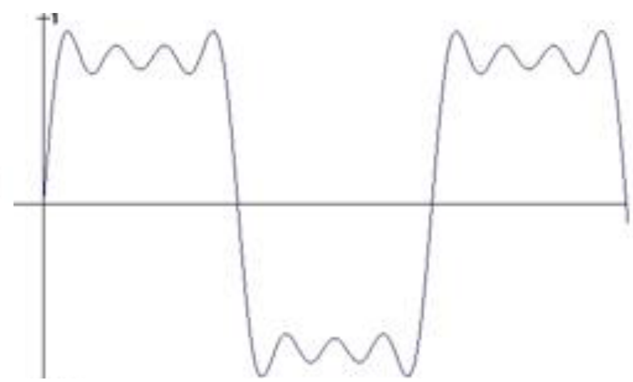
Fourier theory states that any well behaved signal (including images) can be expressed as the sum of sinusoids



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

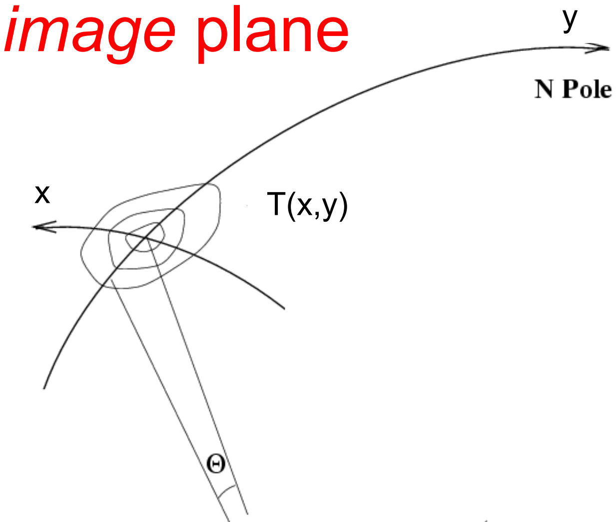
Fourier space/domain

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

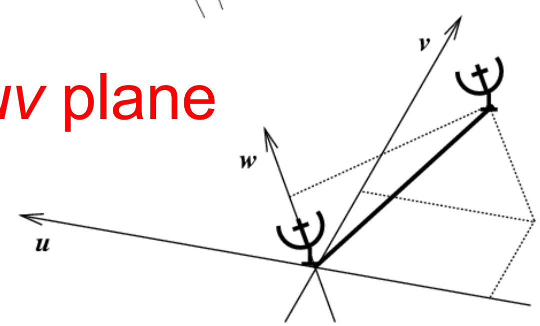
$$T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$$

Image space/domain

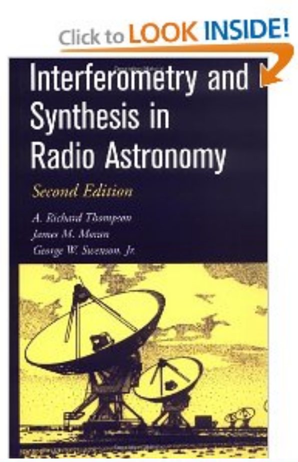
image plane



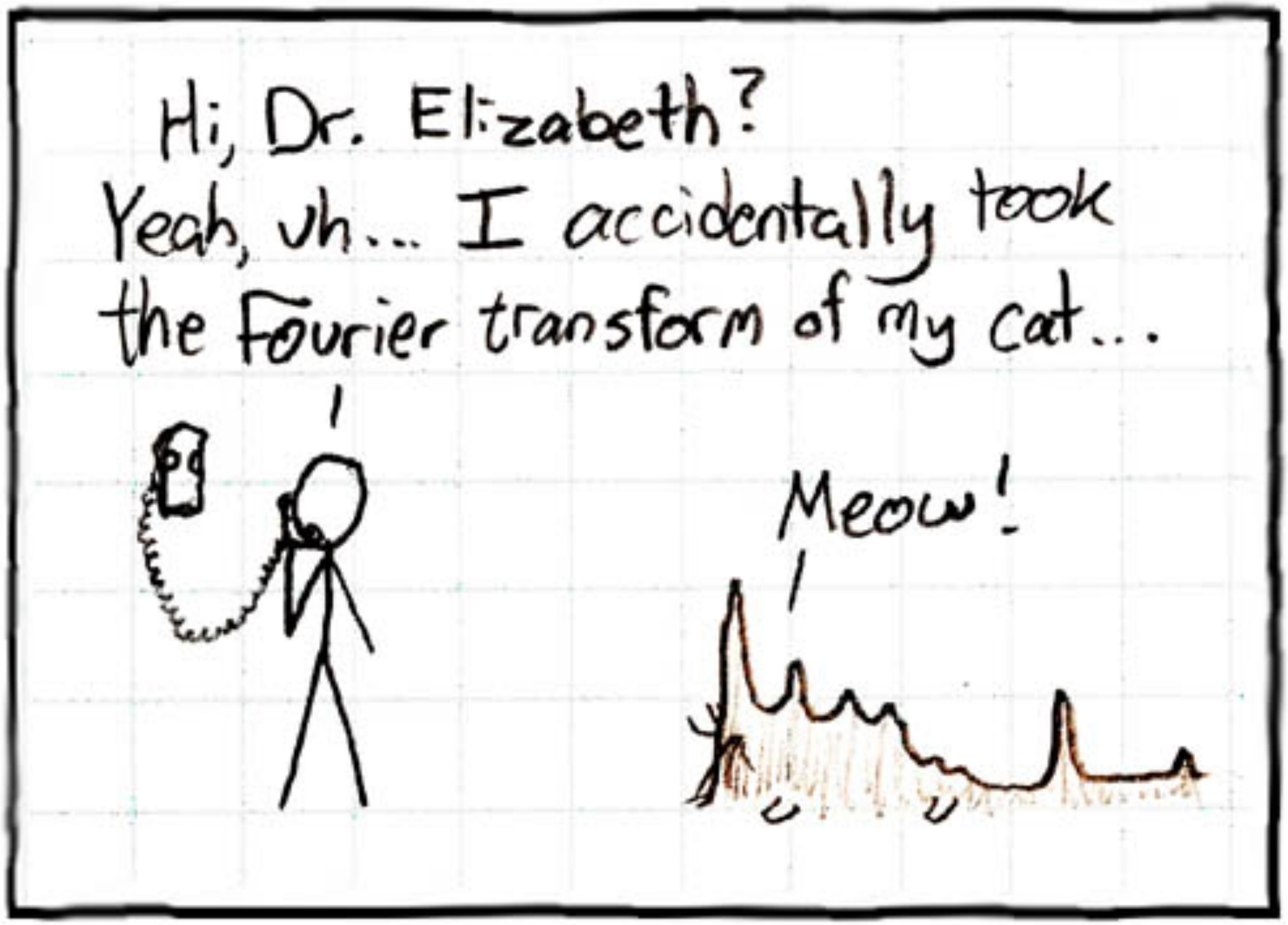
uv plane



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

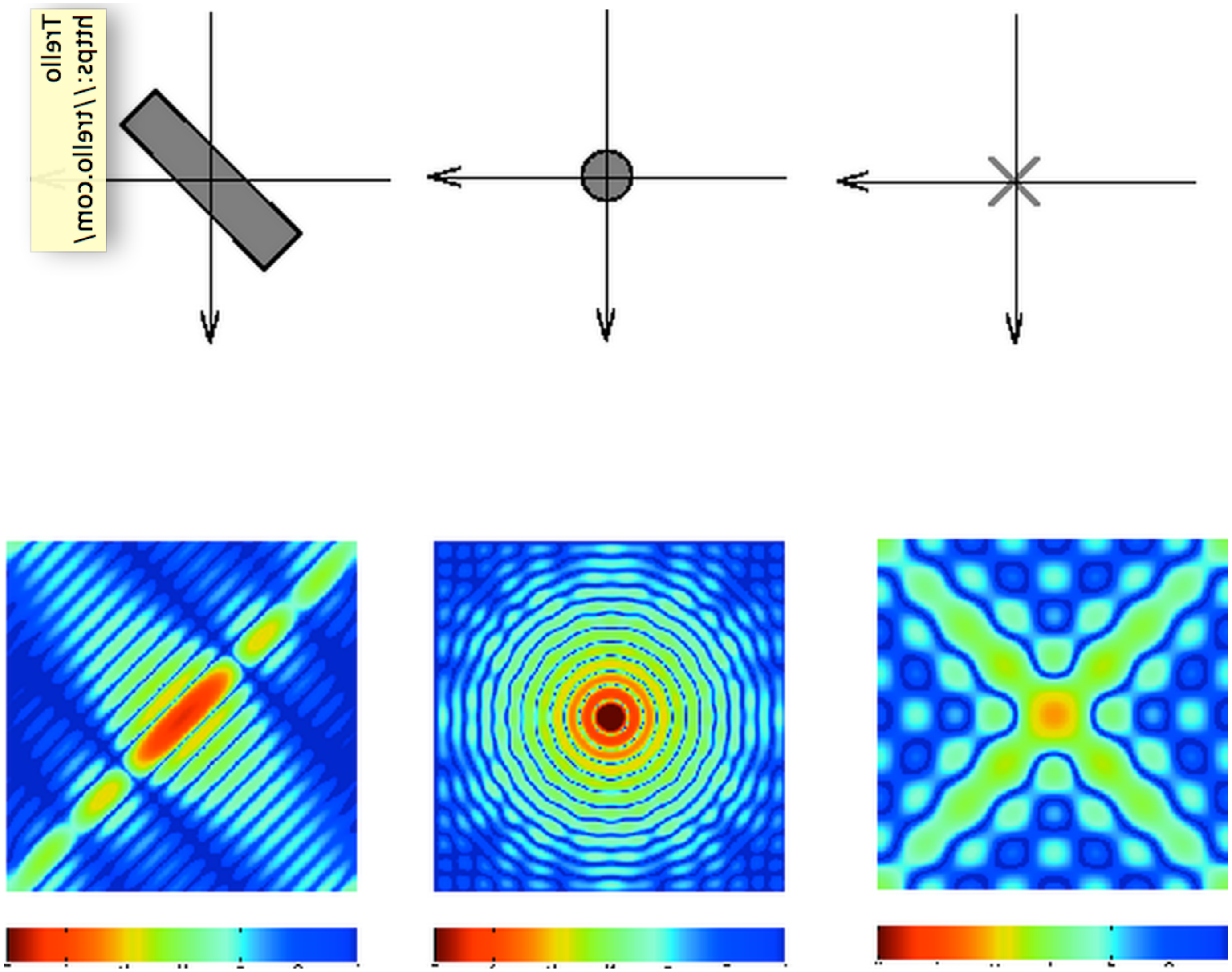


What do fourier transforms actually look like?



xkcd.com

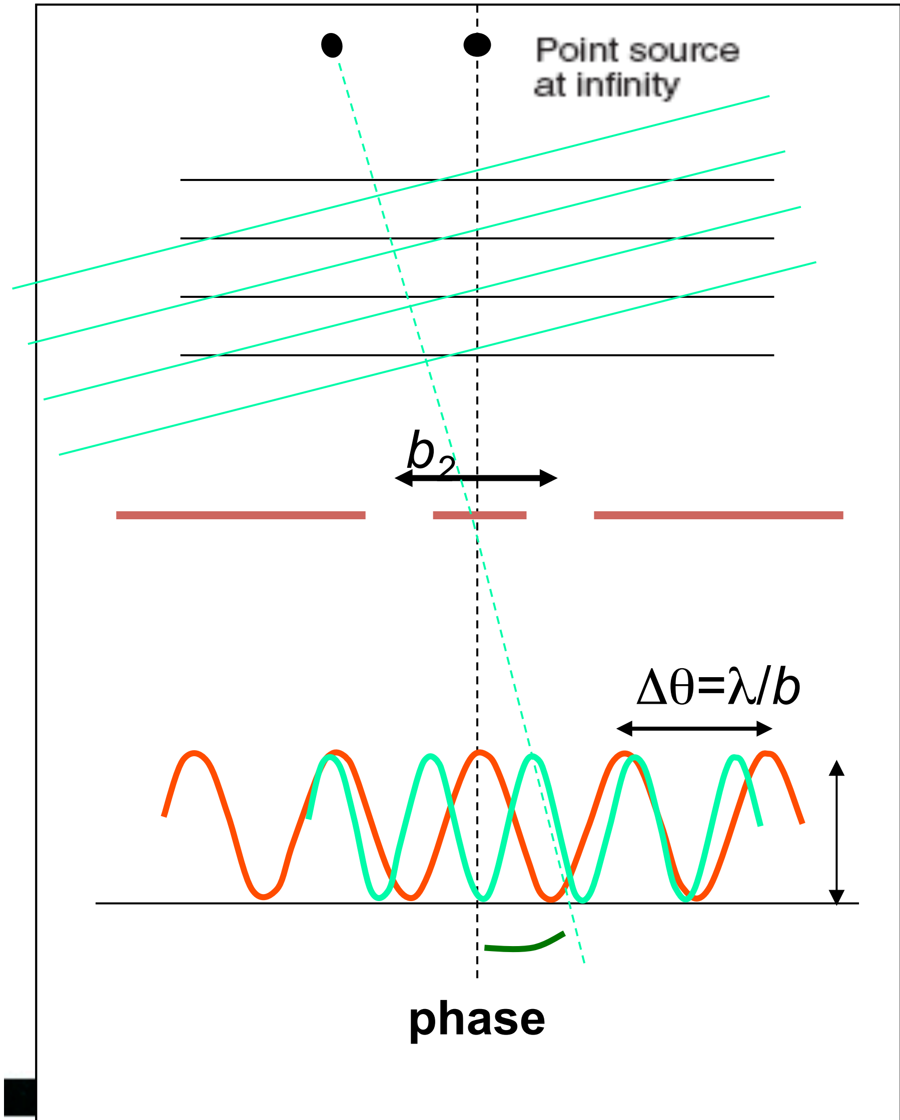
Fourier Transforms of Images

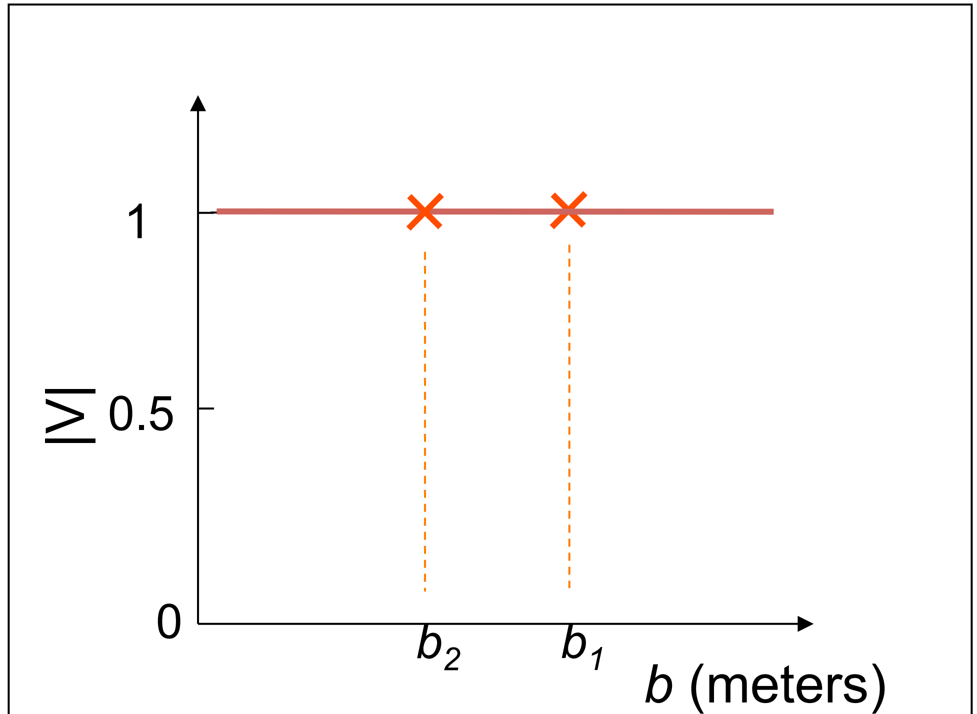


From www.mathworks.com

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





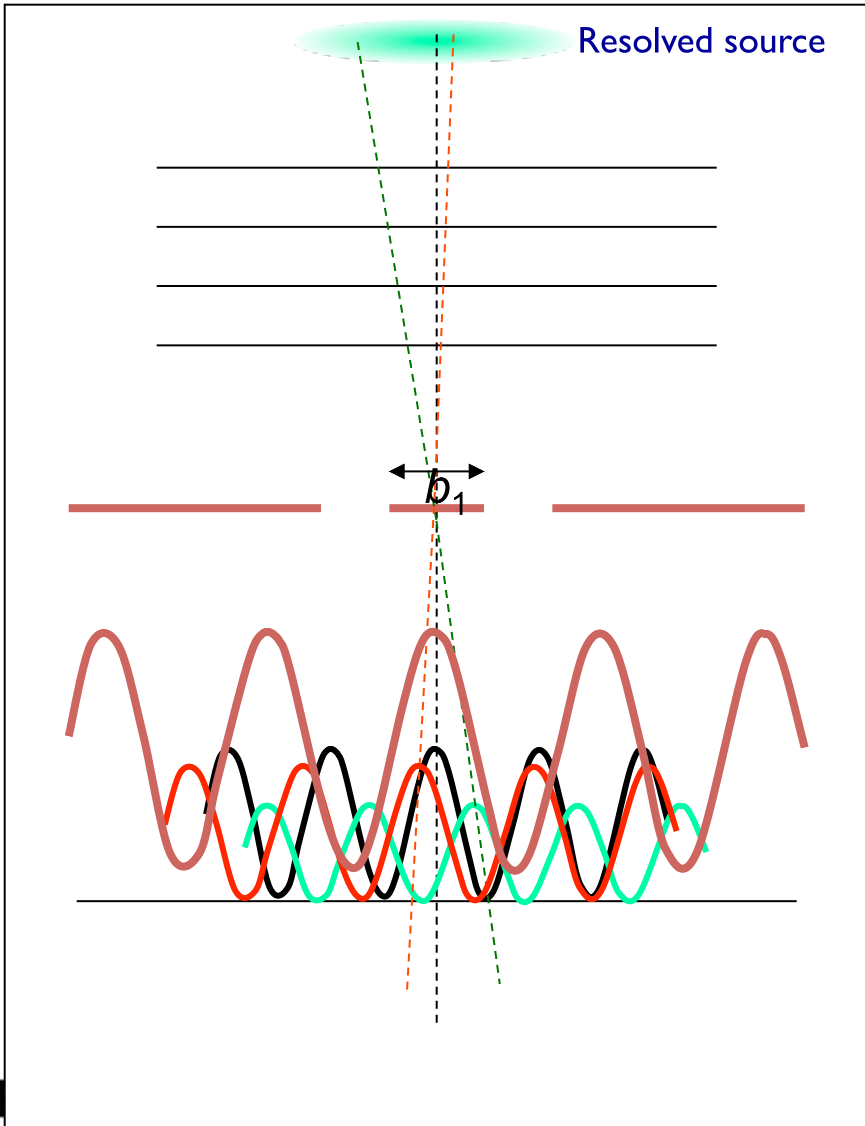
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

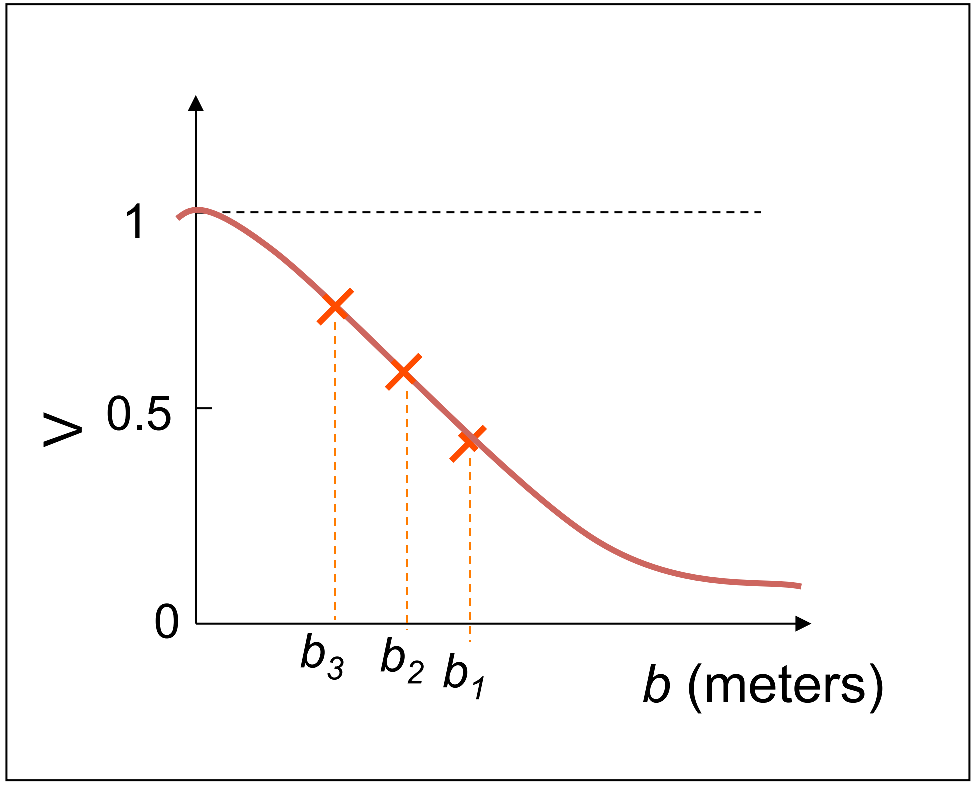
The visibility is a **complex** quantity:

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

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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

Characteristic Angular Scales

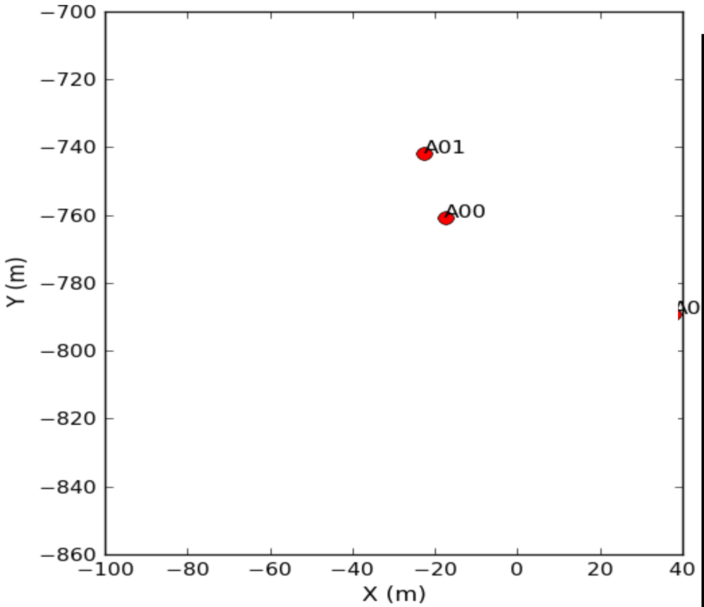
- Angular resolution
  - $\sim \lambda/B_{max}$, where B_{max} is the longest baseline
- Maximum angular scale
  - the source is resolved out if $\theta>\lambda/B_{min}$, where B_{min} is the minimum separation between apertures.
- Field of view of the single aperture
  - $\sim \lambda/D$, where D is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

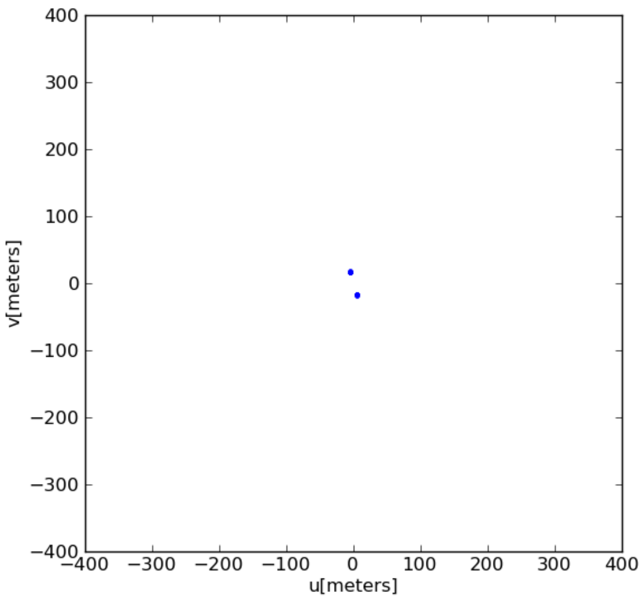
An interferometer is sensitive to a range of angular sizes

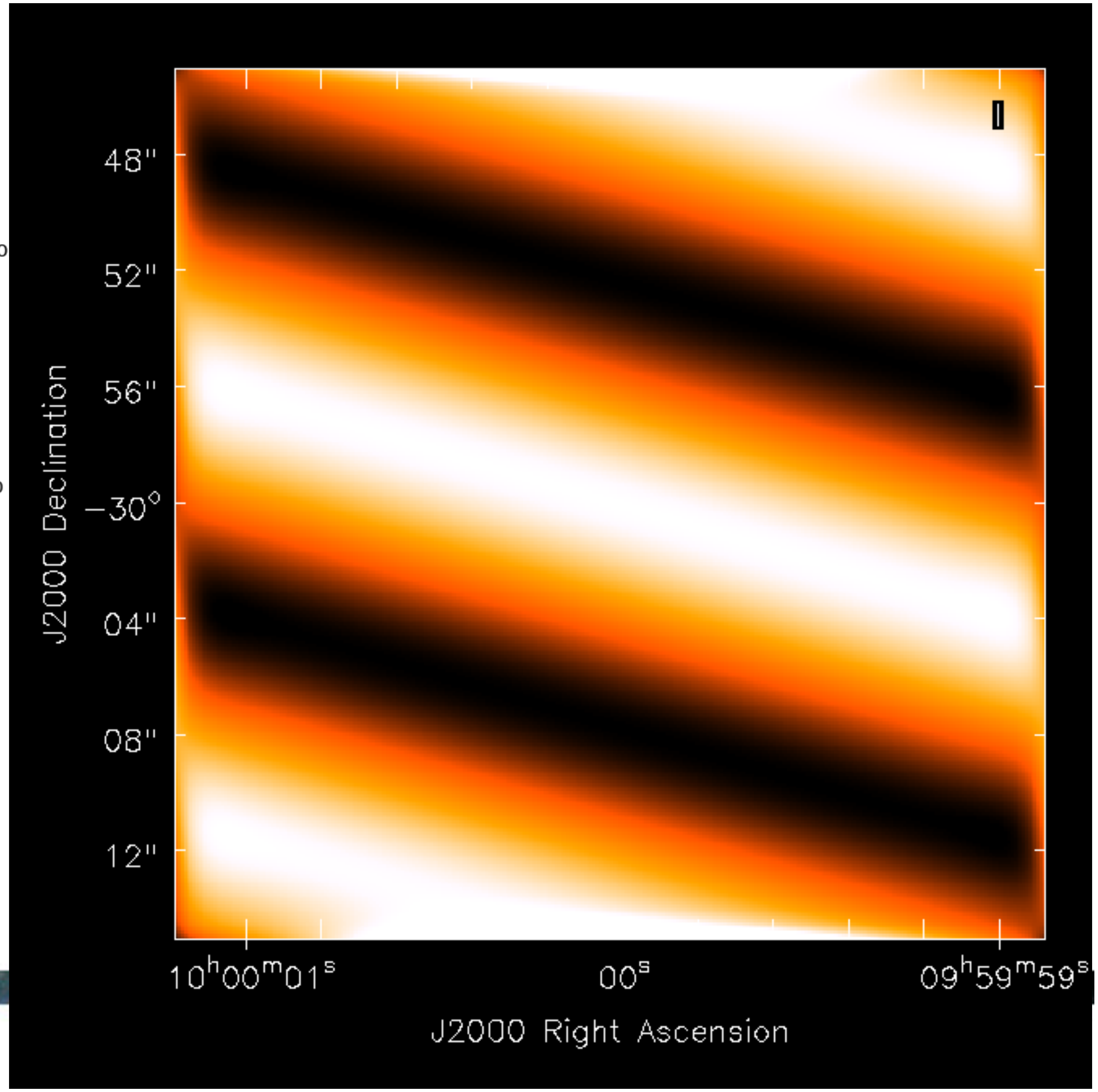
$$\lambda/B_{max} < \theta < \lambda/B_{min}$$

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

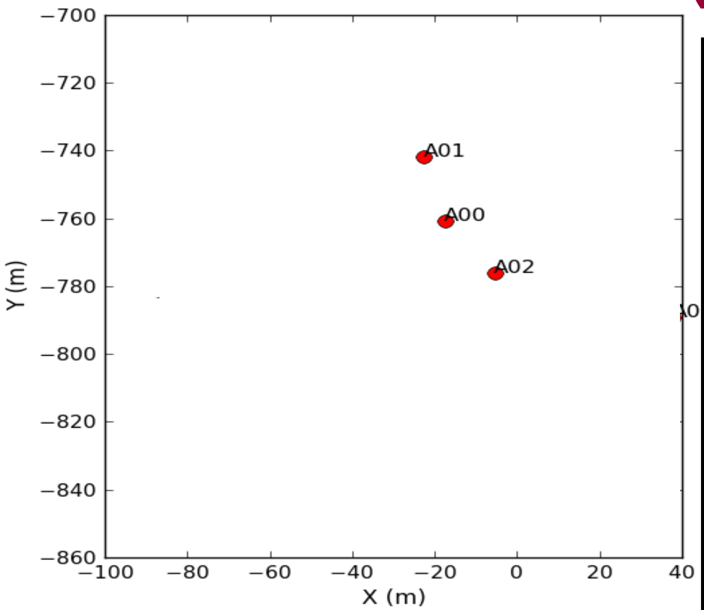
Example: Fringe pattern with 2 Antennas (1 baseline)

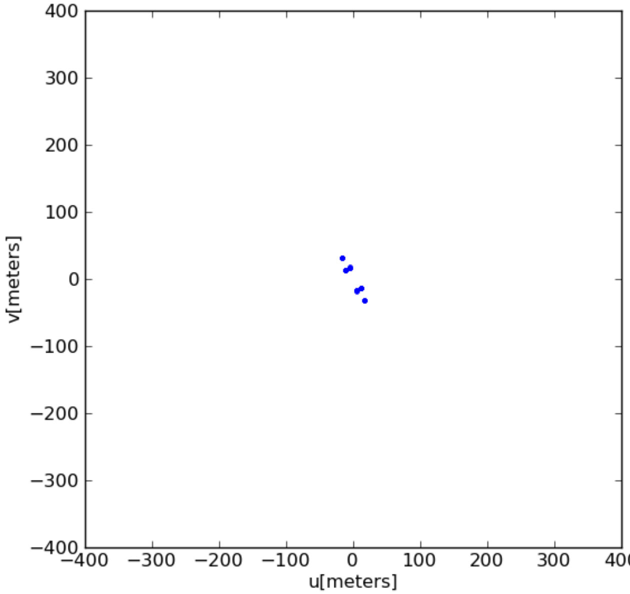


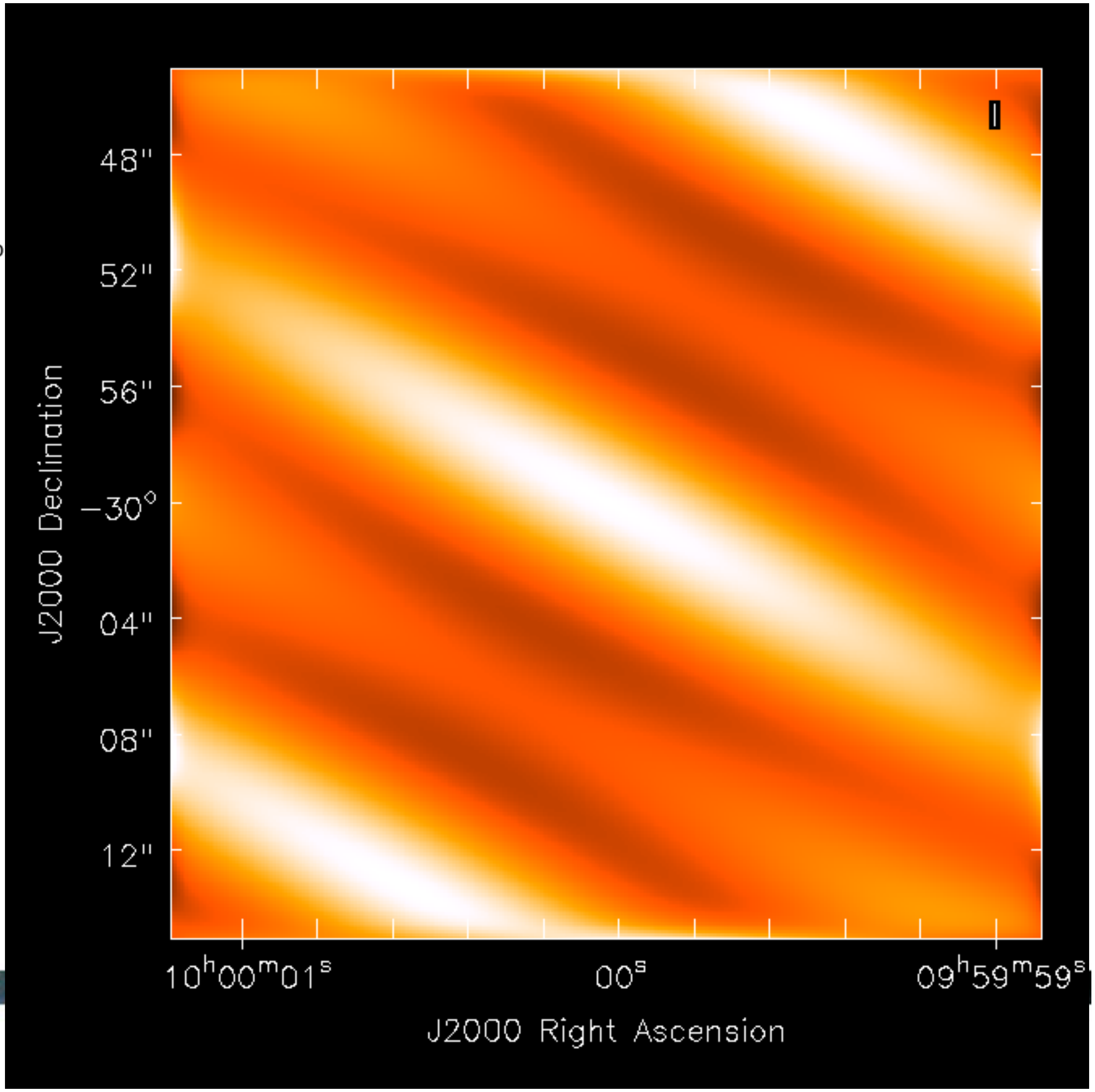




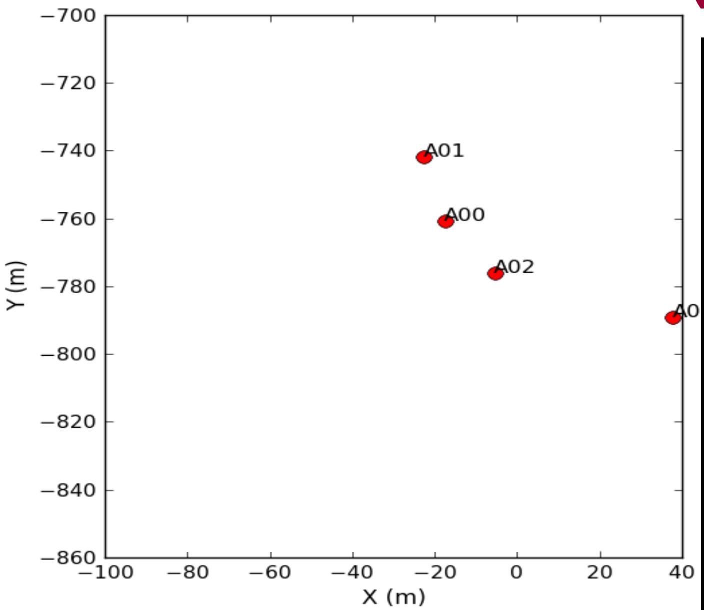
Example: Fringe pattern with 3 Antennas (3 baselines)

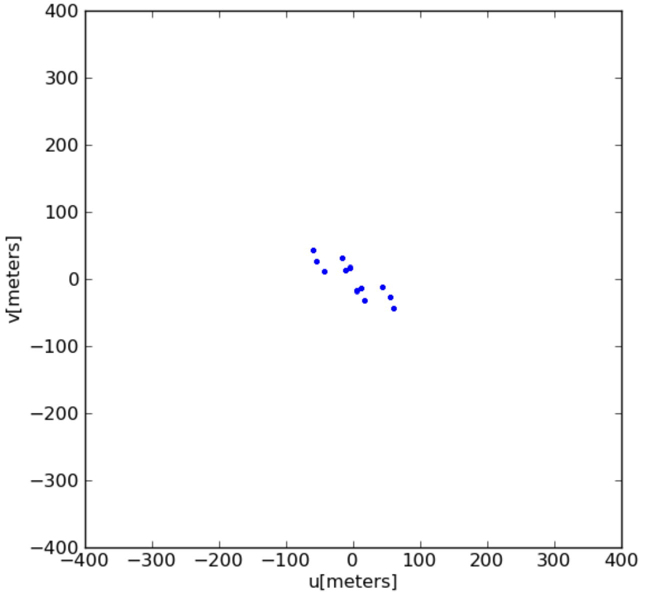


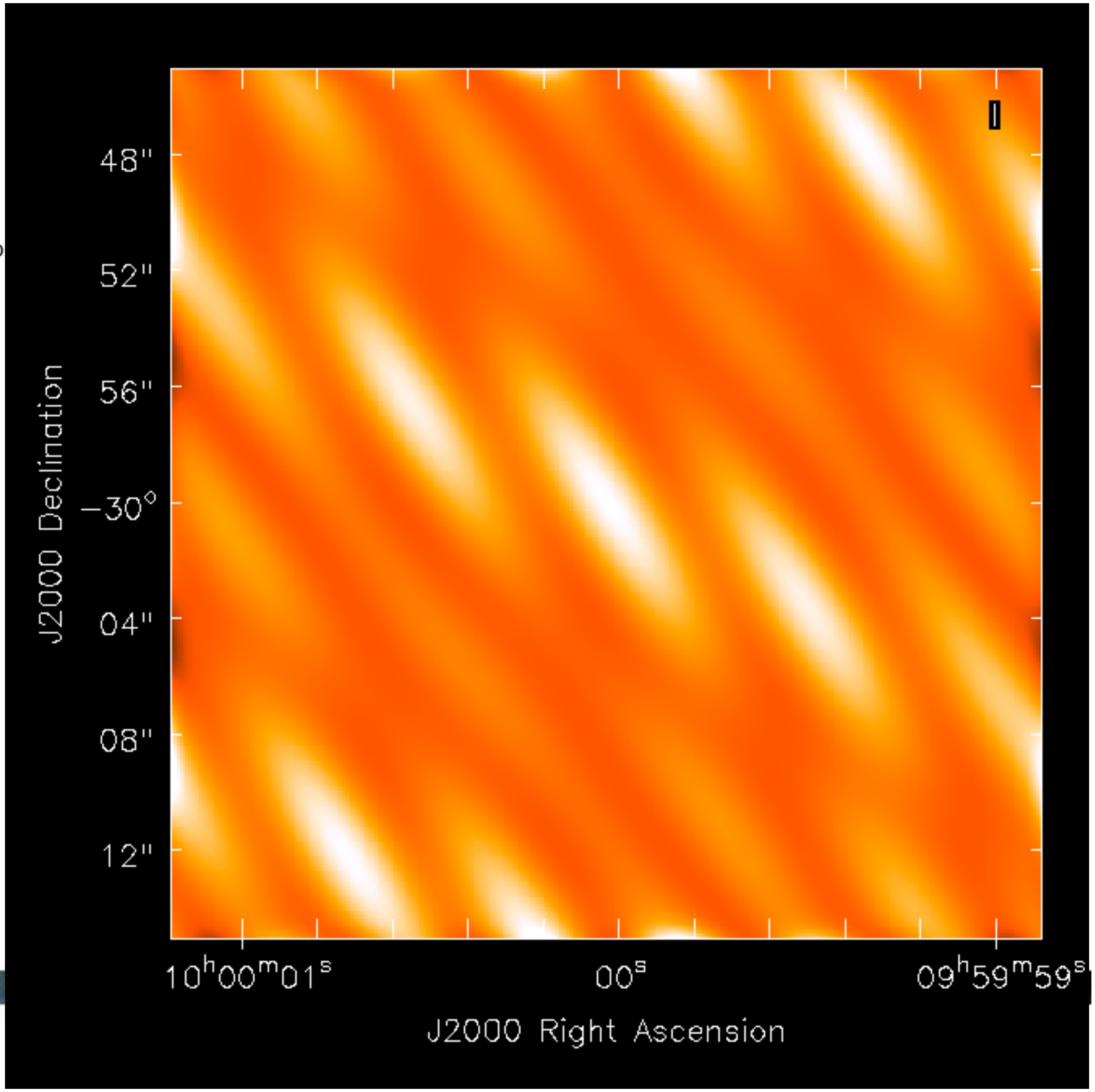




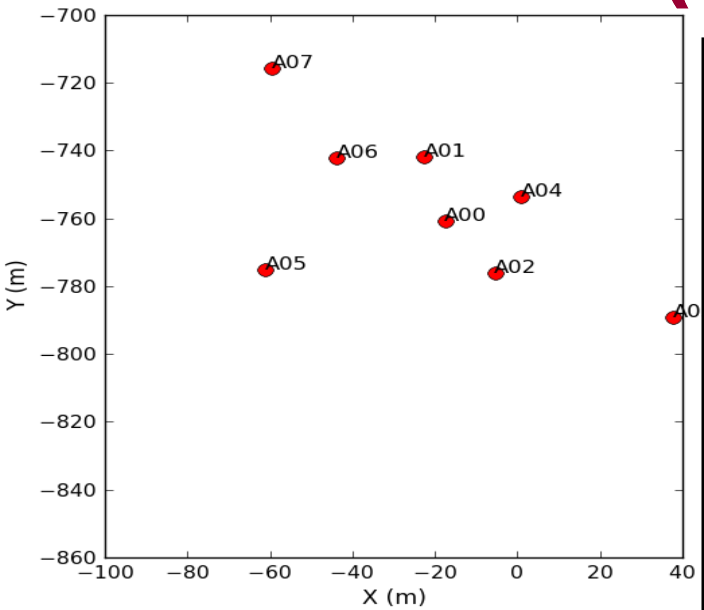
Example: Fringe pattern with 4 Antennas (6 baselines)

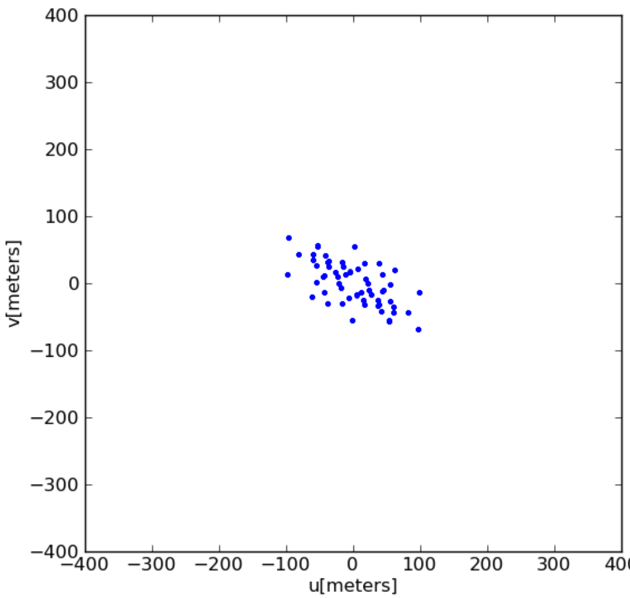


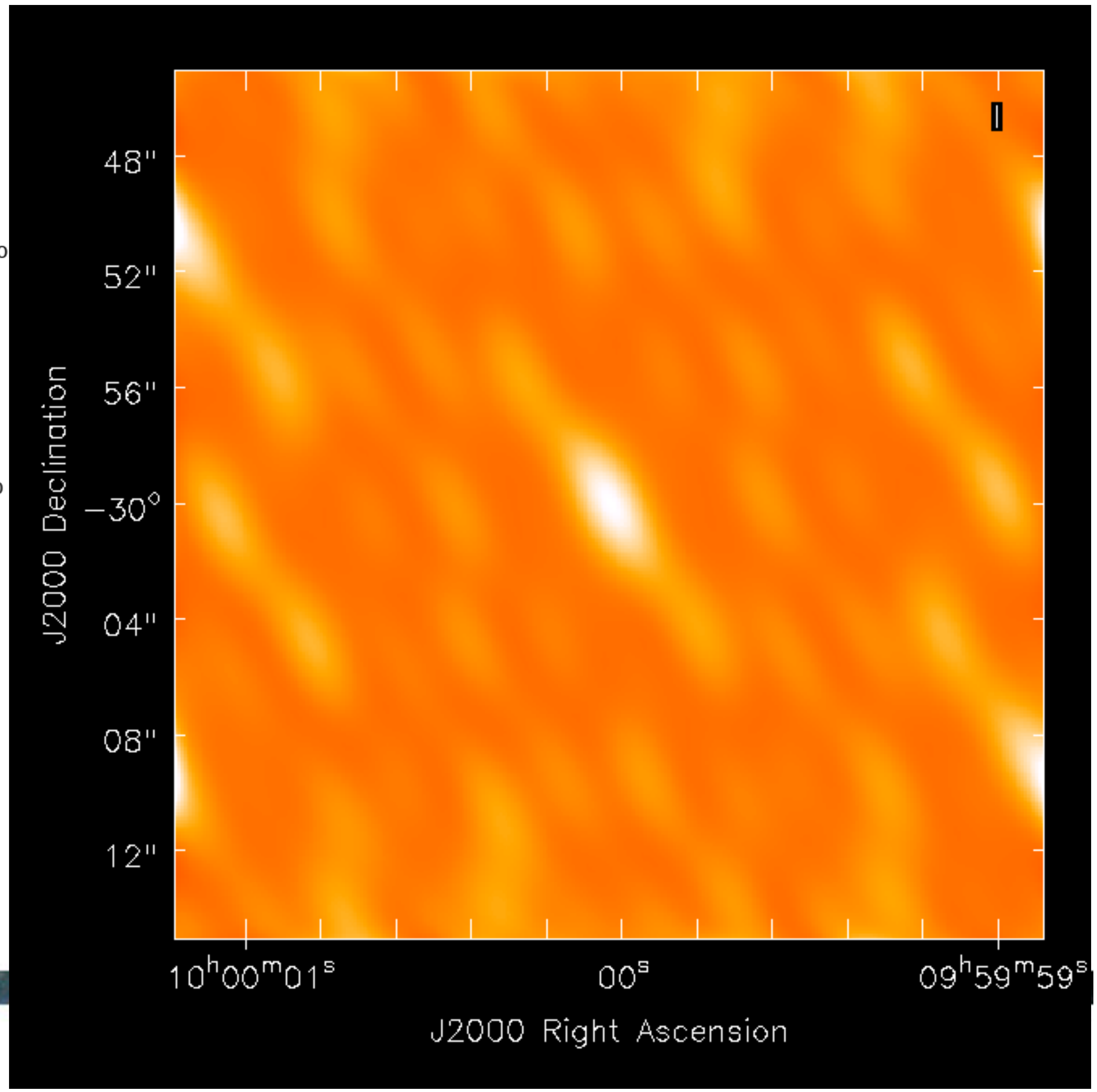




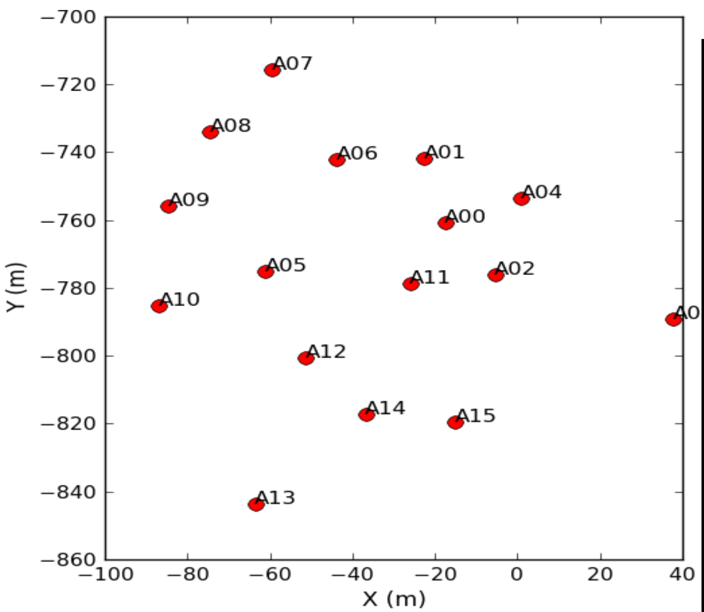
Example: Fringe pattern with 8 Antennas (28 baselines)

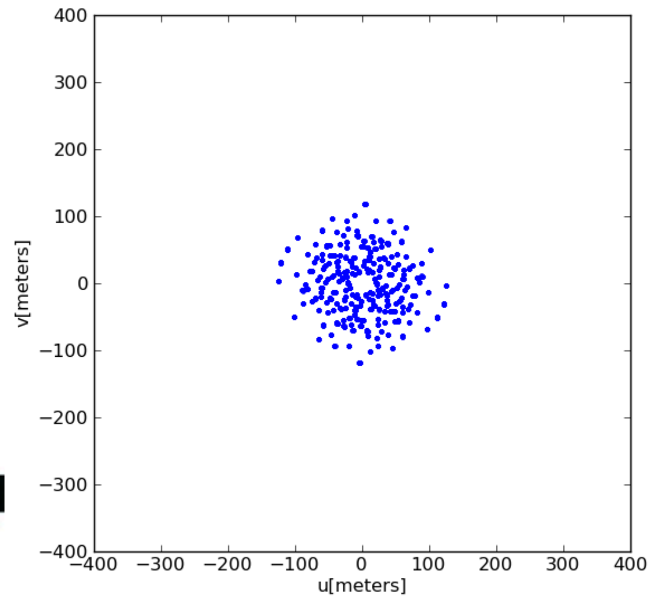


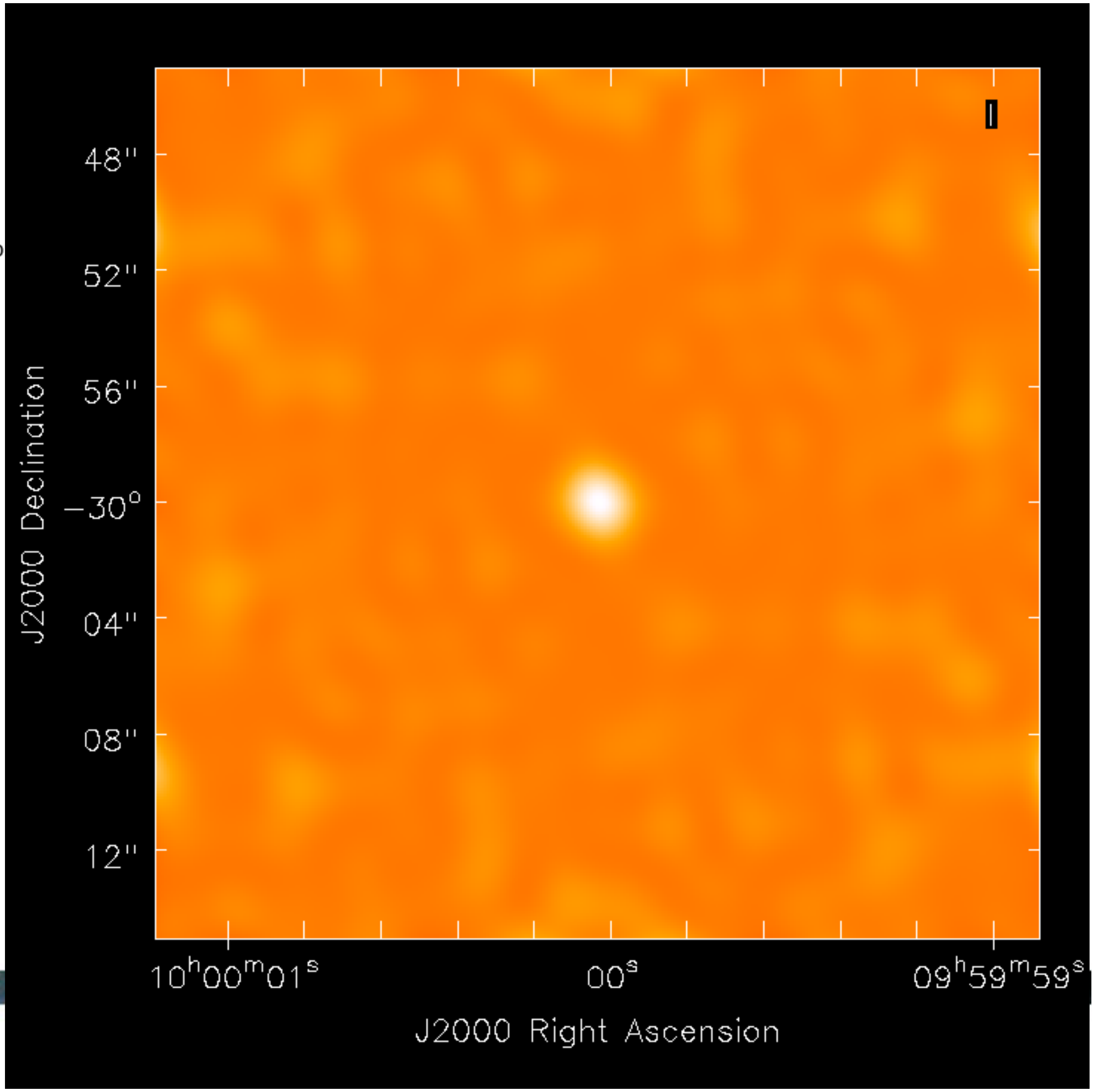




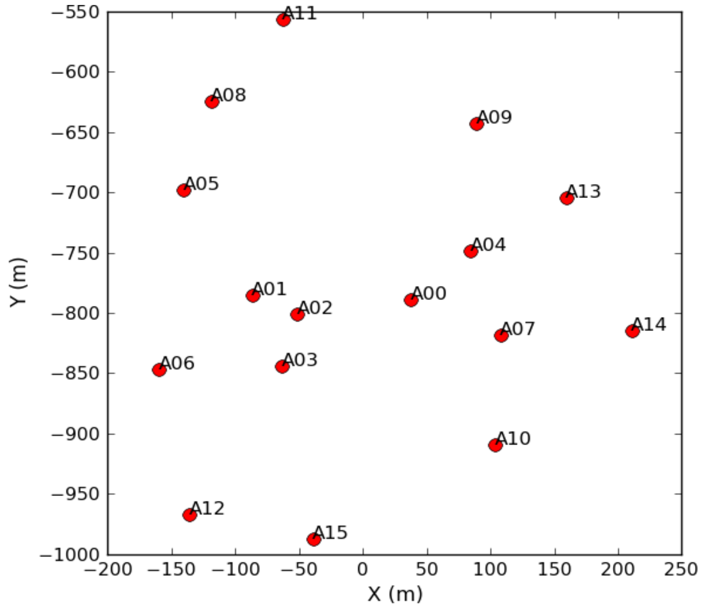
16 Antennas – Compact Configuration

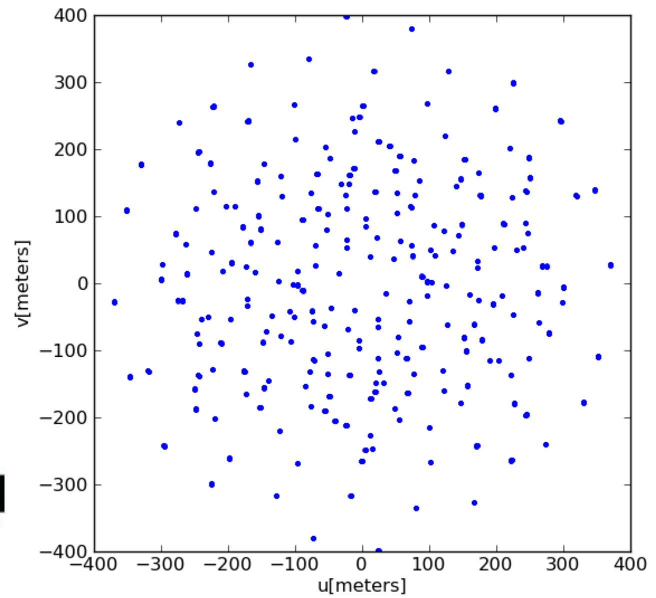


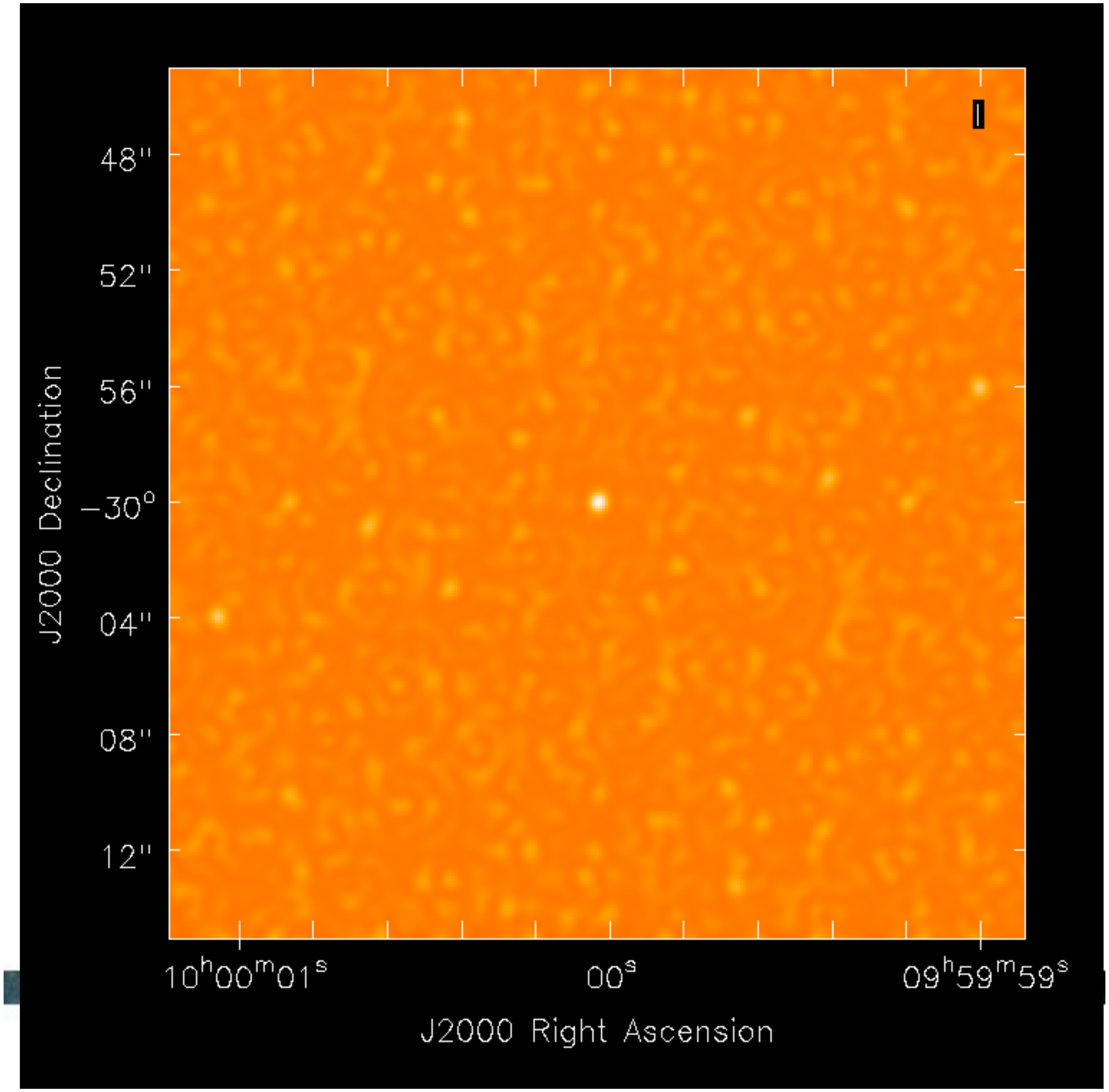




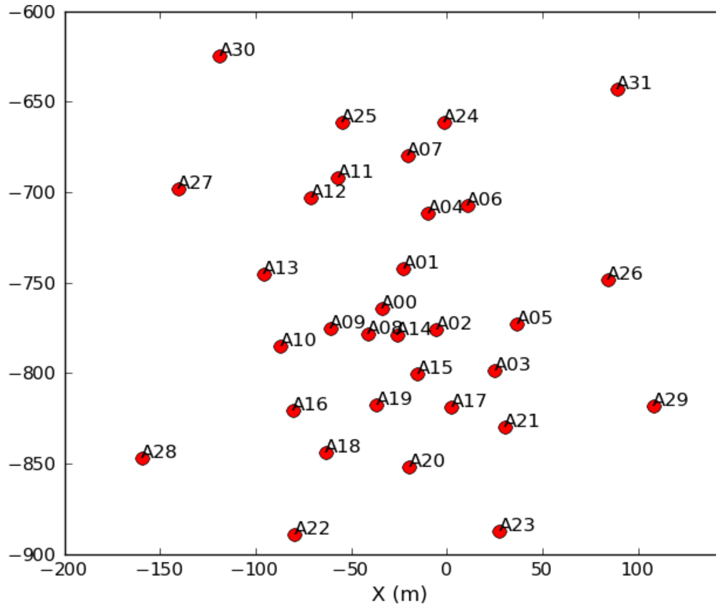
16 Antennas – Extended Configuration

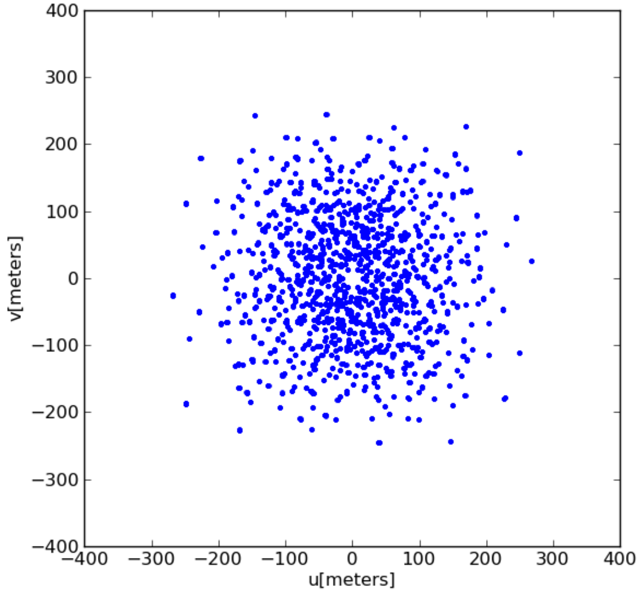


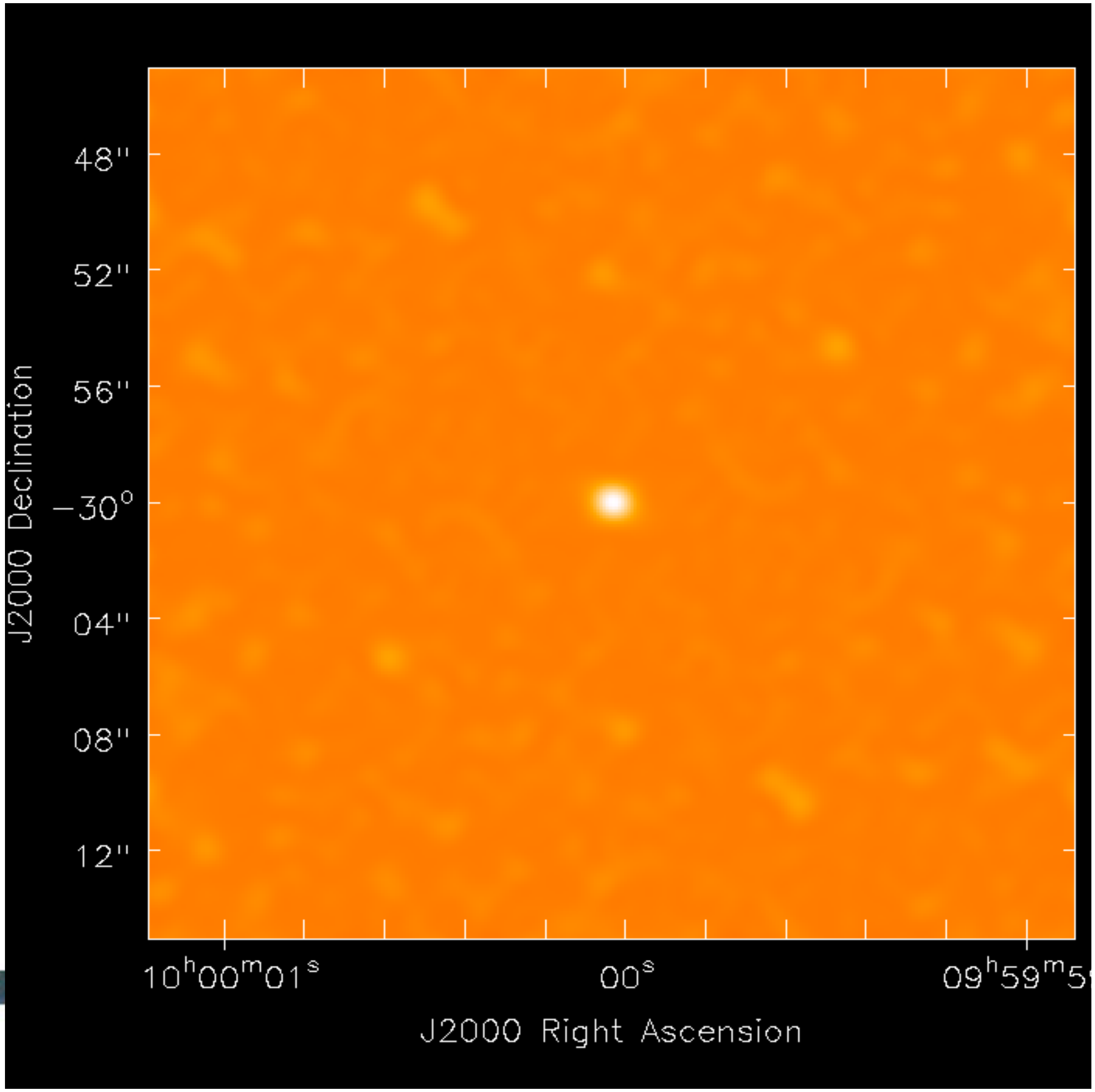




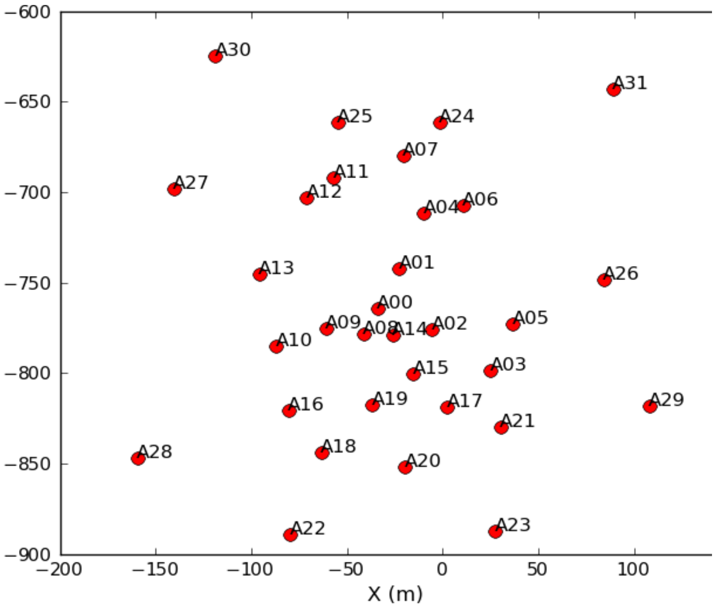
32 Antennas – Instantaneous

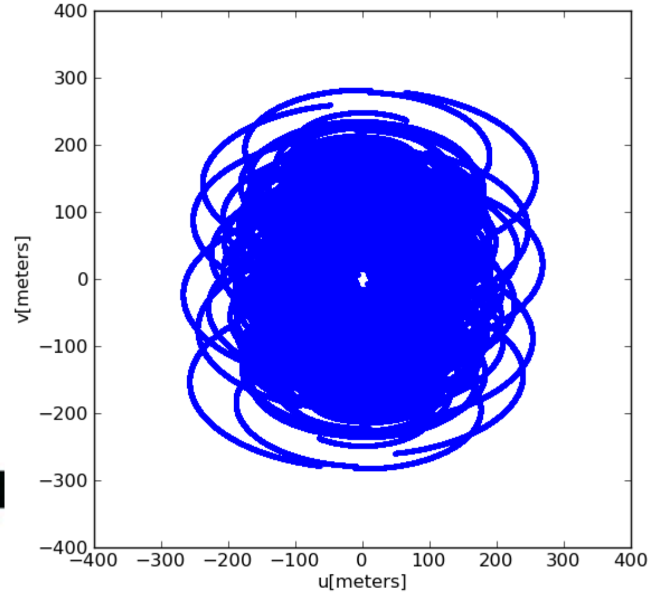


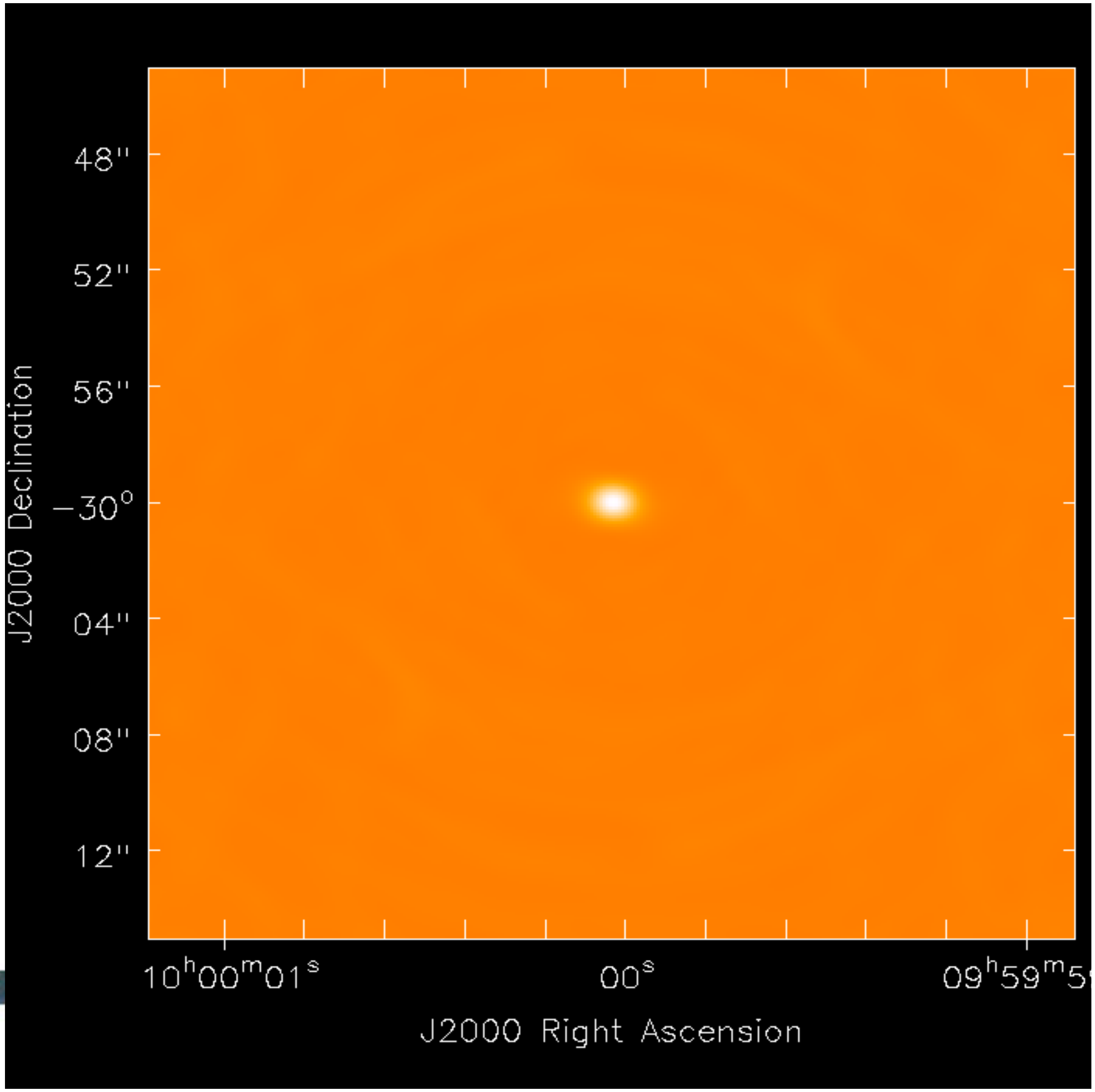




32 Antennas – 8 hours

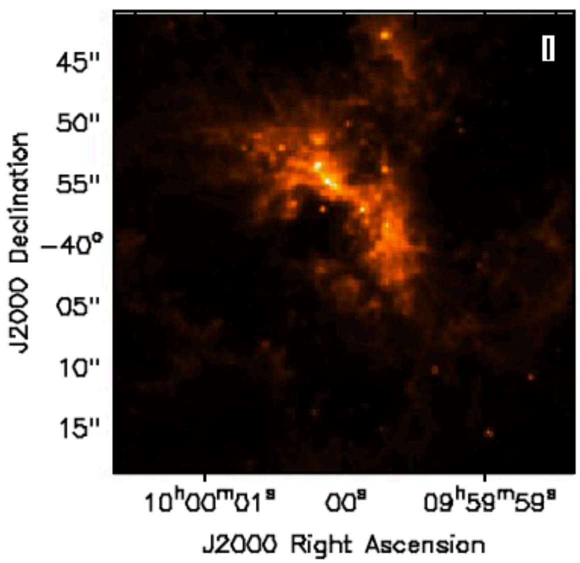




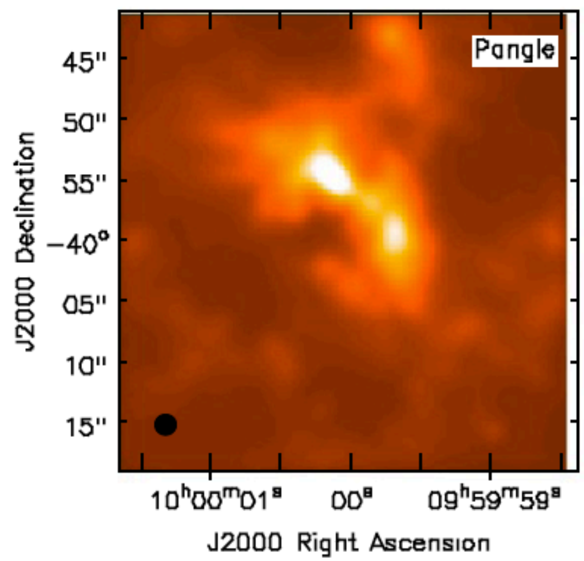


Model: Complicated image

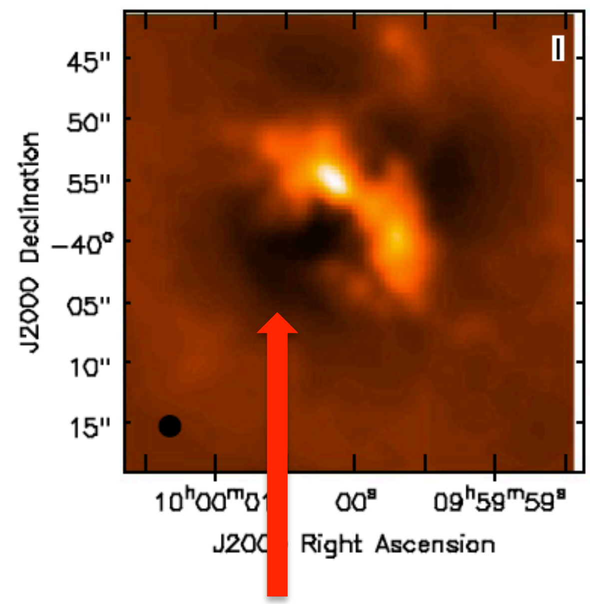
Model Image



Convolved Model



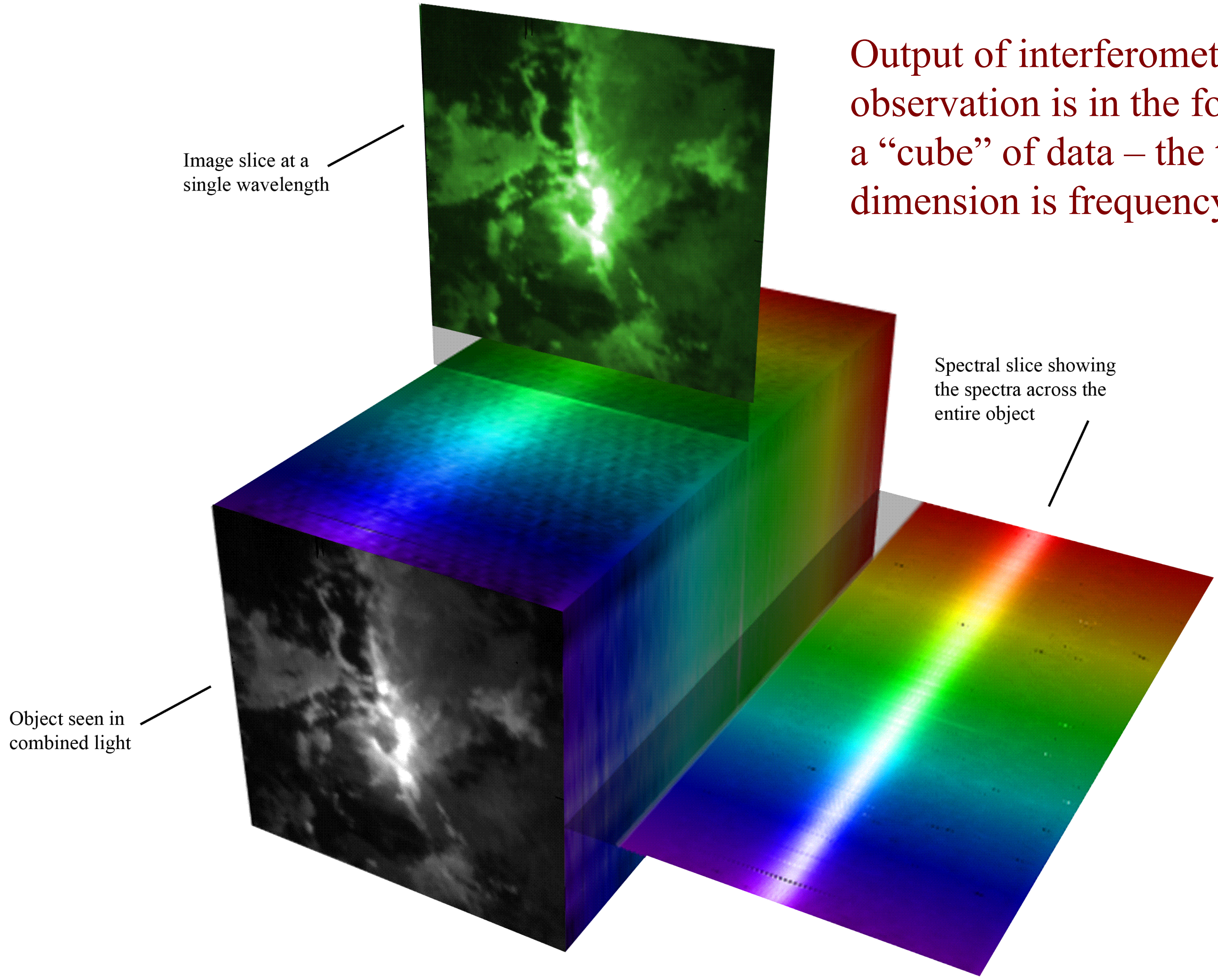
"Observed" Image



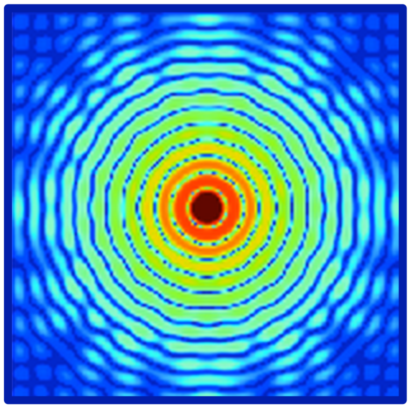
2 hour observation with 32 antennas

Large scale emission: Fill in with shorter baselines

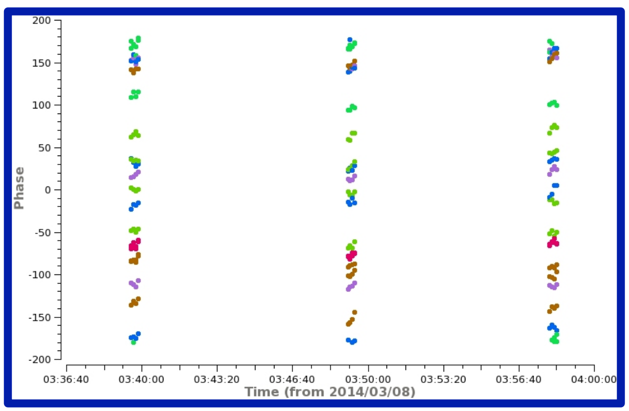
Output of interferometric observation is in the form of a "cube" of data – the third dimension is frequency.



Define what we mean by radio interferomety



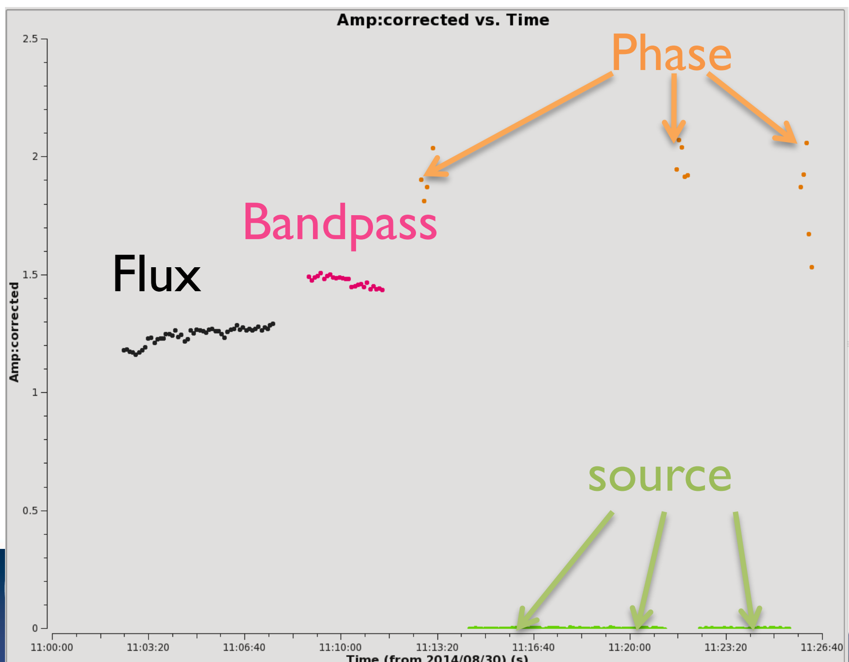
Discuss what interferometers measure

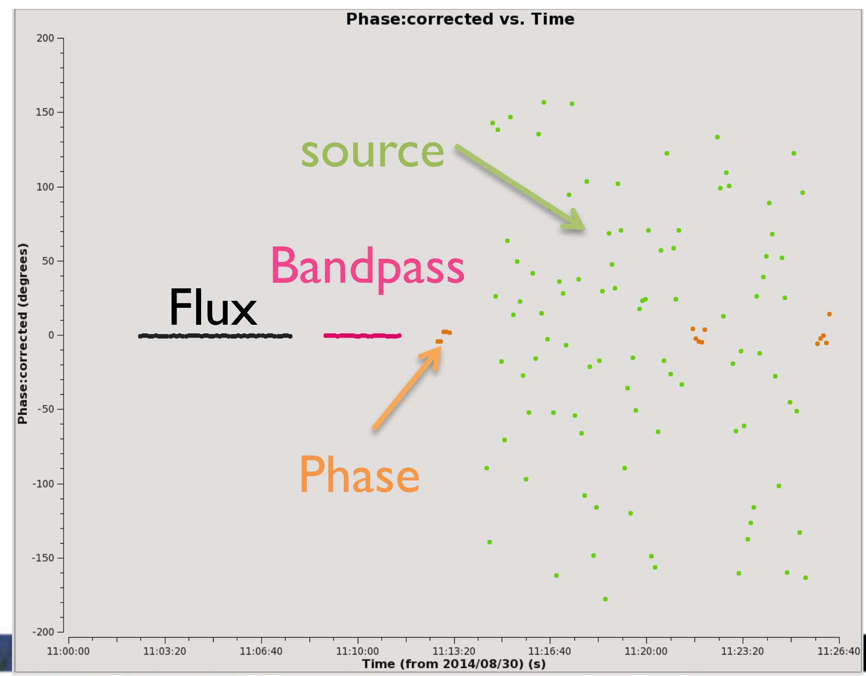


Present an overview of data calibration

How do we go from raw data to a cube?

- Interferometers measure visibilities, i.e., the amplitude and phase of the cross-correlated signals between pairs of antennas, as a function of time and frequency.
- We calibrate these data by determining the complex gains (amplitude and phase) and the frequency response (bandpass) for each antenna.





NRAO

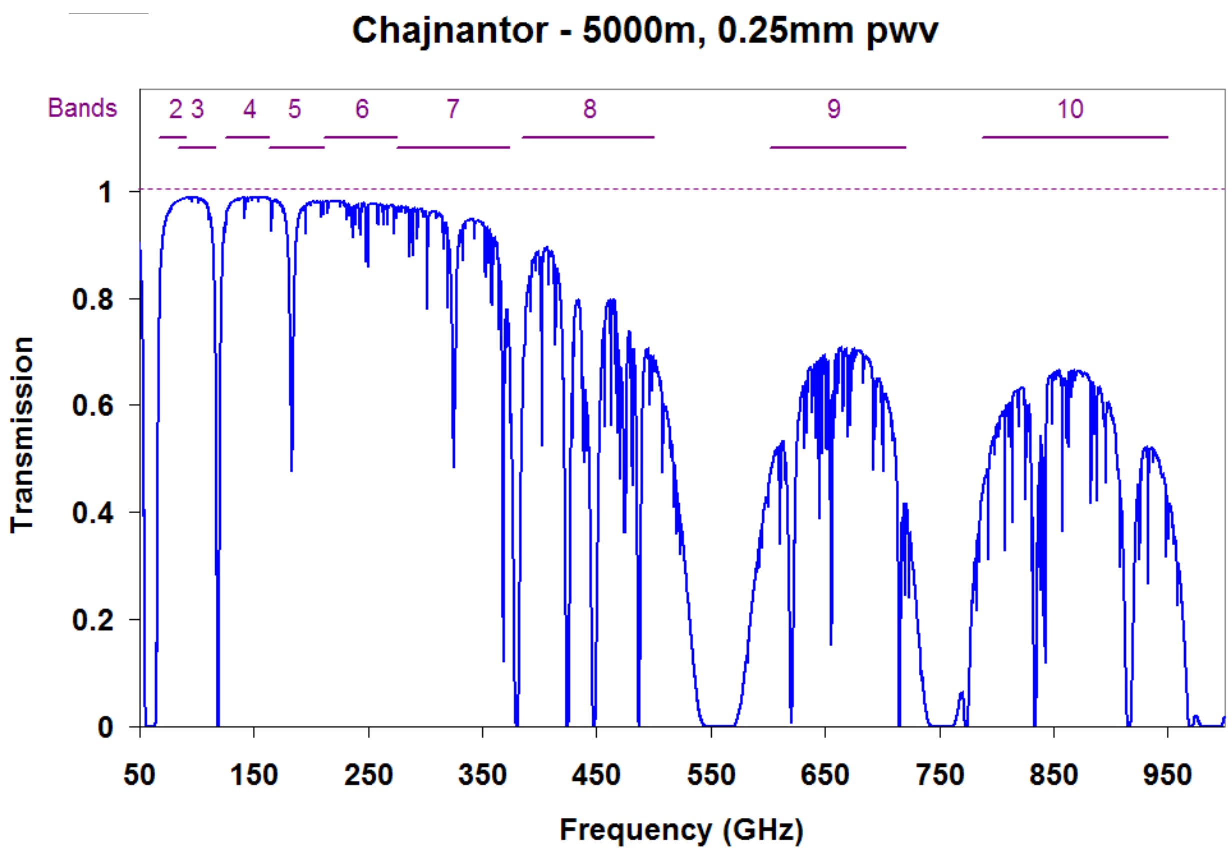
How to choose calibrators

- Bandpass calibrator
  - Corrects amplitude & phase vs. frequency
  - Choose brightest quasar in the sky
  - (Sometimes) assume that corrections are constant in time
- Amplitude calibrator
  - Sets absolute flux of all other sources in observation
  - Choose something bright, compact, and very well known
- Phase calibrator
  - Corrects amplitude and phase vs. time
  - Choose quasar that is:
    - Bright enough to get reasonable signal to noise in (a few) minutes
    - As close as possible to science target

Caveats and site considerations

- Scattered optical light does not present a problem, so usually observations can be made 24 hrs/day
- At very low frequencies (ν<300 MHz, λ>1m), signal increasingly degraded by variable ionospheric refraction
- At high frequencies (ν>300 GHz, λ<1mm), emission is absorbed by water and oxygen in the atmosphere
- In the vicinity of 1GHz, man-made interference is the largest problem
- Over much of the radio range, observations can be made in all but the worst weather.

Atmospheric Transmission in the mm/ submm wavelength range

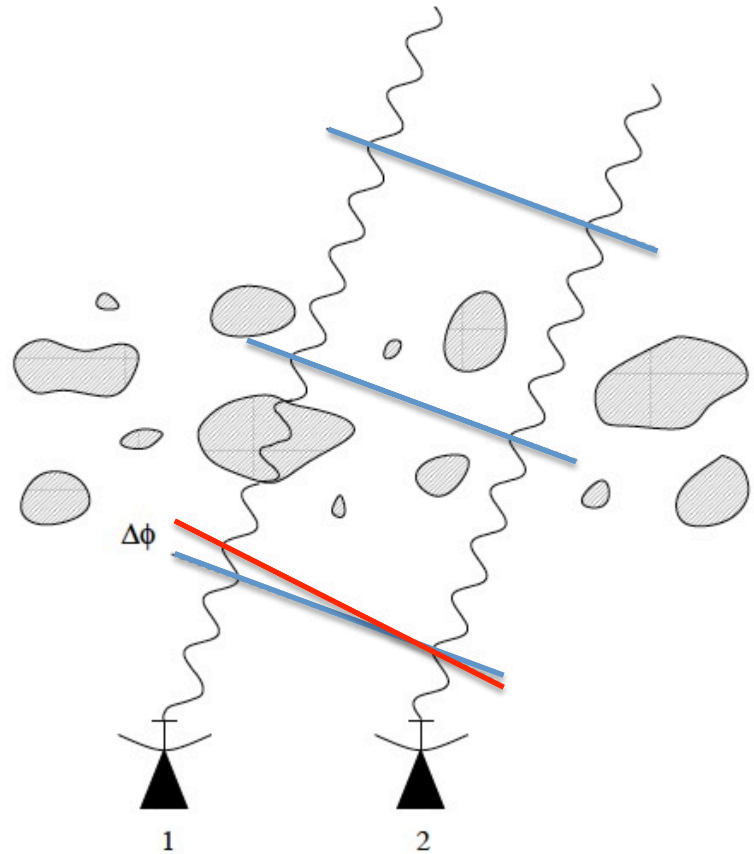


Earth's atmospheric lines block access to some spectral regions except at Earth's highest driest site. ALMA's spectral reach enables study of the Universe in all mm/submm windows for which transmission is better than 50%

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.

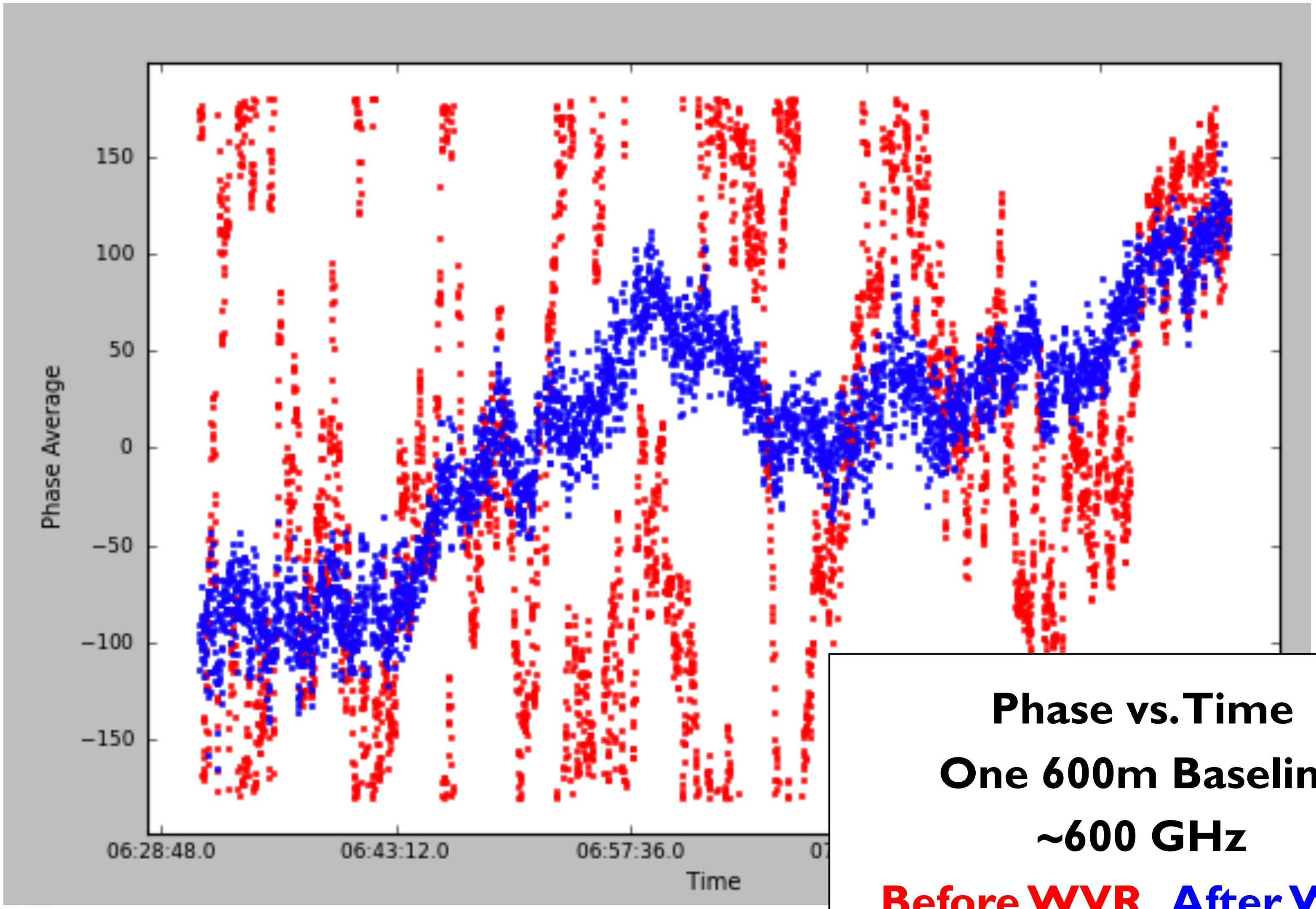


Gain (or Phase) Calibration

Determine the variations of phase and amplitude with time

- At high frequencies, water creates the most phase fluctuation. We can use water vapor radiometers to measure the amount of water and convert that to estimated phase
- Then we observe a point source near the science target and measure the changes with time. We use this to derive a model to correct the science target. Most important quality of a gain calibrator is proximity to science target

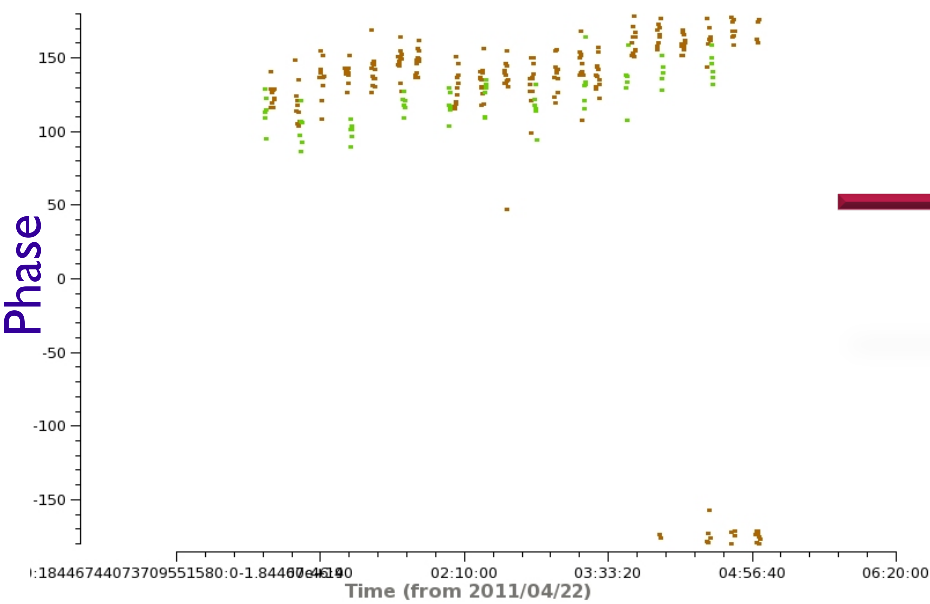
Water Vapor Correction on ALMA

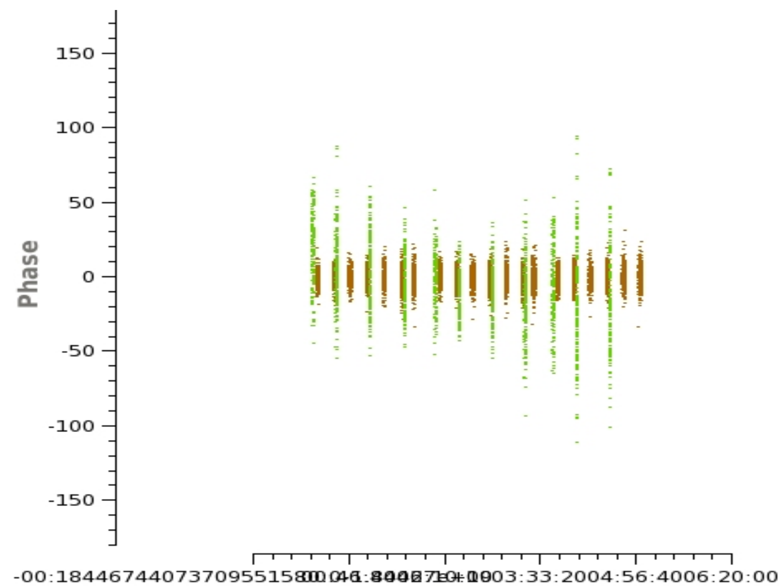


Phase vs. Time
One 600m Baseline
~600 GHz
Before WVR, After WVR

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.

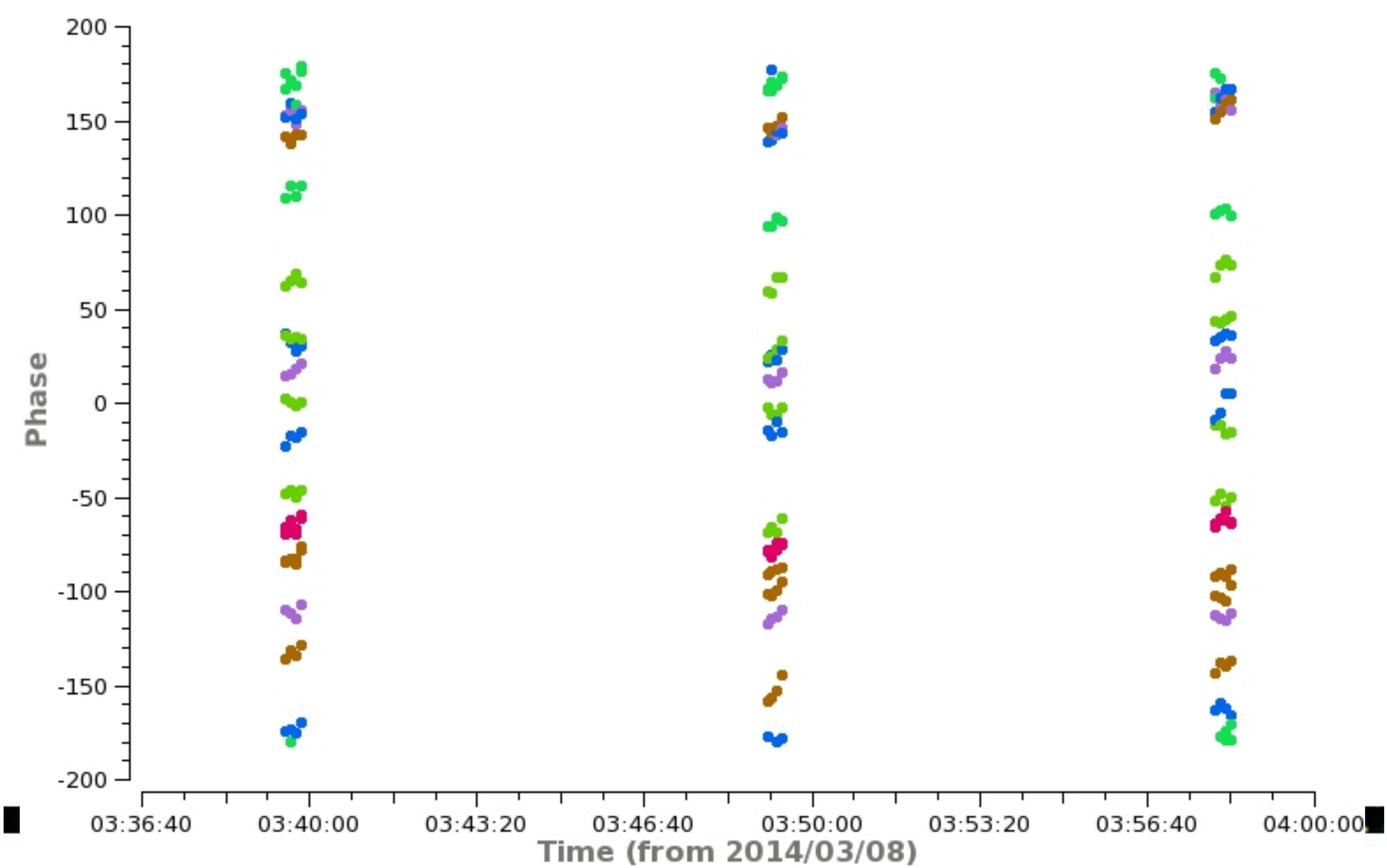




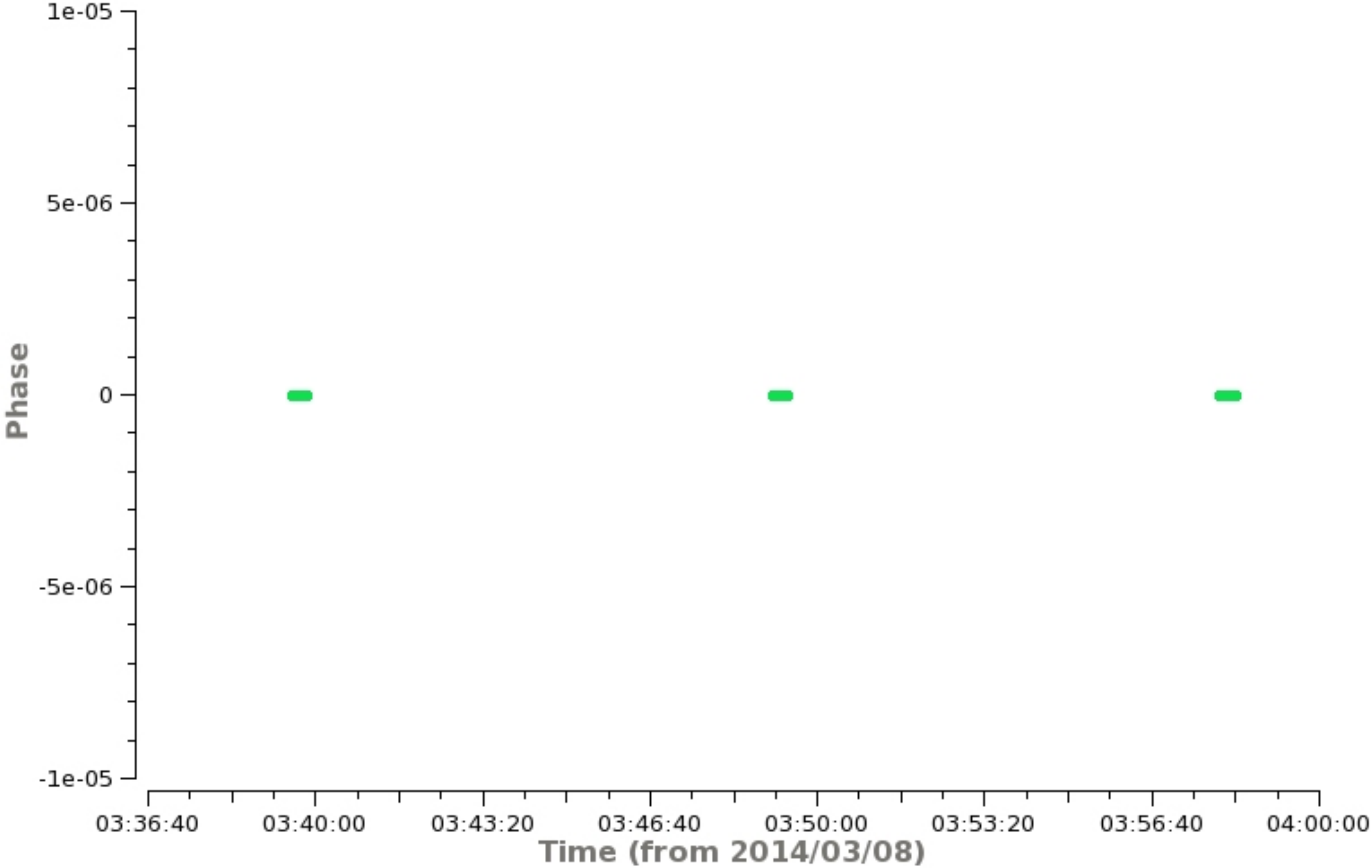
Time

Corrected using point source model

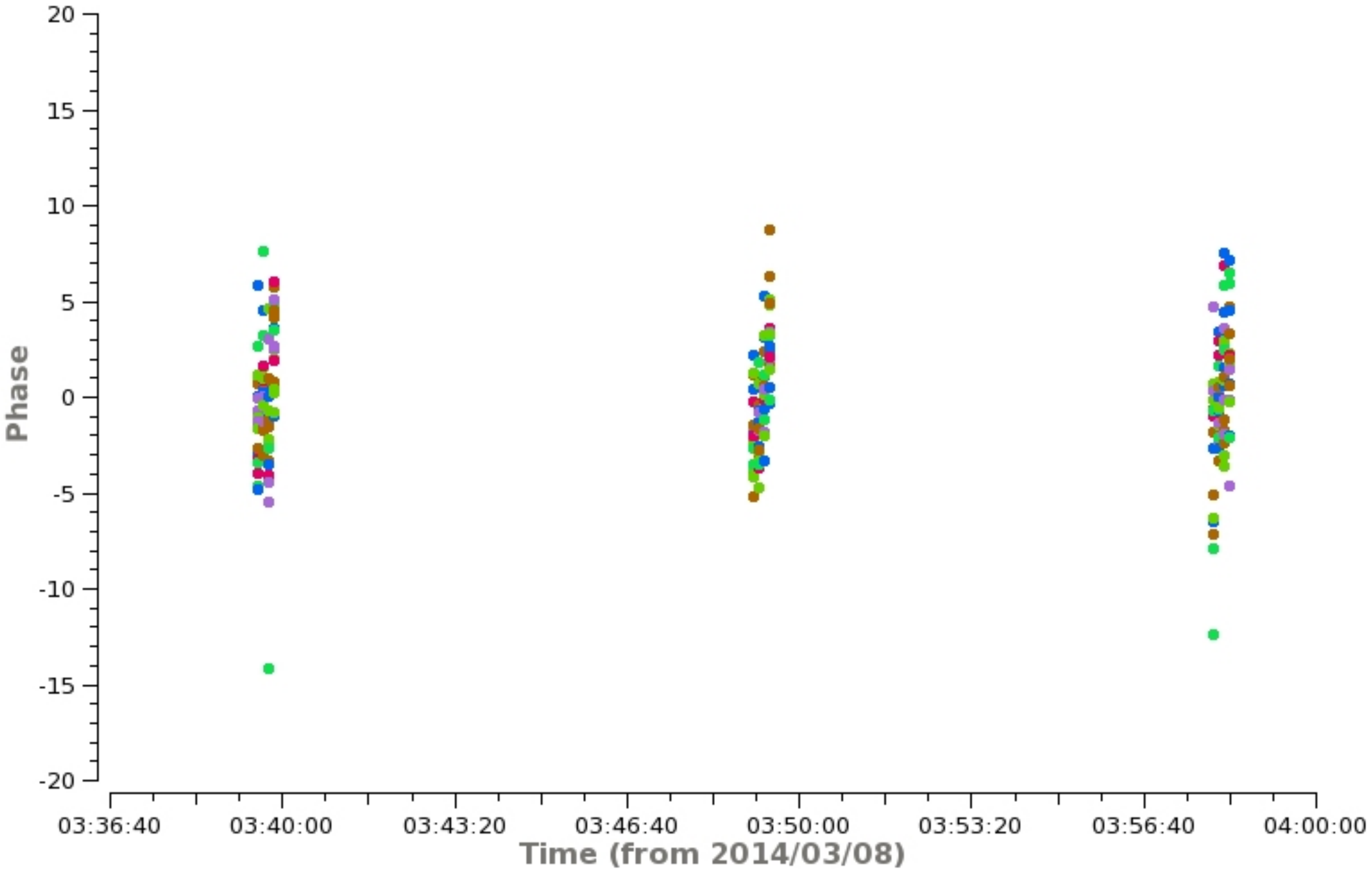
Phasecal Phase vs. Time (Before)



Phasecal Phase vs. Time (Model)



Phasecal Phase vs. Time (After)



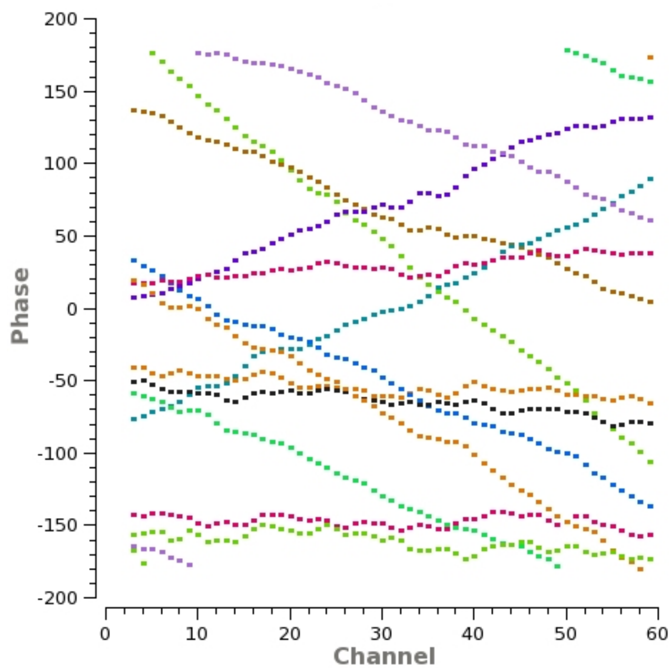
Bandpass Calibration

- Receiver response and changes in elevation or weather conditions can result in variations in bandpass. These can appear in both phase and amplitude. To correct them, you need to observe a point source with high signal to noise ratio. This is particularly important if you are observing weak spectral lines.

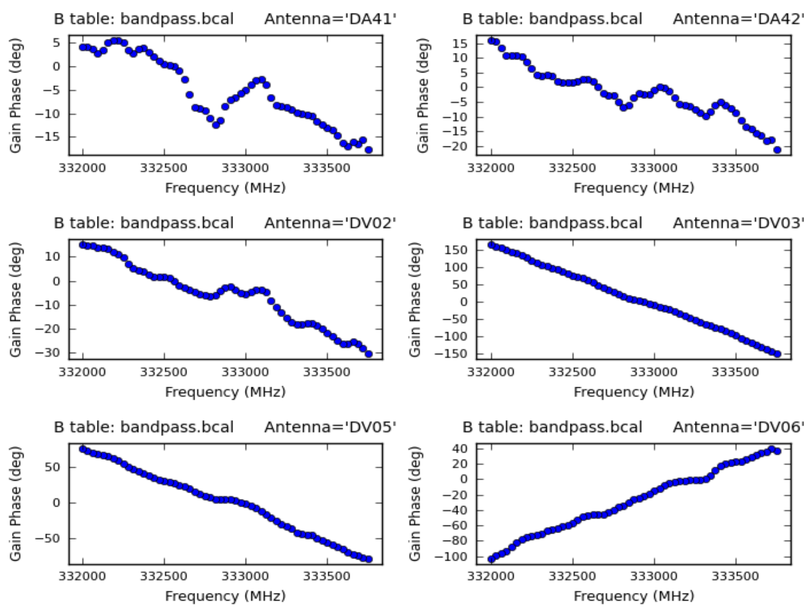
Bandpass Calibration: Phase

The bandpass is measured using baselines, but the corrections are usually made for each antenna.

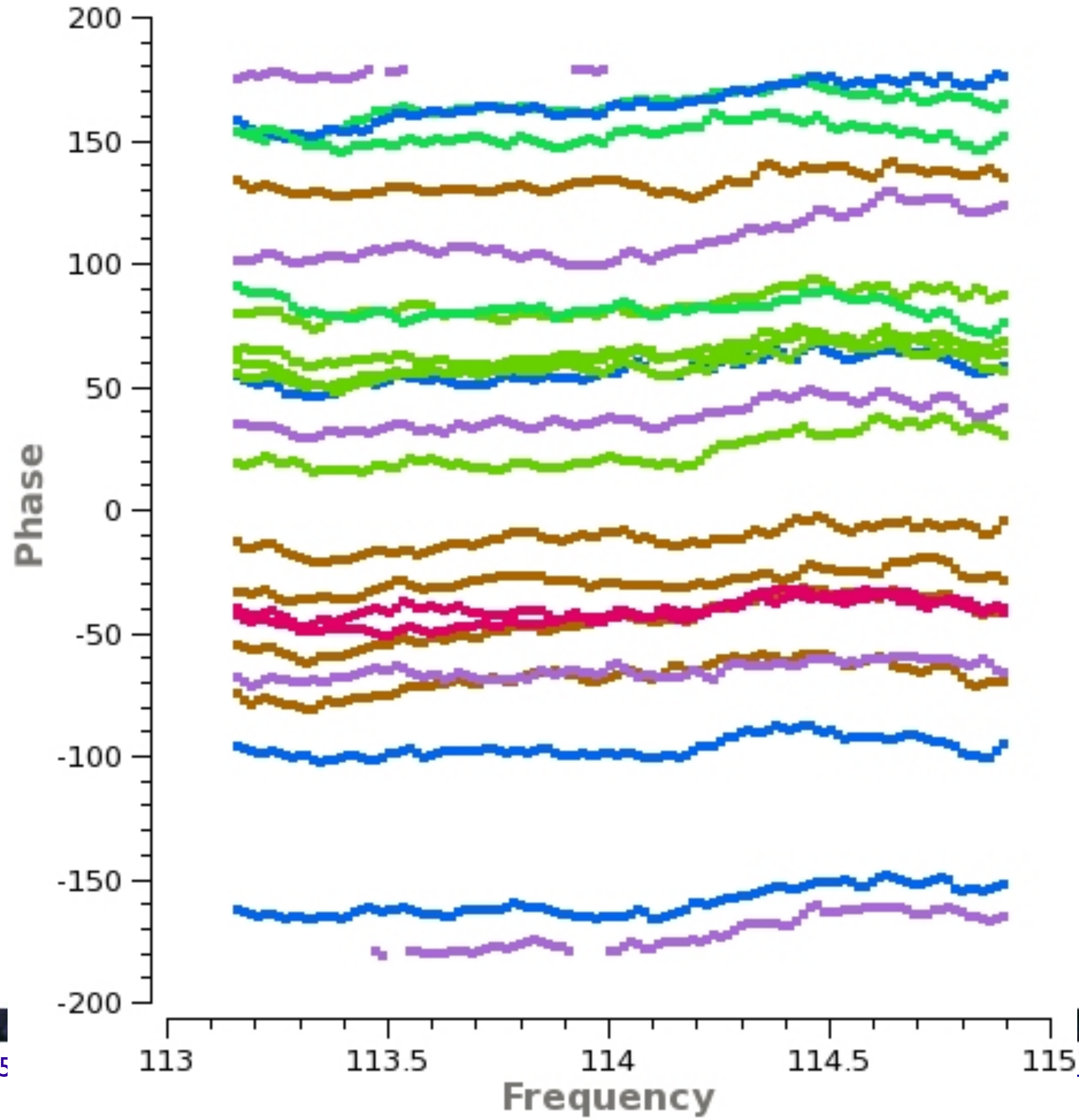
Baselines to one antenna



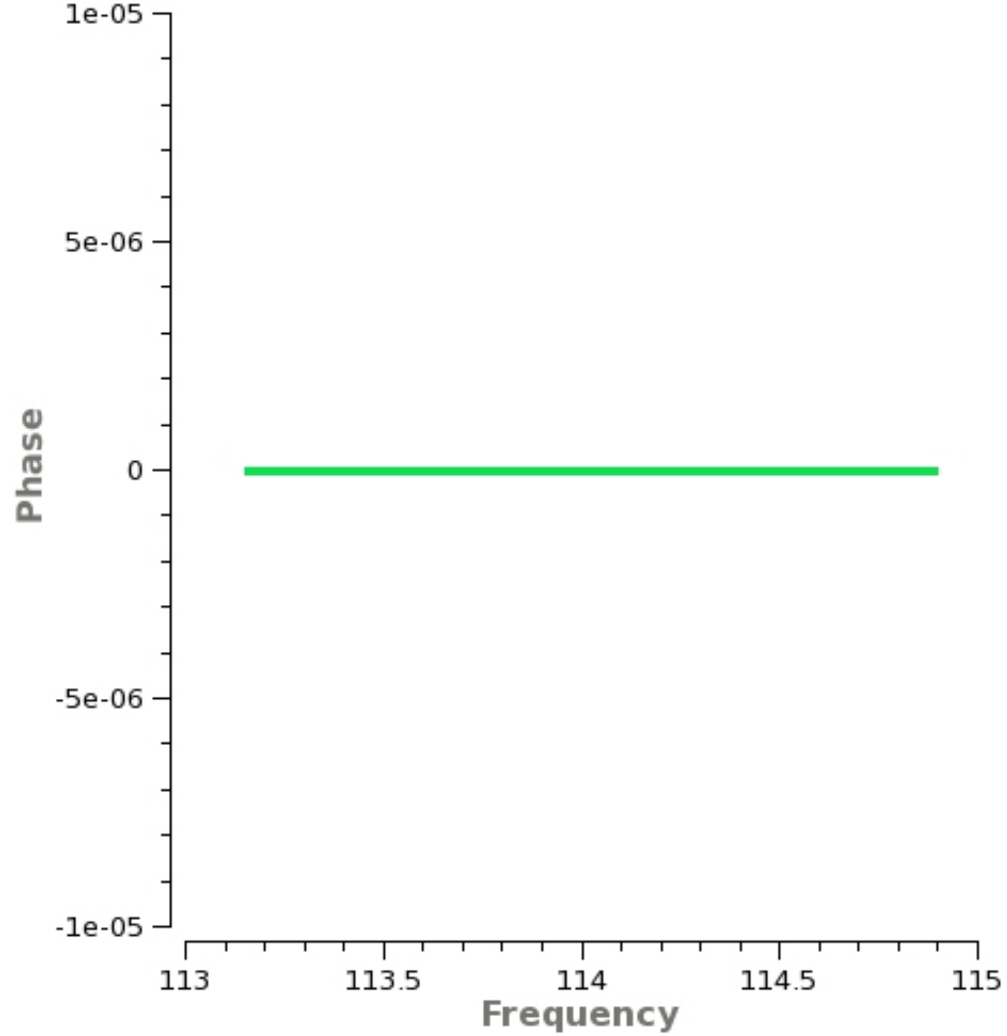
Antenna-based Bandpass Solutions



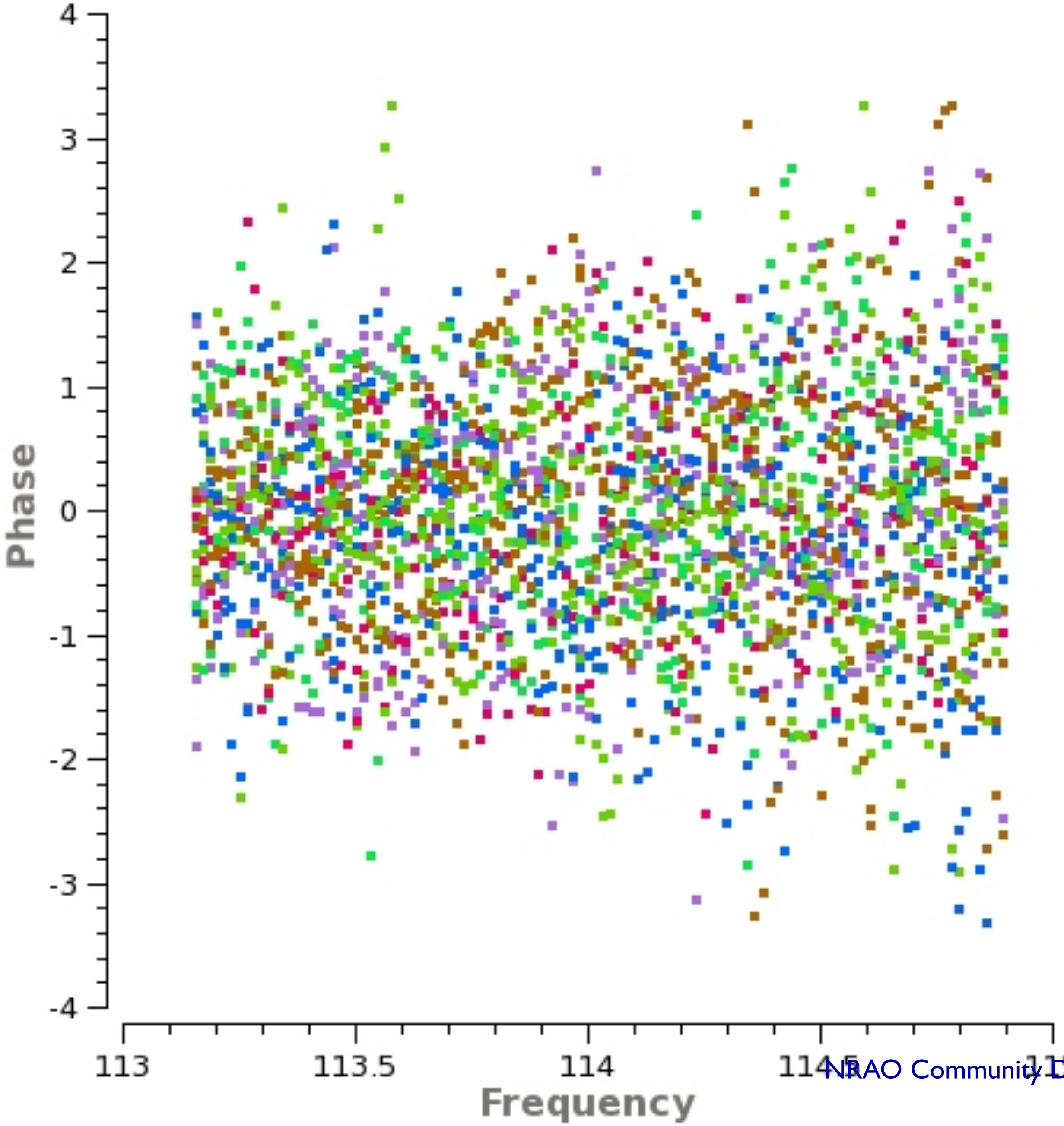
Bandpass Phase vs. Frequency (Before)



Bandpass Phase vs. Frequency (Model)

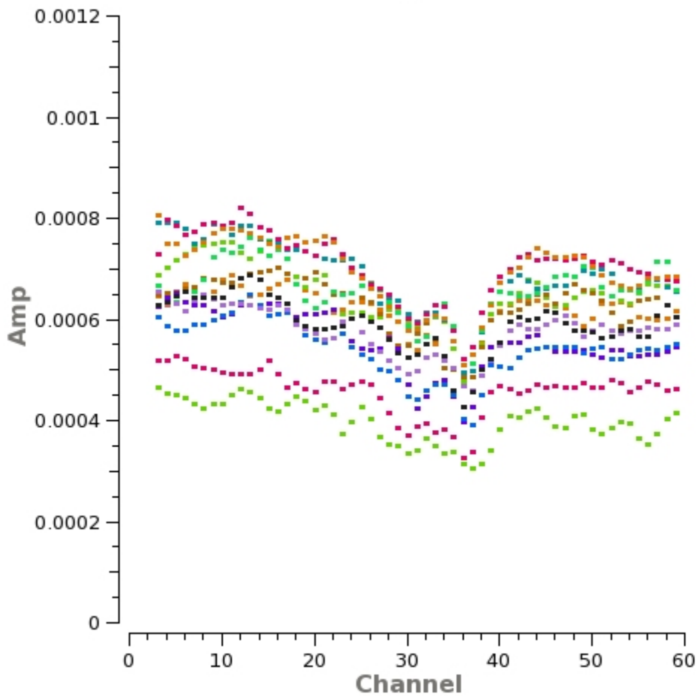


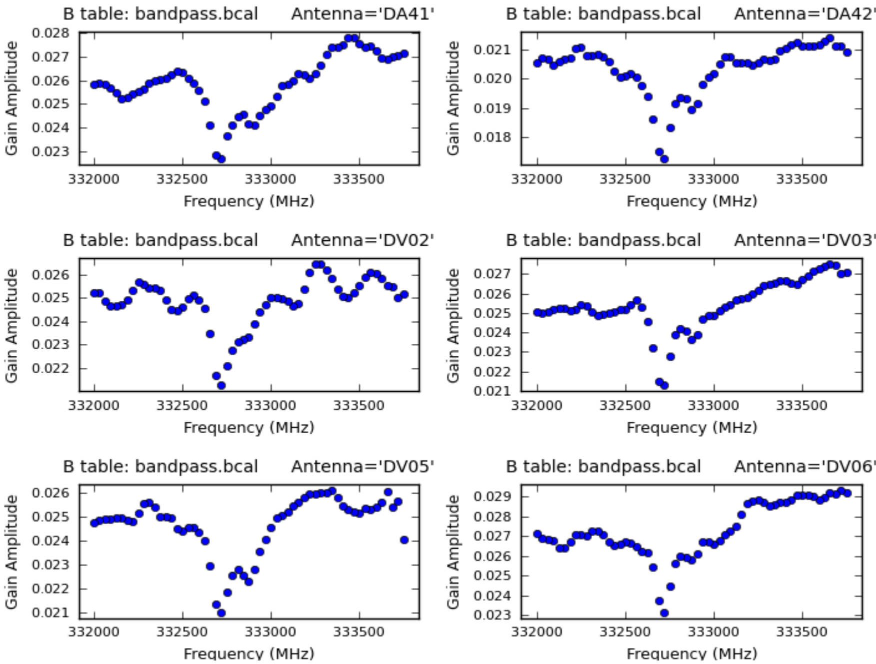
Bandpass Phase vs. Frequency (After)



Bandpass Calibration: Amplitude

Baselines to one antenna





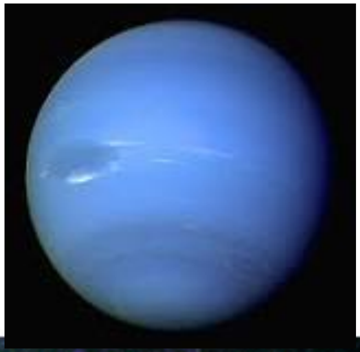
Amplitude Before Bandpass Calibration

Antenna-based Bandpass Solution

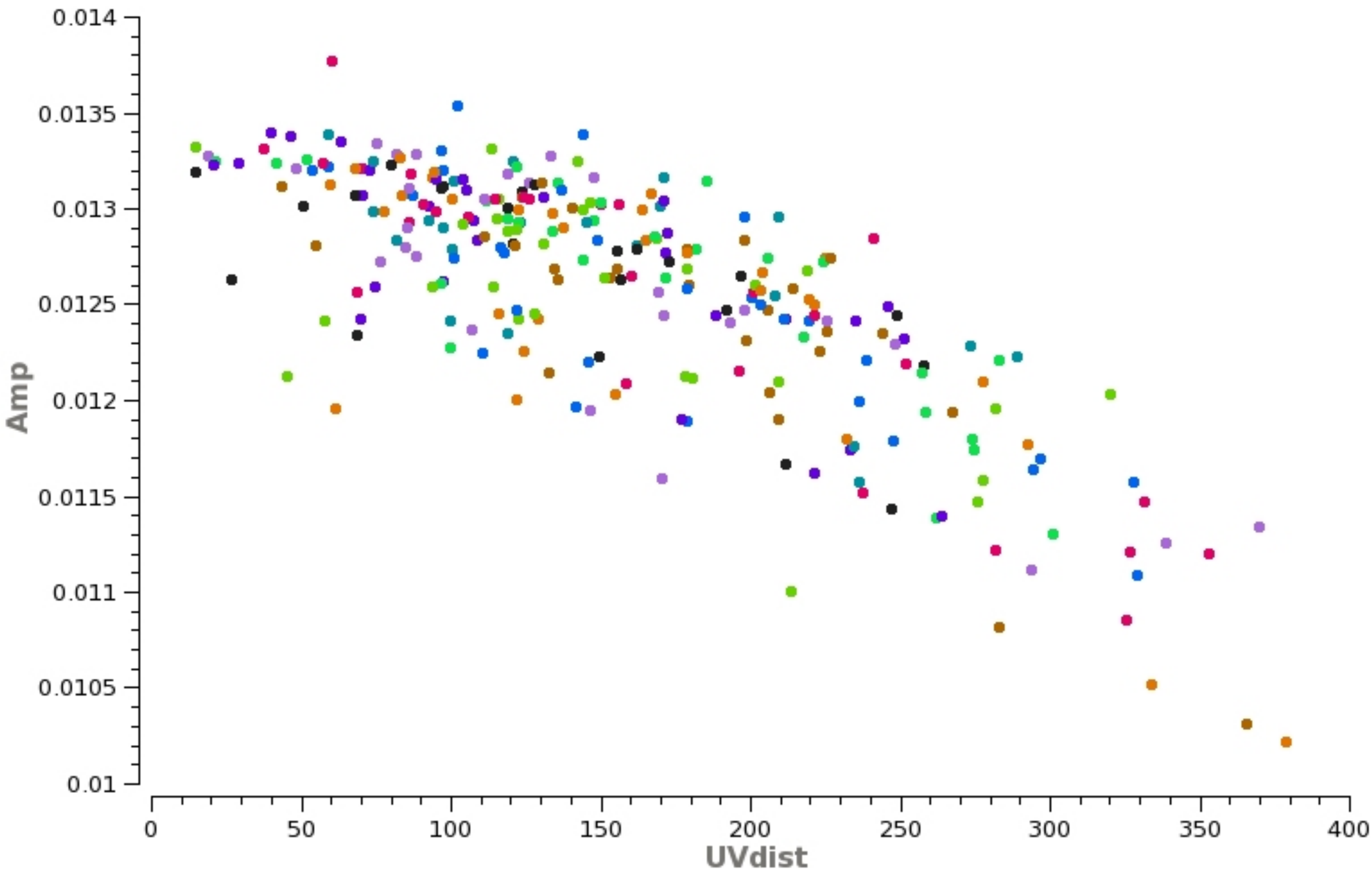
Flux (or Amplitude) Calibration

Two Steps:

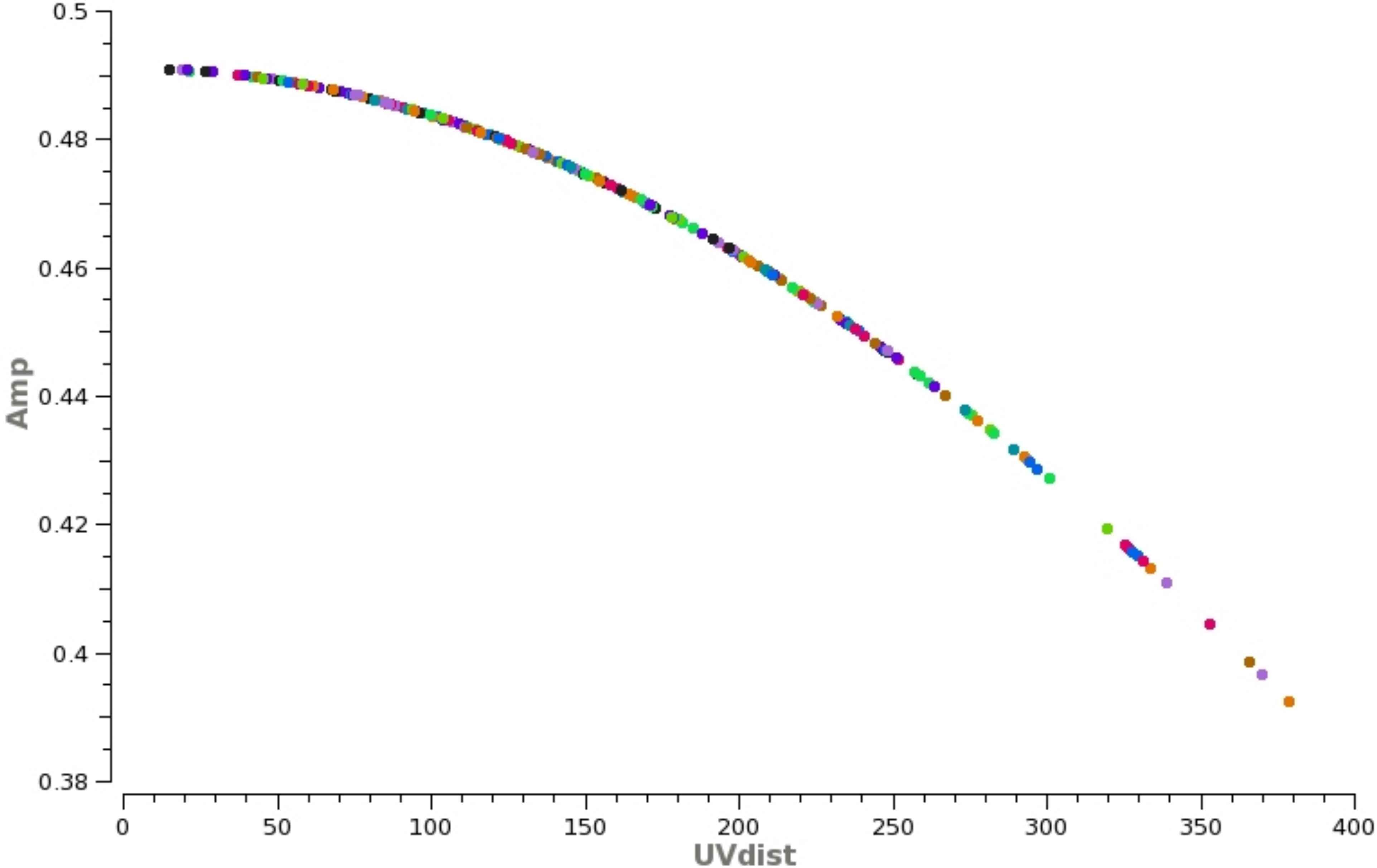
- Use calibration devices of known temperature (hotload and ambient load) to measure System Temperature frequently.
- Use a source of known flux to convert the signal measured at the antenna to common unit (Janskys). If the source is resolved, or has spectral lines, it must be very well modeled.
- The derived amplitude vs. time corrections for the flux calibrator are applied to the science target.



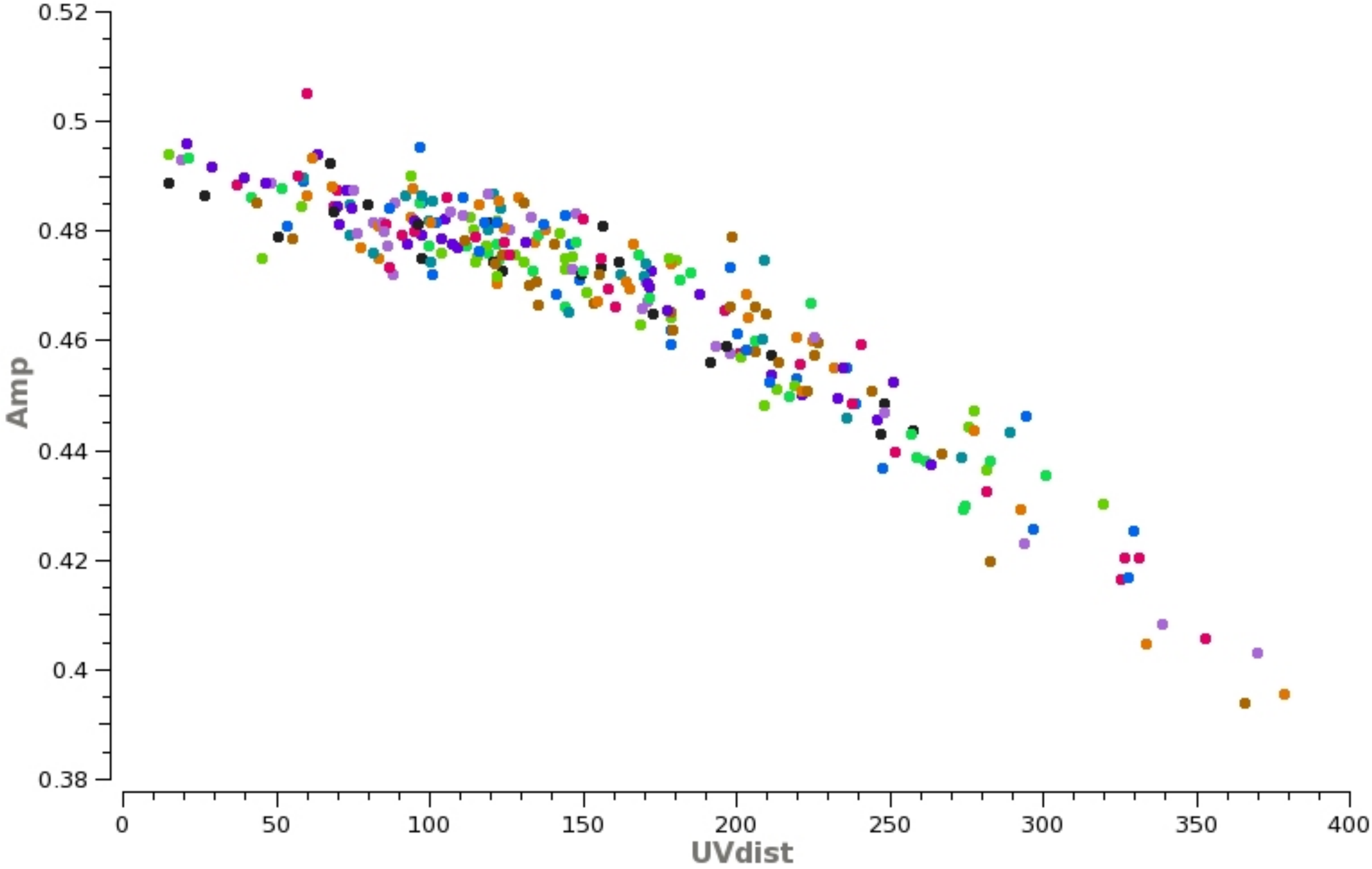
Ampcal Amplitude vs. uv-distance (Before)



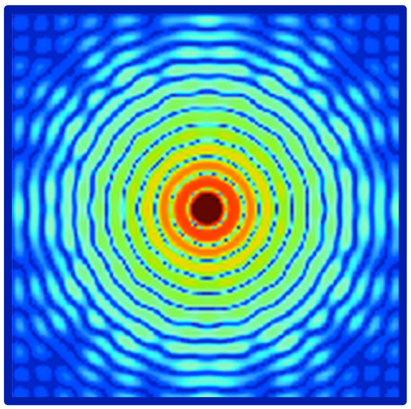
Ampcal Amplitude vs. uv-distance (Model)



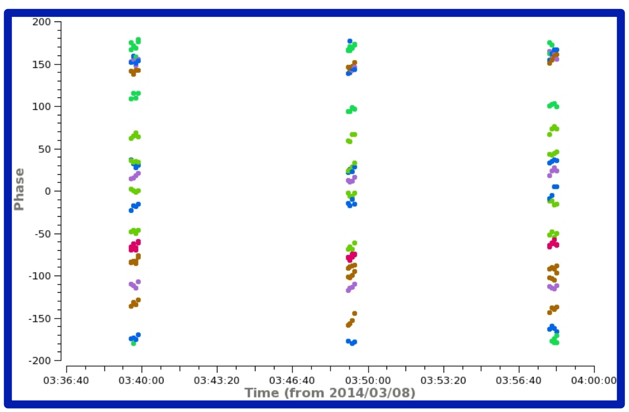
Ampcal Amplitude vs. uv-distance (After)



Define what we mean by radio interferometry



Discuss what interferometers measure



Present an overview of data calibration

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

- Virtual Radio Interferometer
  http://www.narrabri.atnf.csiro.au/astronomy/vri.html

For more info:

http://www.almaobservatory.org

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