

Introduction to Radio Interferometry



**Alison Peck, Jim Braatz, Ashley Bemis
(NRAO)**

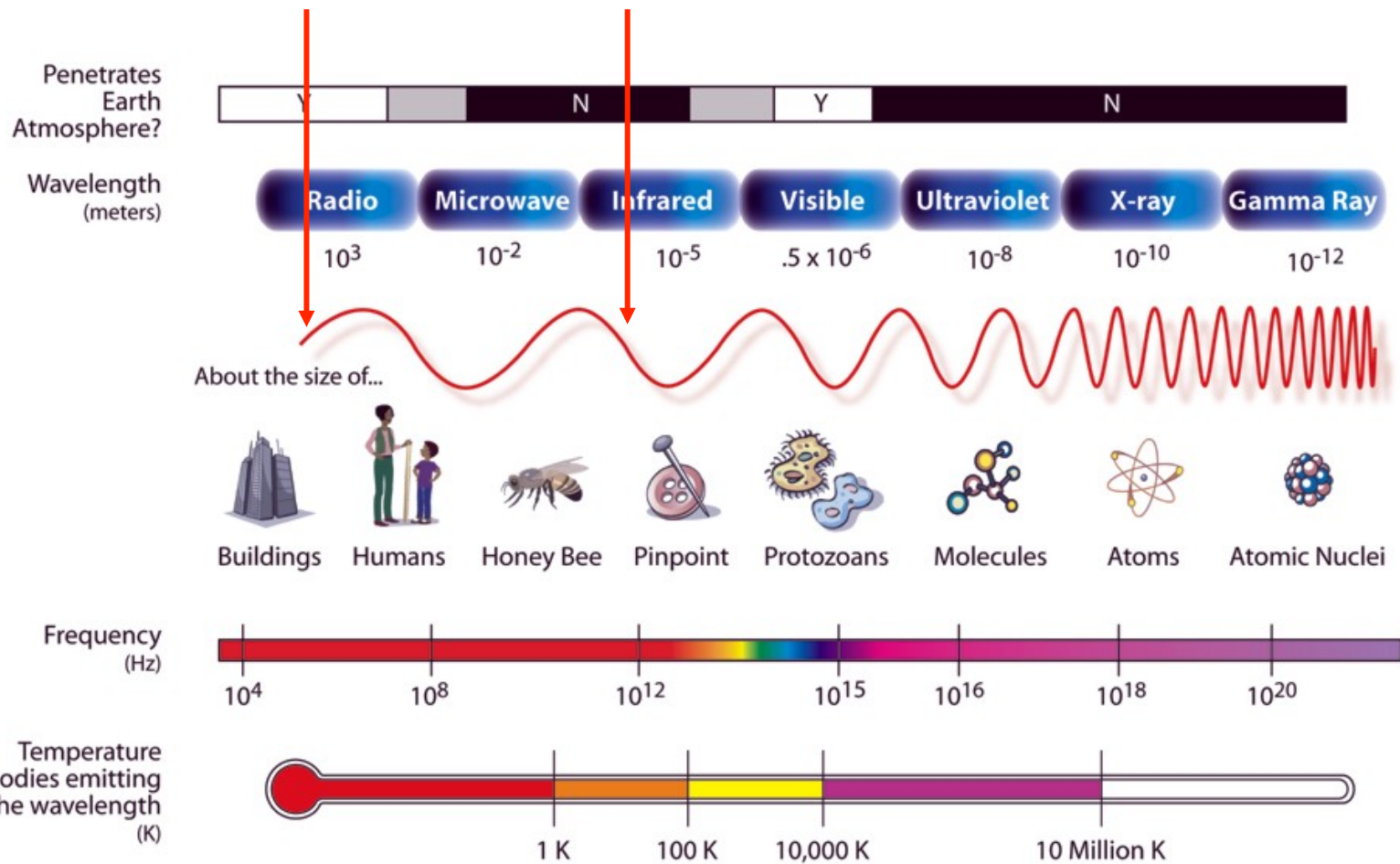
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array



Radio Astronomy

Now used to refer to most telescopes using heterodyne technology

THE ELECTROMAGNETIC SPECTRUM



What is heterodyne?

Technique 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.

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

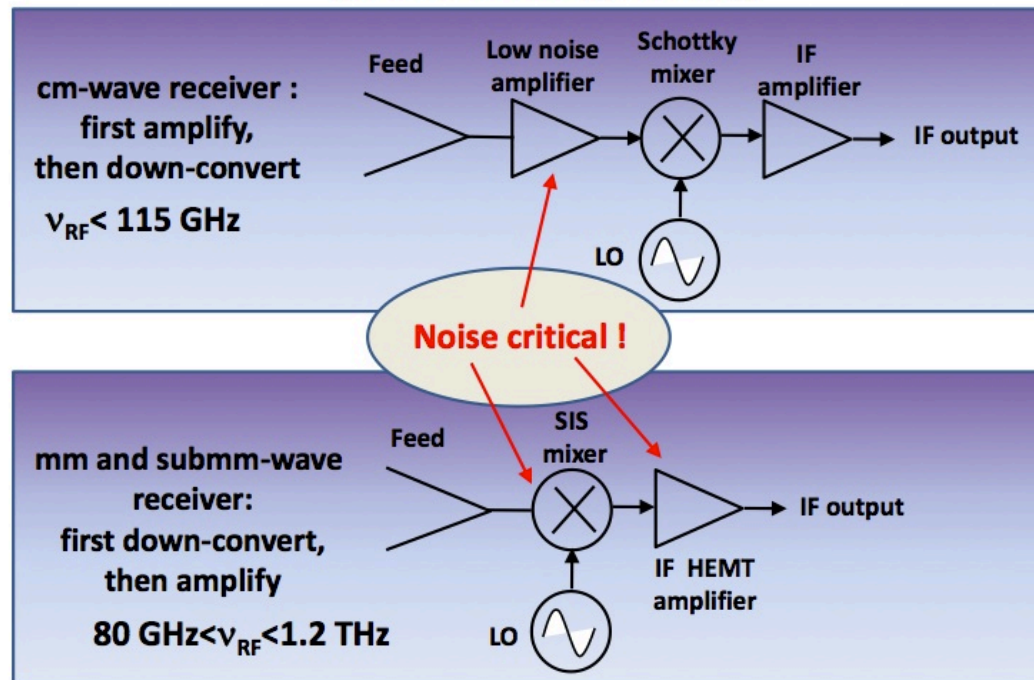


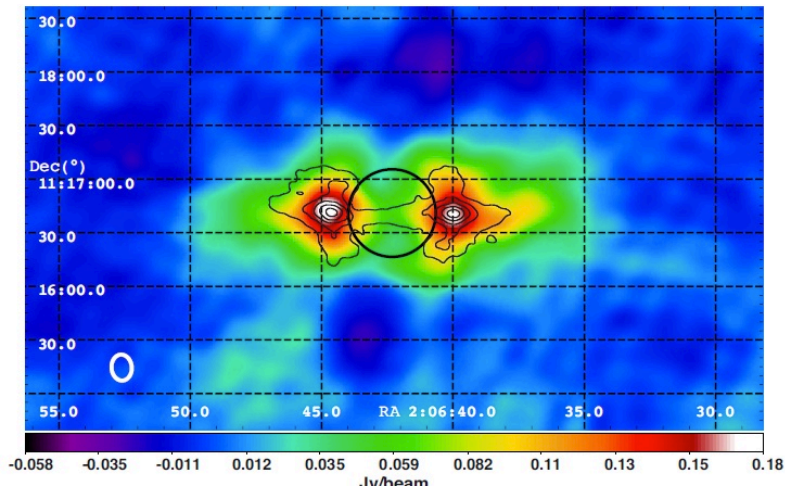
Image from Alessandro Navarrini (IRAM)

Long wavelength means no glass mirrors



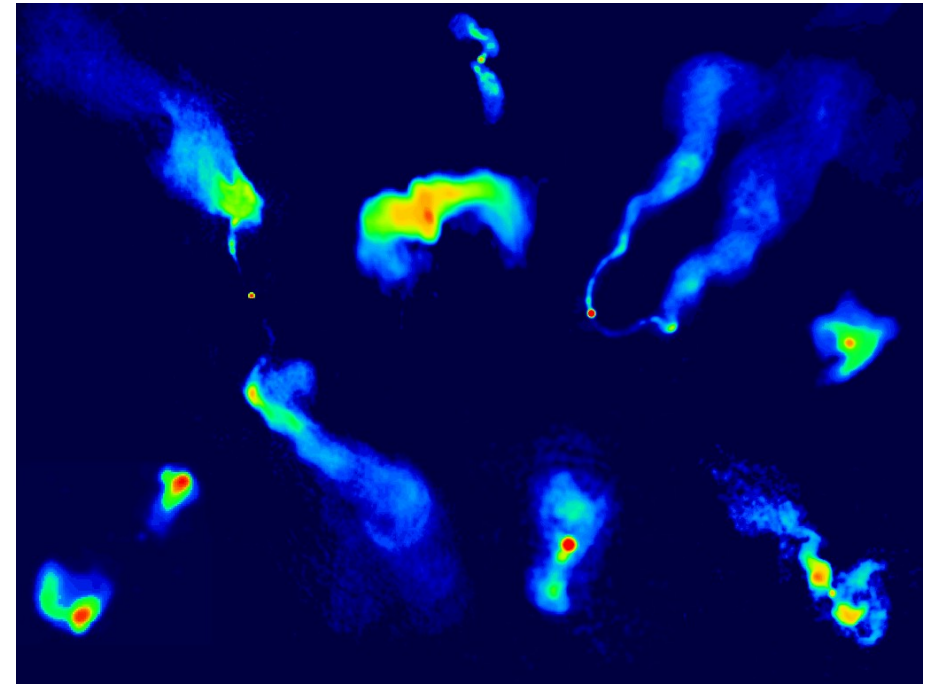
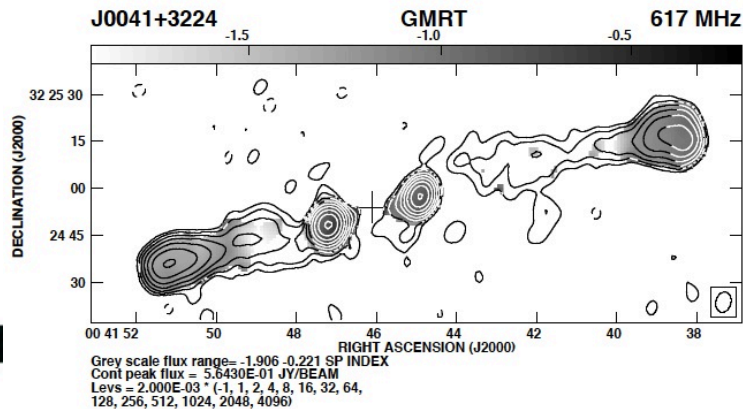
What should we observe?

At low frequencies (MHz-GHz):



Jupiter's radiation belt at 100MHz

Relic emission from old radio galaxies



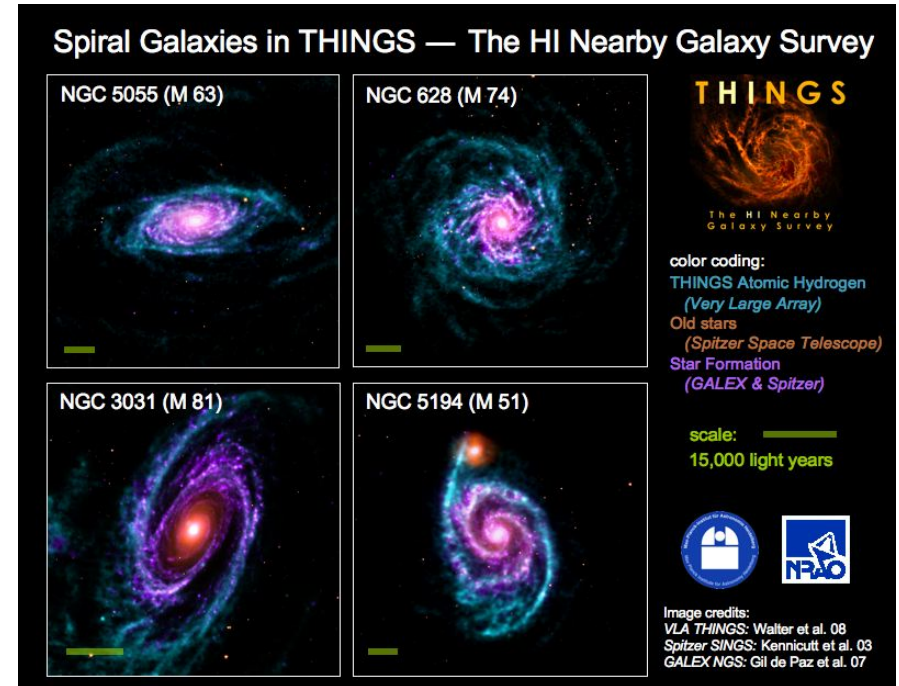
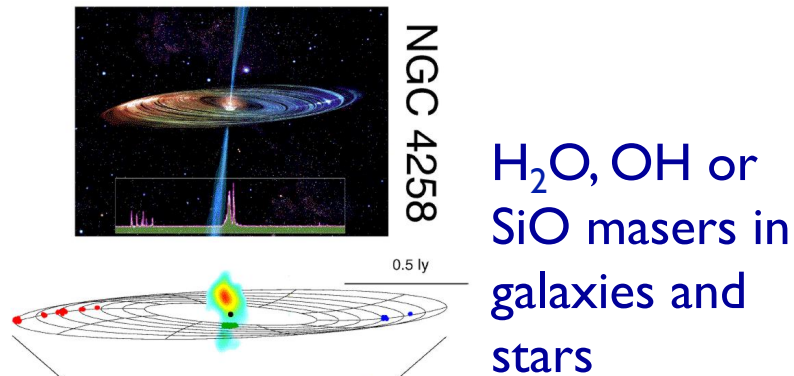
Synchrotron emission from extended radio galaxies (5 GHz)

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

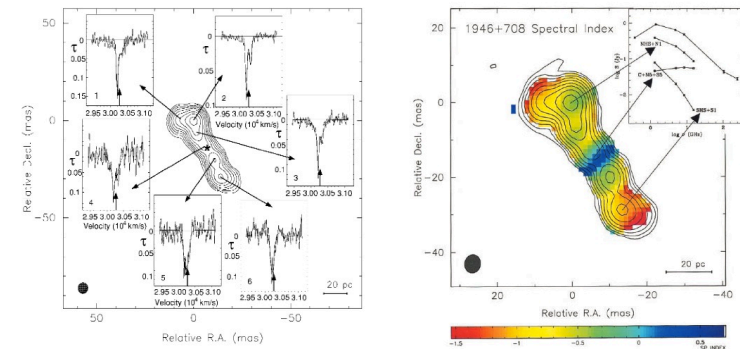
- Images from NRAO Image Gallery
<http://images.nrao.edu/>

What should we observe?

At low frequencies (MHz-GHz):

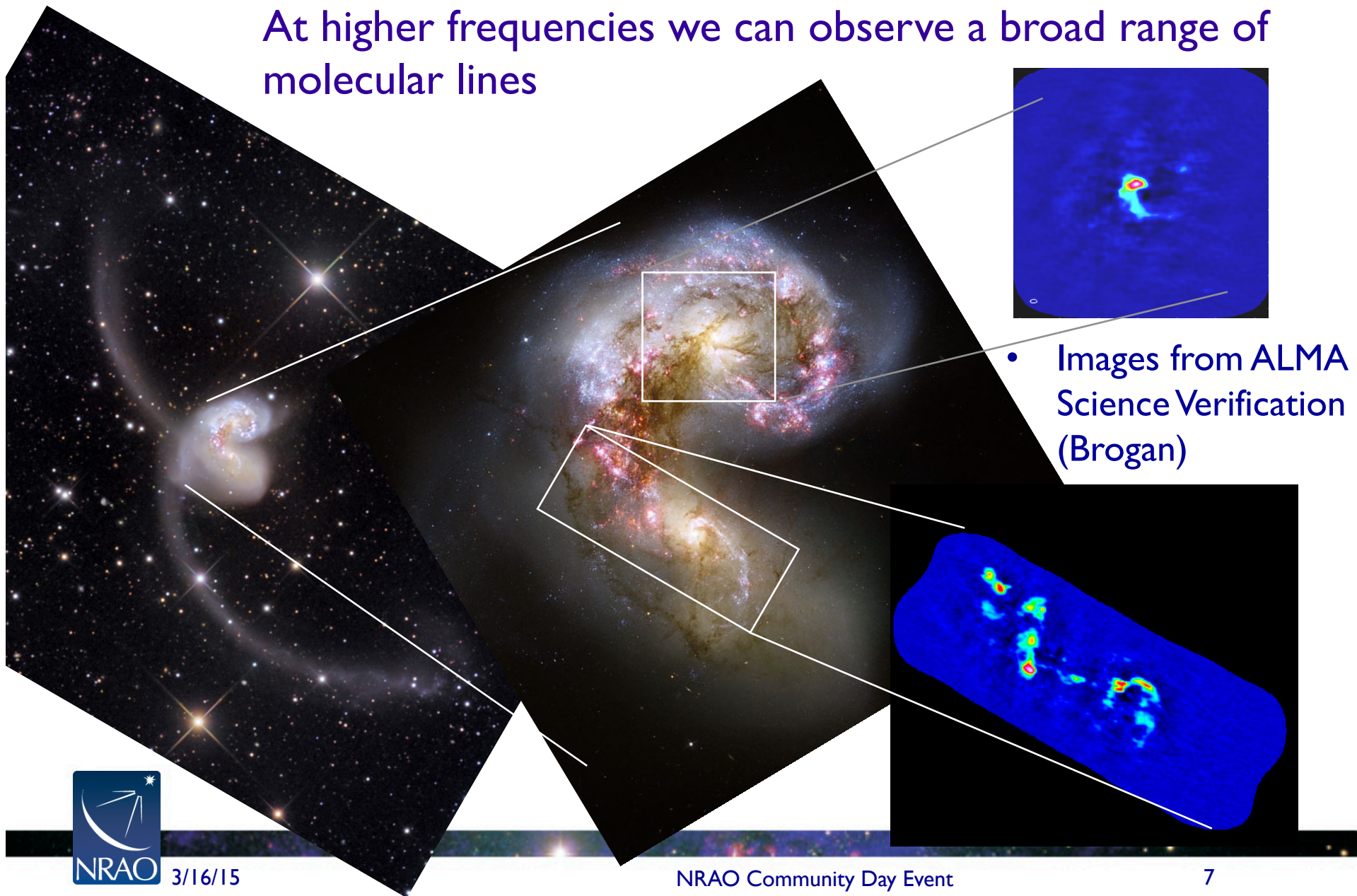


HI emission and absorption, free-free absorption in galaxies



What should we observe?

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



Resolution of Observations

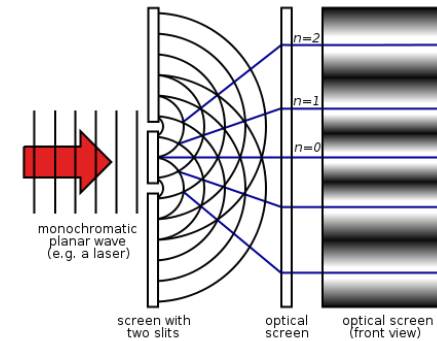
- Angular resolution for most telescopes $\sim \lambda/D$
 - D is the diameter of the telescope, λ is wavelength of observation
- Hubble Space Telescope resolution $\sim 0.05''$
 - $D = 2.4\text{m}$, $\lambda \sim 500\text{nm}$
- For mm wavelength observations, one would need a 5km diameter antenna to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

This is interferometry

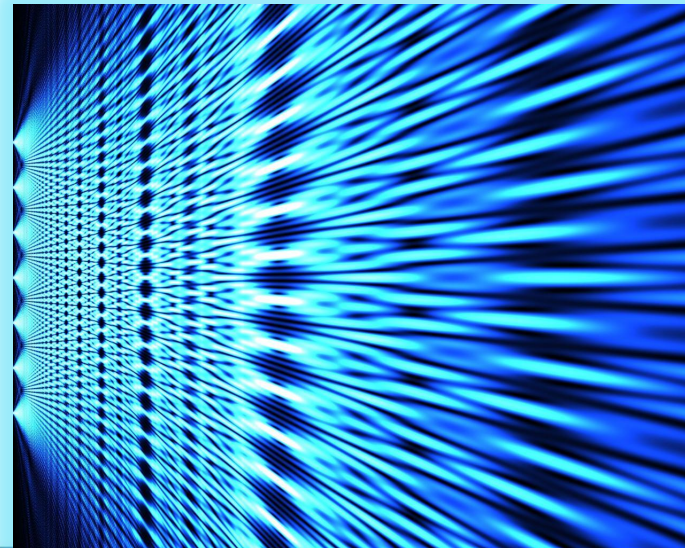


What is an interferometer?

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

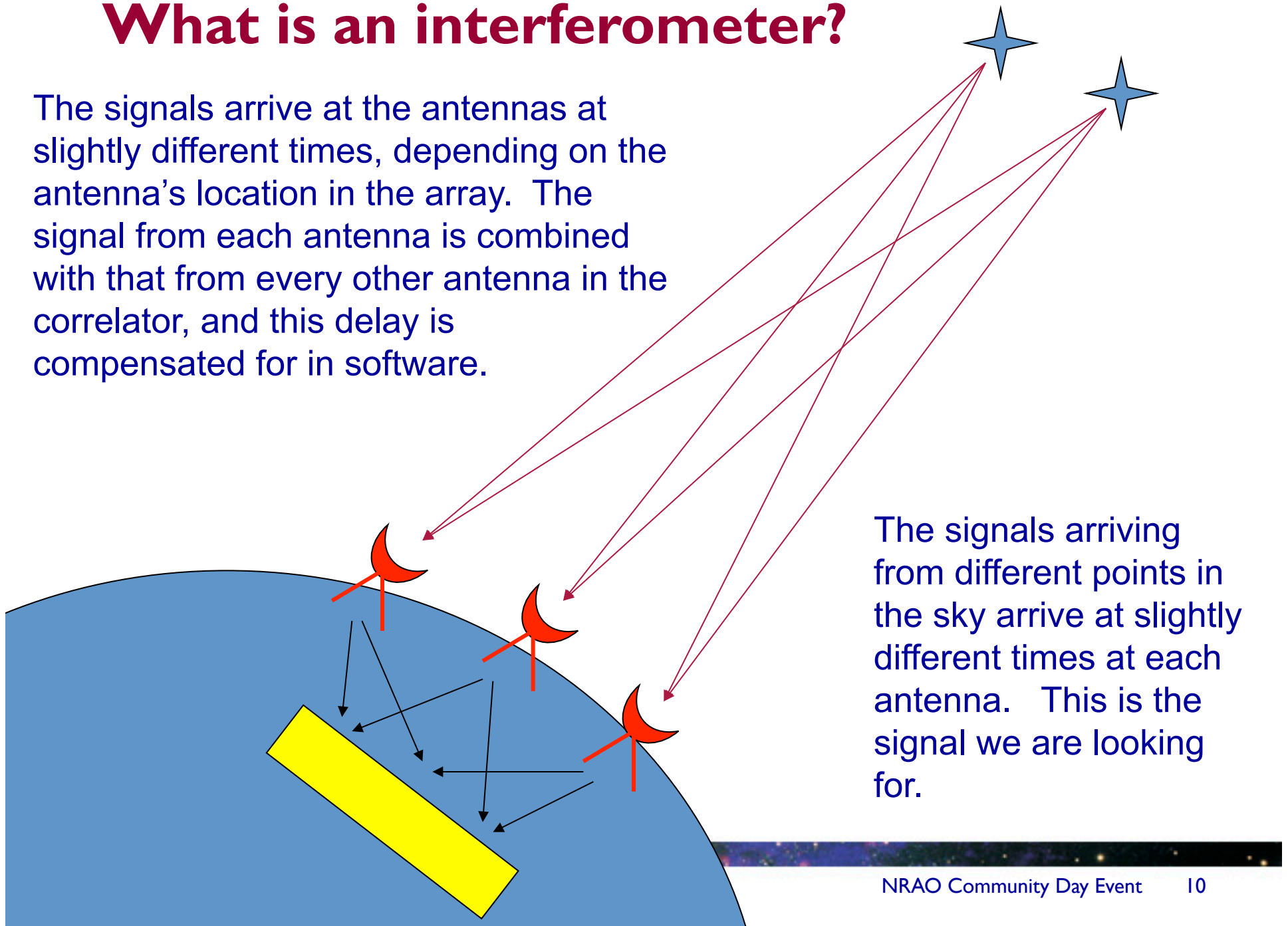


- ◆ More antennas is like having more slits. With more information, you can make much more detailed images.



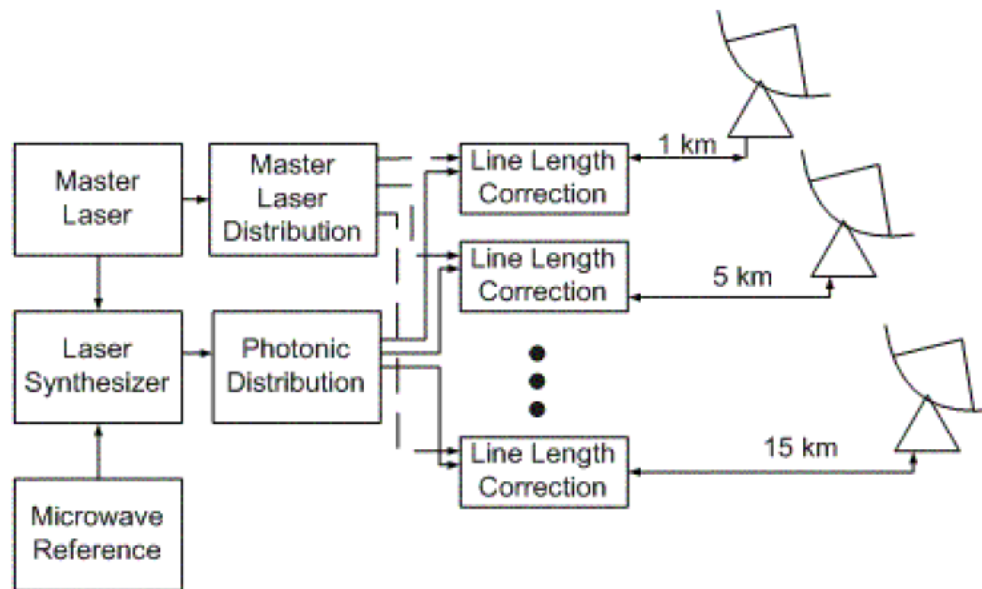
What is an interferometer?

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.



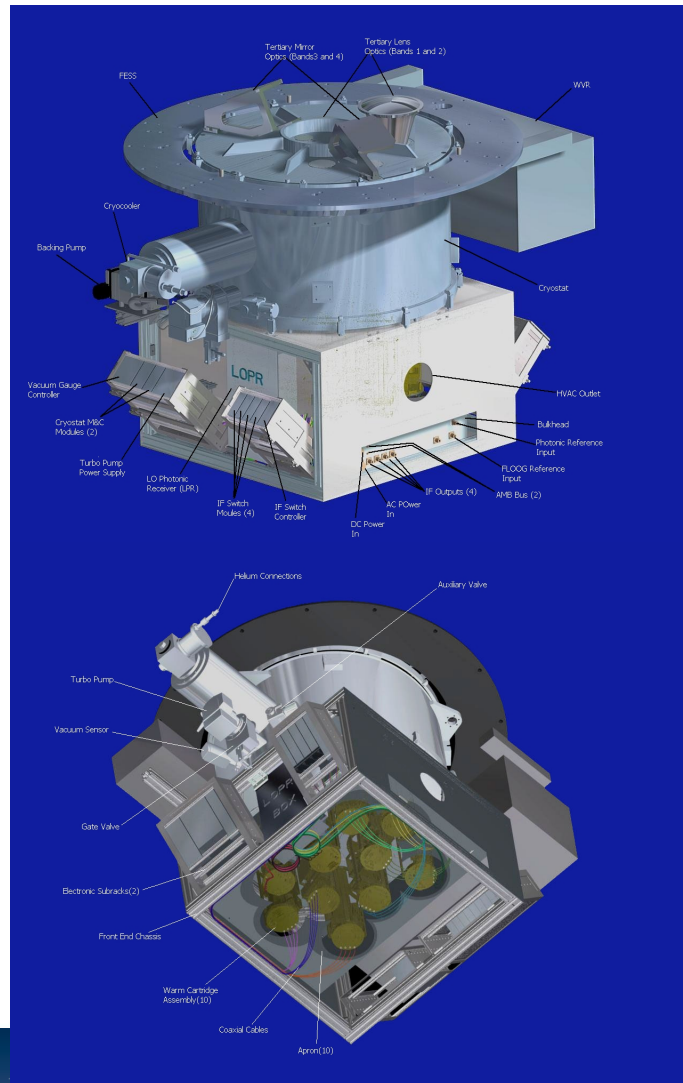
The signals arriving from different points in the sky arrive at slightly different times at each antenna. This is the signal we are looking for.

Precise Timing Required to synchronize signals



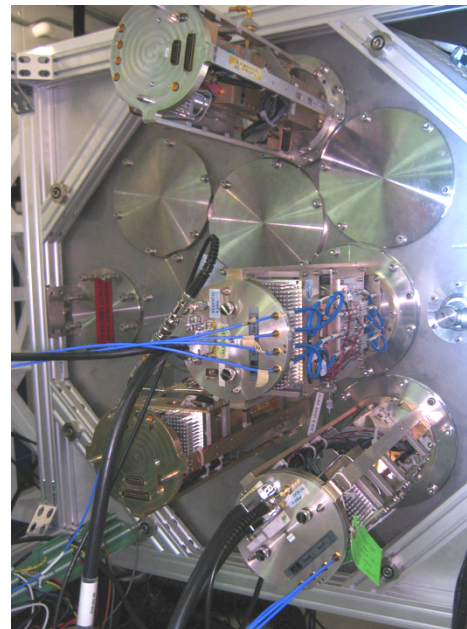
Reference signal can be generated at radio frequencies, but ALMA makes extensive use of photonics to stabilize the fiber between antennas and to synchronize the receivers which has to be done at the ~ 25 femto-second level.

The Front End houses the receivers



ALMA

Band 3

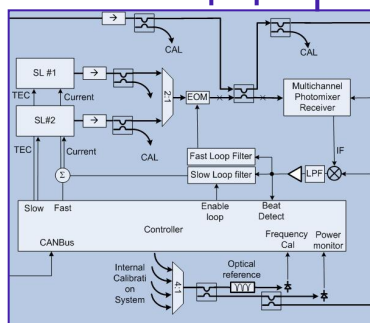


Band 9

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

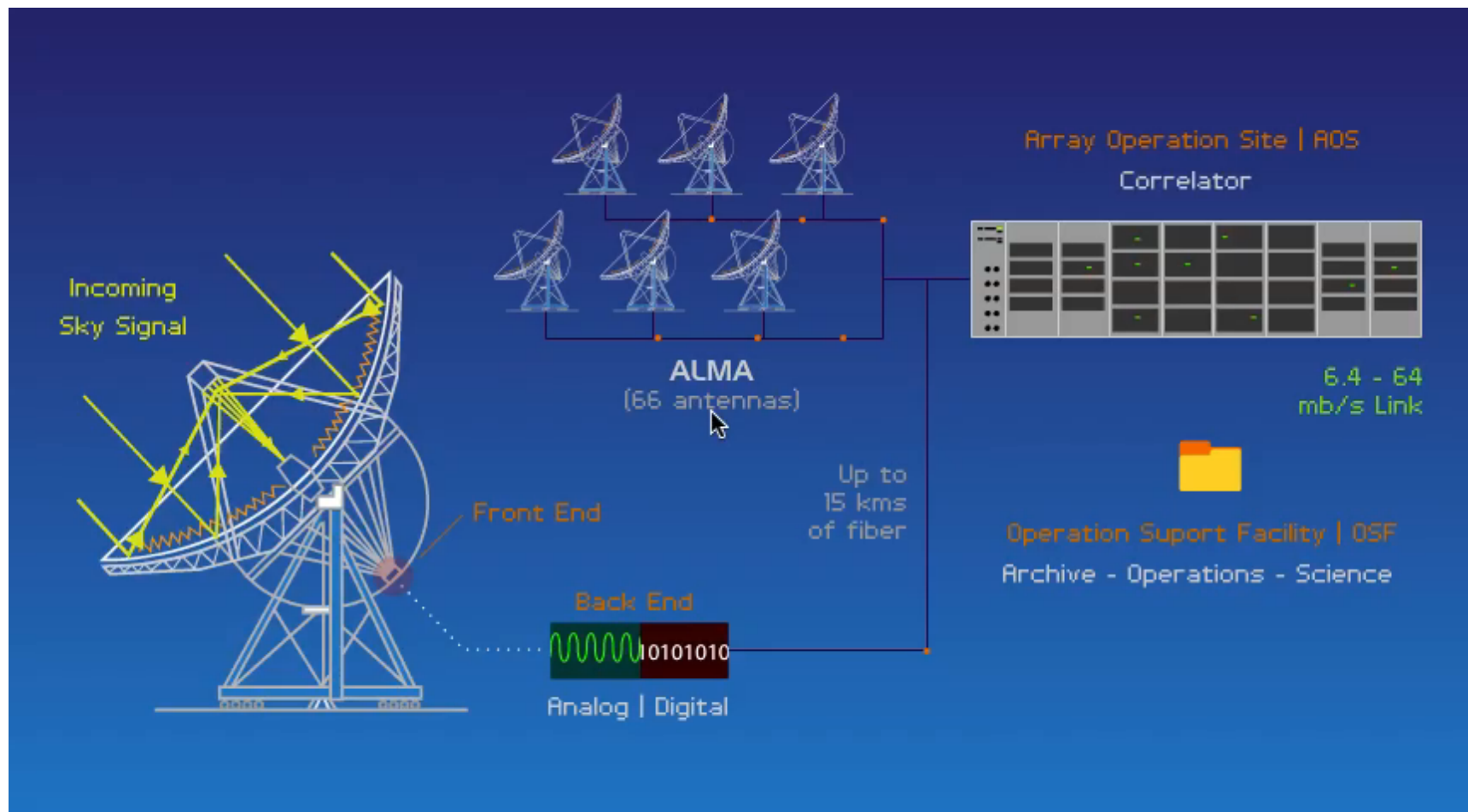
Band 7

Band 6



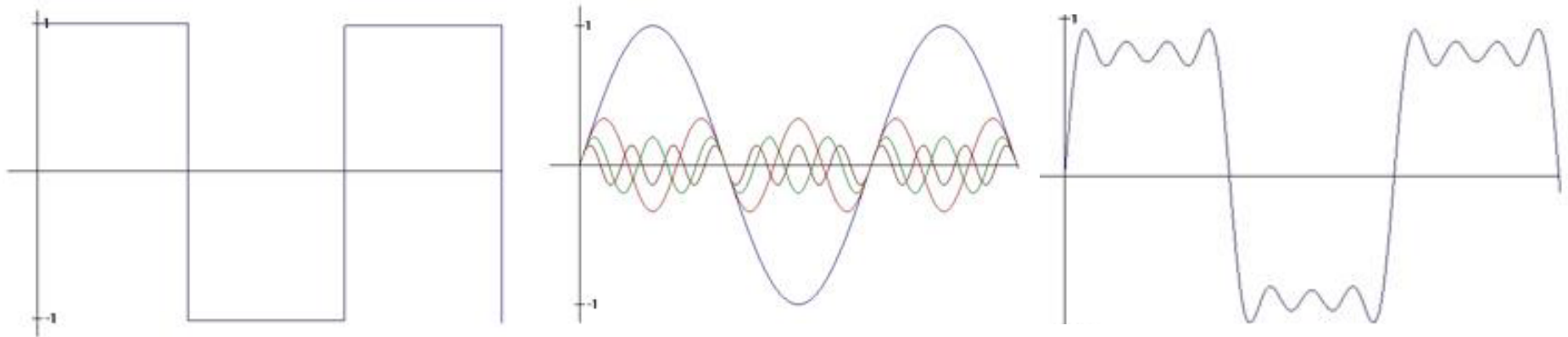
Signals are amplified and digitized at the antennas and then combined in the correlator.

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

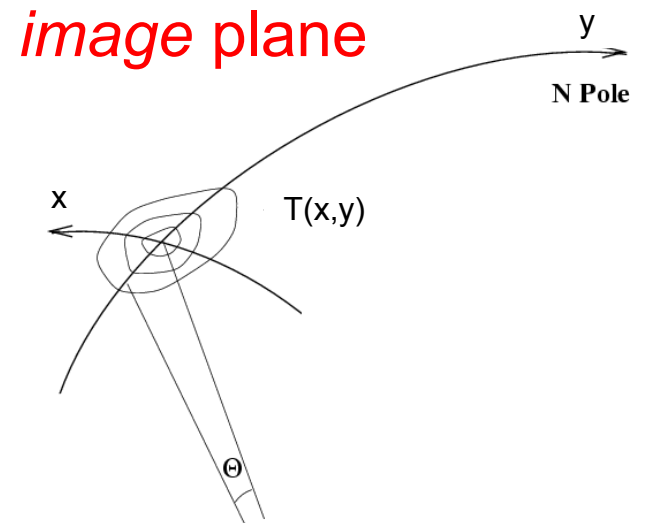
Fourier space/domain

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

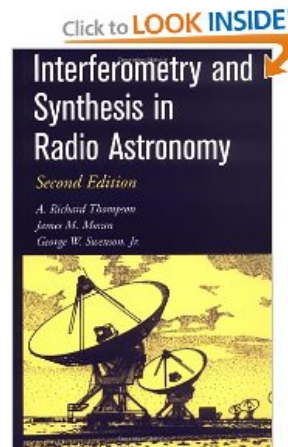
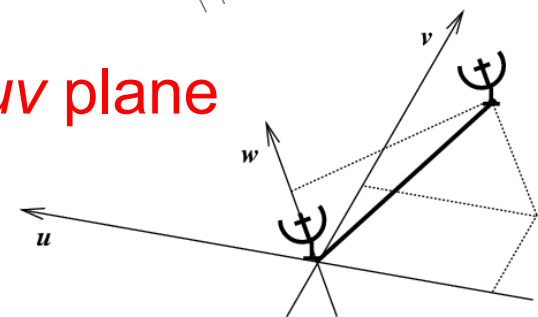
$$T(x, y) = \iint V(u, v) e^{-2\pi i(ux + vy)} du dv$$

Image space/domain

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



uv plane

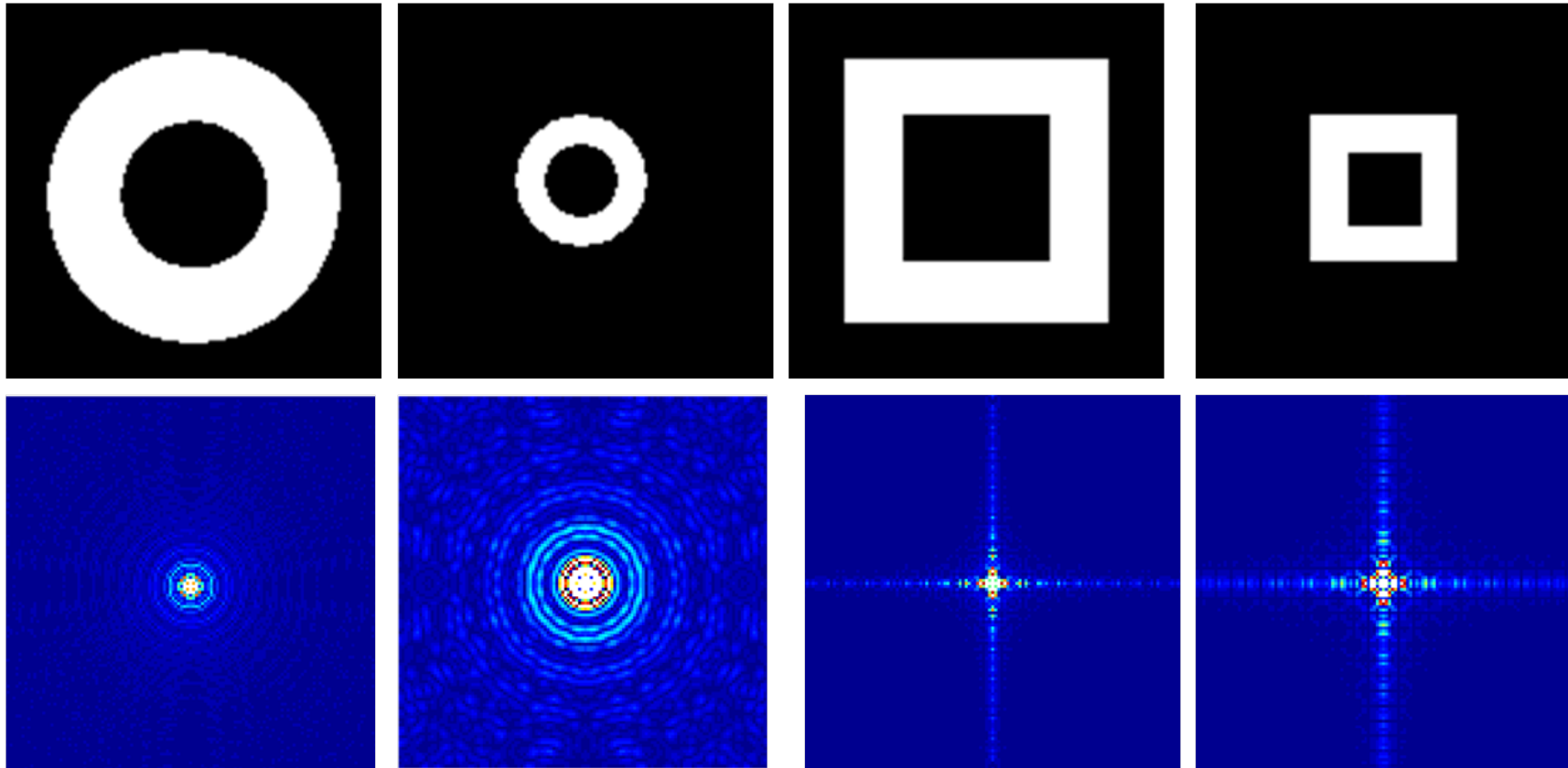


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NRAO Community Day Event

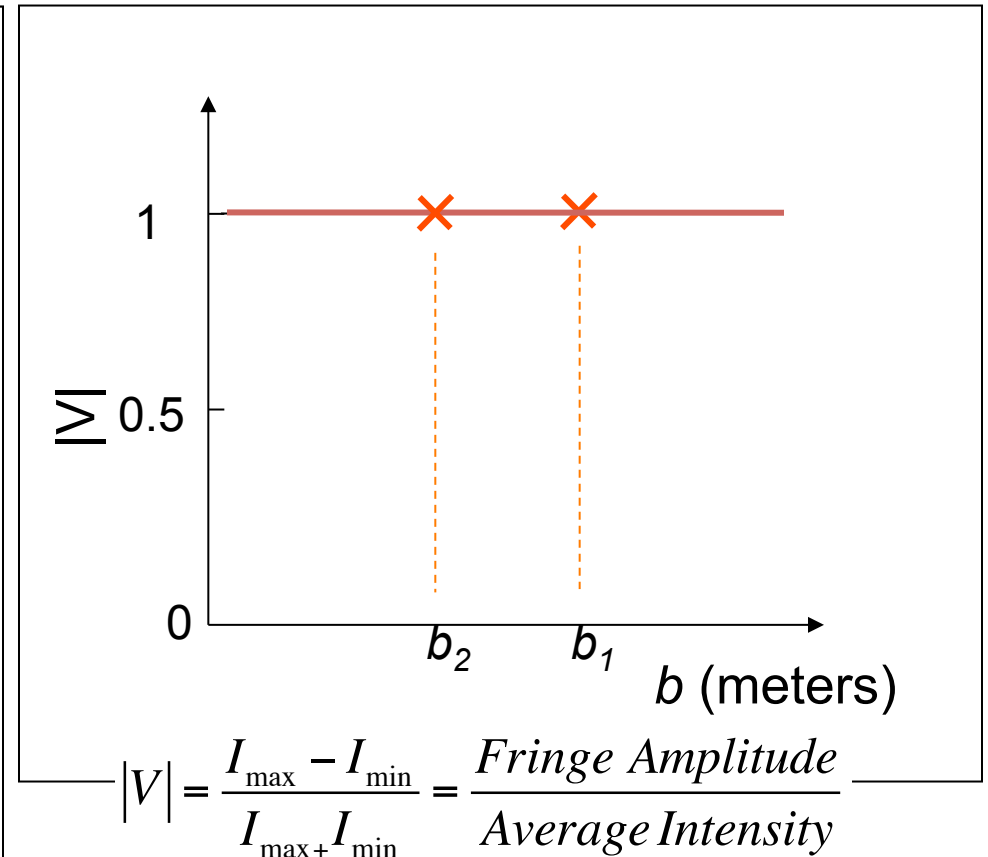
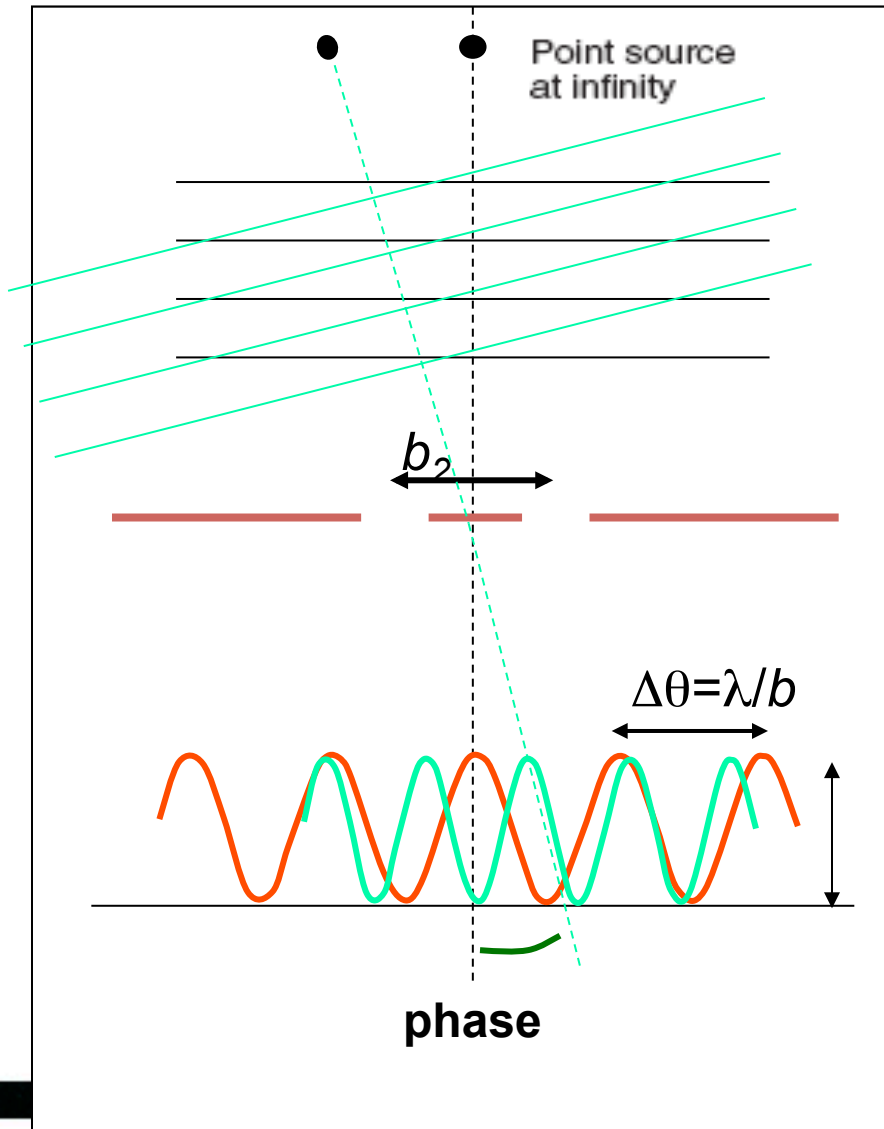
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Fourier Transforms of Images



Visibility and Sky Brightness

Graphic courtesy Andrea Isella

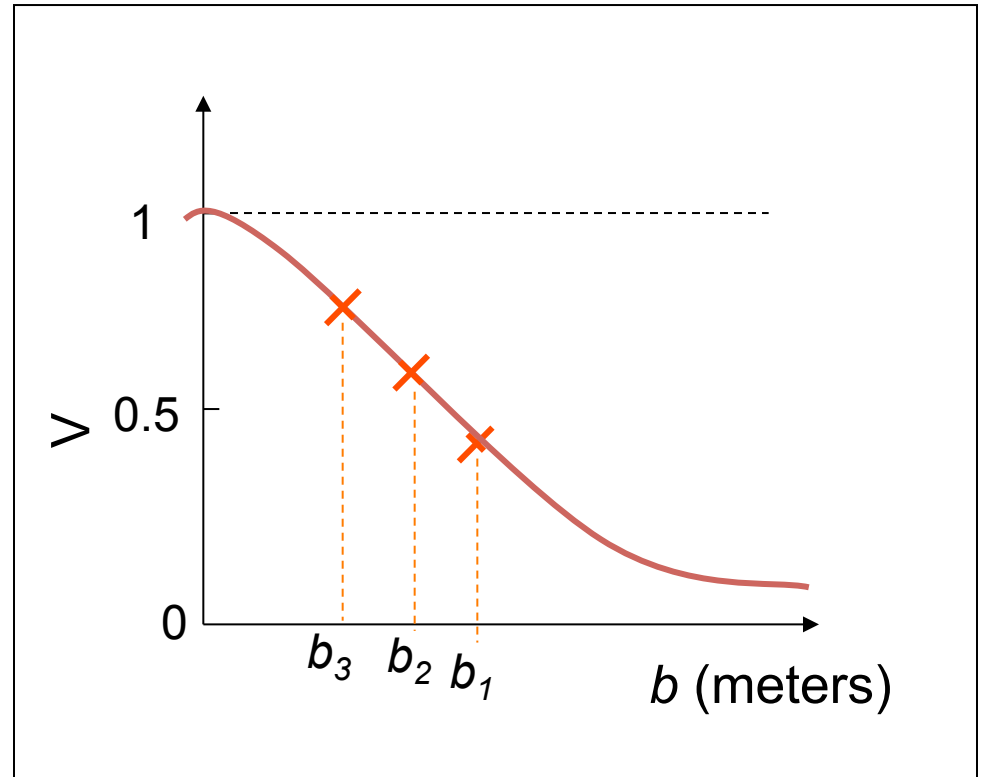
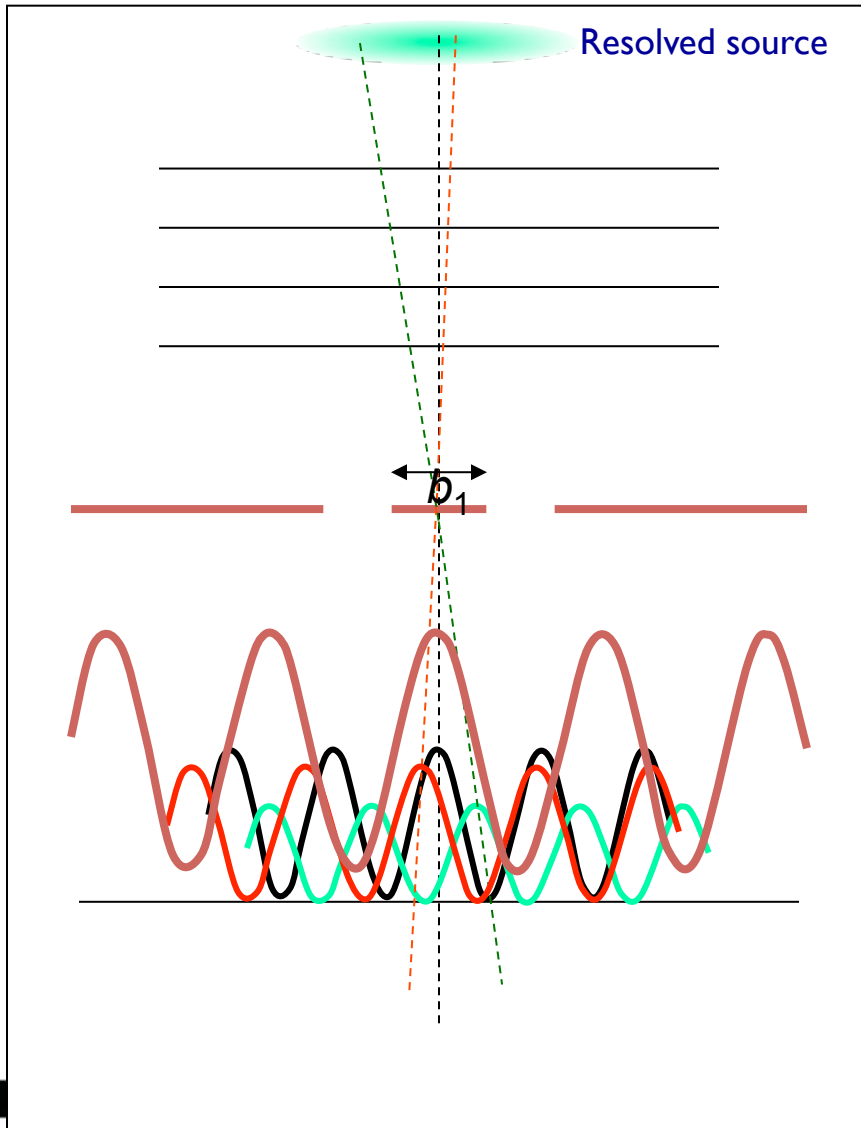


The visibility is a **complex** quantity:

- **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
 - $\sim \lambda/B_{\max}$, 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
 - $\sim \lambda/D$, 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.

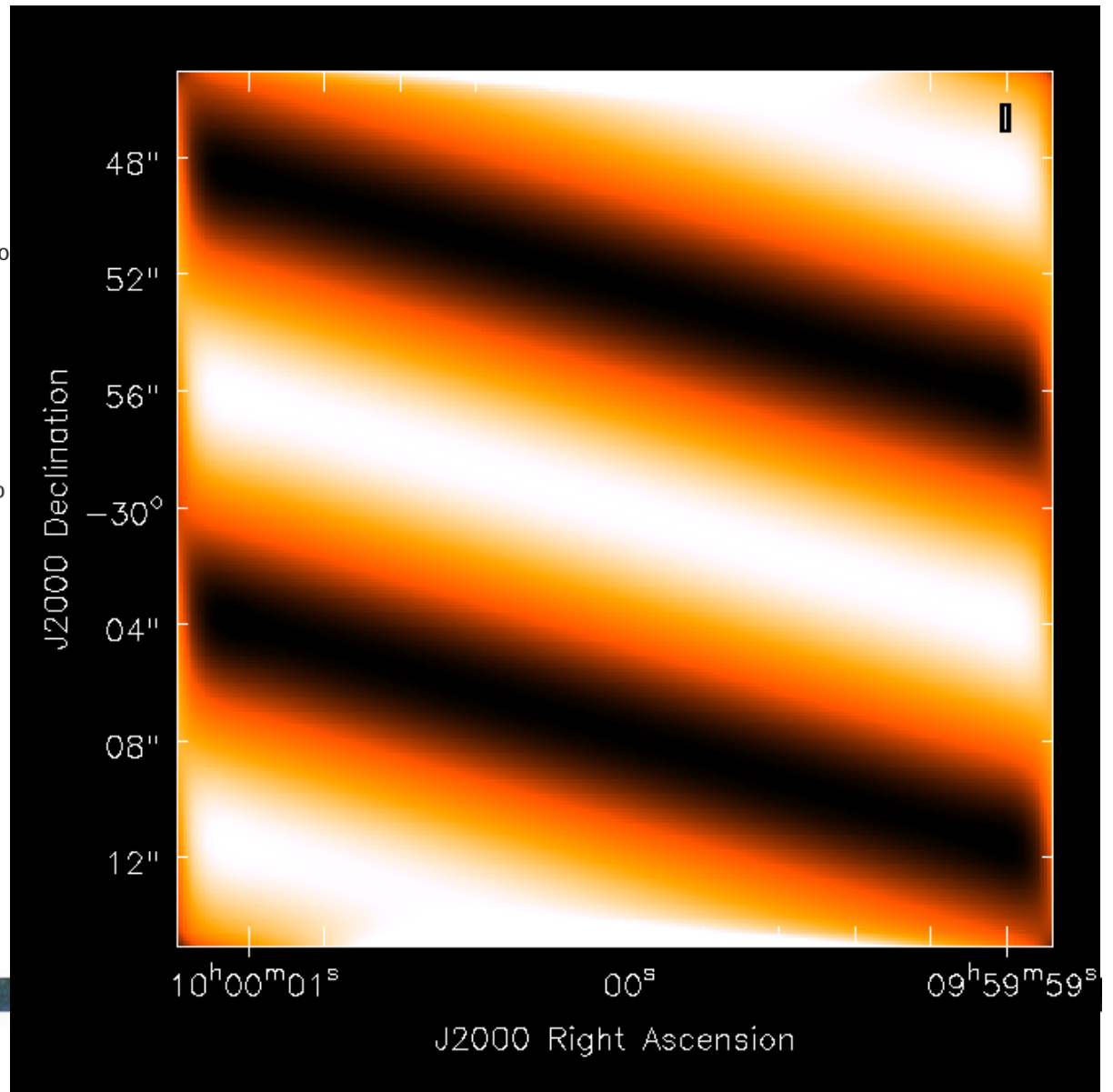
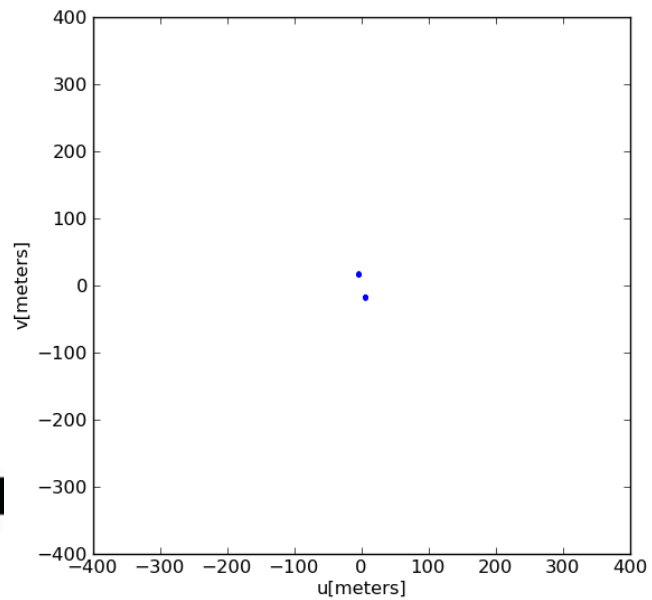
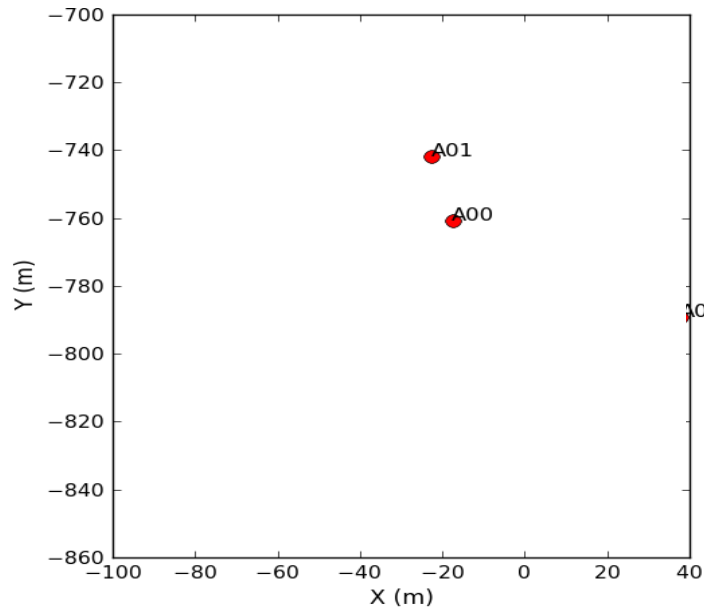
An interferometer is sensitive to a range of angular sizes

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

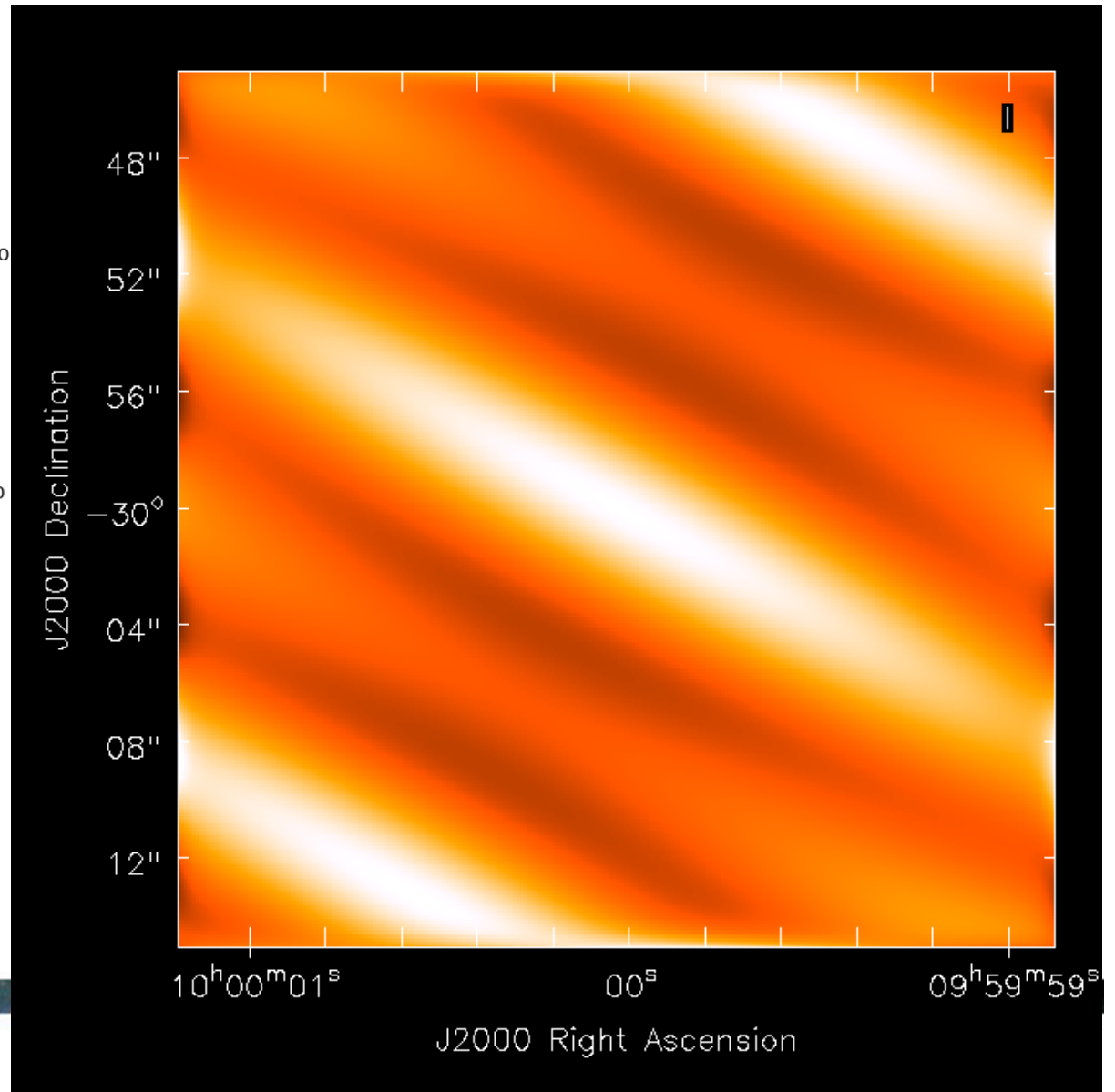
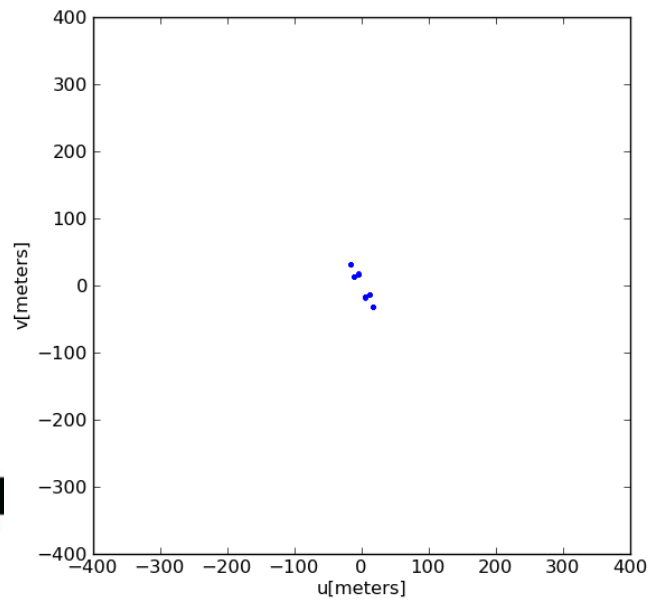
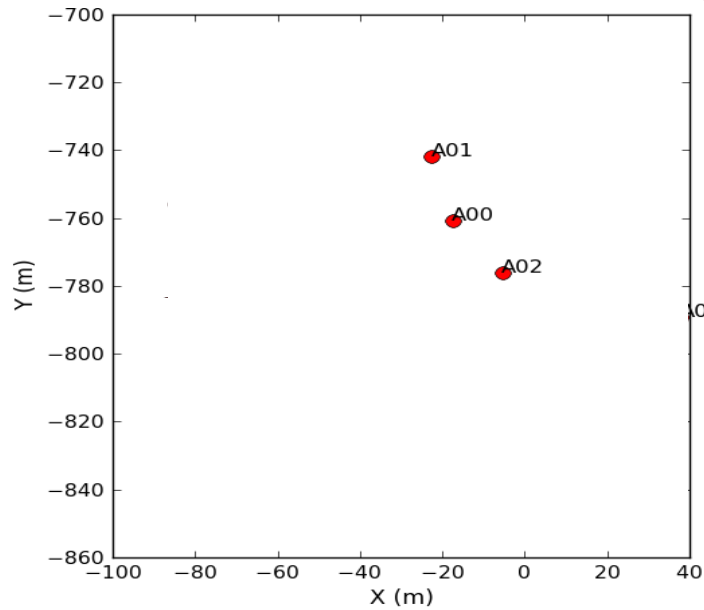
Since $B_{\min} > D$, an interferometer is not sensitive to the large angular scales and cannot recover the total flux of resolved sources



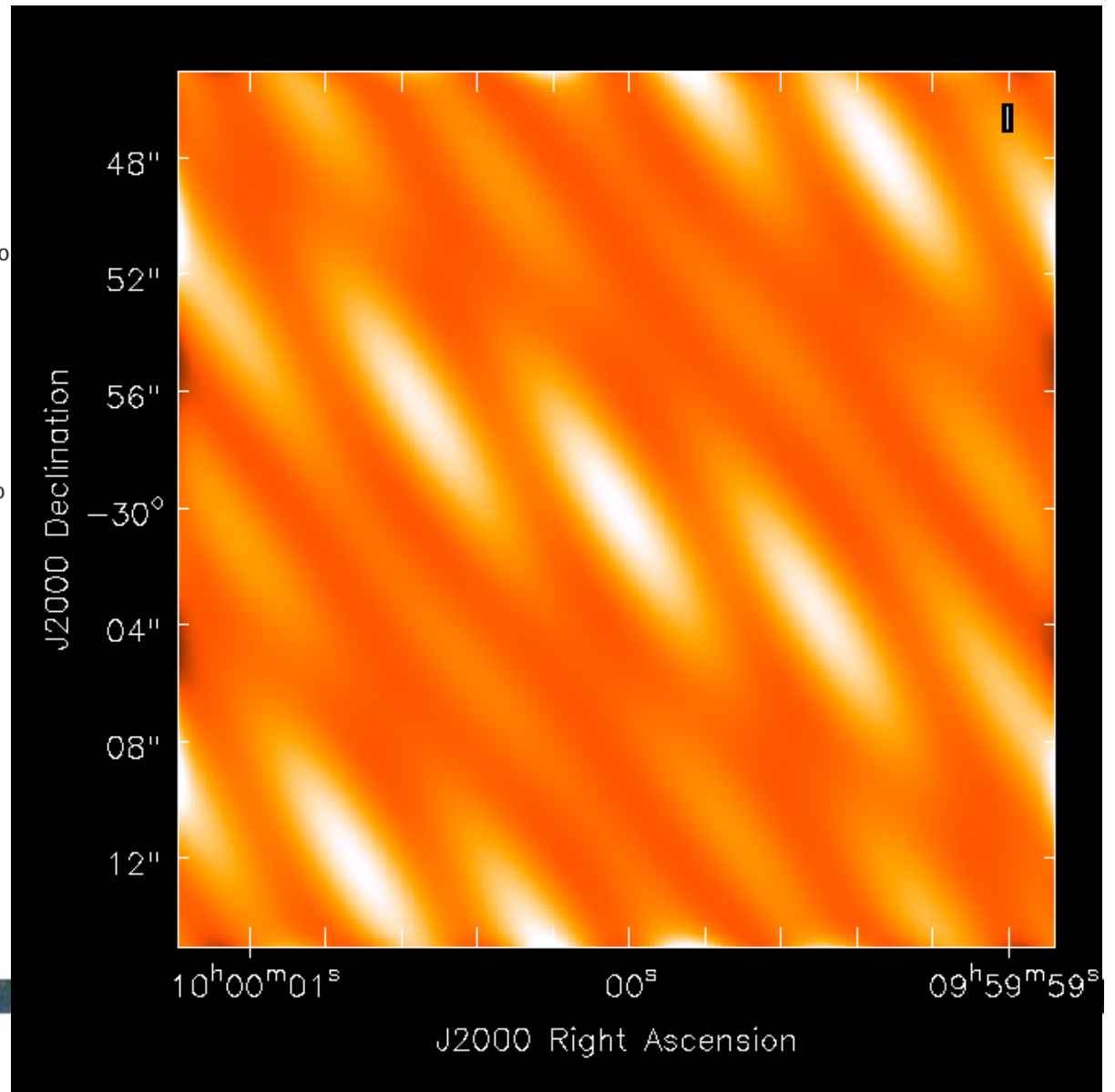
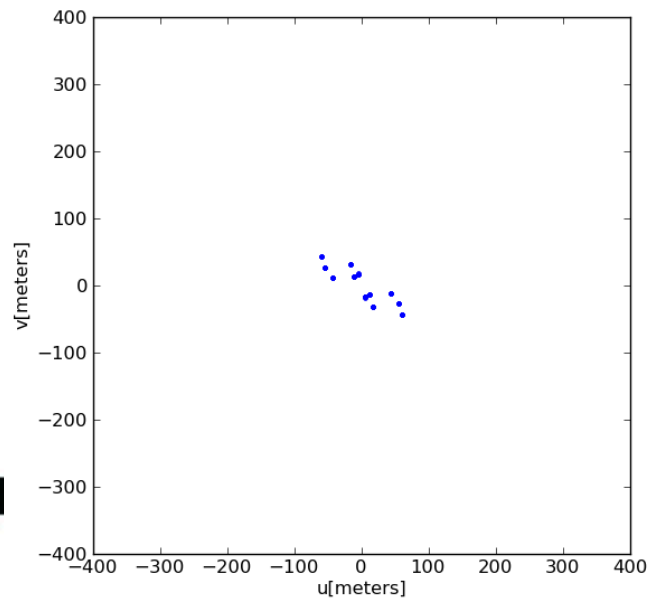
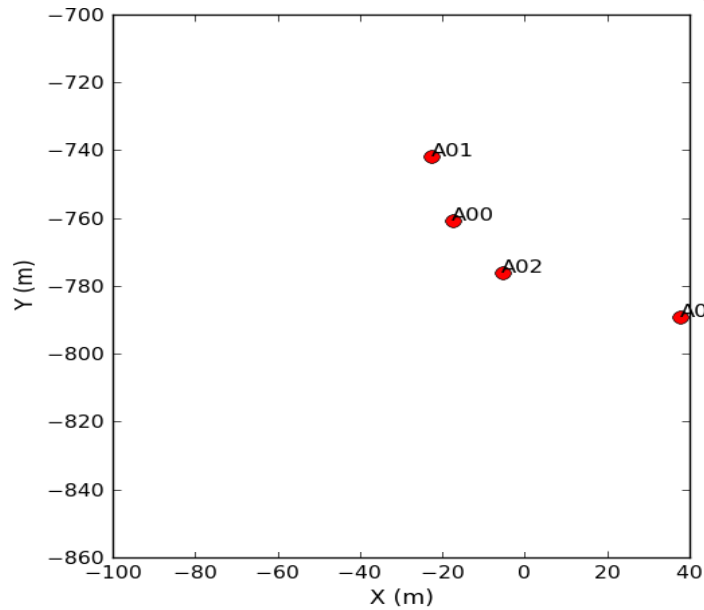
Example: Fringe pattern with 2 Antennas (1 baseline)



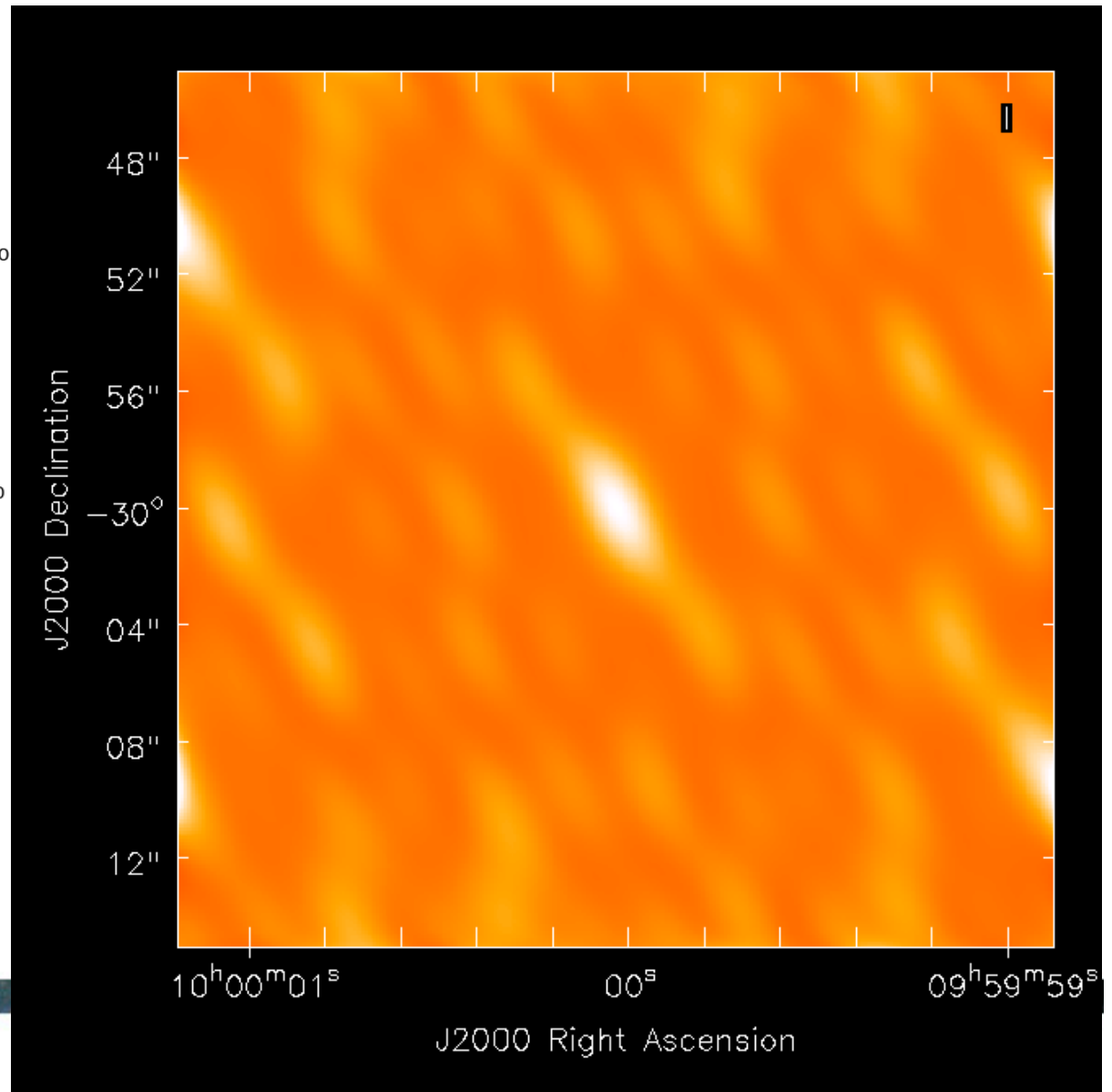
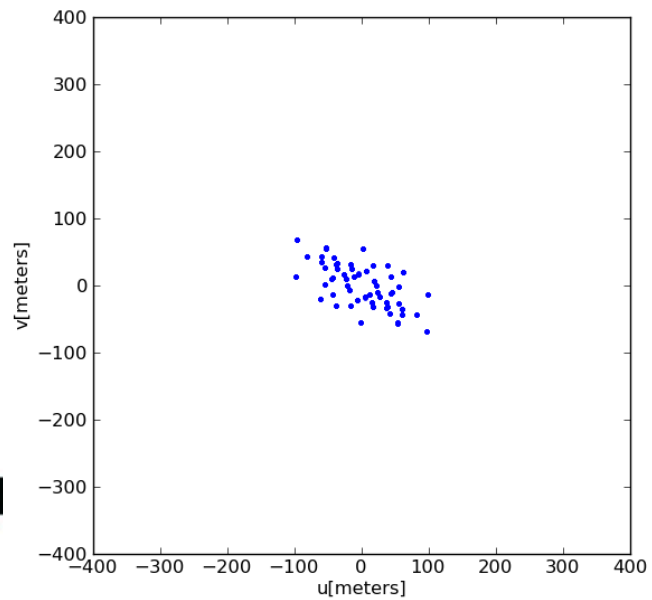
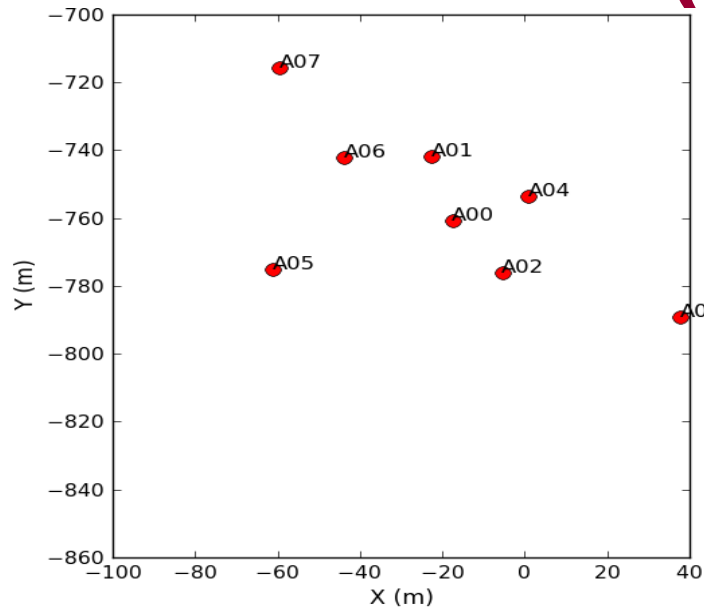
Example: Fringe pattern with 3 Antennas (3 baselines)



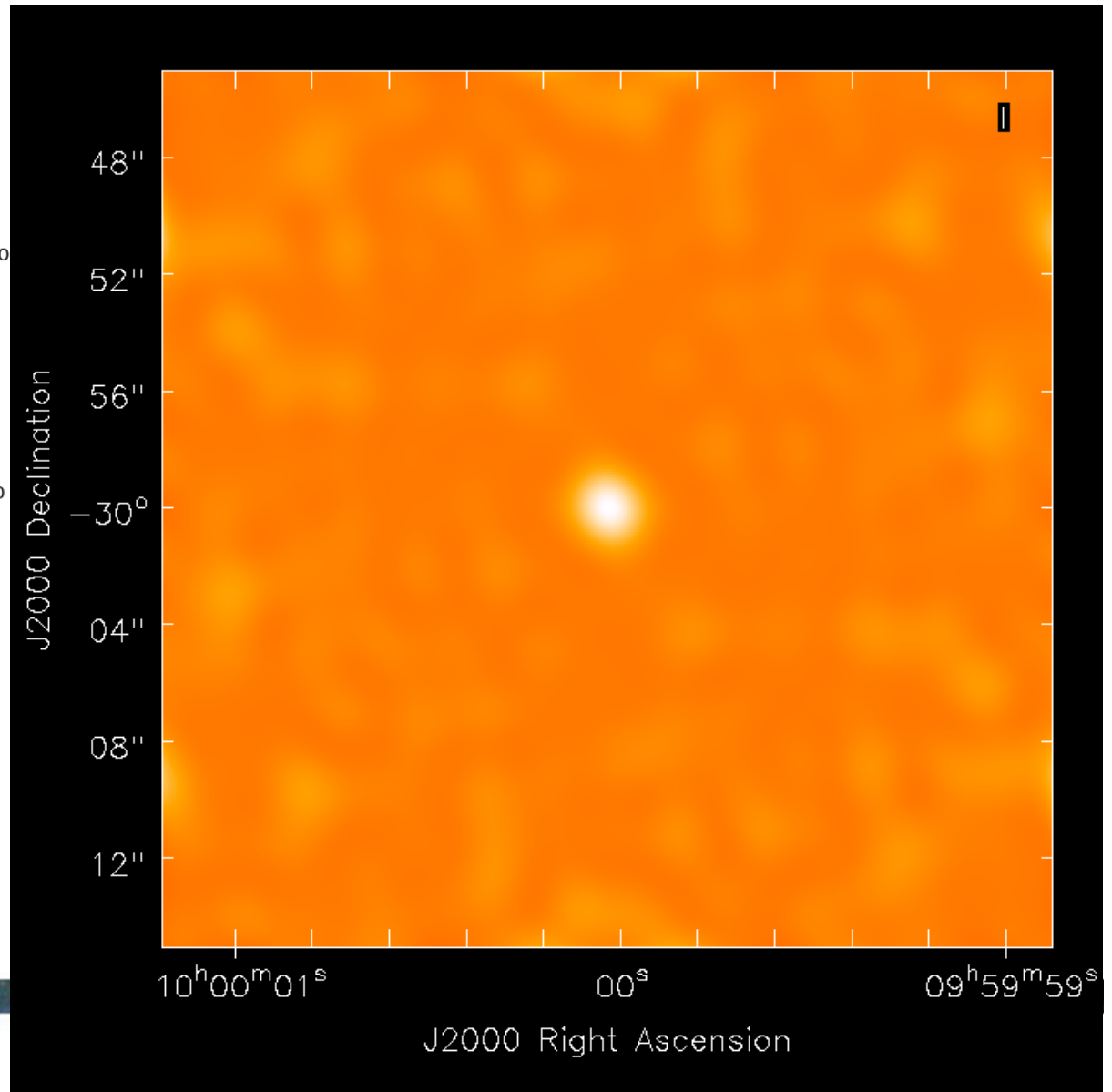
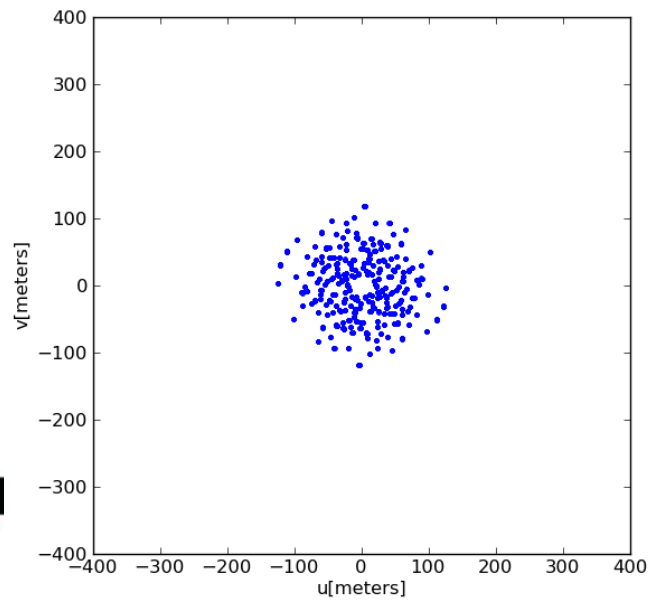
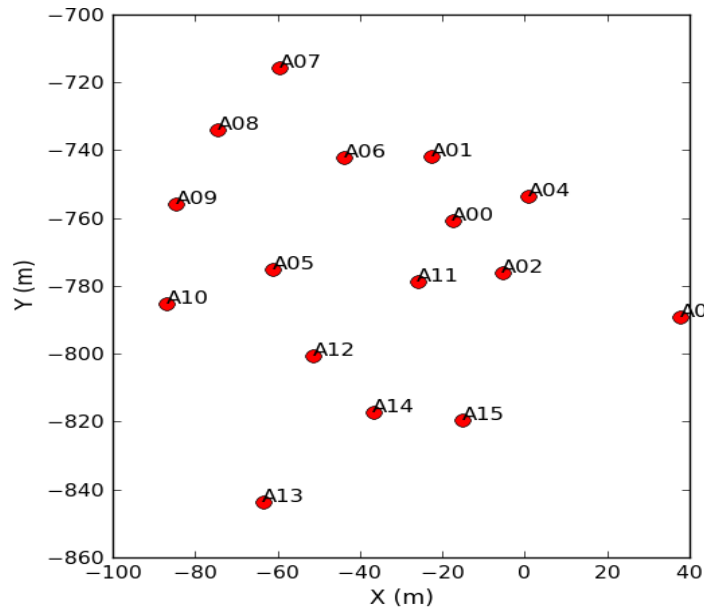
Example: Fringe pattern with 4 Antennas (6 baselines)



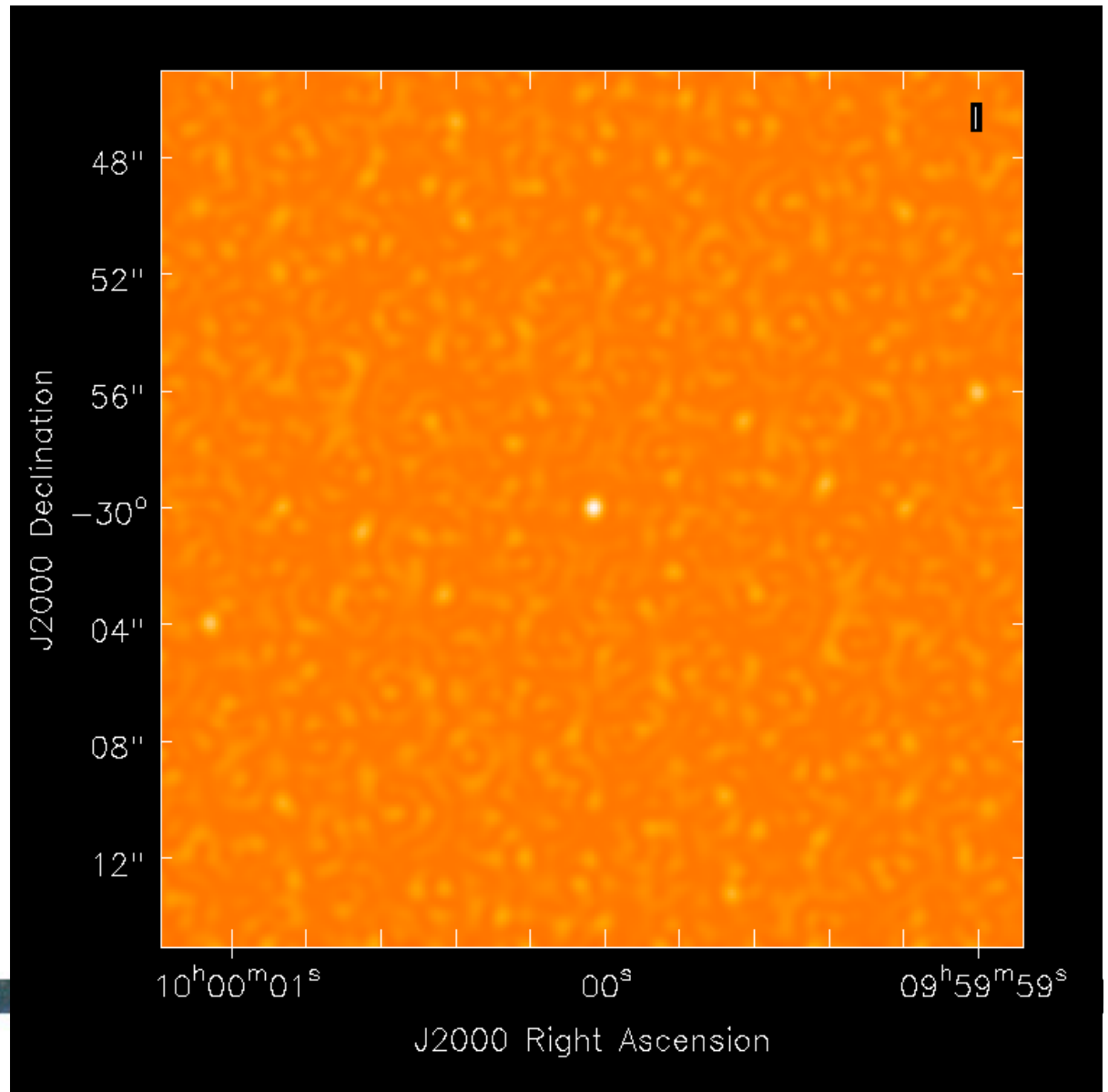
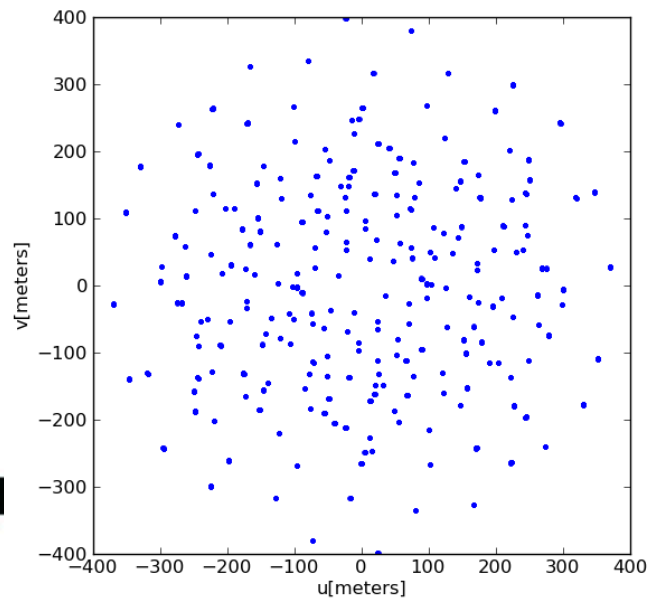
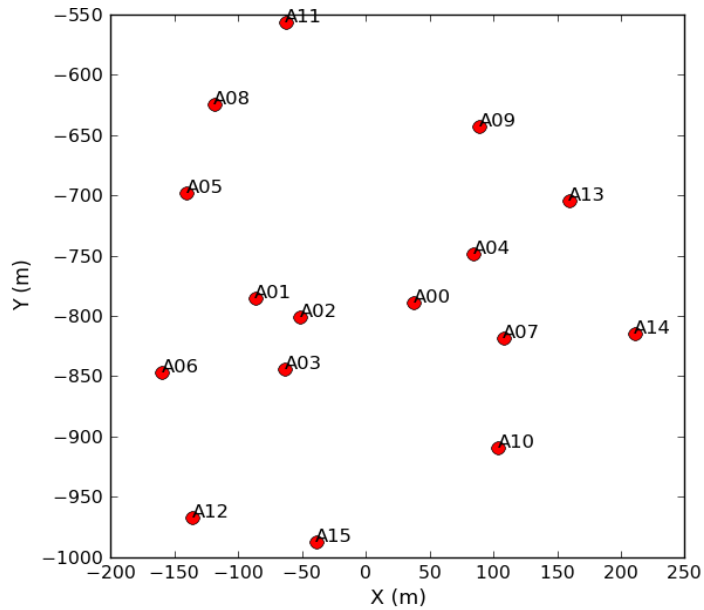
Example: Fringe pattern with 8 Antennas (28 baselines)



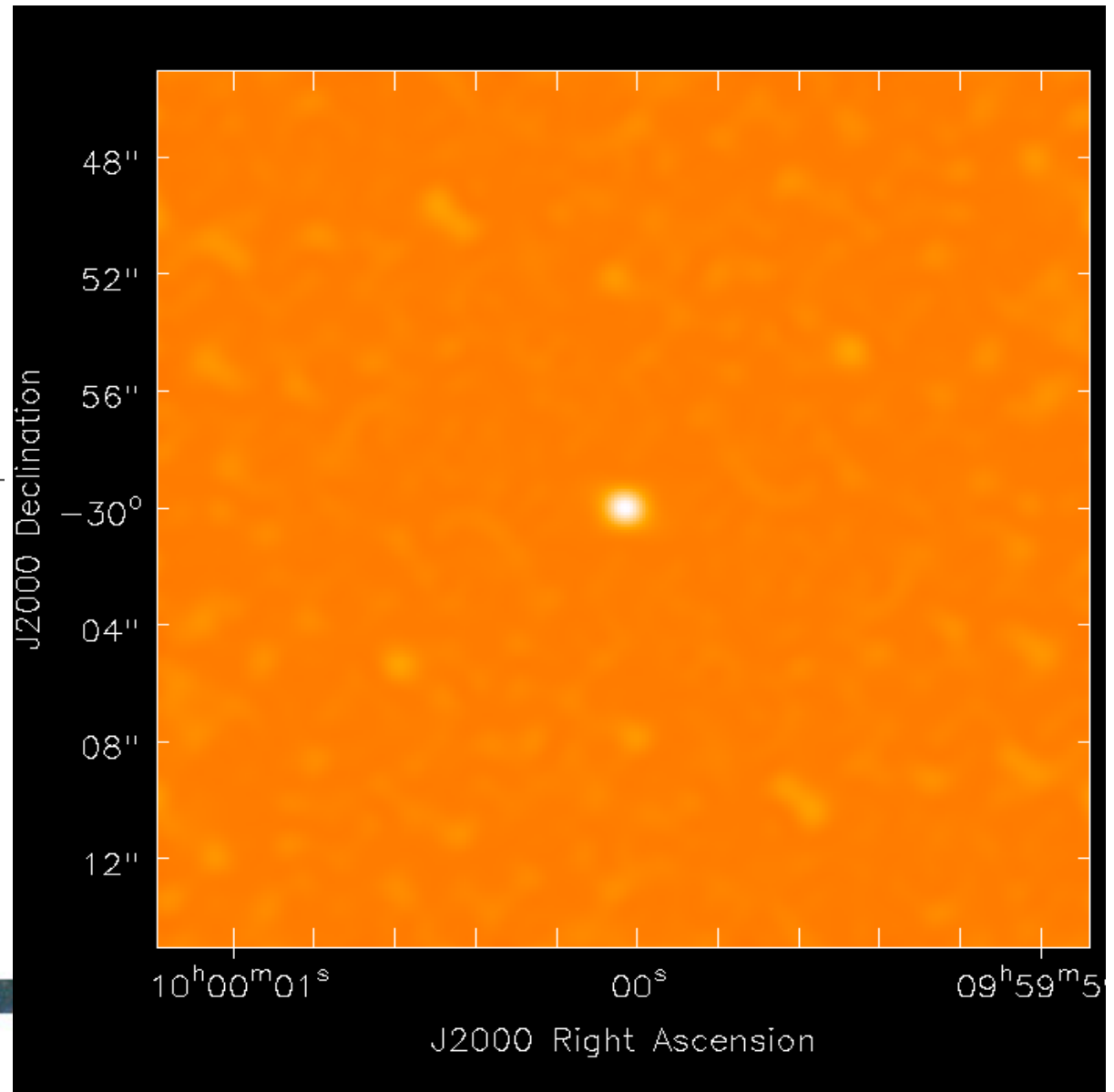
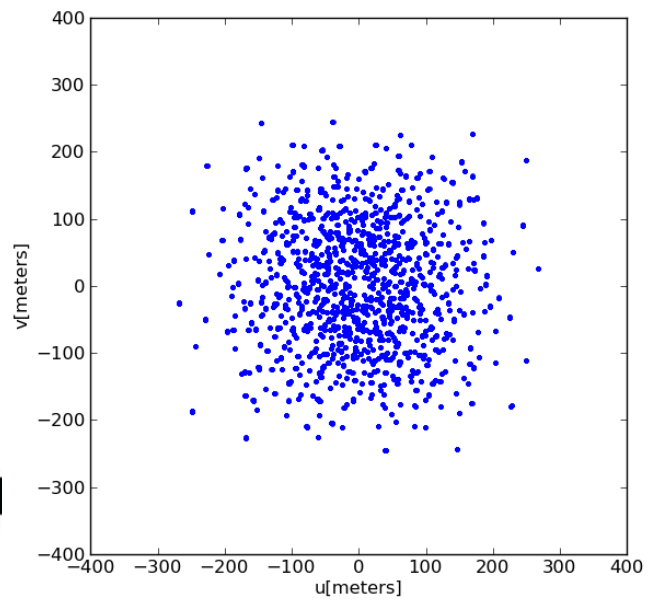
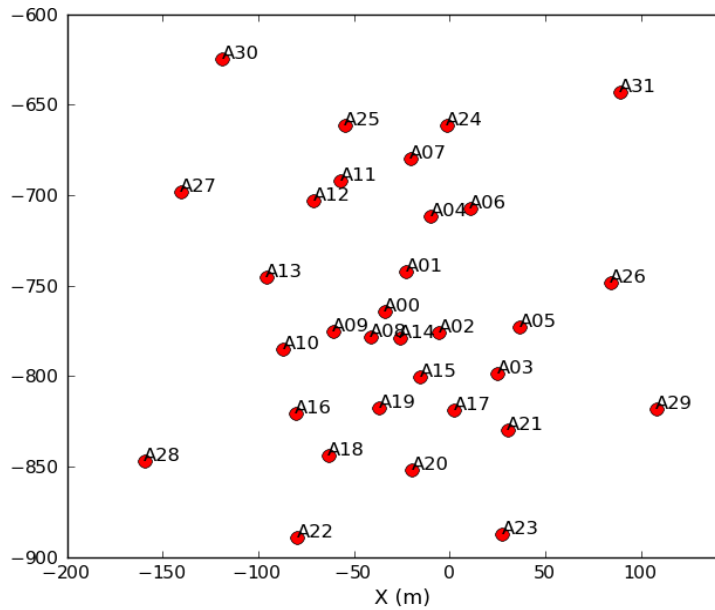
16 Antennas – Compact Configuration



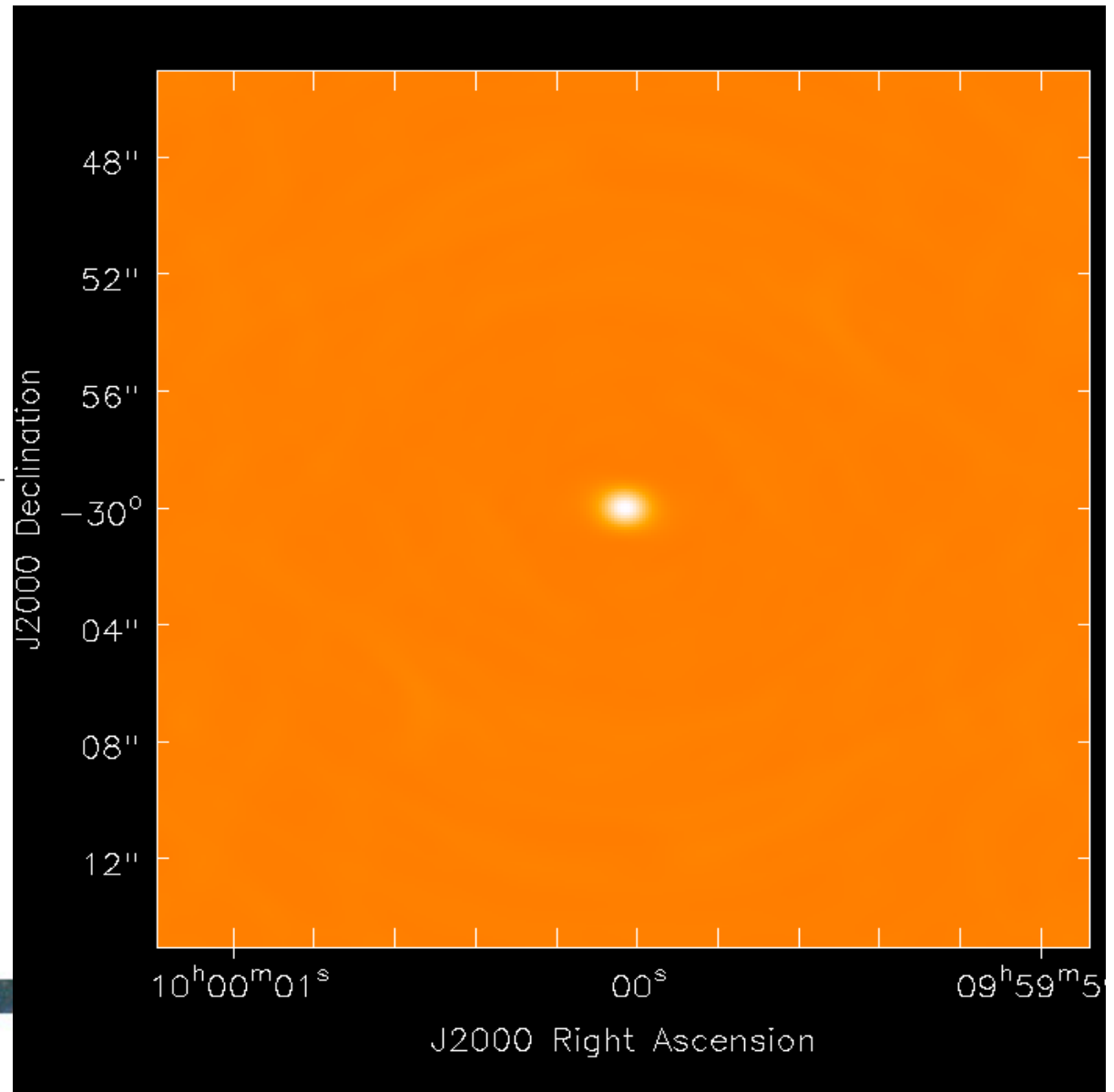
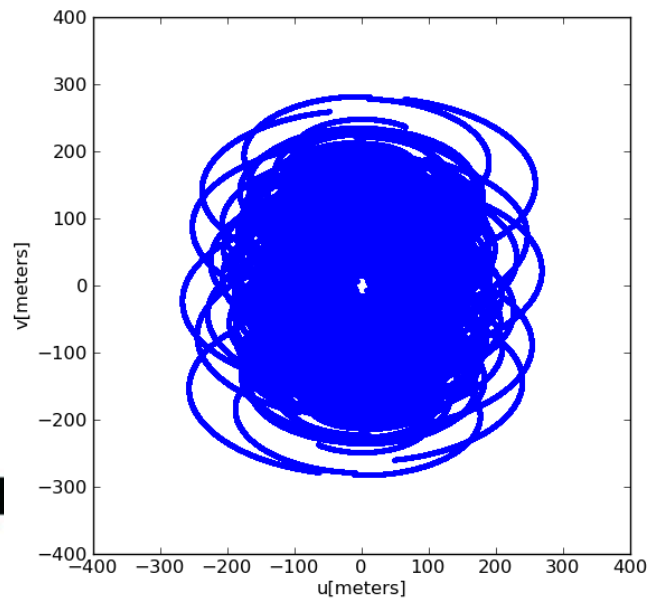
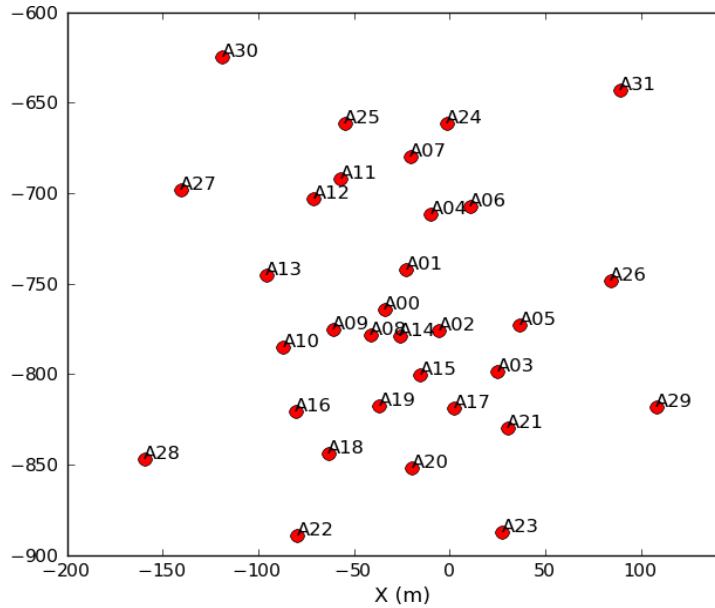
16 Antennas – Extended Configuration



32 Antennas – Instantaneous

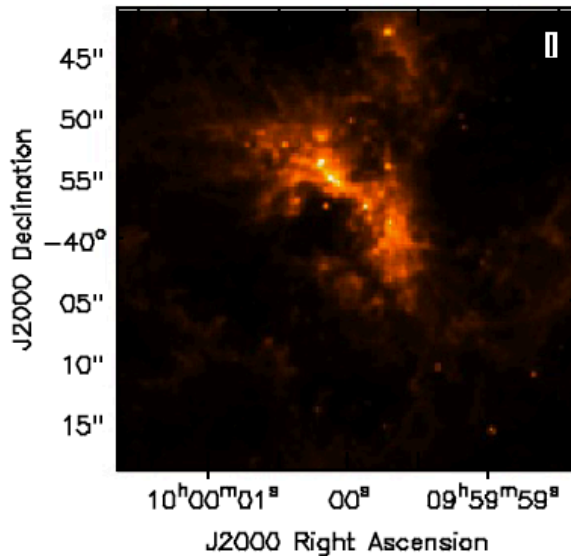


32 Antennas – 8 hours

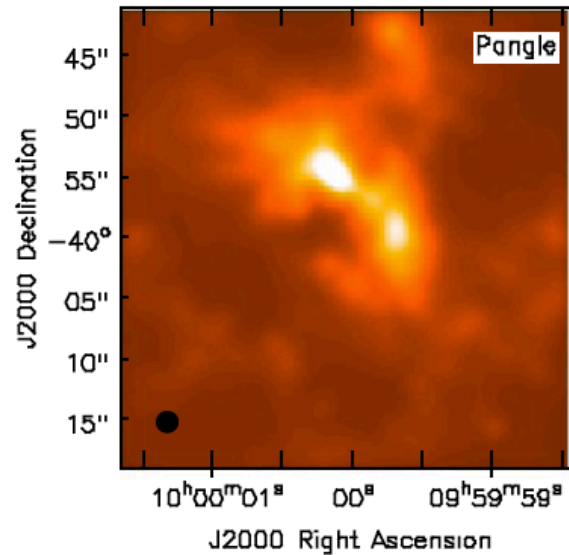


Model: Complicated image

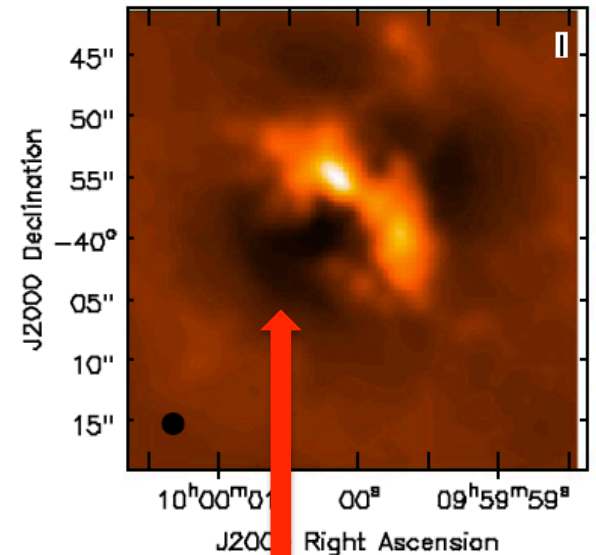
Model Image



Convolved Model



“Observed” Image



2 hour observation with
32 antennas

Large scale emission: Fill
in with shorter baselines

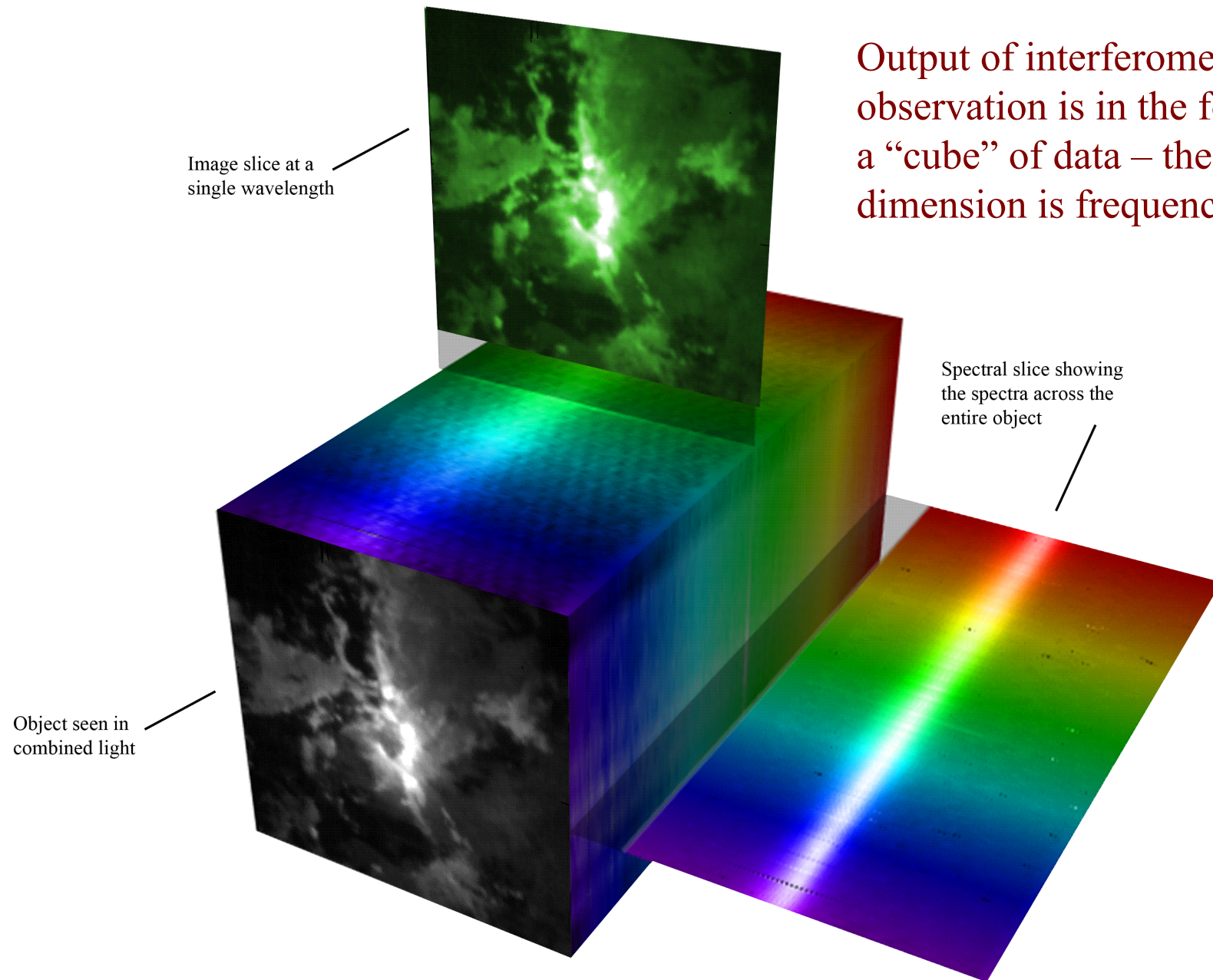


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NRAO Community Day Event

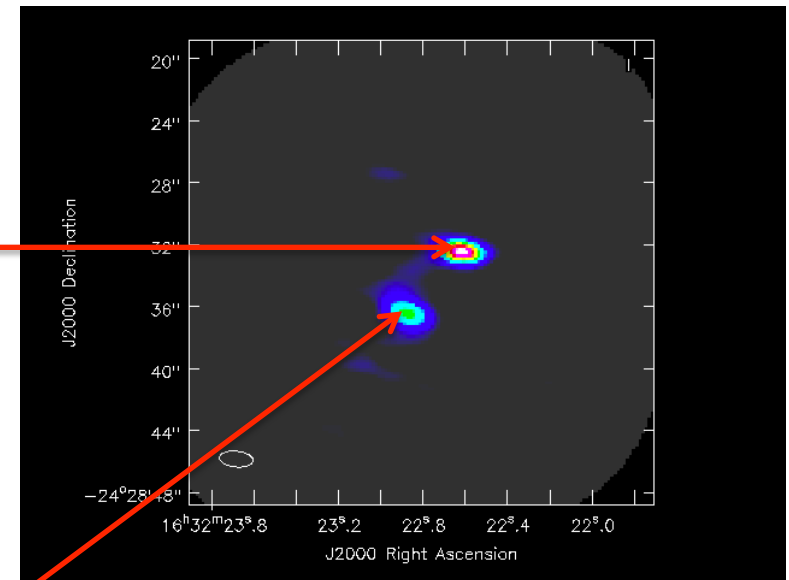
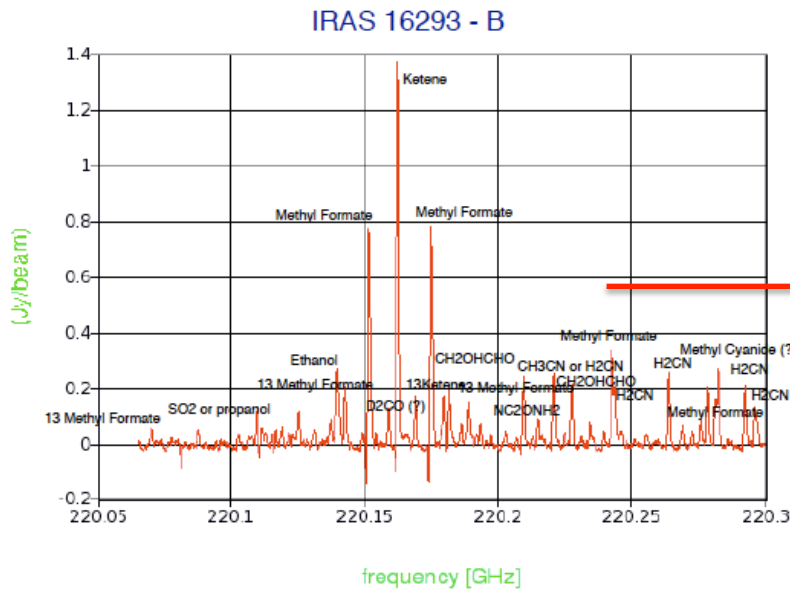
30

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



Interesting result not always an image

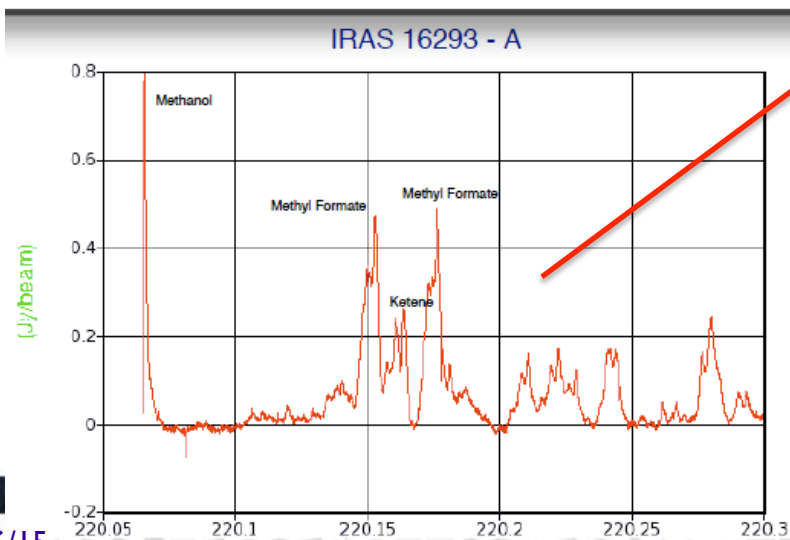
Band 6



J. Turner & ALMA CSV team

Young Low Mass Stars: IRAS 16293

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



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IRAO Community Day Event

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Amplitudes and Phases

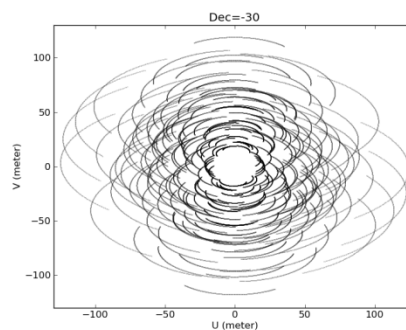
Each pair of antennas (ie each baseline) will generate a visibility (amplitude and phase)

Every integration: time interval

Every channel: frequency interval

More baselines means better u,v coverage, better image fidelity

The goal of calibration is to correct these amplitudes and phases for atmospheric and instrumental effects



Caveats and site considerations

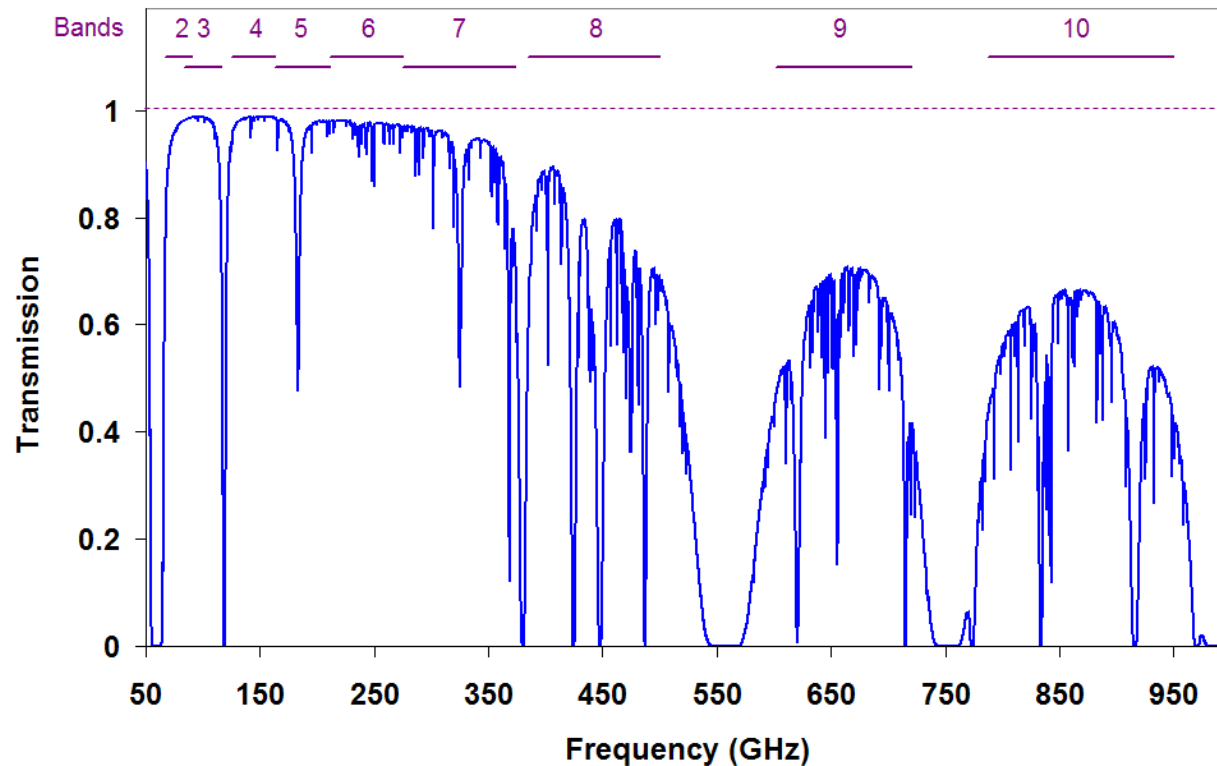
- Scattered optical light does not present a problem, so usually observations can be made 24 hrs/day
- At very low frequencies ($\nu < 300$ MHz, $\lambda > 1$ m), signal increasingly degraded by variable ionospheric refraction
- At high frequencies ($\nu > 300$ GHz, $\lambda < 1$ mm), emission is absorbed by water and oxygen in the atmosphere
- In the vicinity of 1 GHz, 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



Chajnantor - 5000m, 0.25mm pwv



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:

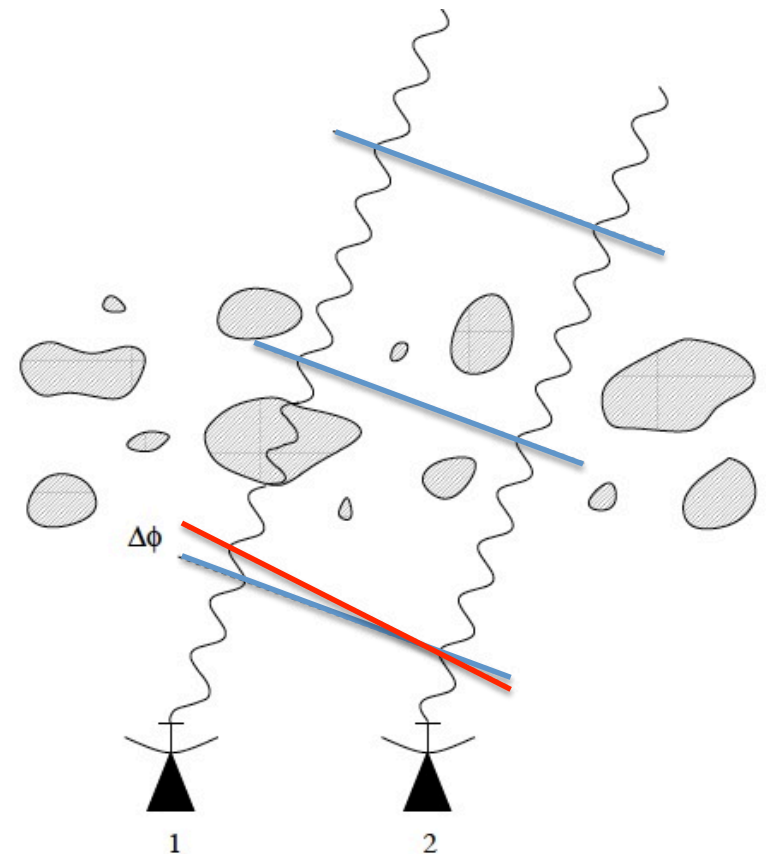
- Gain calibrator to solve for atmospheric and instrumental variations with time: Reasonably bright quasar **near** science target
- Bandpass calibrator to solve for instrumental effects and variations with frequency
Usually bright quasar
- Absolute flux calibrator to scale amplitudes
Solar system object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



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.



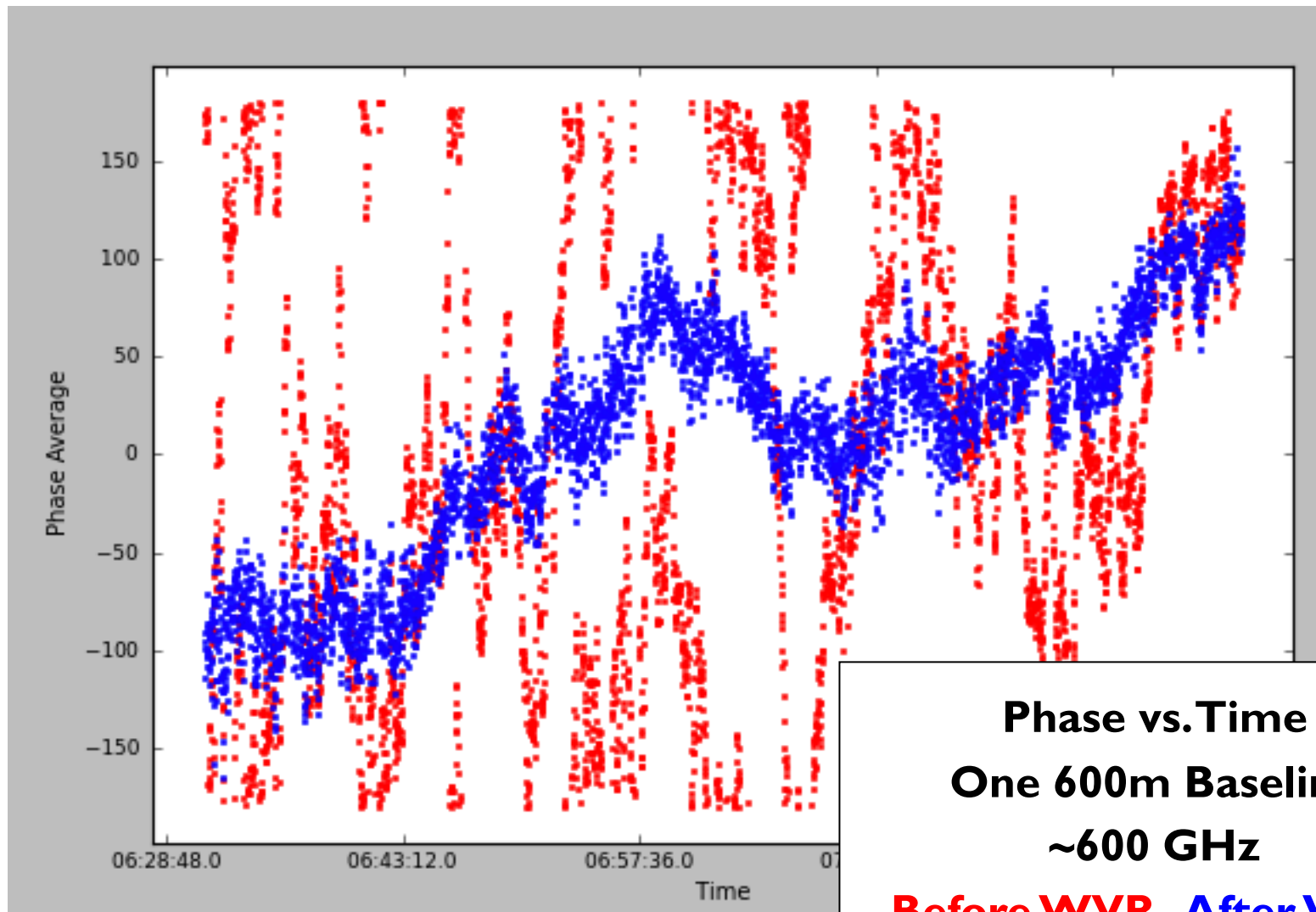
Gain (or Phase) Calibration

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



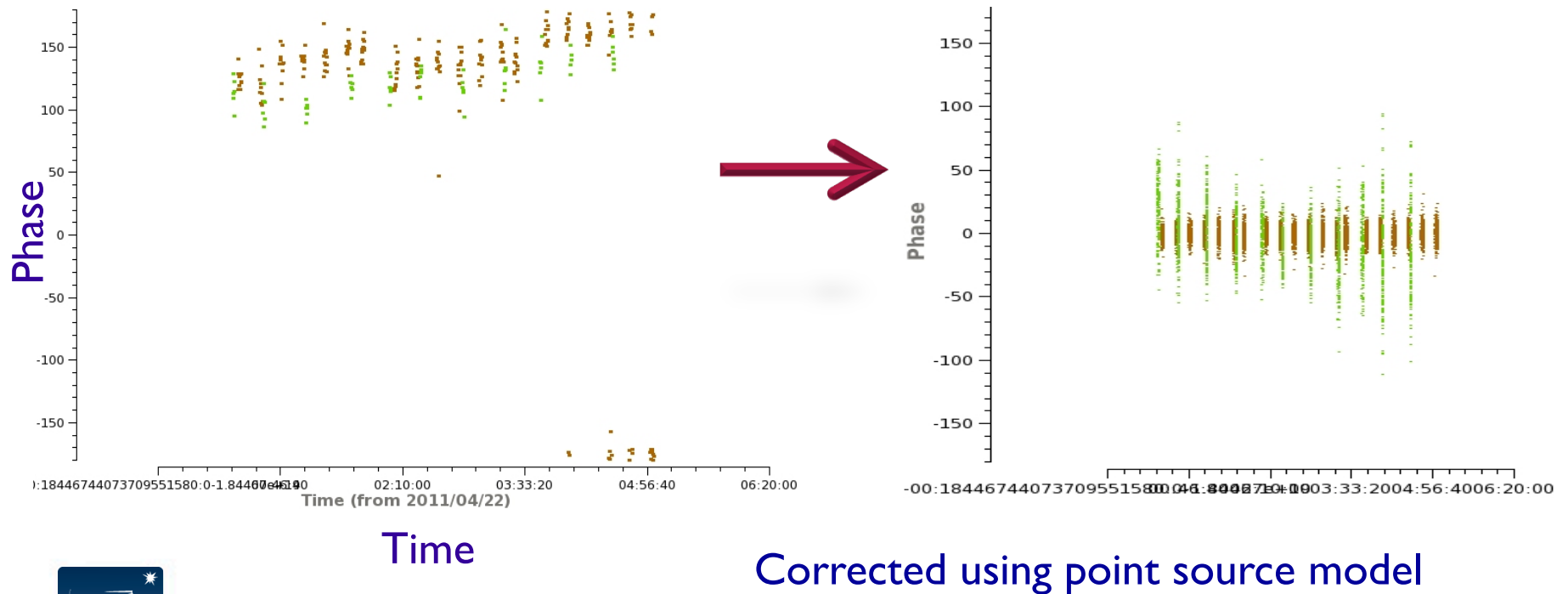
Water Vapor Correction on ALMA



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.

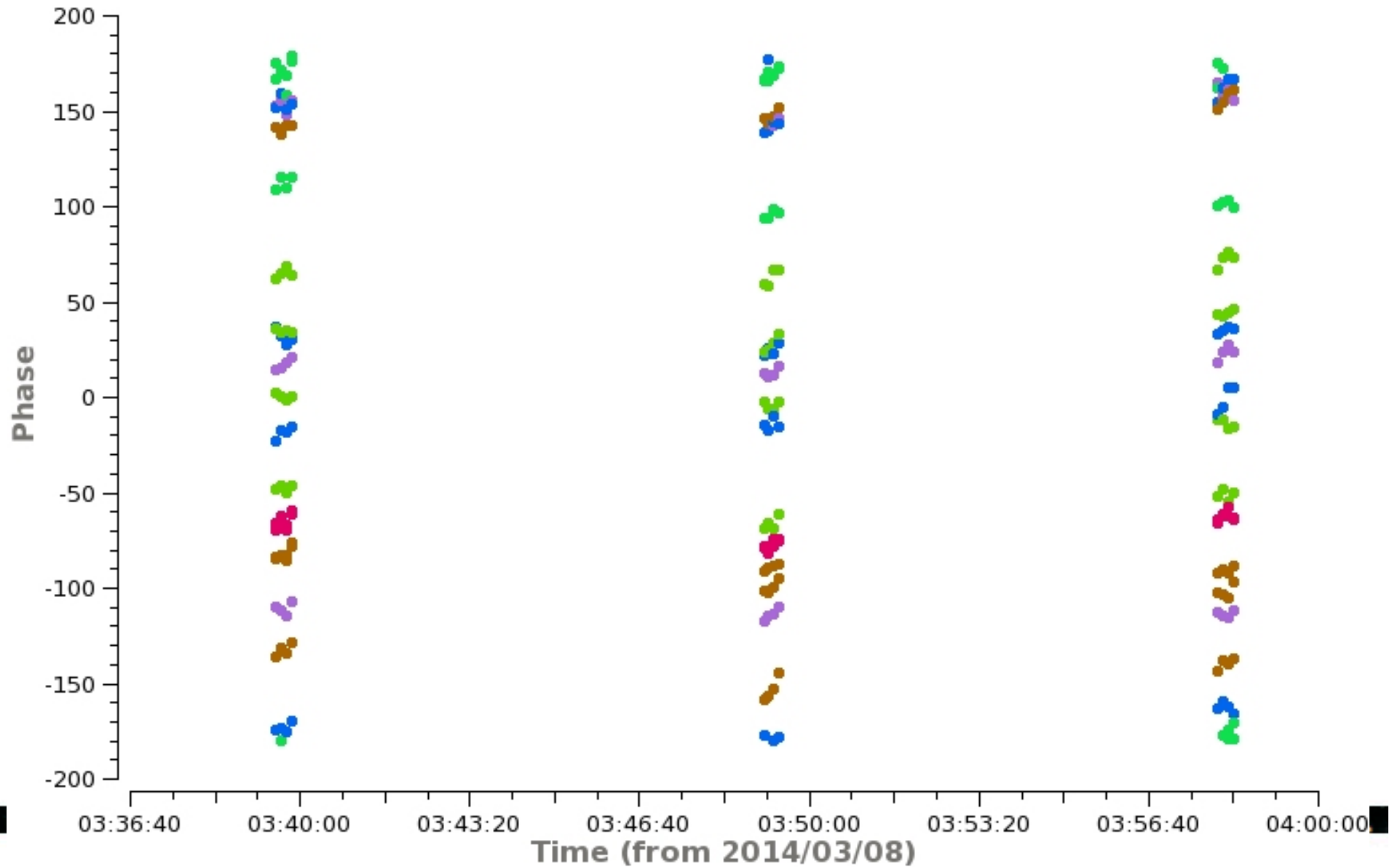


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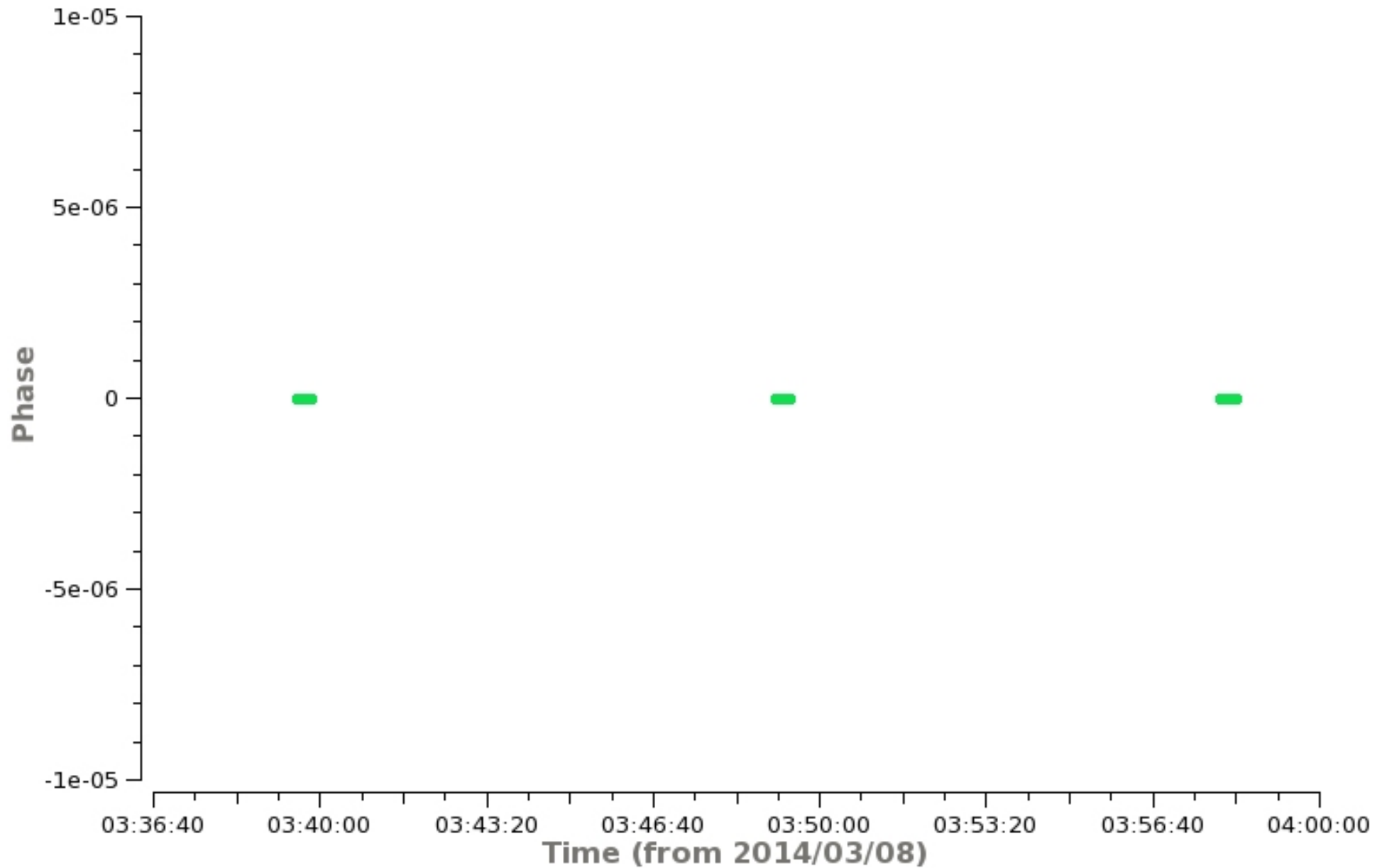
NRAO Community Day Event

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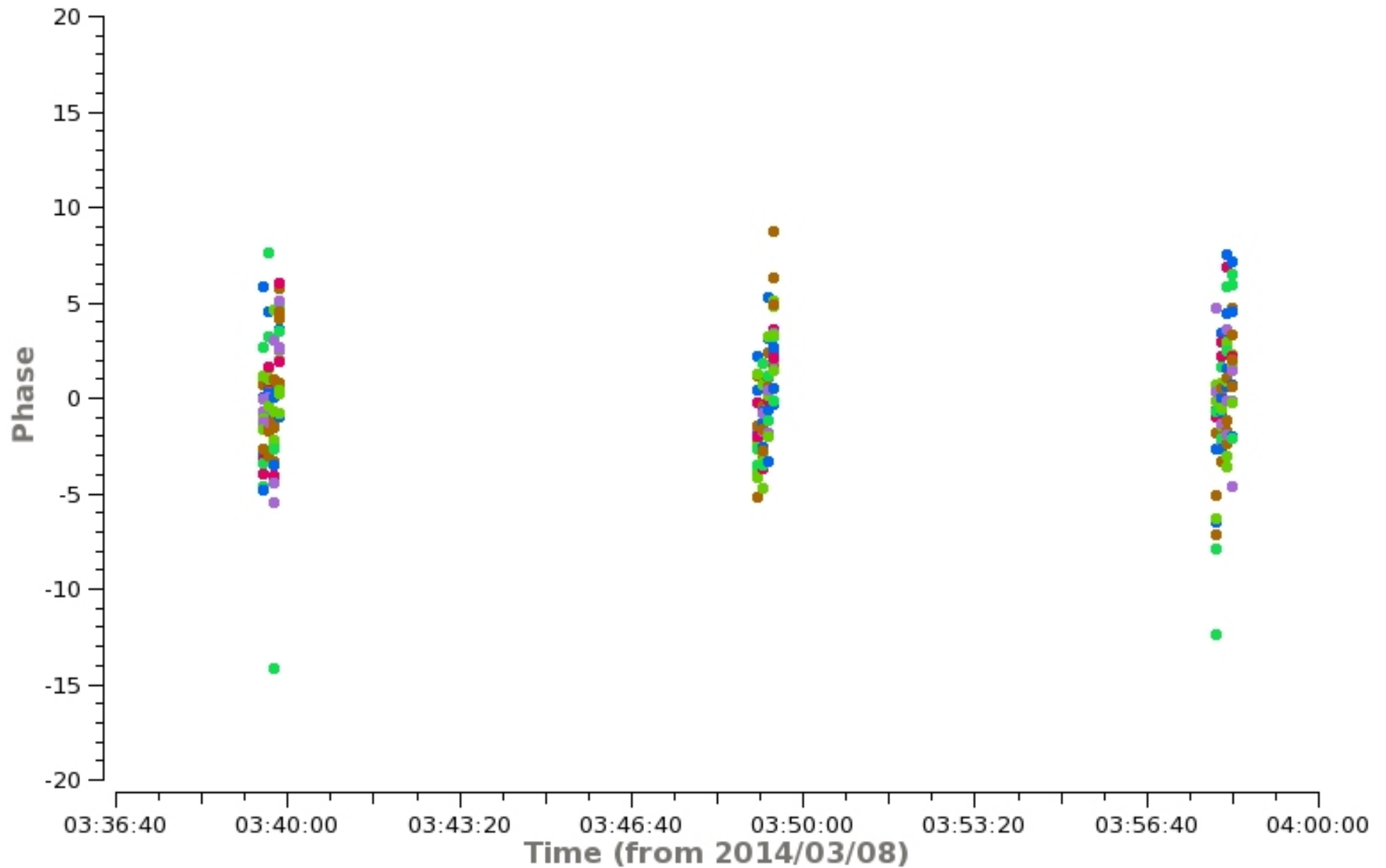
Phasecal Phase vs. Time (Before)



Phasecal Phase vs. Time (Model)



Phasecal Phase vs. Time (After)



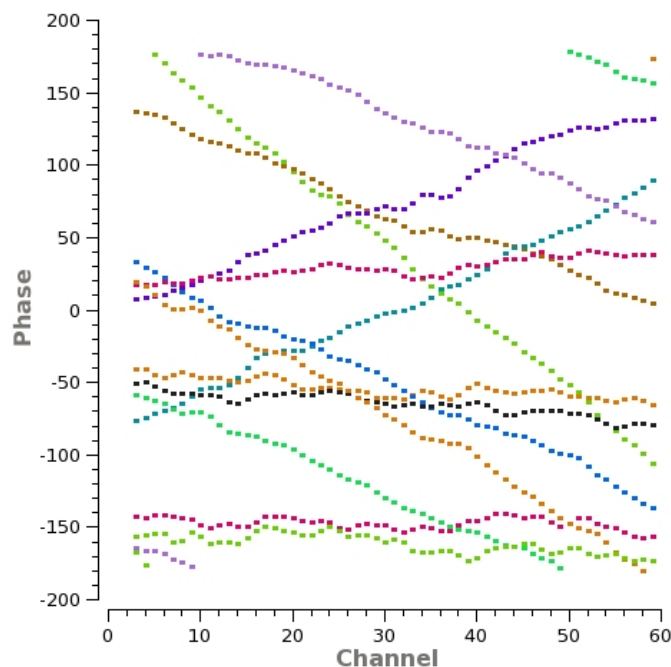
Bandpass Calibration

- 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.

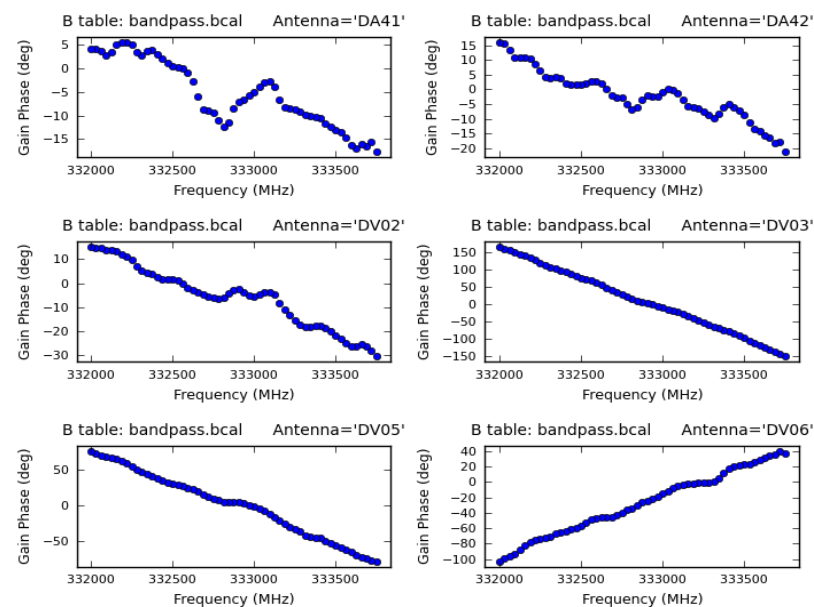
Bandpass Calibration: Phase

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

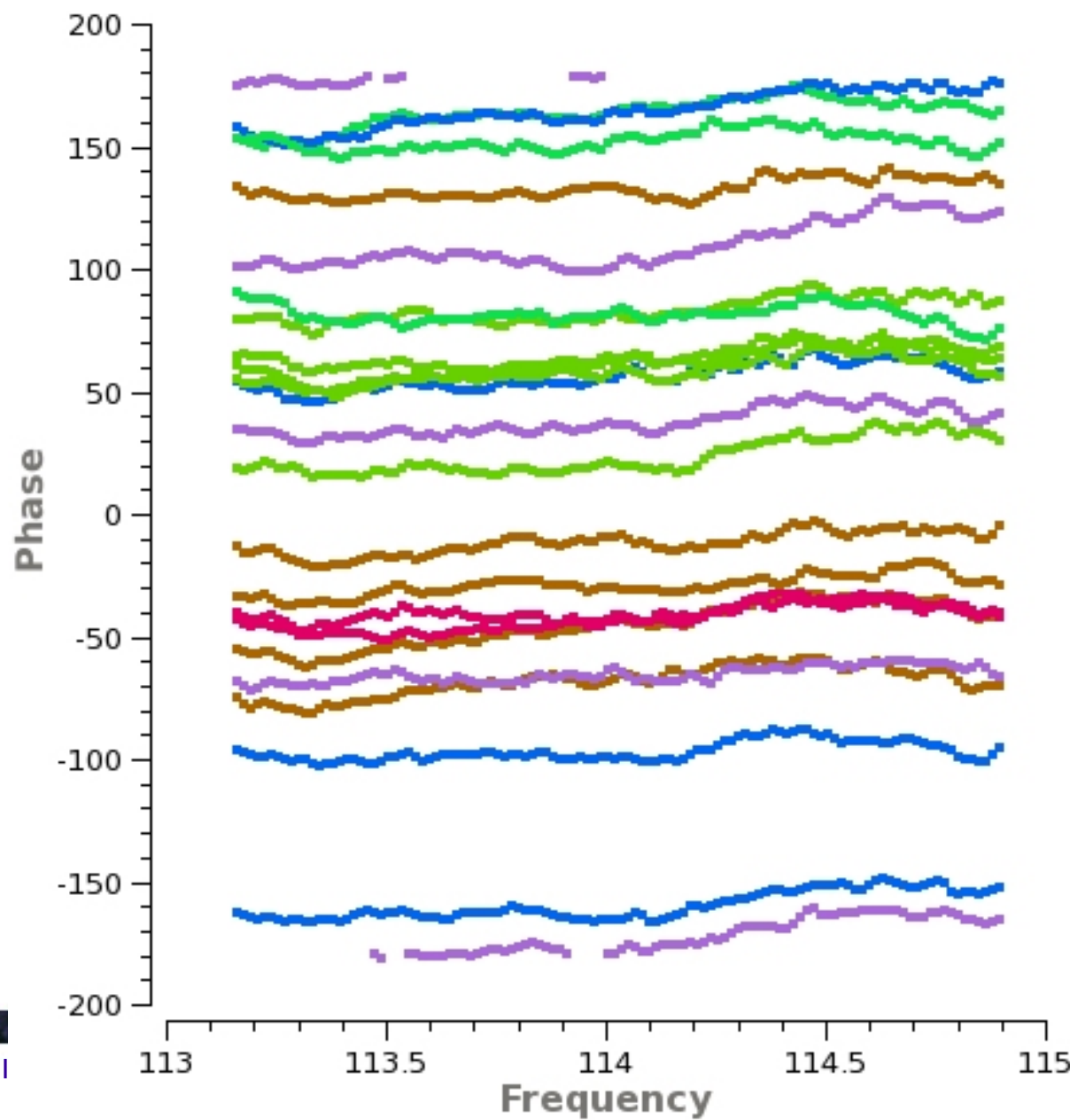
Baselines to one antenna



Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)

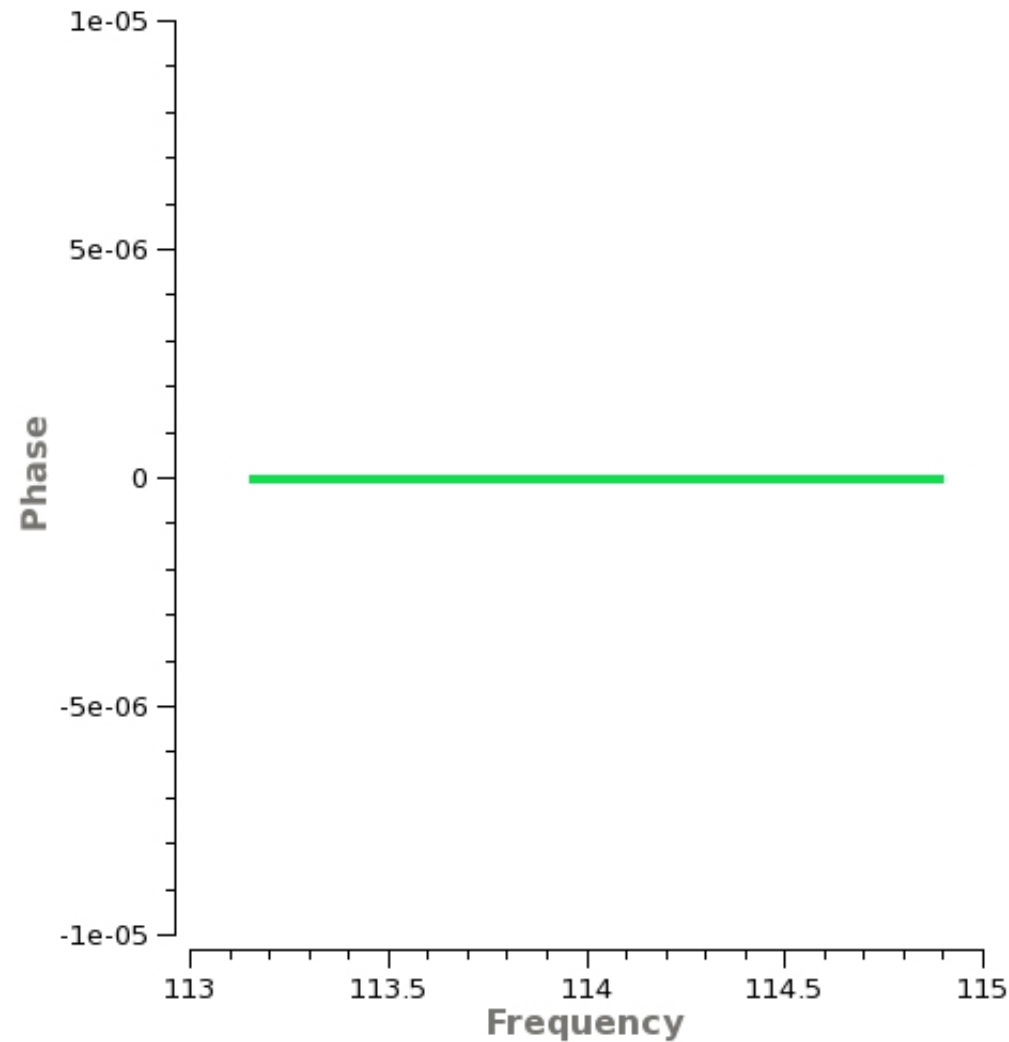


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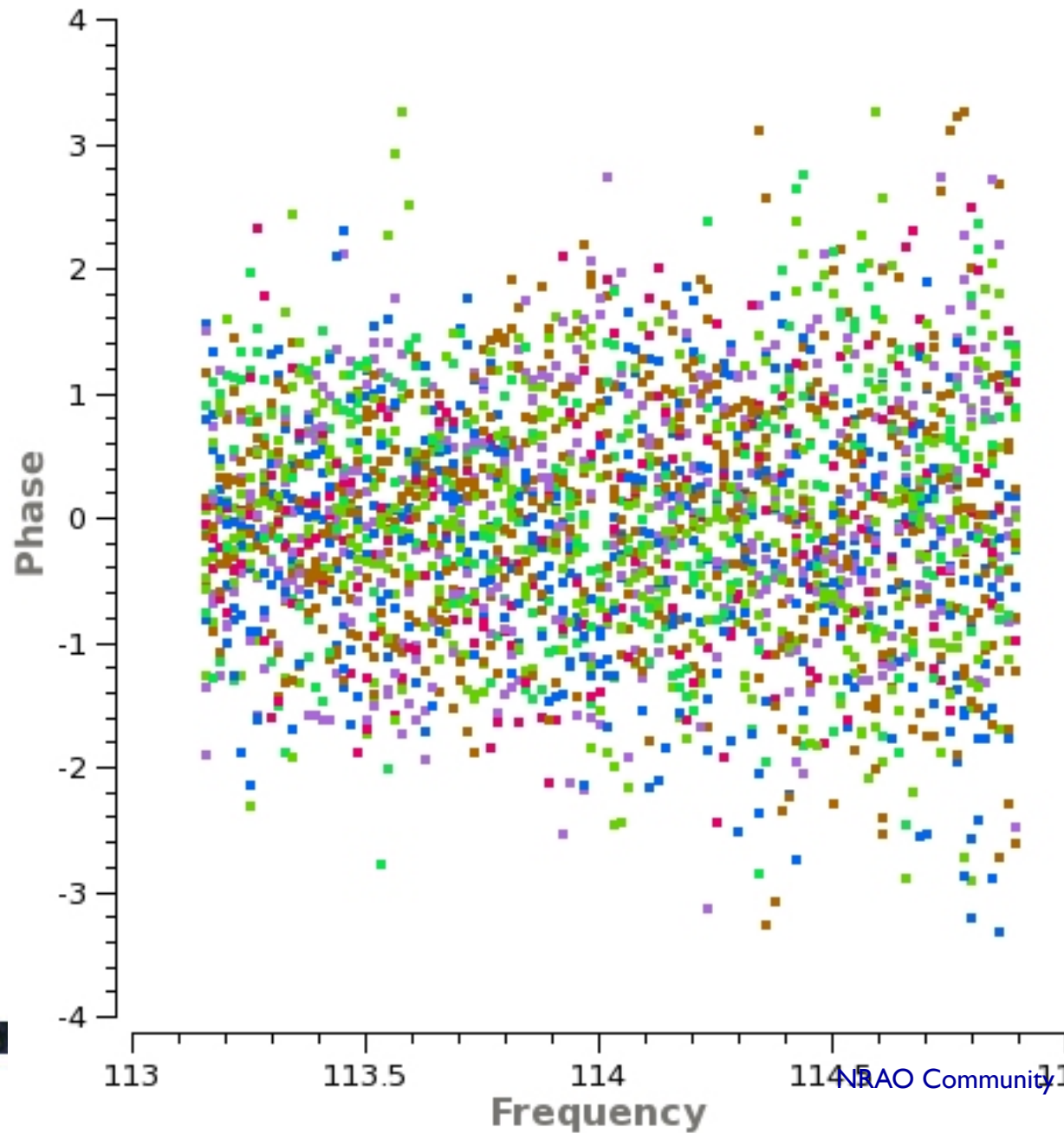
Unity Day Event

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Bandpass Phase vs. Frequency (Model)



Bandpass Phase vs. Frequency (After)



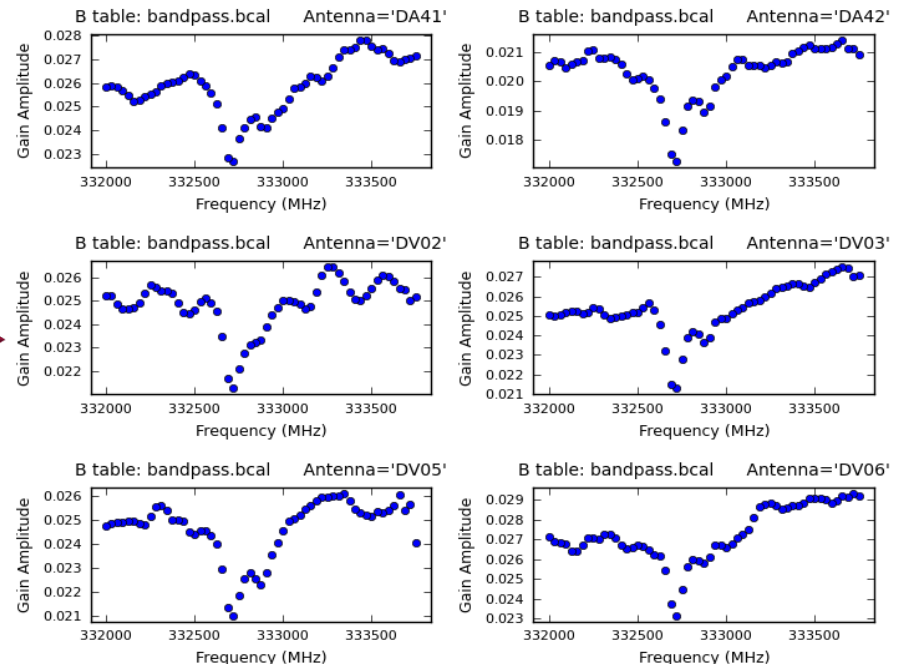
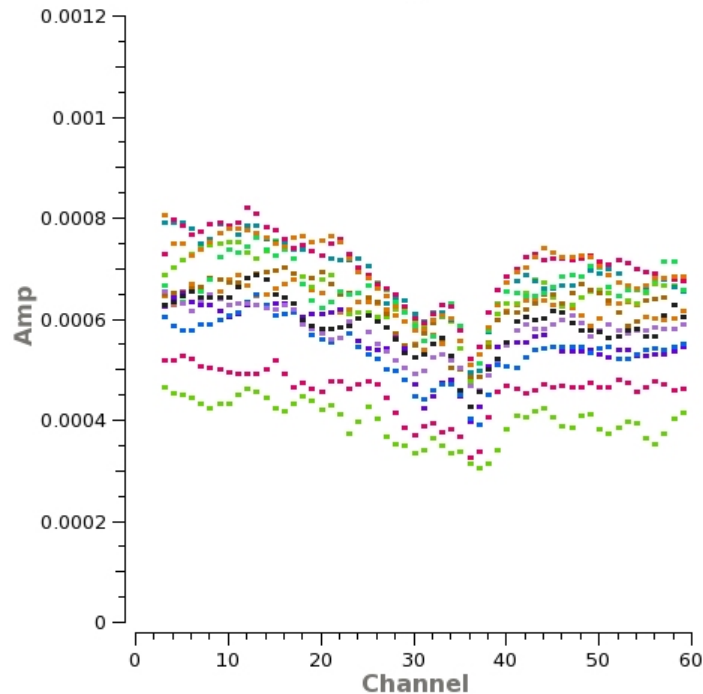
3/16/15

NRAO Community Day Event

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Bandpass Calibration: Amplitude

Baselines to one antenna



Amplitude Before Bandpass Calibration

Antenna-based Bandpass Solution

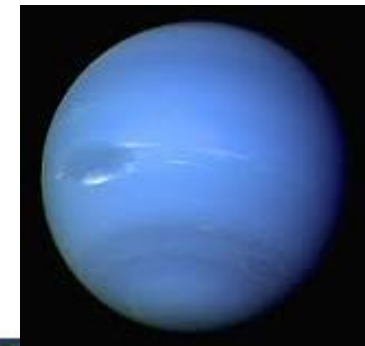


3/16/15

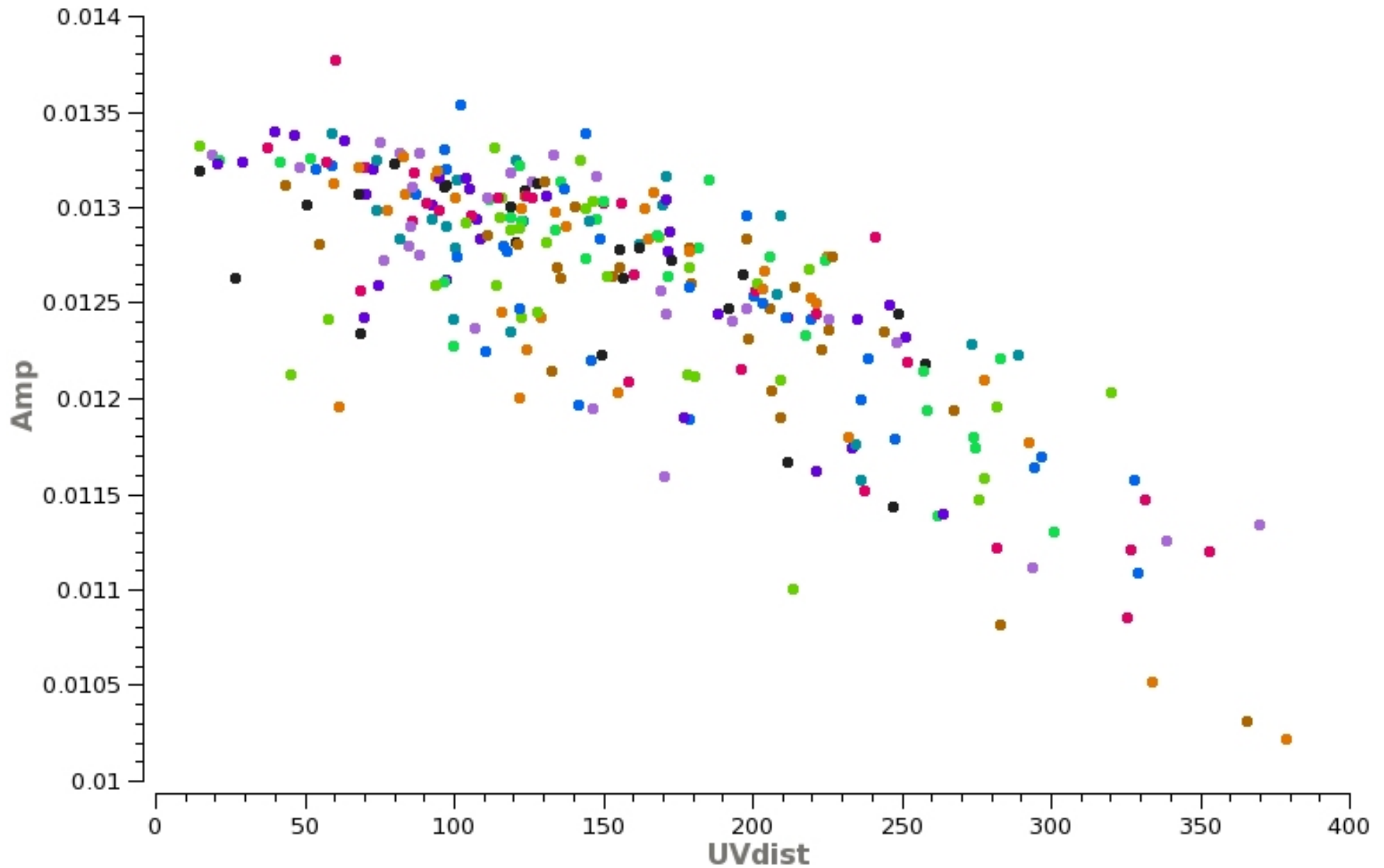
Flux (or Amplitude) Calibration

Two Steps:

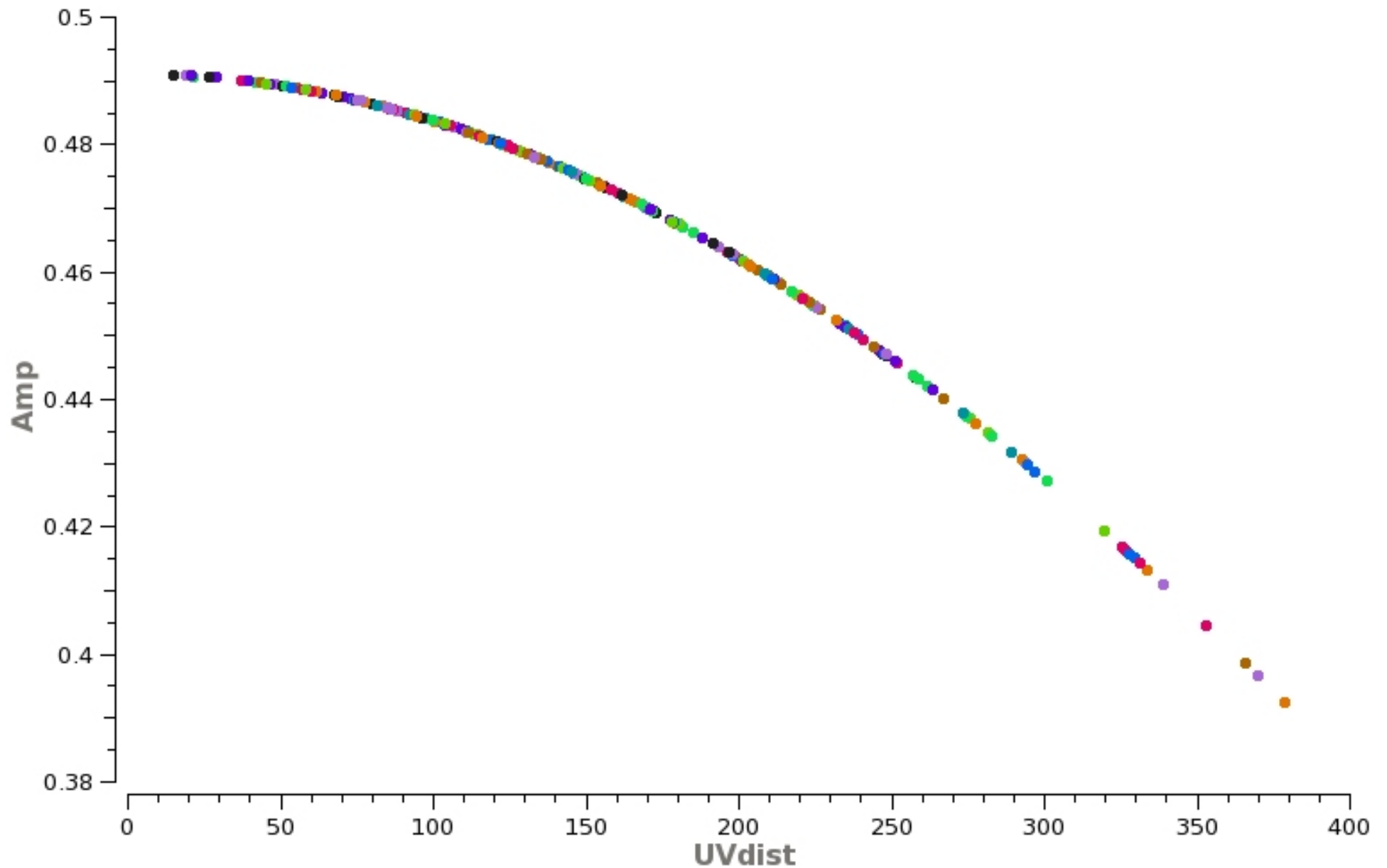
- Use calibration devices of known temperature (hotload and ambient load) to measure System Temperature frequently.
- Use a source of known flux to convert the signal measured at the antenna to common unit (Janskys). If the source is resolved, or has spectral lines, it must be very well modeled.
- The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



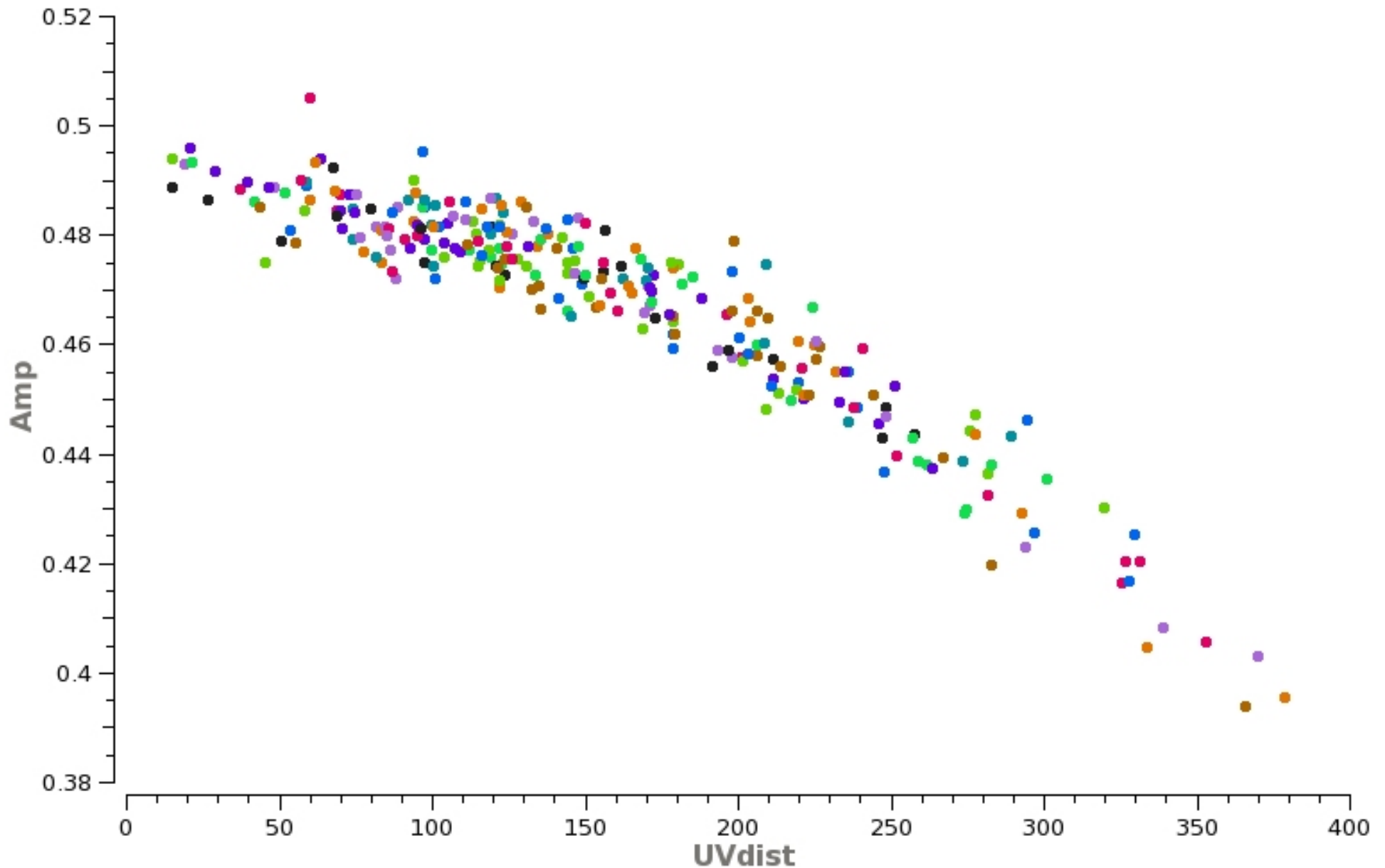
Ampcal Amplitude vs. uv-distance (Before)



Ampcal Amplitude vs. uv-distance (Model)



Ampcal Amplitude vs. uv-distance (After)



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



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.

