Introduction to Radio Interferometry

Cassie Reuter

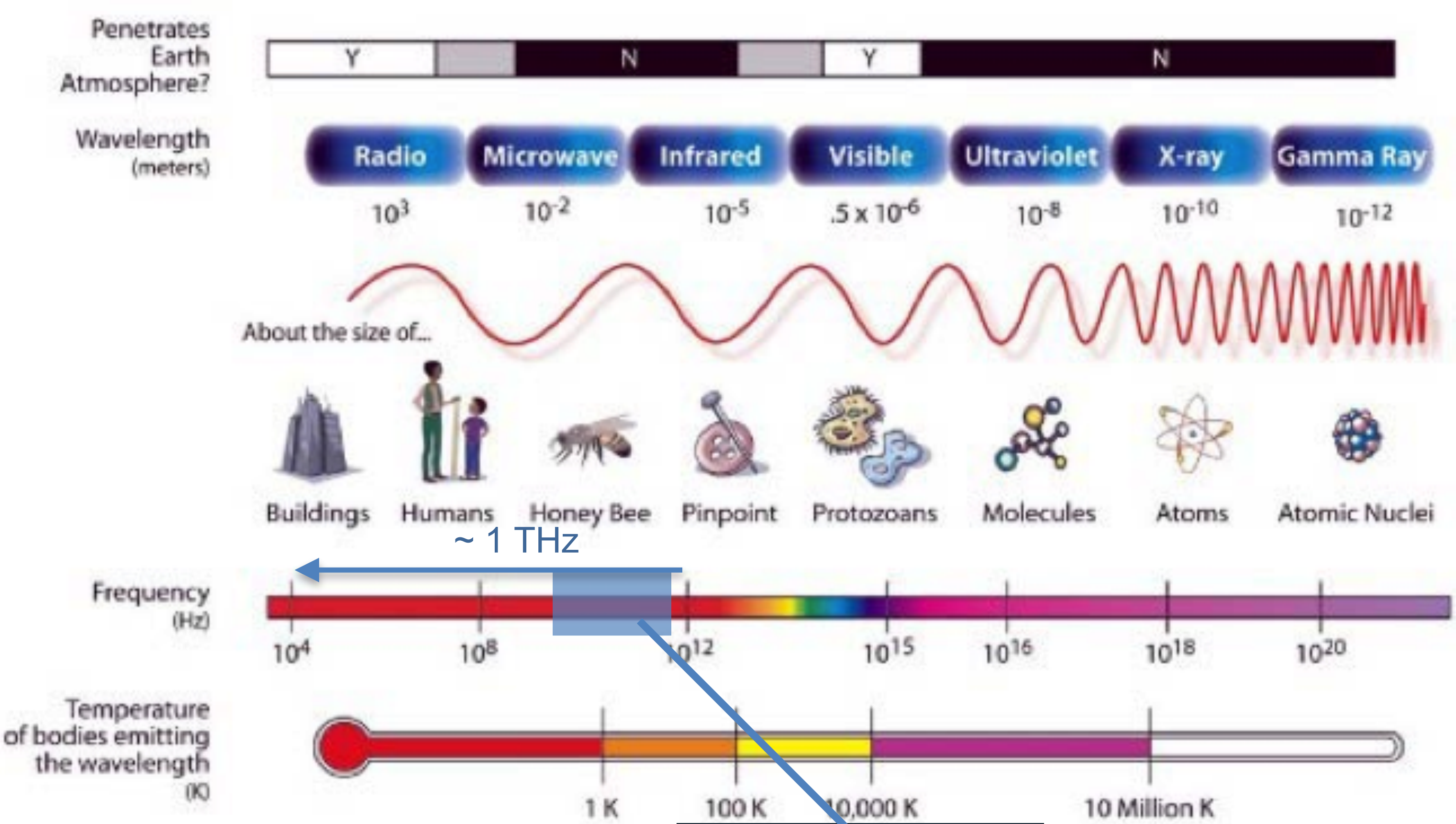
Authors: Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

Brief Outline

- Why Radio Astronomy
- What is interferometry?
- Fourier transforms
- UV plane sampling
- Calibration

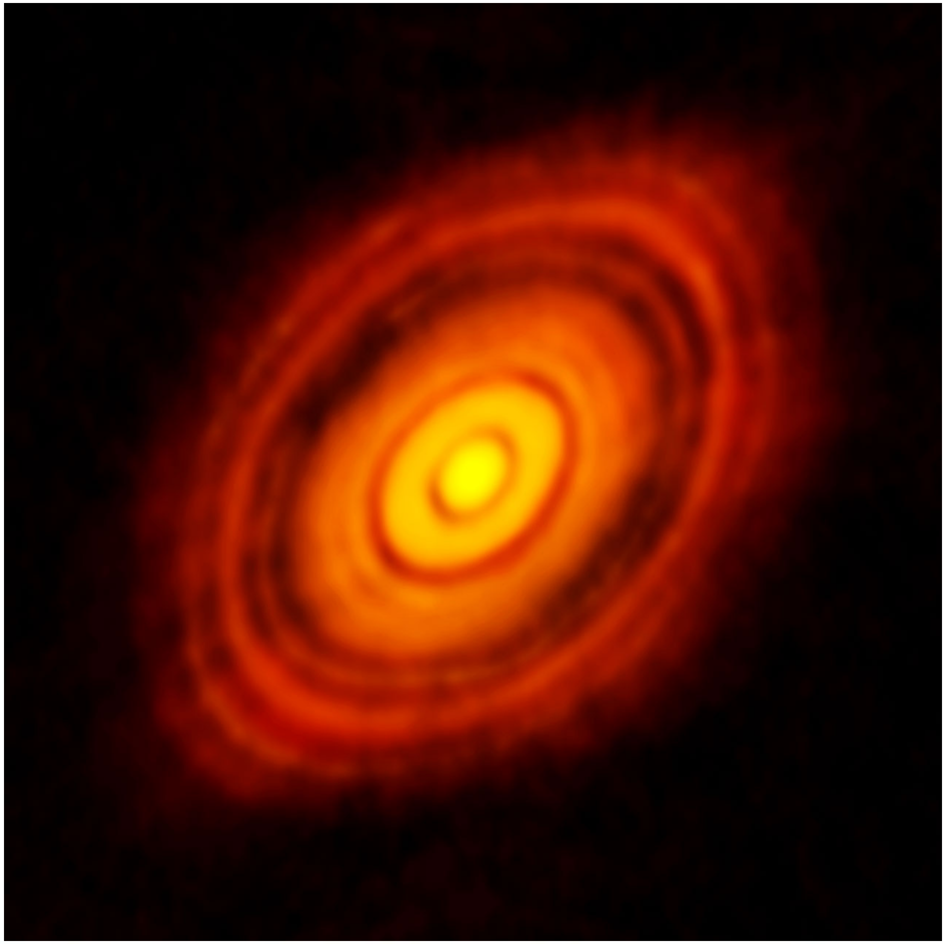
What is radio astronomy?



ALMA
~84 - 950 GHz
~3 - 0.3 mm

What can you observe?

Protoplanetary discs like this one around HL Tauri!

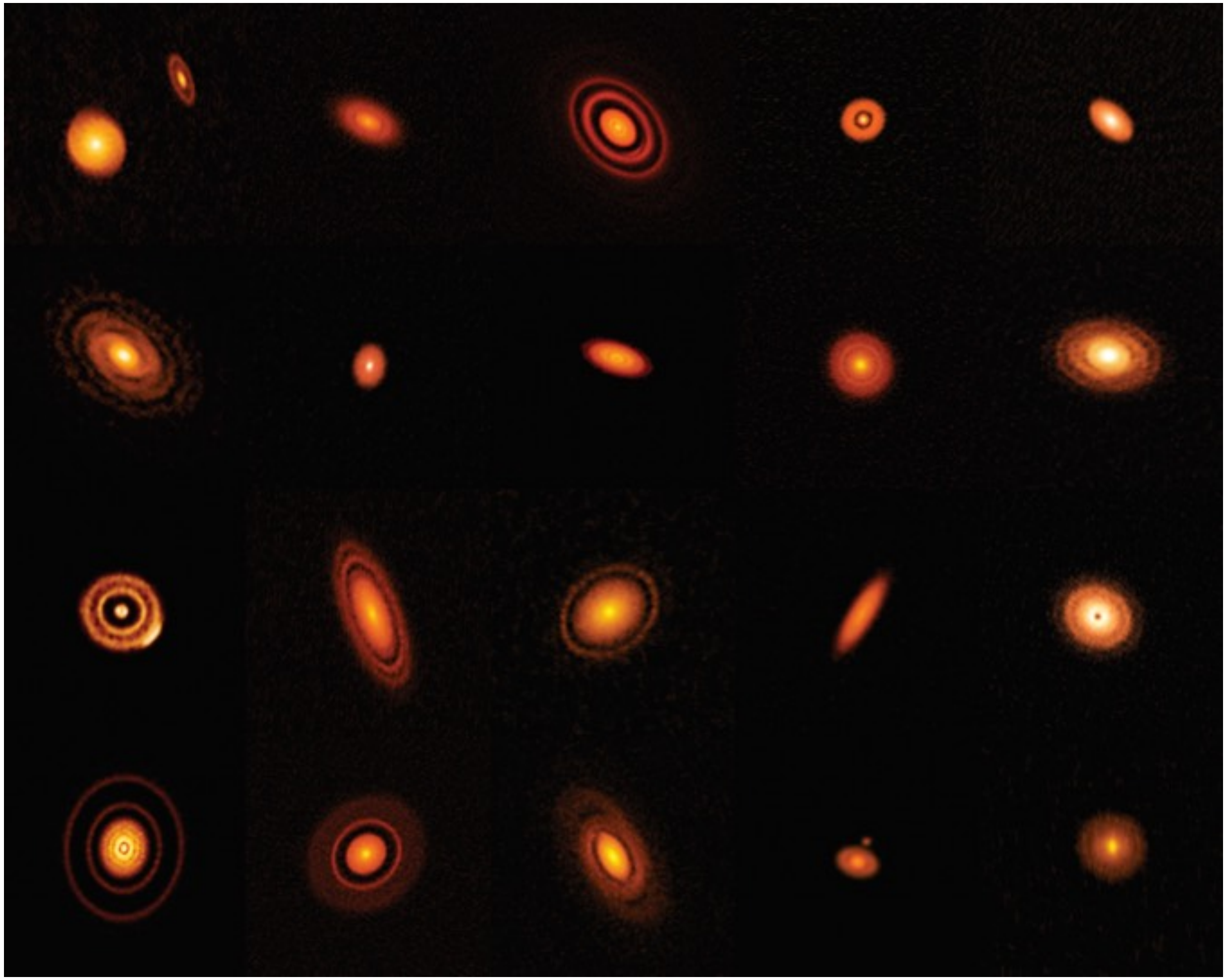


arXiv:1503.02649

Credit: ALMA (NRAO/ESO/NAOJ)

What can you observe?

A Protoplanetary Zoo!



arXiv: 1812.04040

Credit: ALMA (NRAO/ESO/NAOJ)

What can you observe?

A Star sprinkled with salt!

arxiv: 1901.04489

Credit: NRAO/AUI/NSF; S. Dagnello

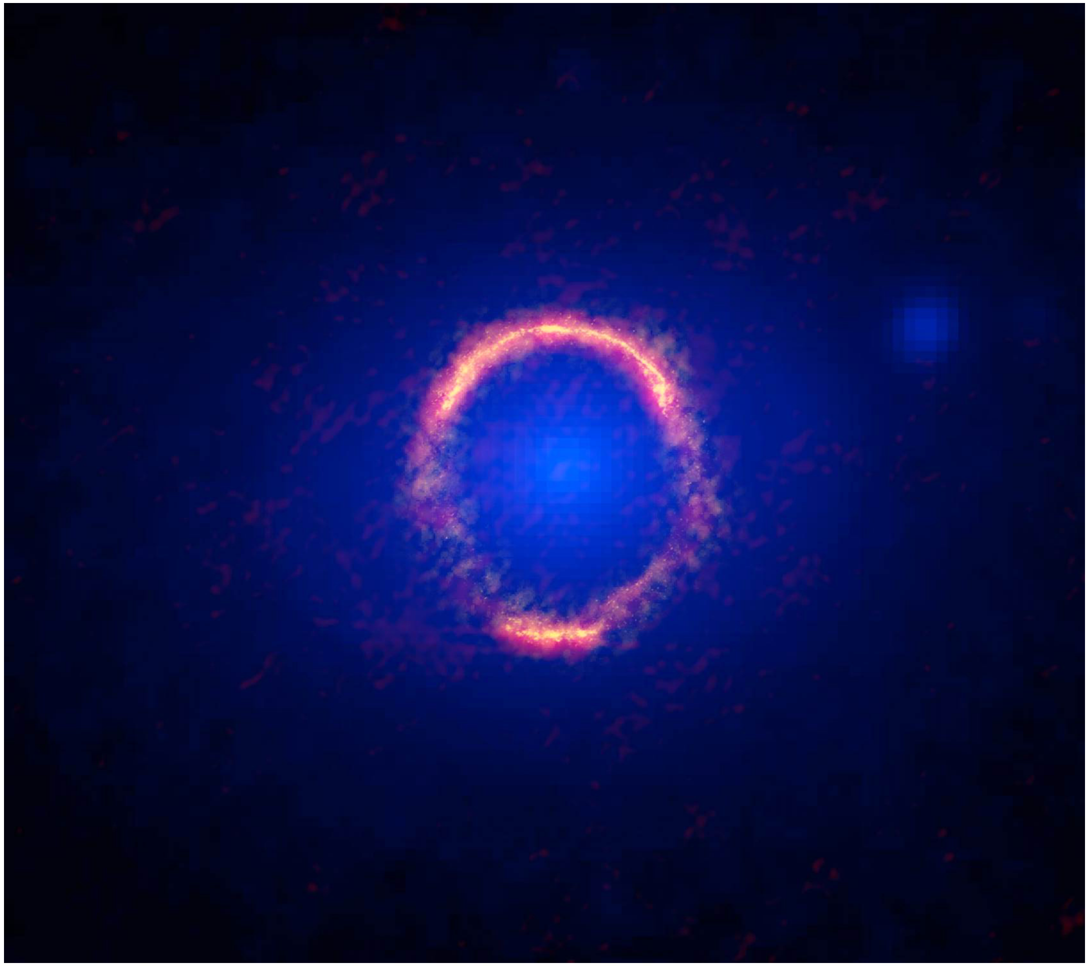
What can you observe?

We can observe a broad range of molecular lines

ALMA (ESO/NAOJ/NRAO). Visible light image: the NASA/ESA Hubble Space Telescope

What can we observe?

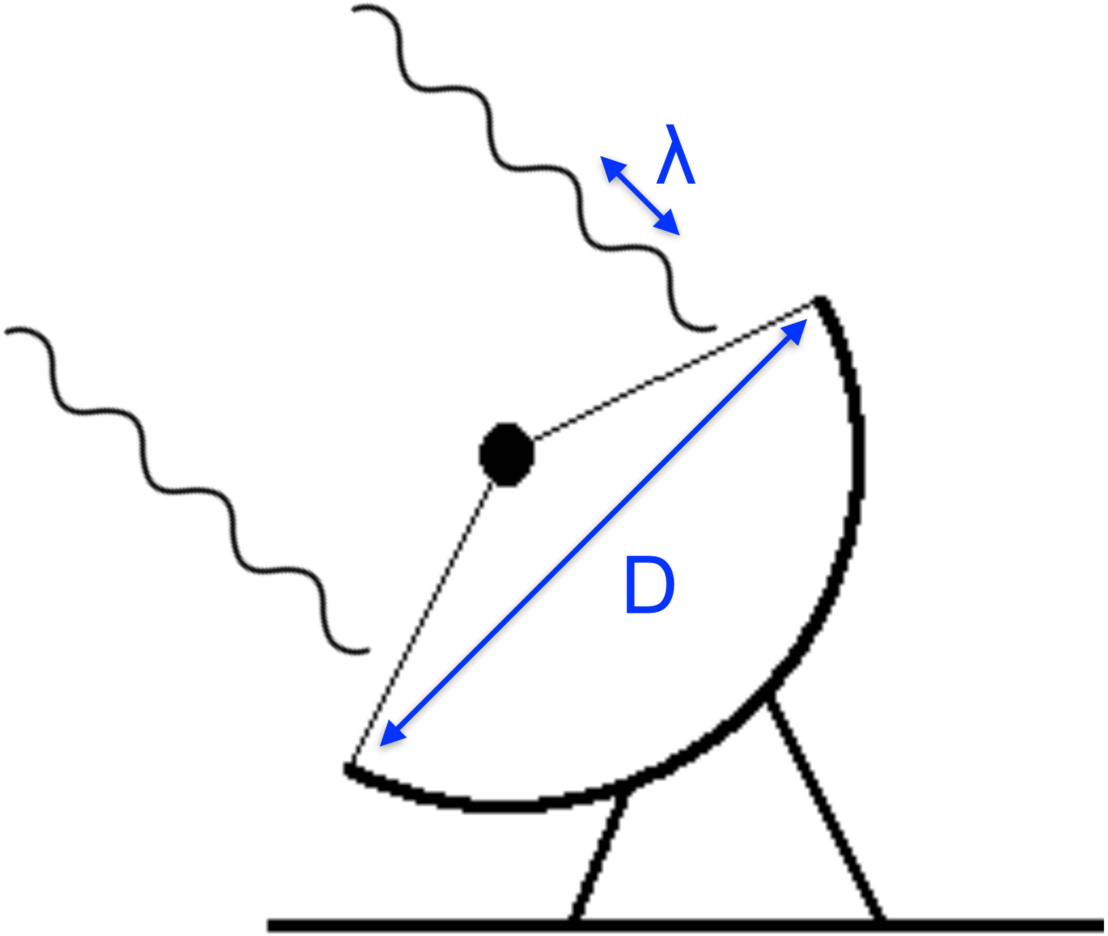
Gravitational lensing of high-z galaxies



arXiv:1601.01388

Credit: ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF; NASA/ESA Hubble, T. Hunter (NRAO).

Diffraction theory



A single telescope has a resolution of ~ λ/D

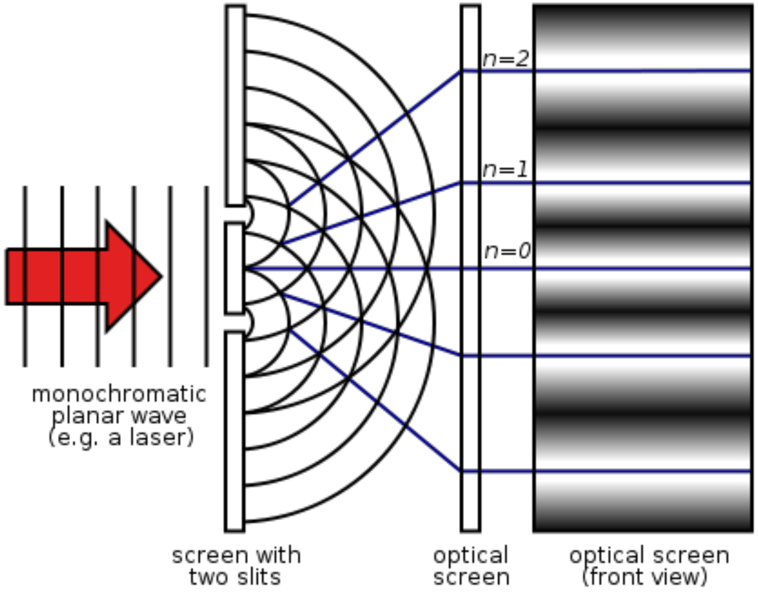
For the Hubble Space Telescope:

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

To reach that resolution at λ ~1mm, we would need a ~2 km-diameter dish!

What is an interferometer?

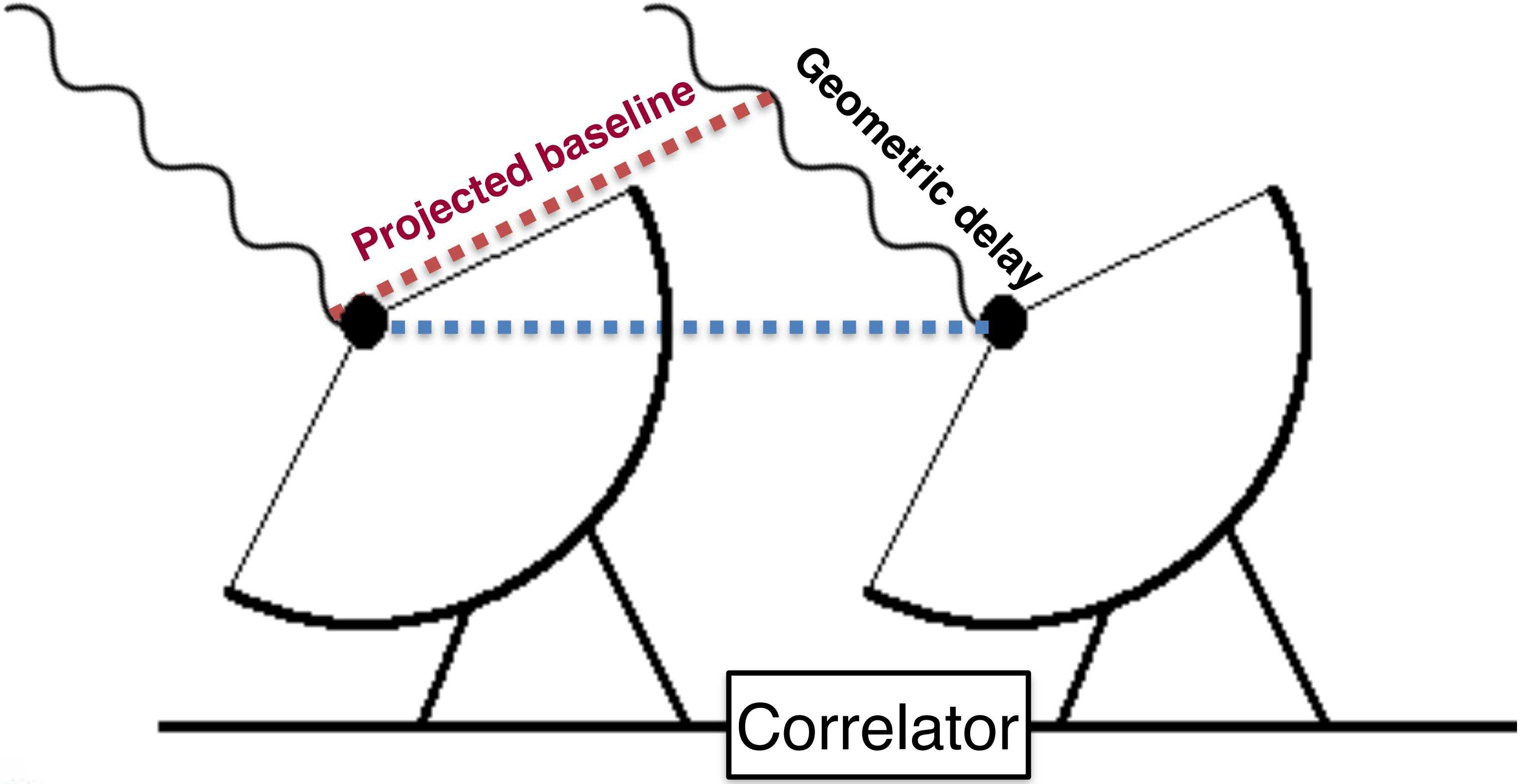
An *interferometer* measures the interference pattern produced by multiple apertures



So, let’s add an aperture!

Projected baseline width plays the role of D in λ/D

Bigger baselines = better resolution!

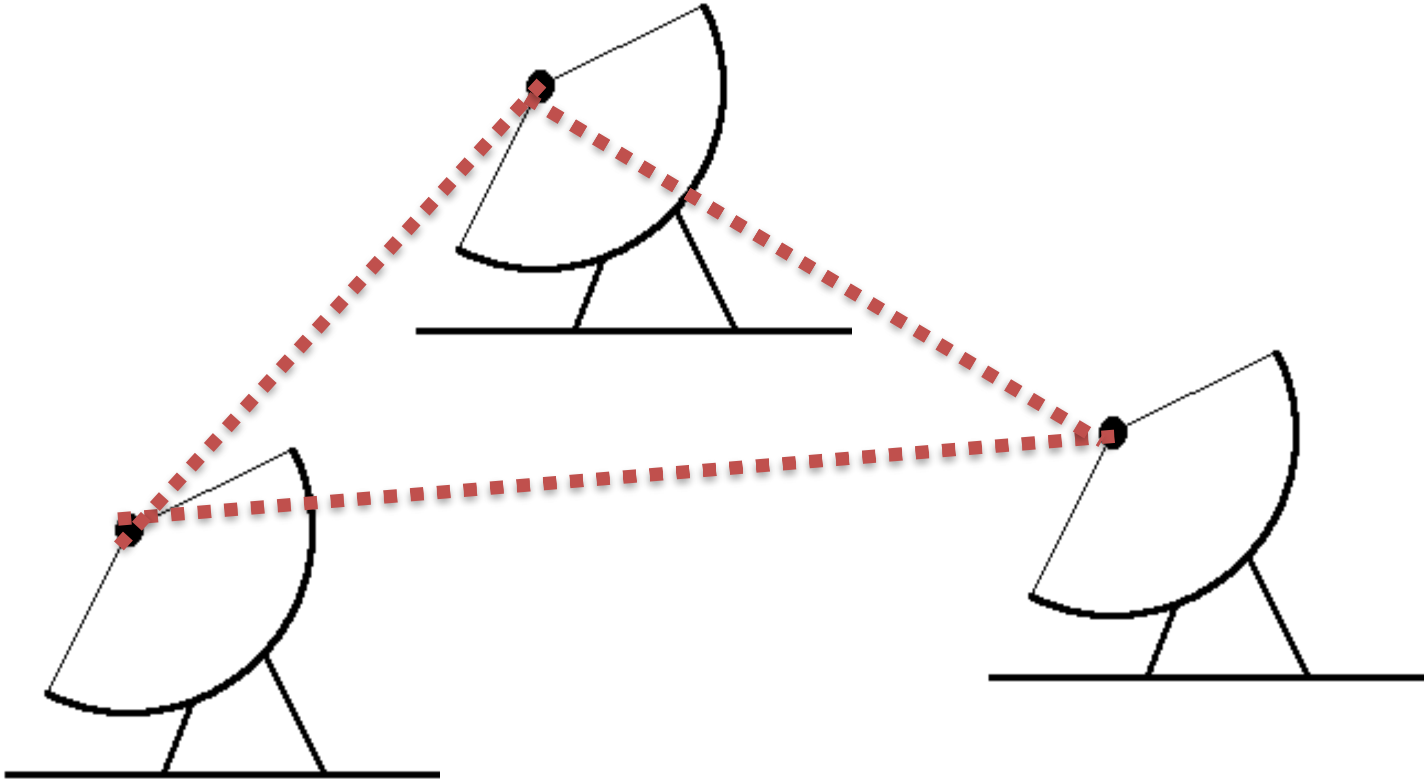


What happens with one more telescope?

One pair of antennas = one baseline

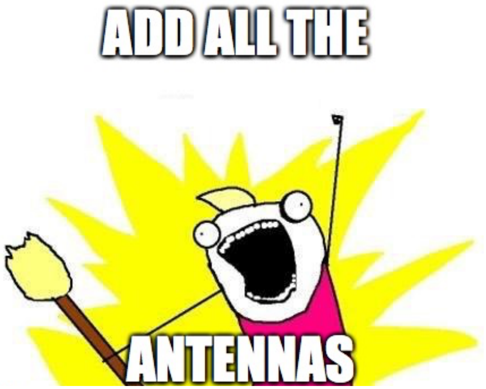
Each pair of antennas samples the source **twice.**

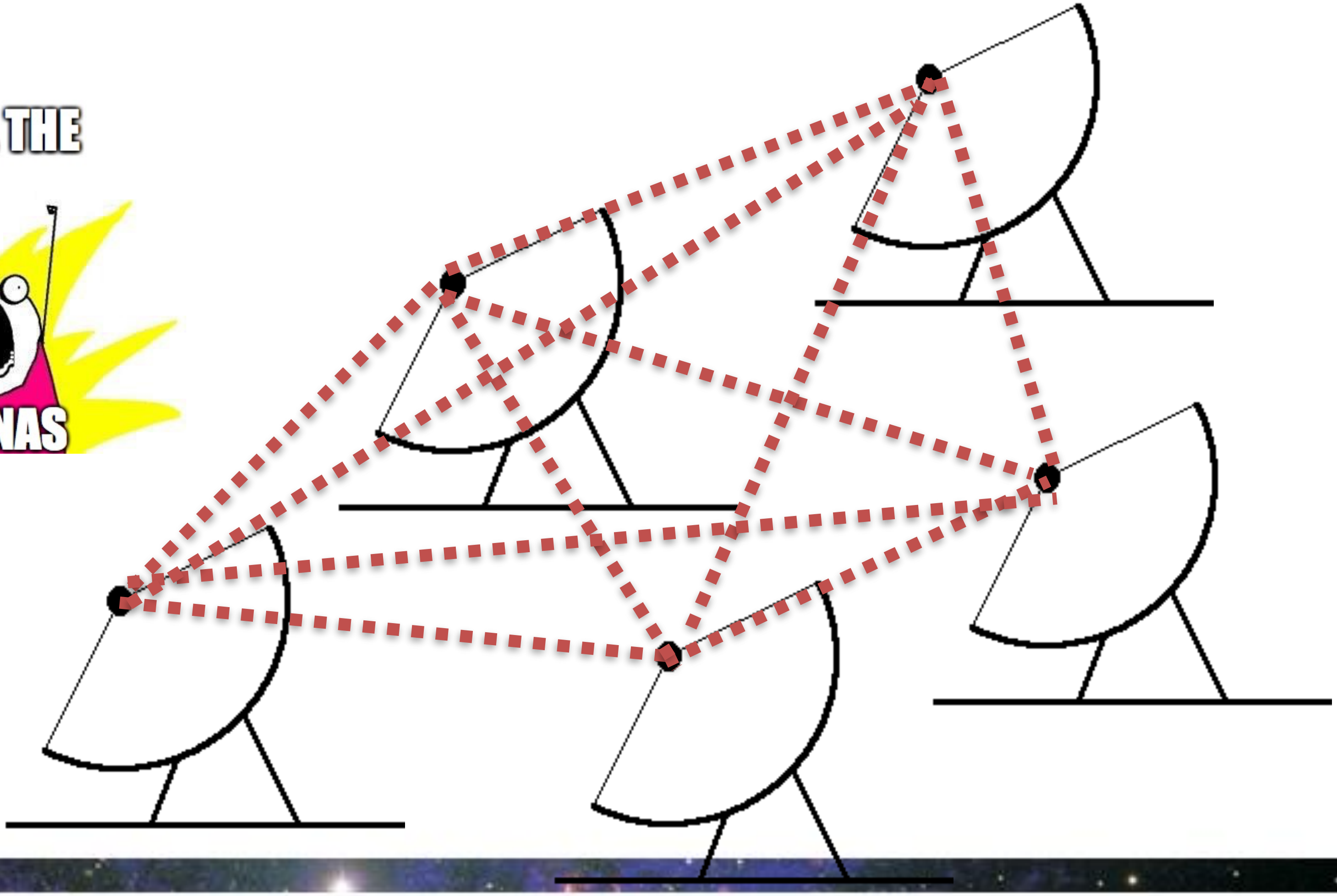
For **3 antennas**, we get **3 baselines,**
so we are sampling the source a total of **6 times**



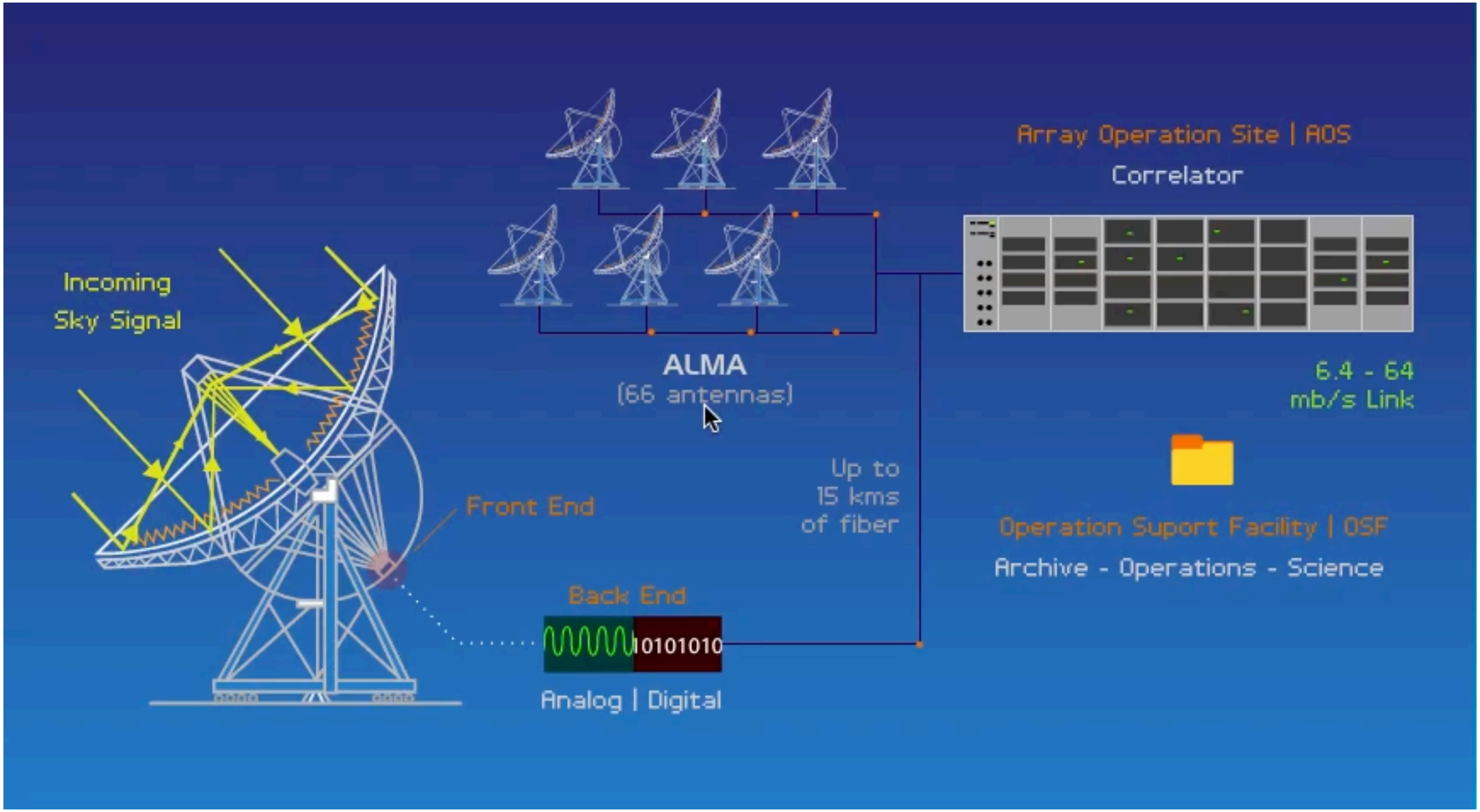
What happens with more telescopes?

For **N antennas**, we get **N(N-1) samples** at a time, increasing our sensitivity



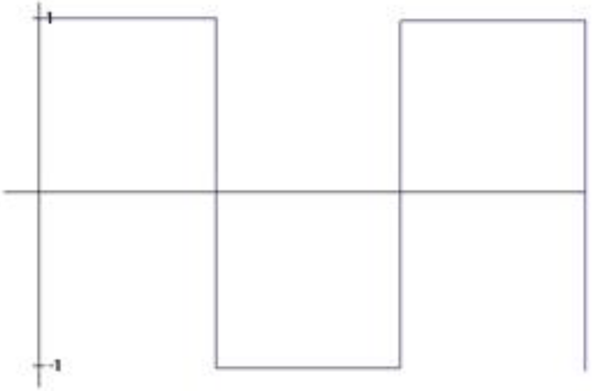


An Interferometer In Action



Introducing the Fourier Transform

Fourier theory states that any well behaved signal (including images) can be expressed as the sum of sinusoids WITHOUT loss of information



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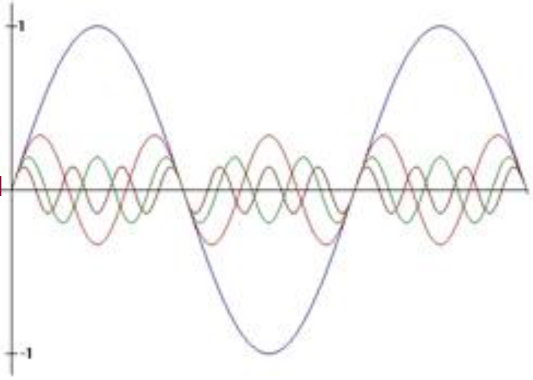

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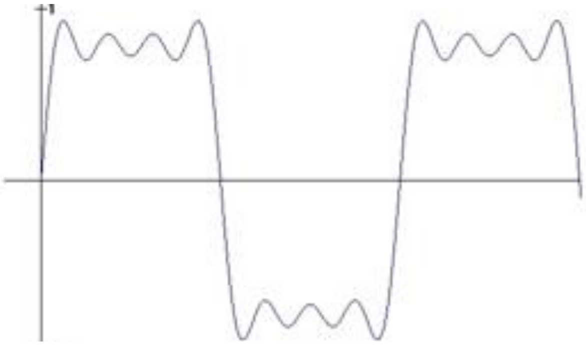


Reference signal

4 sinusoids (signal)

Sum of reference & signal

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

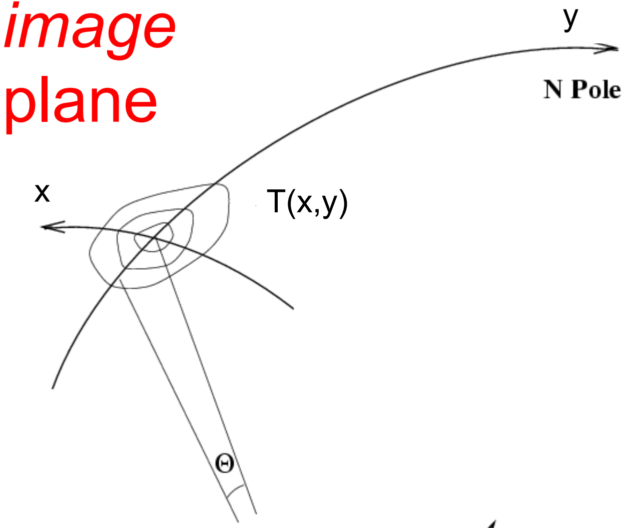
Fourier space/

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

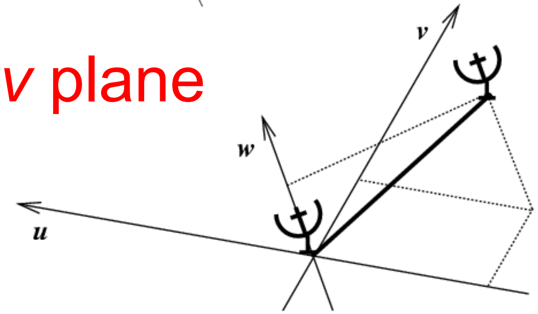
Image space/

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

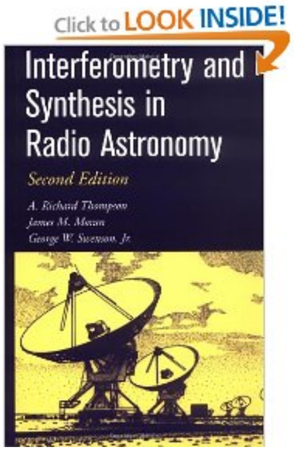
image plane



uv plane



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



Click to LOOK INSIDE!

Interferometry and Synthesis in Radio Astronomy

Second Edition

A. Richard Thompson
James M. Moran
George W. Swenson, Jr.

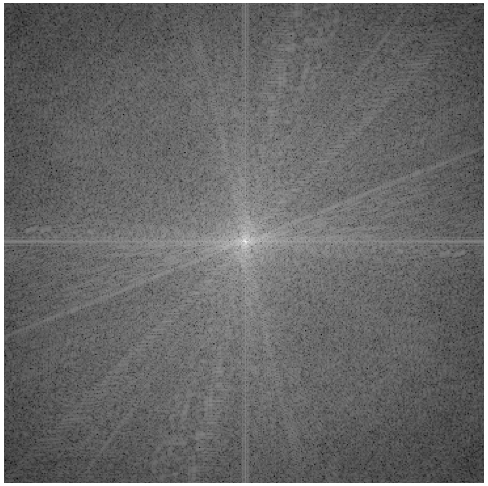
What Are Visibilities?

Each V(u,v) contains information on T(x,y) everywhere

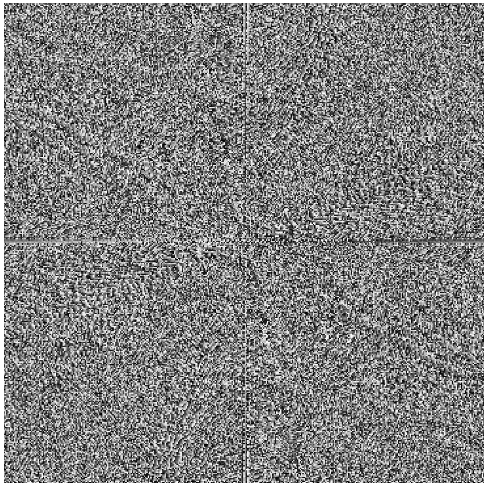
Each V(u,v) is a complex quantity

T(x,y)

FT →

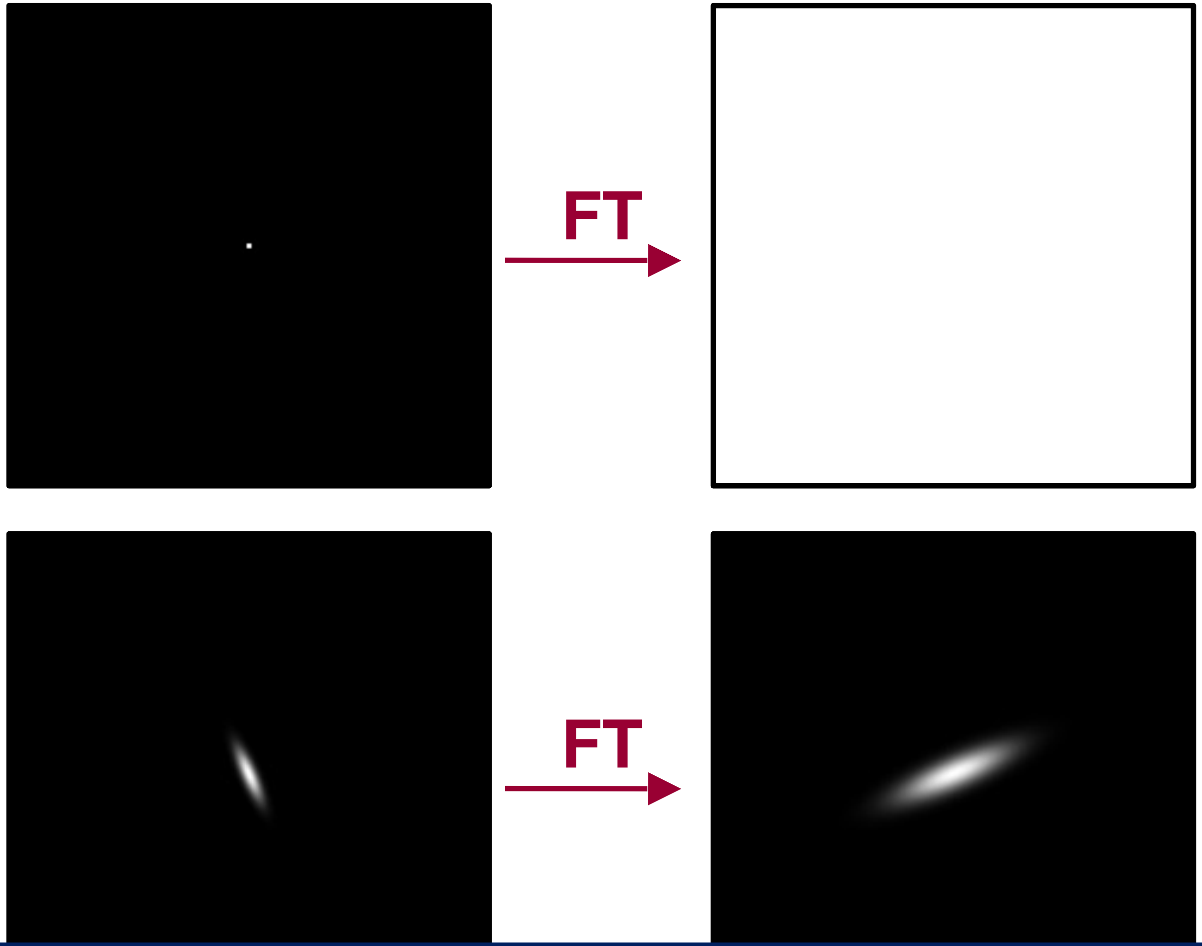


V(u,v) amplitude



V(u,v) phase

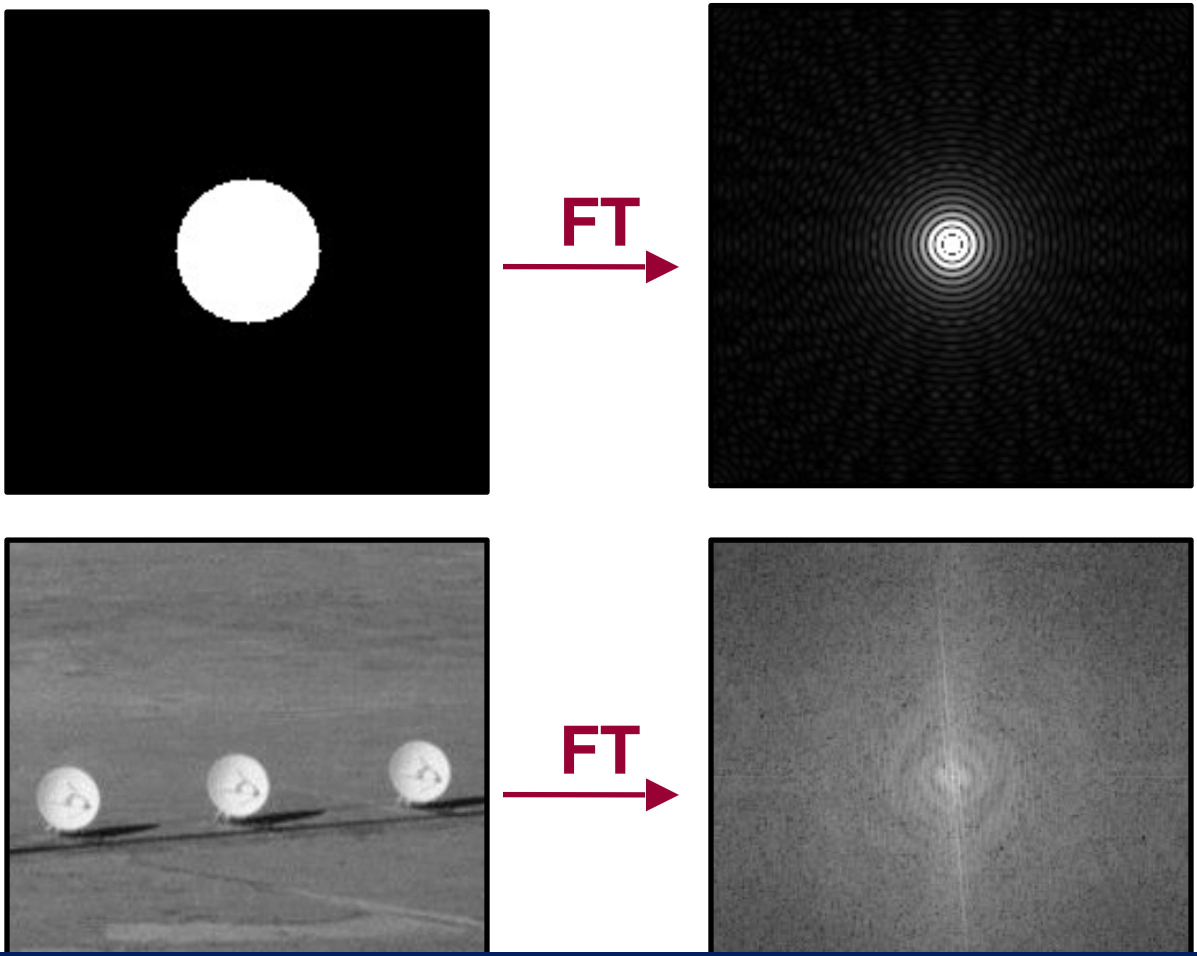
Examples of 2D Fourier Transforms



Rule of Thumb #1:

Narrow features <—> Wide features

Examples of 2D Fourier Transforms



T(x,y)

V(u,v) amplitude

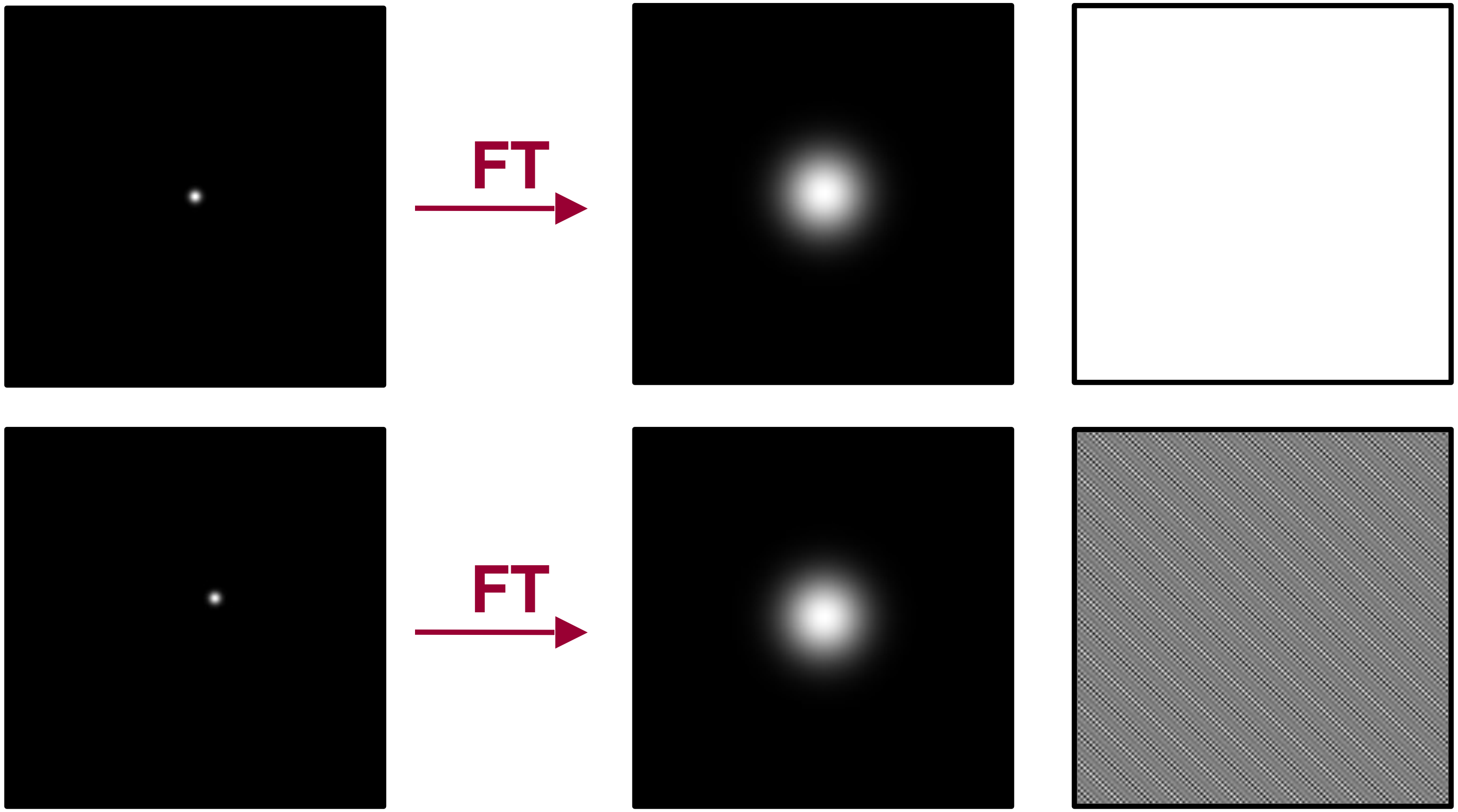
Uniform Disk → **FT** → **Bessel Function**

VLA Antennas → **FT** → **Bessel Function!**

Rule of thumb #2:

Edges -> high spatial features

Examples of 2D Fourier Transforms



T(x,y)

V(u,v) amplitude

V(u,v) phase

Centered Gaussian

FT

Offset Gaussian

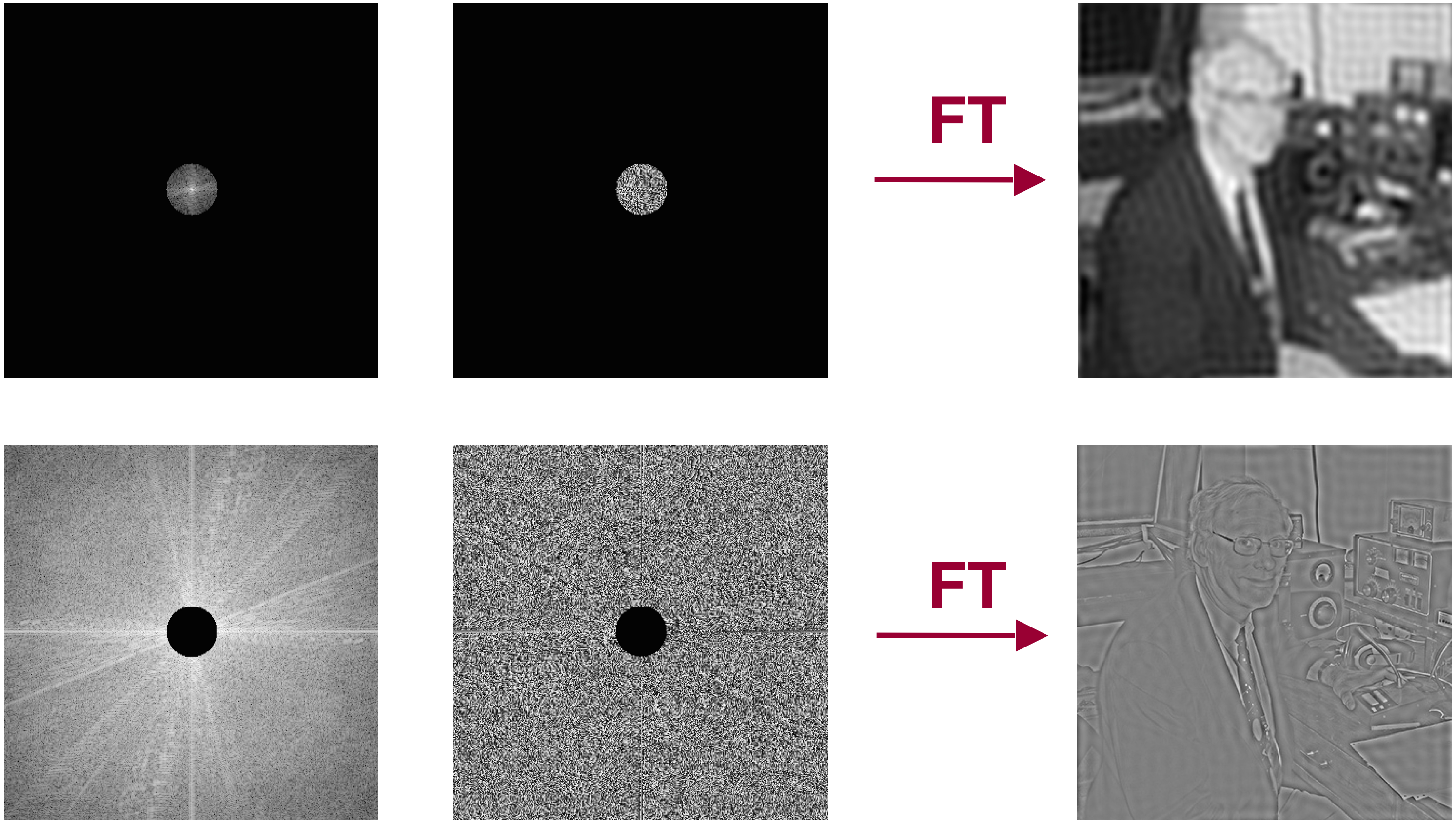
FT

Rule of thumb #3:

Amplitude = ‘how much’

Phase = ‘where’

Implications of (u,v) Coverage



V(u,v) amplitude

V(u,v) phase

T(x,y)

Missing High Spatial Frequencies

FT

Missing Low Spatial Frequencies

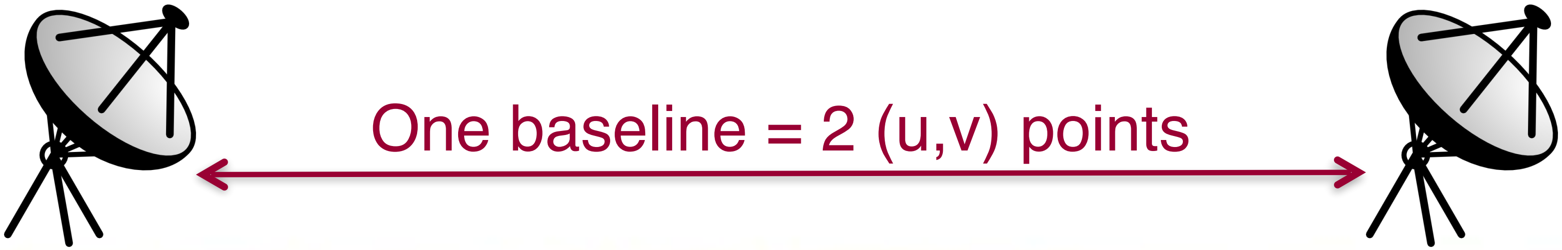
FT

Basics of Aperture Synthesis

One pair of antennas = one baseline

For **N antennas**, we get **N(N-1) samples** at a time

How do we fill in the rest of the (u,v) plane?



One baseline = 2 (u,v) points

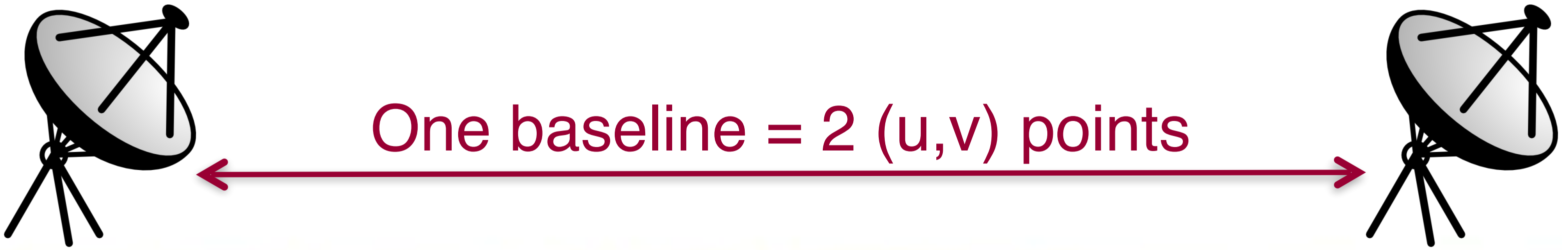
Basics of Aperture Synthesis

One pair of antennas = one baseline

For **N antennas**, we get **N(N-1) samples** at a time

How do we fill in the rest of the (u,v) plane?

1. Rearrange the antennas


One baseline = 2 (u,v) points

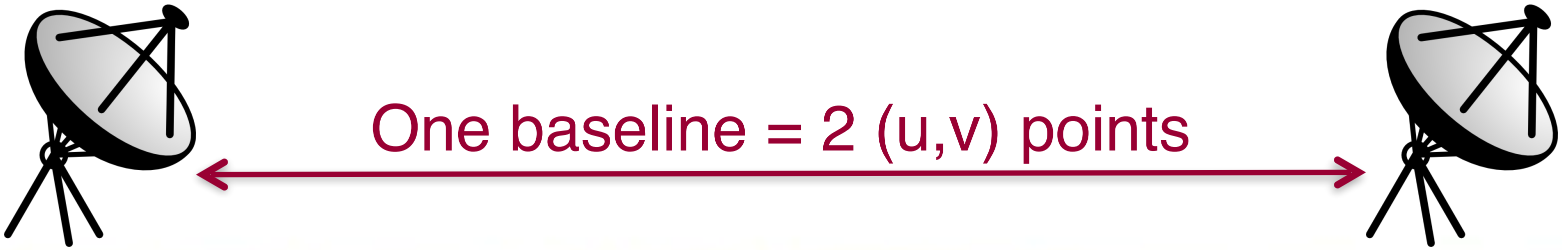
Basics of Aperture Synthesis

One pair of antennas = one baseline

For **N antennas**, we get **N(N-1) samples** at a time

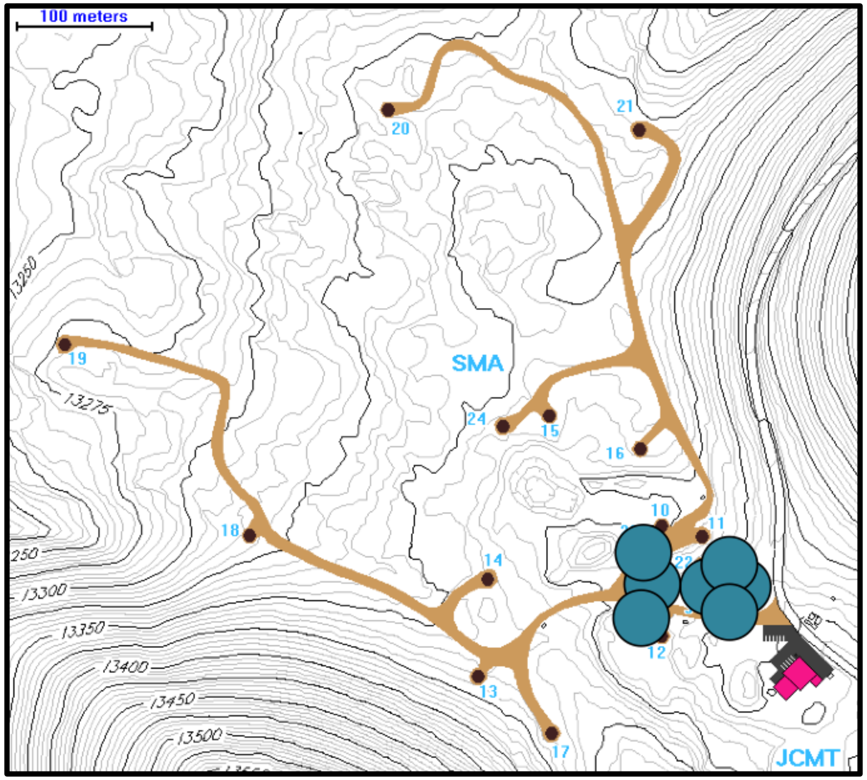
How do we fill in the rest of the (u,v) plane?

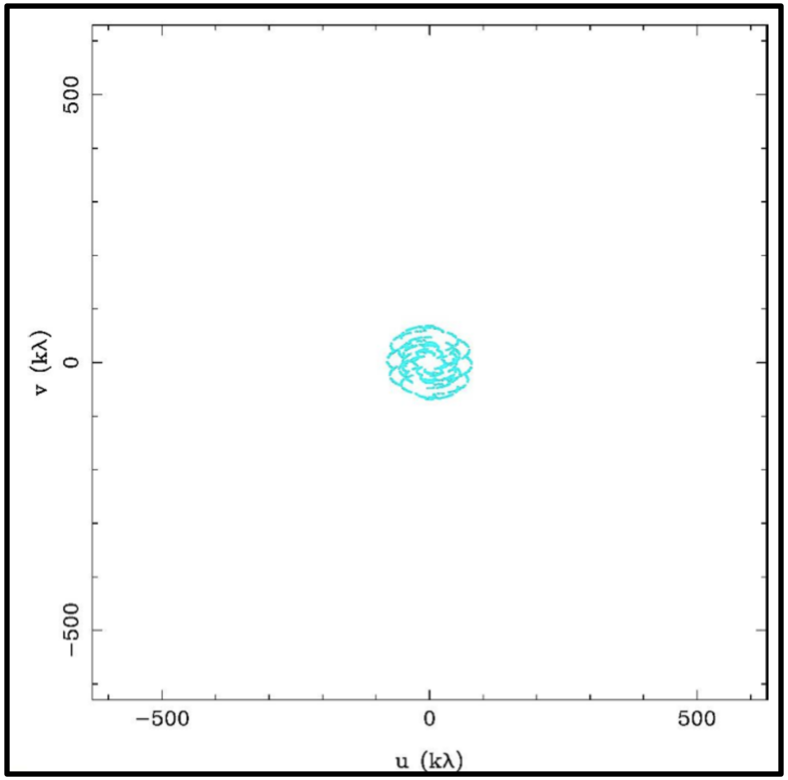
1. Rearrange antennas
2. Earth’s rotation



One baseline = 2 (u,v) points

Method 1: Reconfigure your antennas



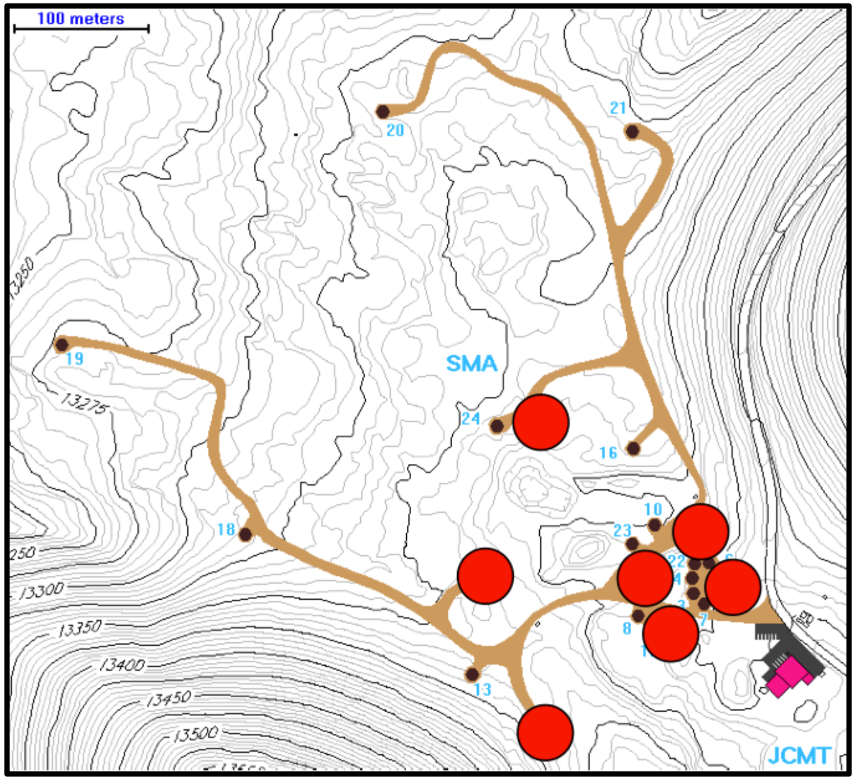


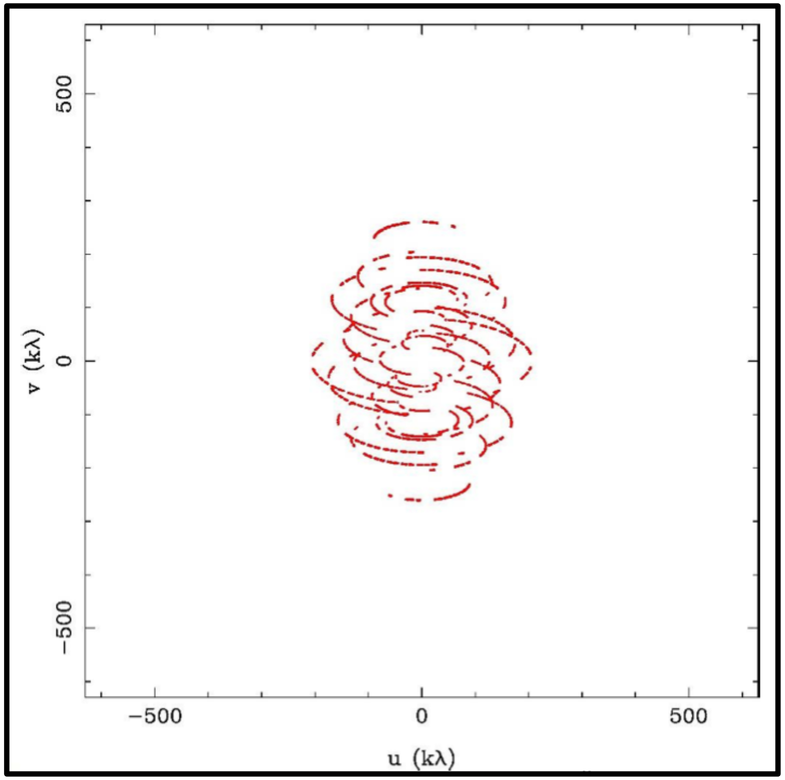
Compact SMA configuration

(compact baselines)

345 GHz, DEC = +22

Method 1: Reconfigure your antennas



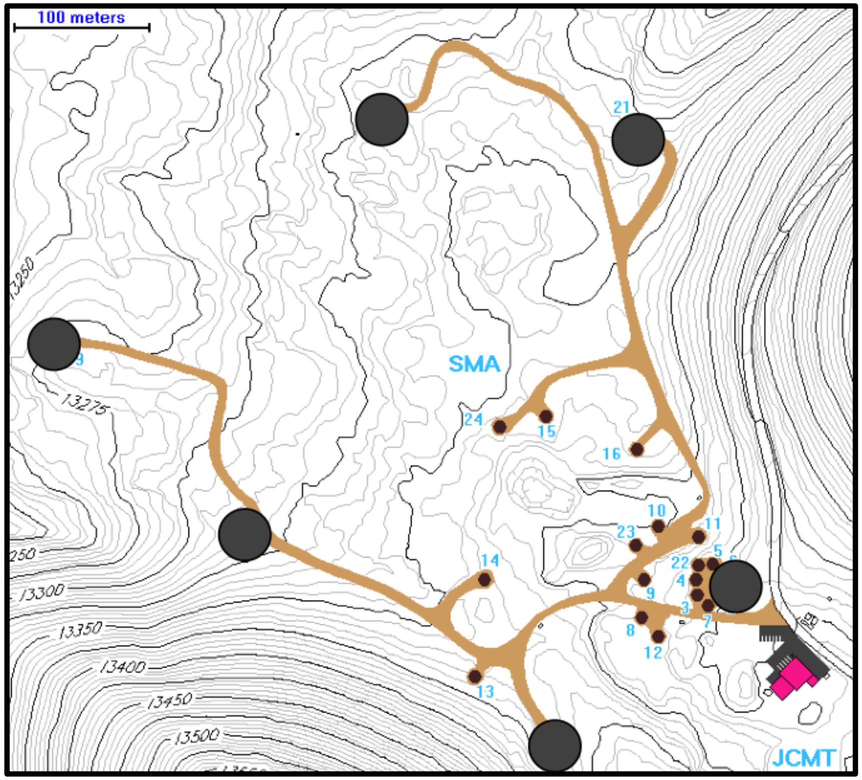


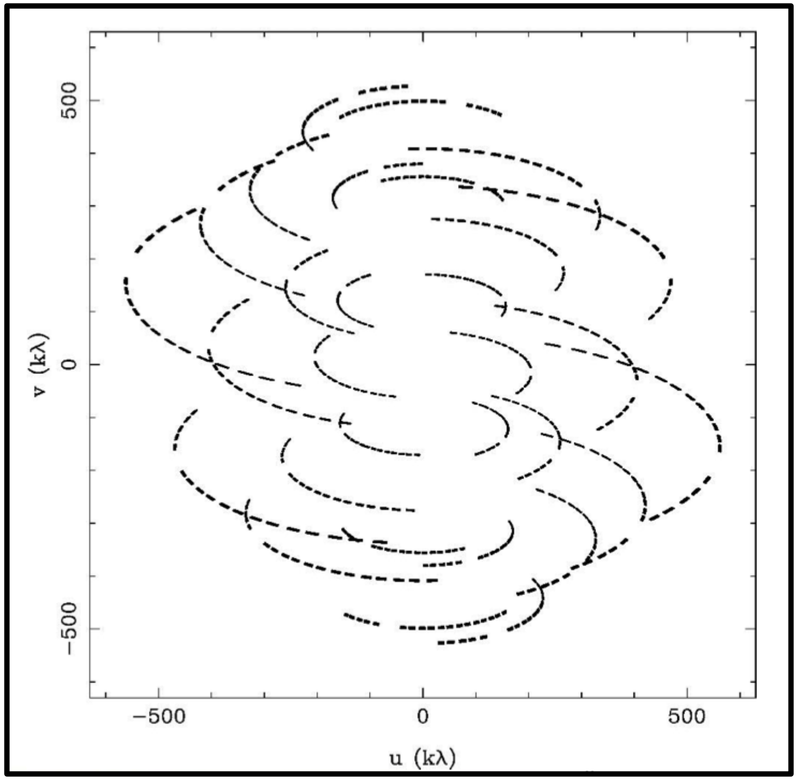
Extended SMA configuration

(extended baselines)

345 GHz, DEC = +22

Method 1: Reconfigure your antennas



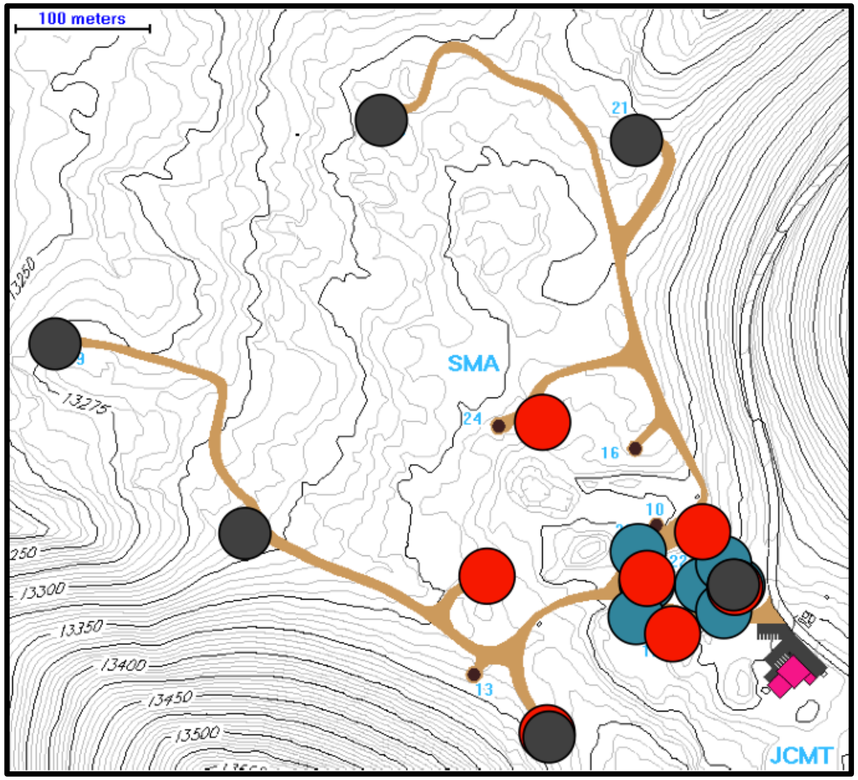


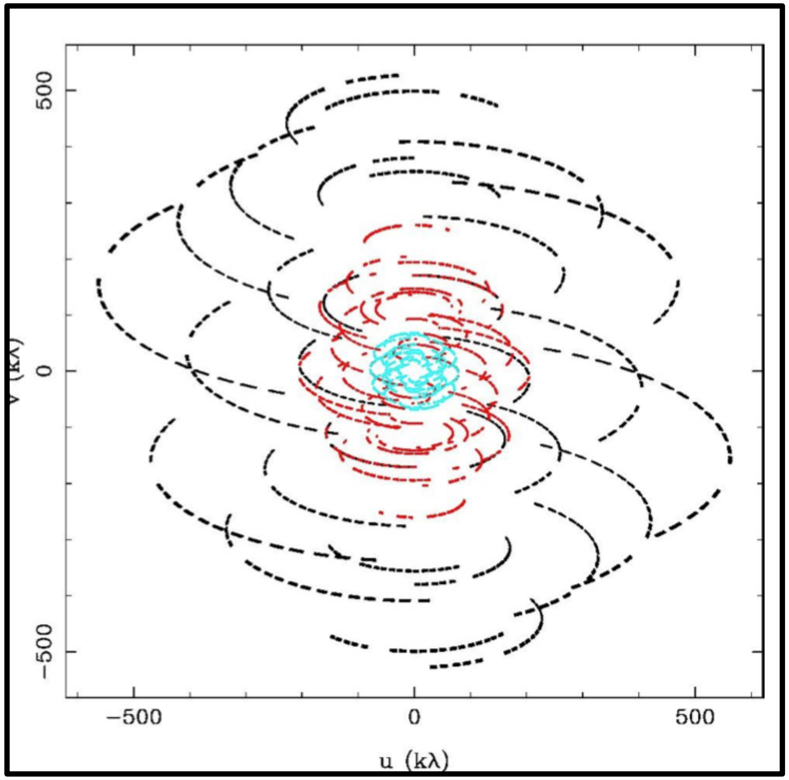
Very Extended SMA configuration

(most extended baselines)

345 GHz, DEC = +22

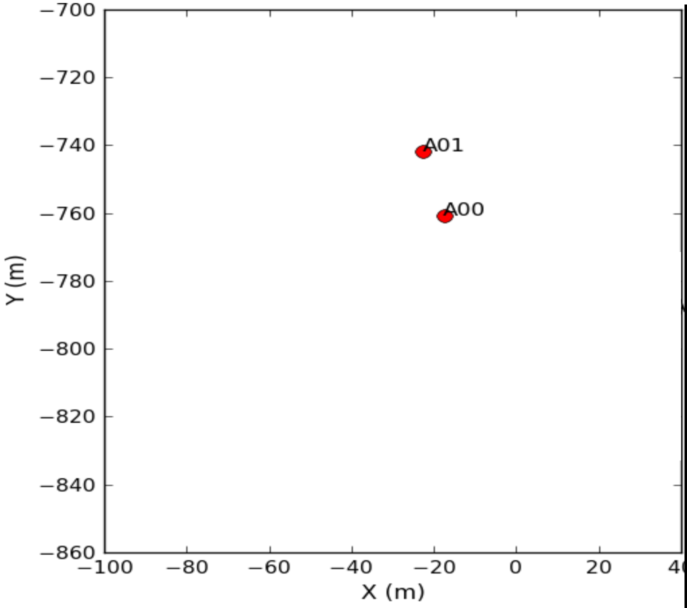
Method 1: Reconfigure your antennas

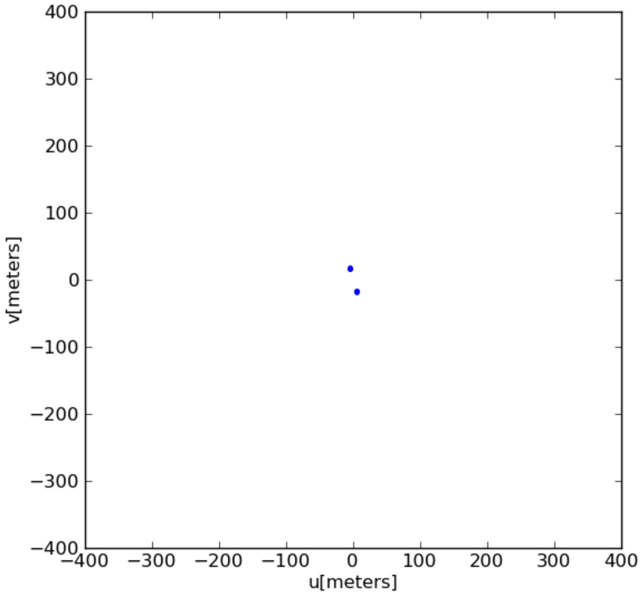


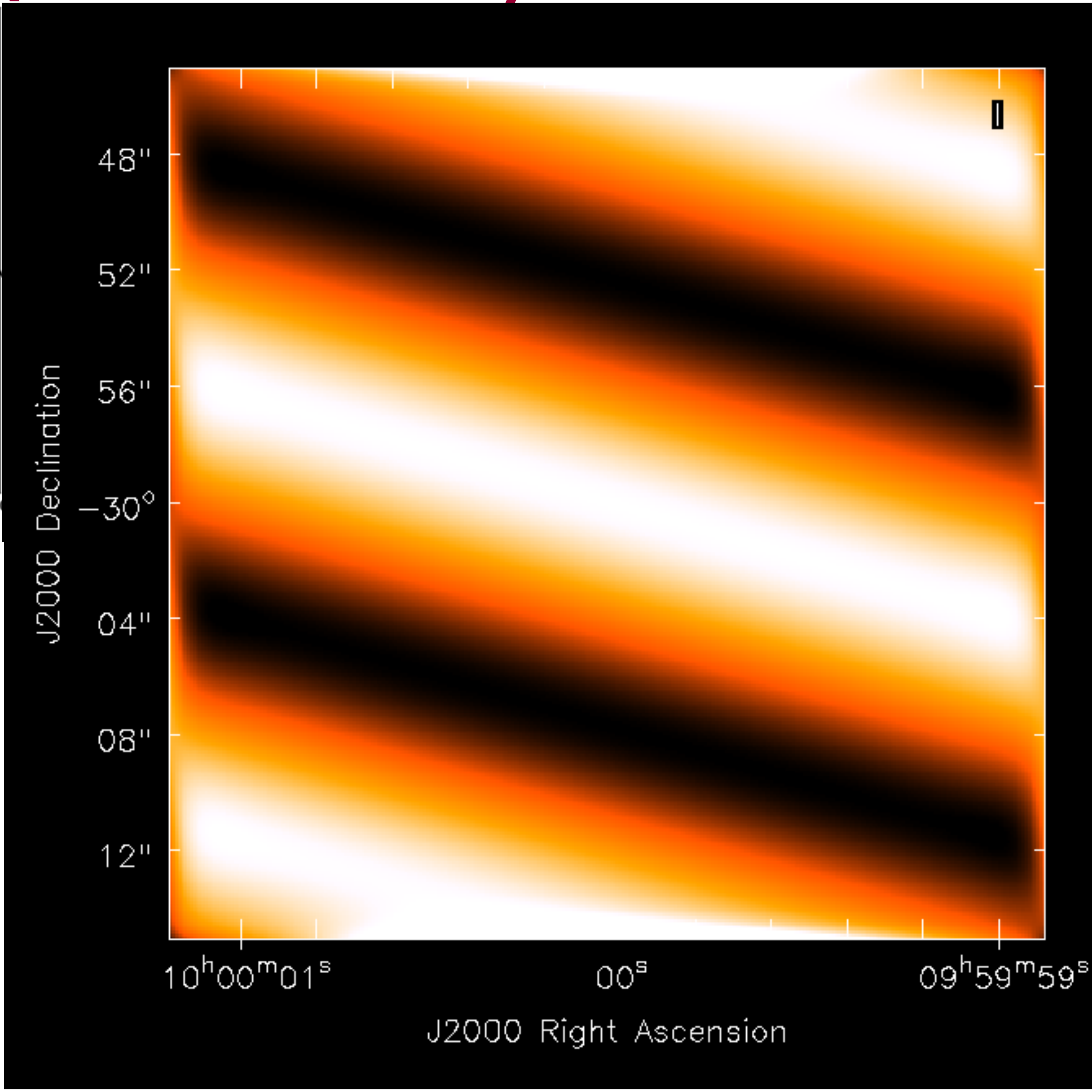


Combine multiple configurations to get the most complete coverage of the (u,v) plane

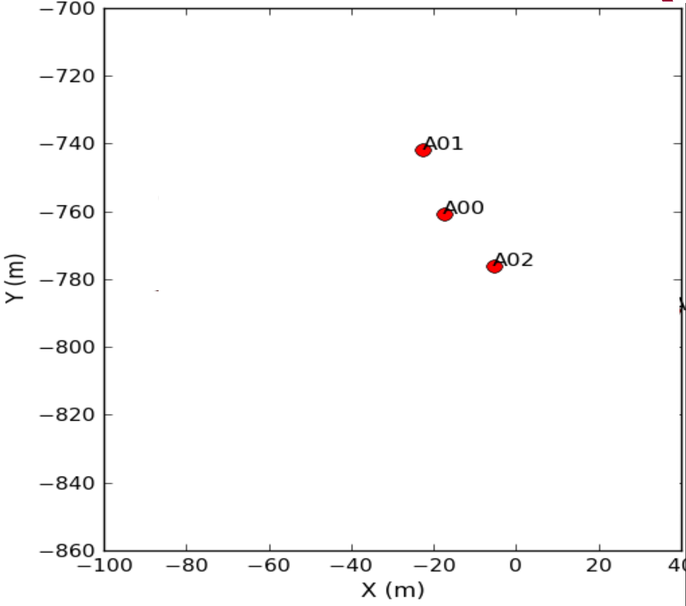
Example: Fringe pattern with 2 Antennas (one baseline)

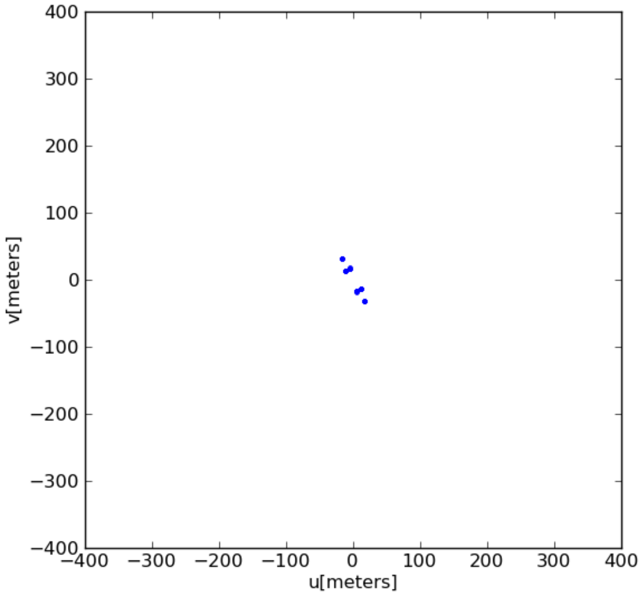


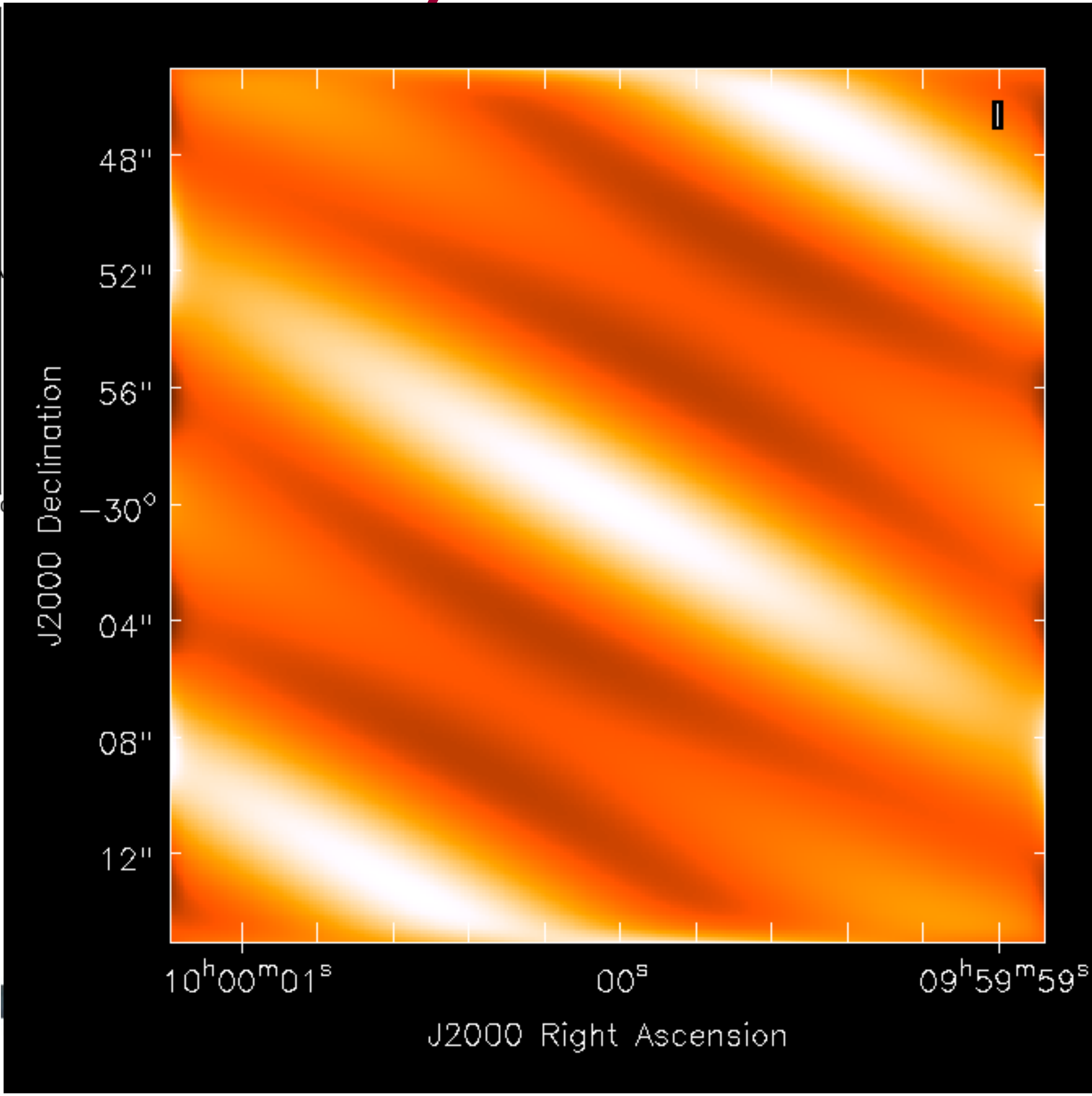




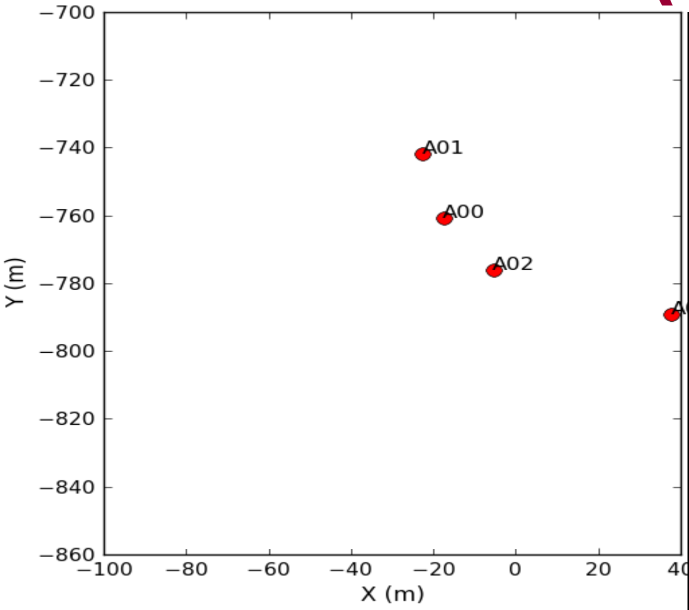
Example: Fringe pattern with 3 Antennas (3 baselines)

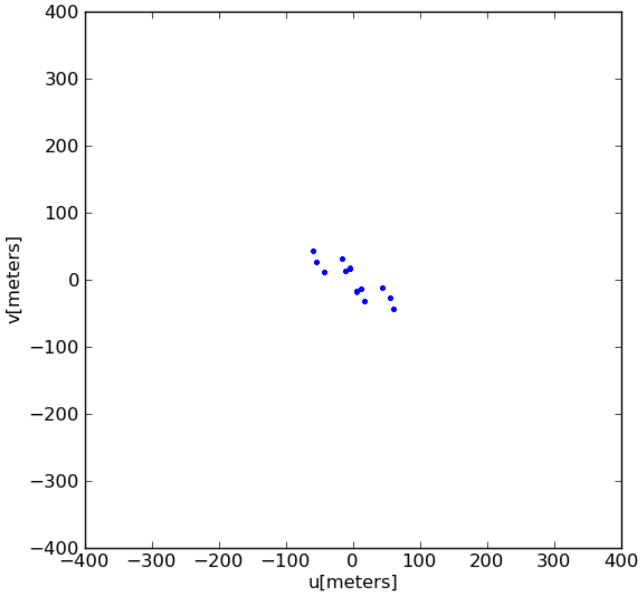


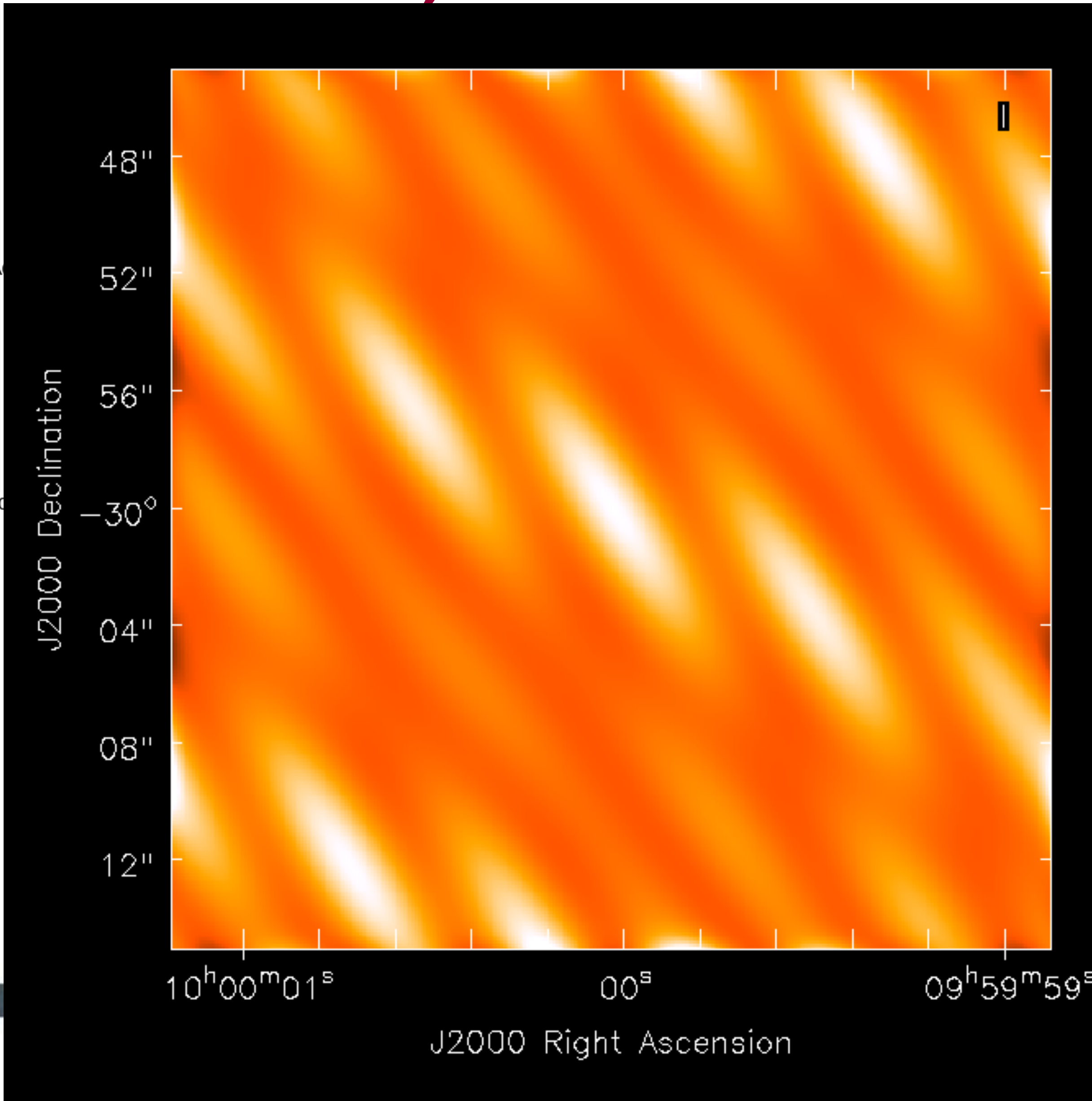




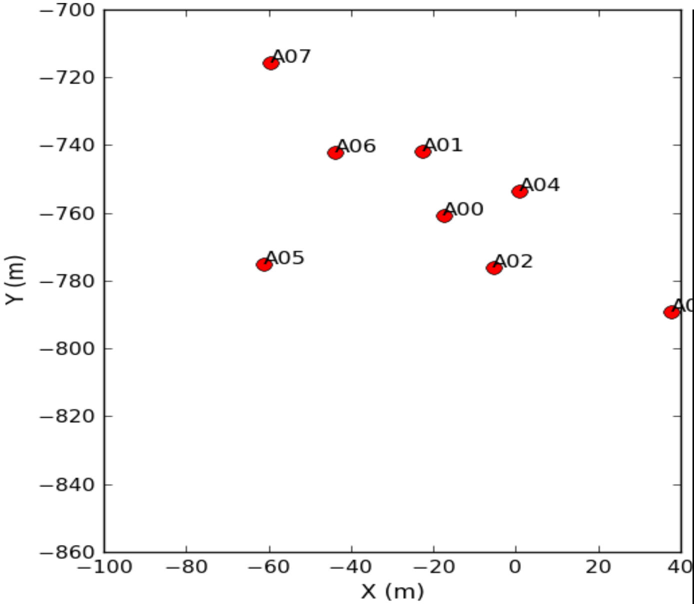
Example: Fringe pattern with 4 Antennas (6 baselines)

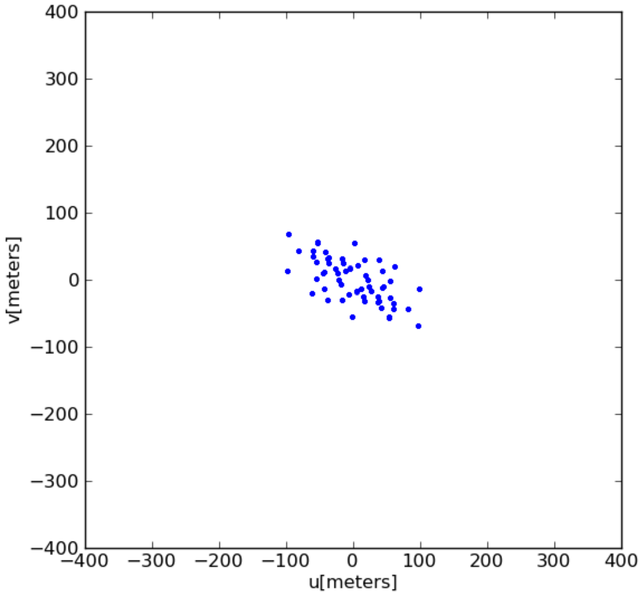


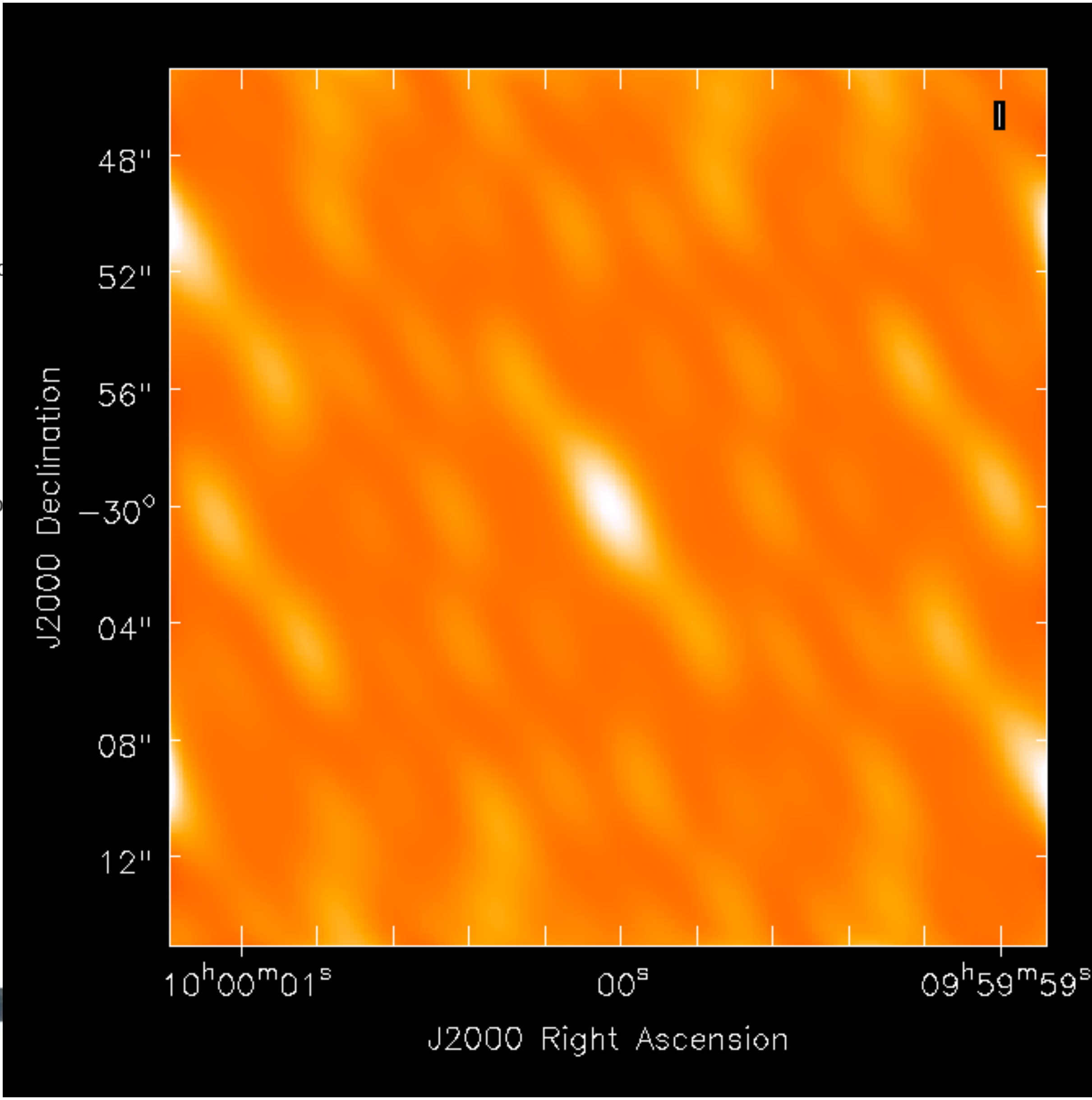




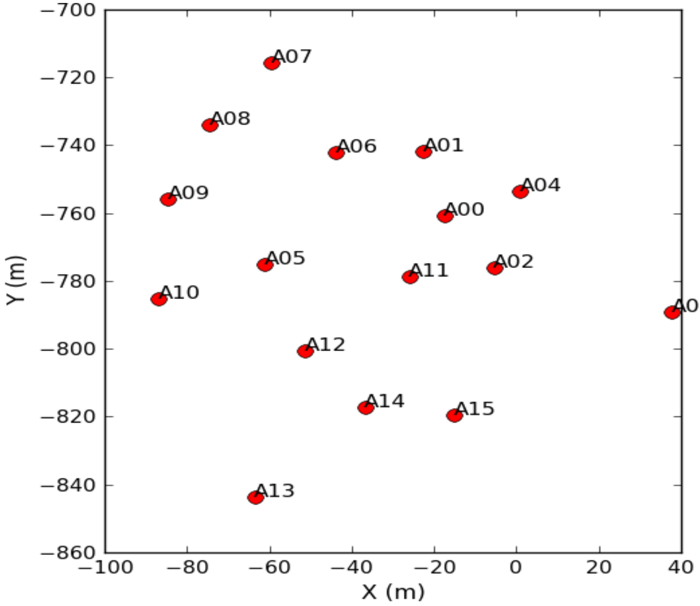
Example: Fringe pattern with 8 Antennas (28 baselines)

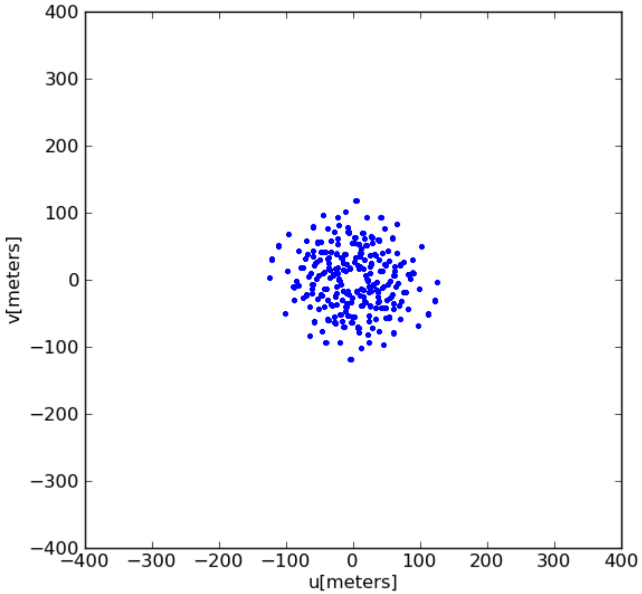


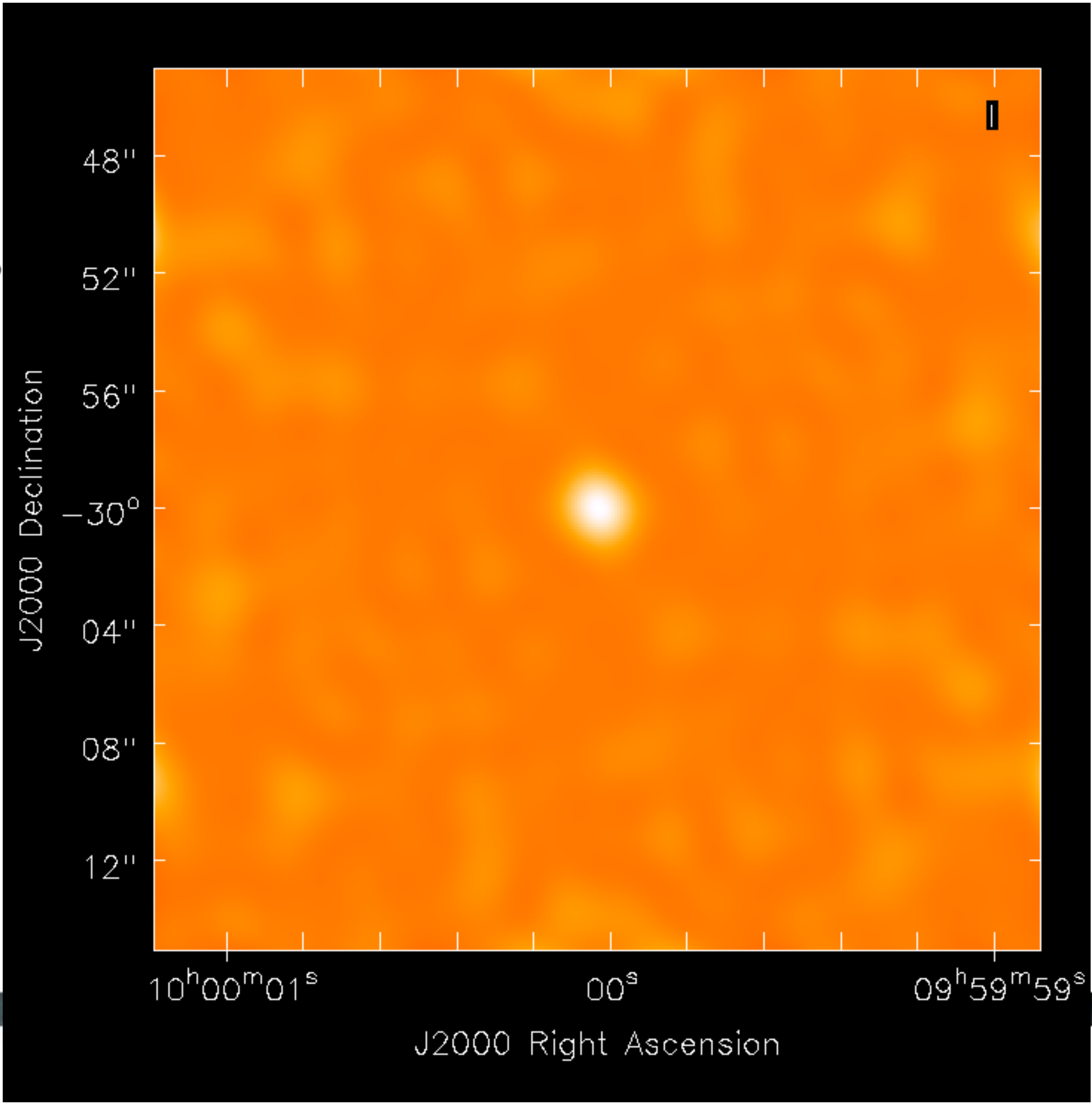




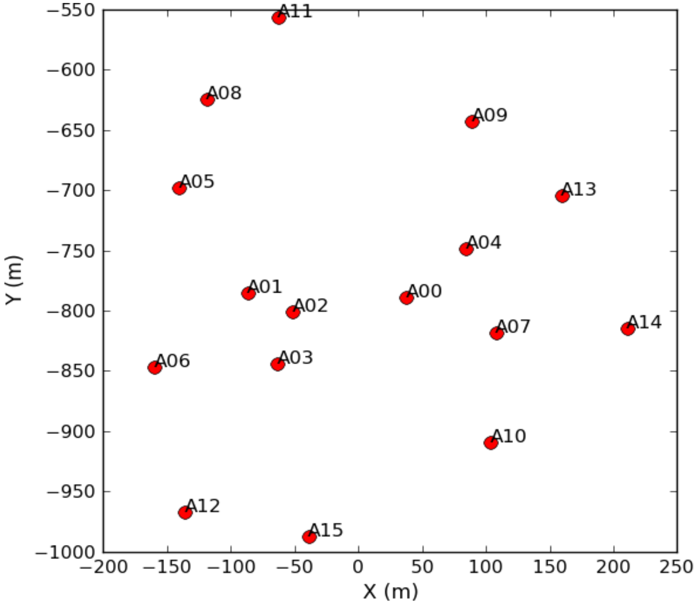
16 Antennas – Compact Configuration

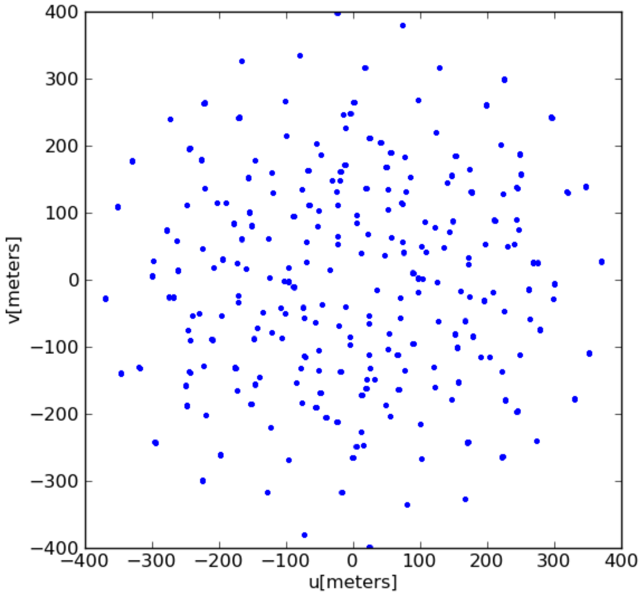


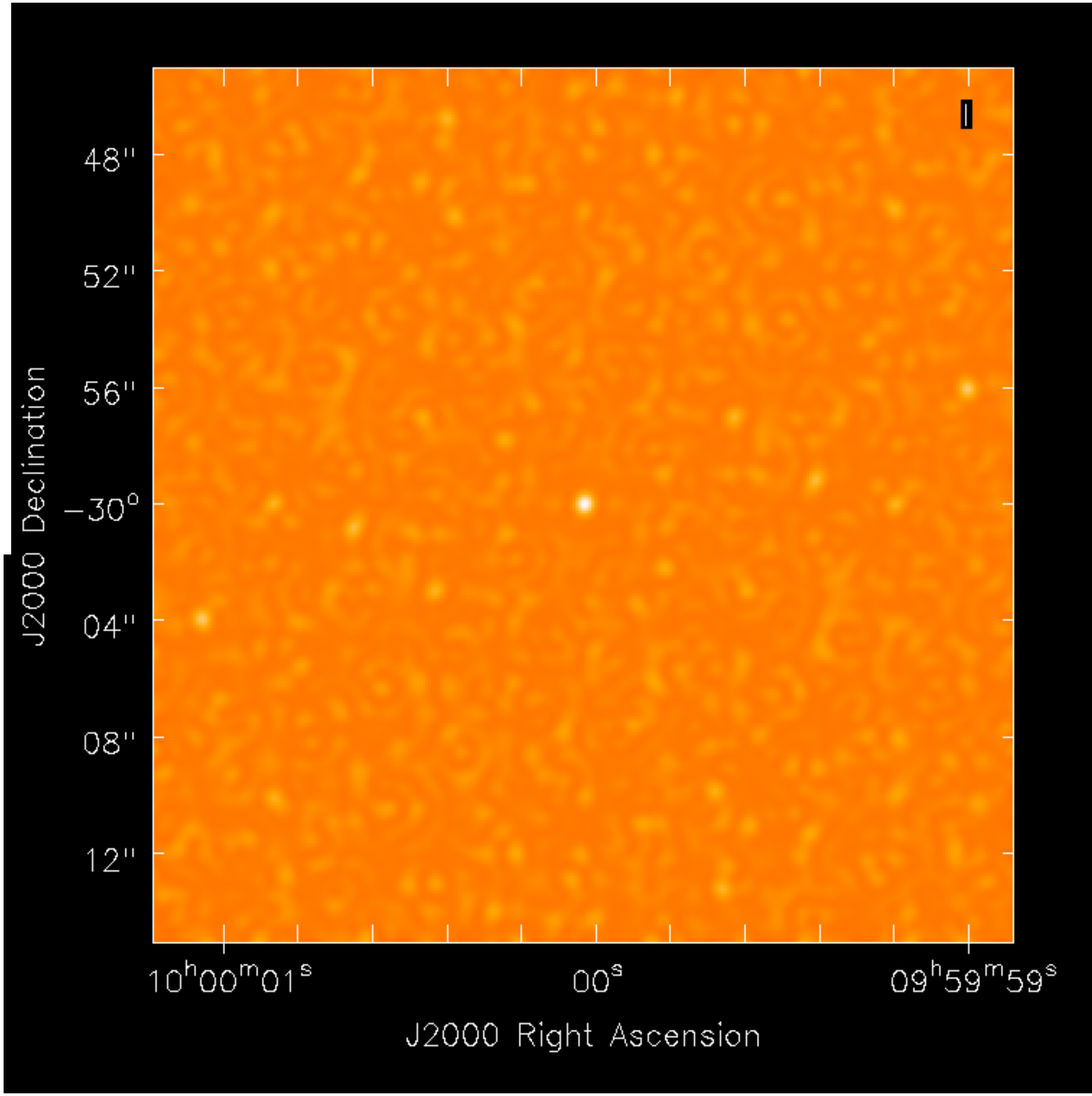




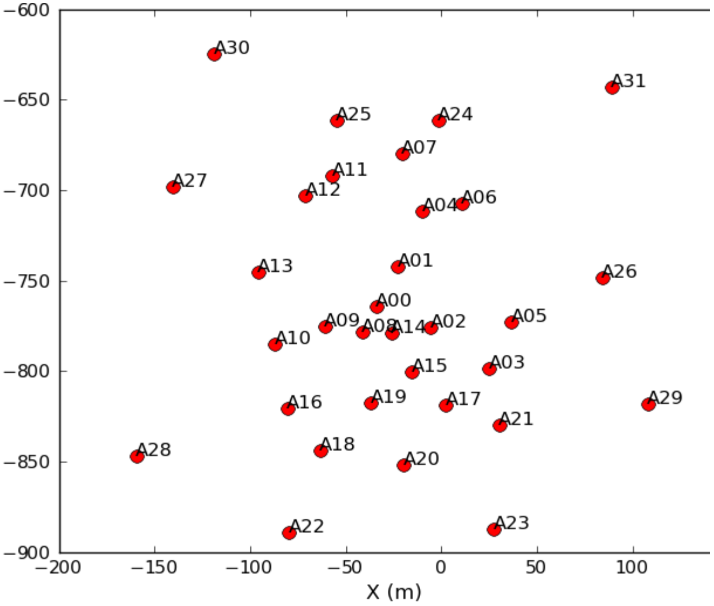
16 Antennas – Extended Configuration

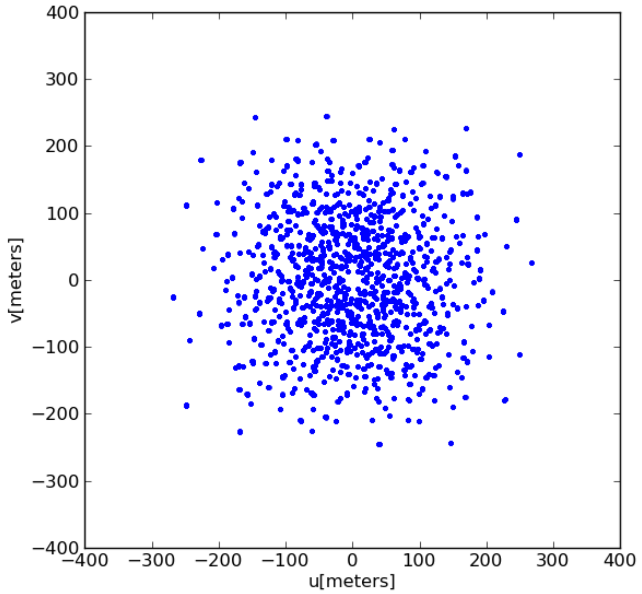


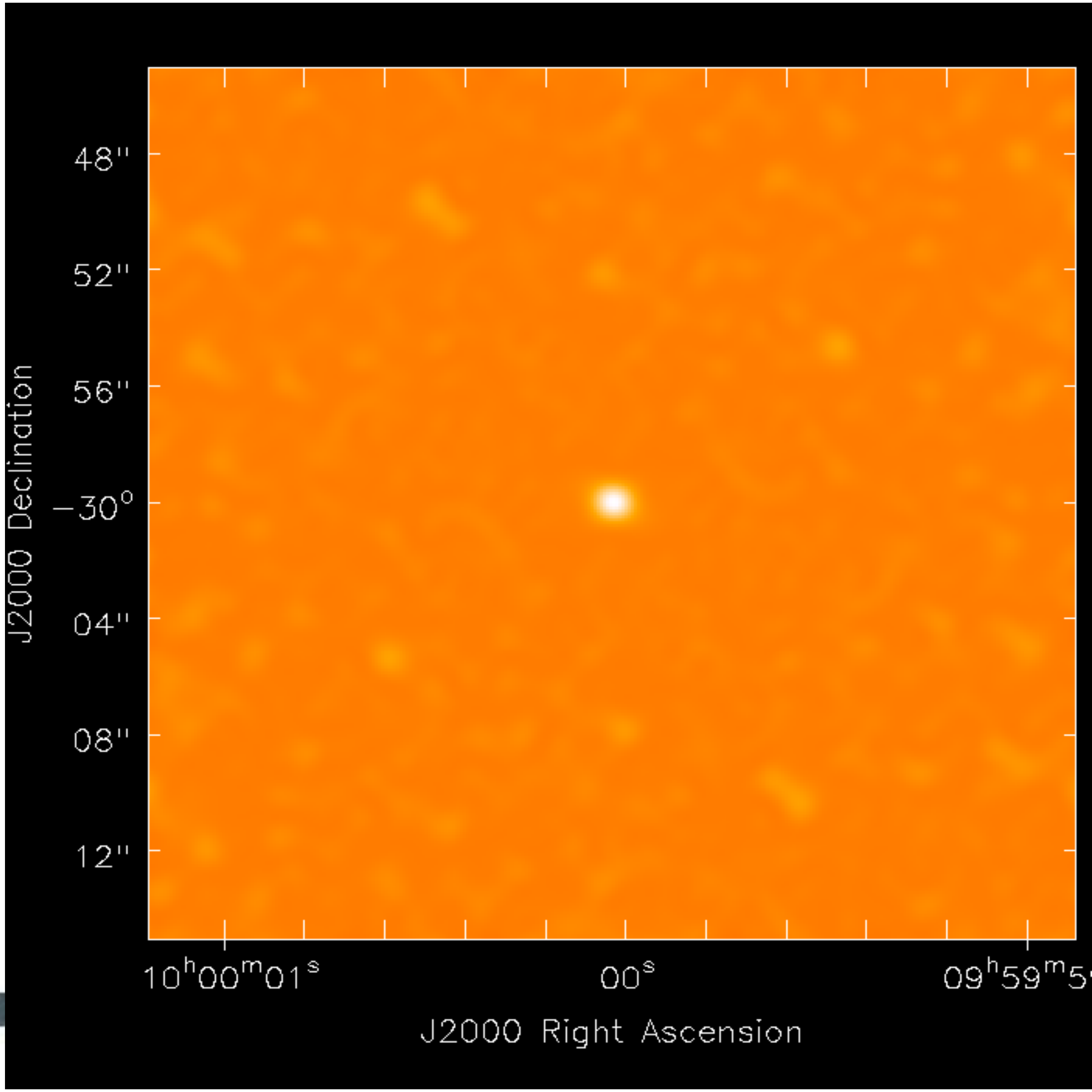




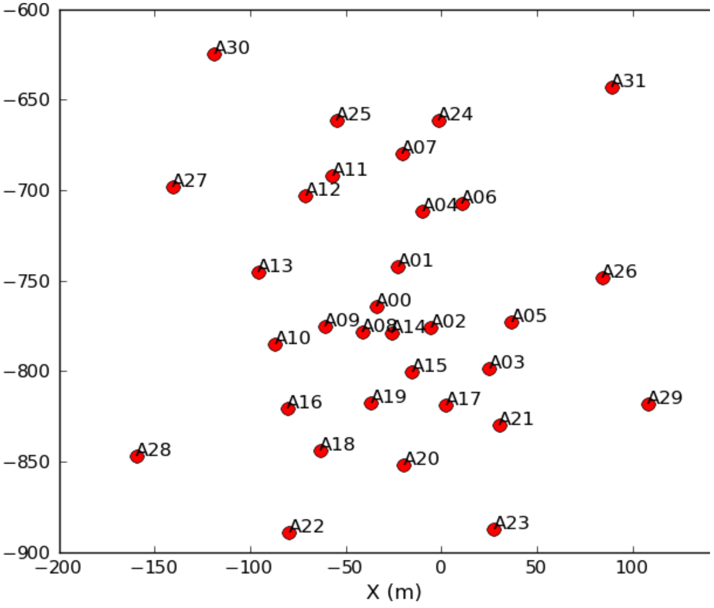
32 Antennas – Instantaneous

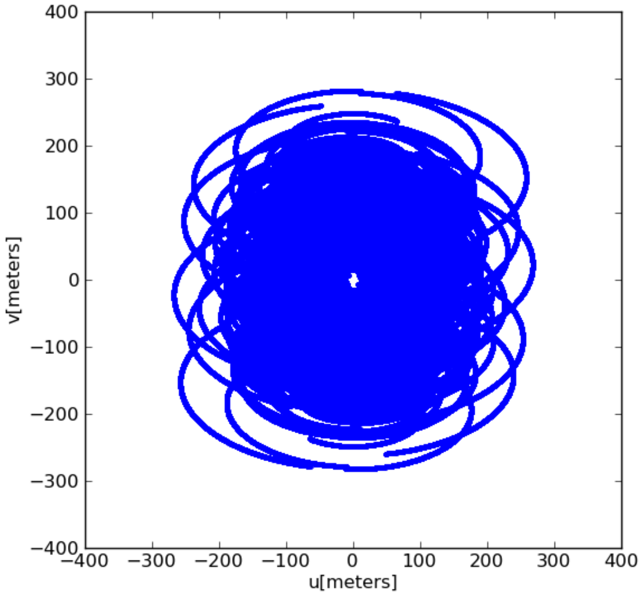


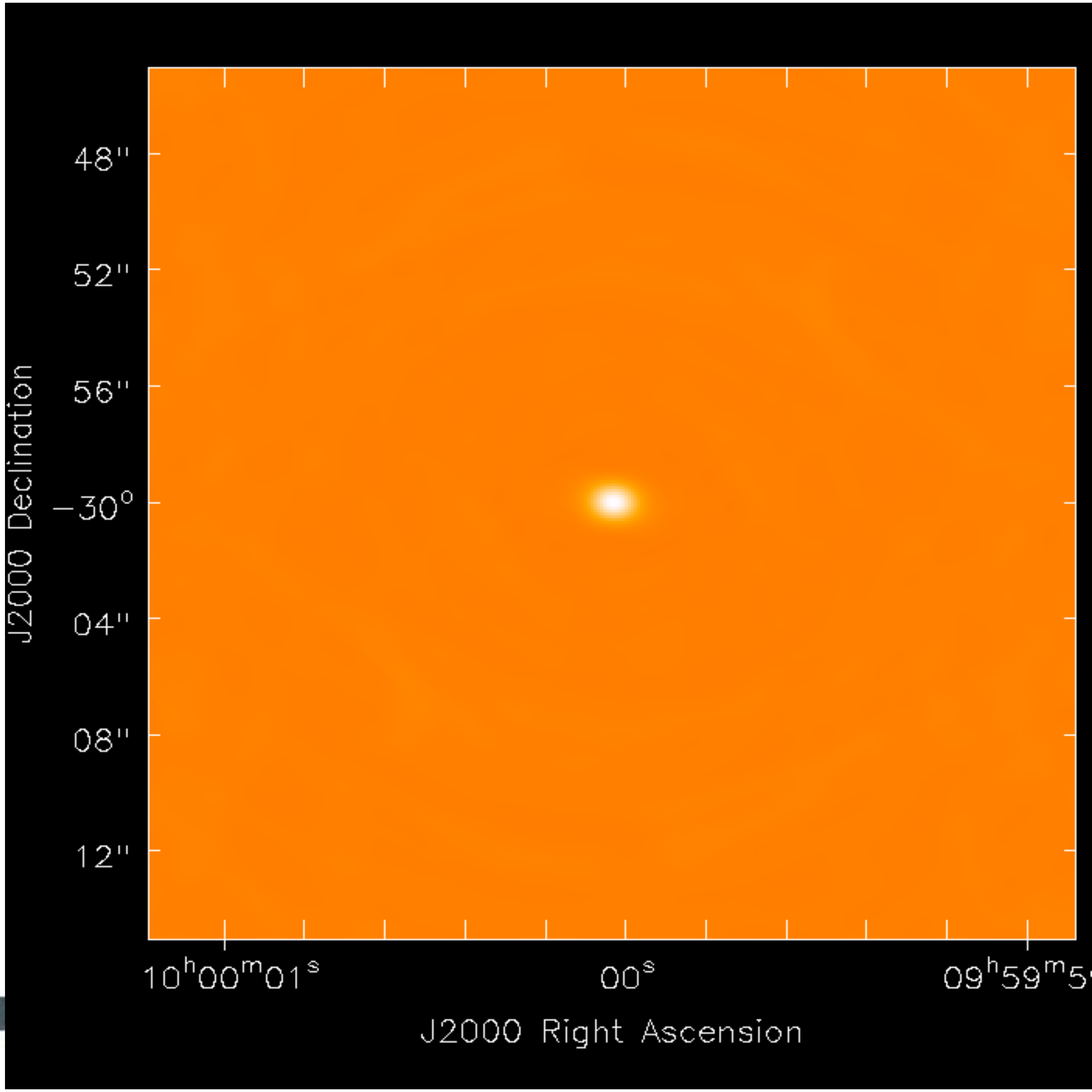




32 Antennas – 8 hours

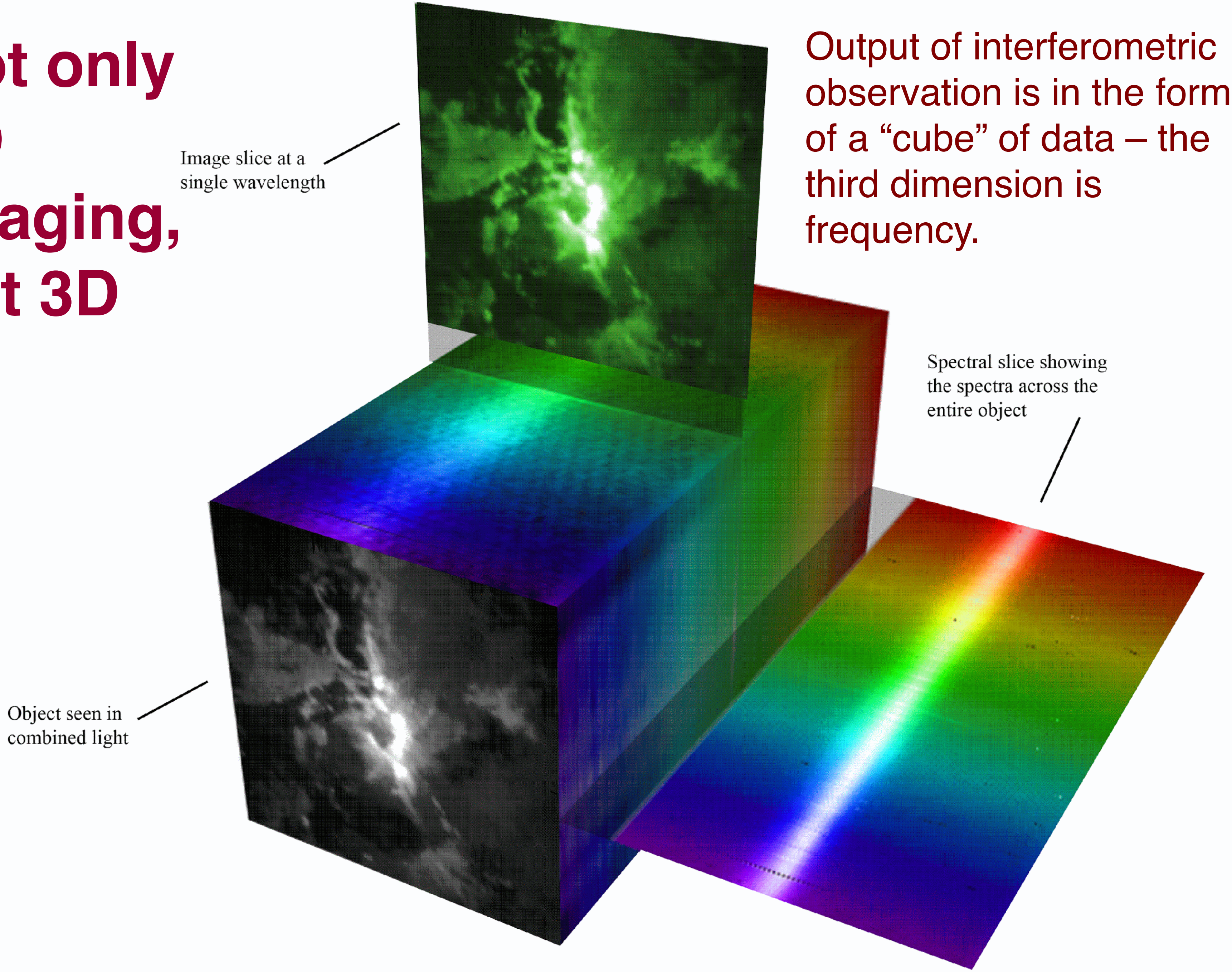




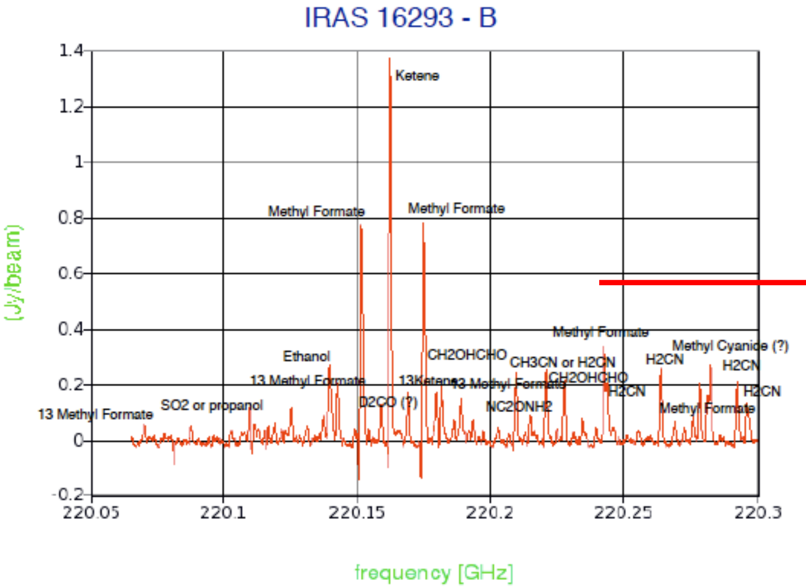


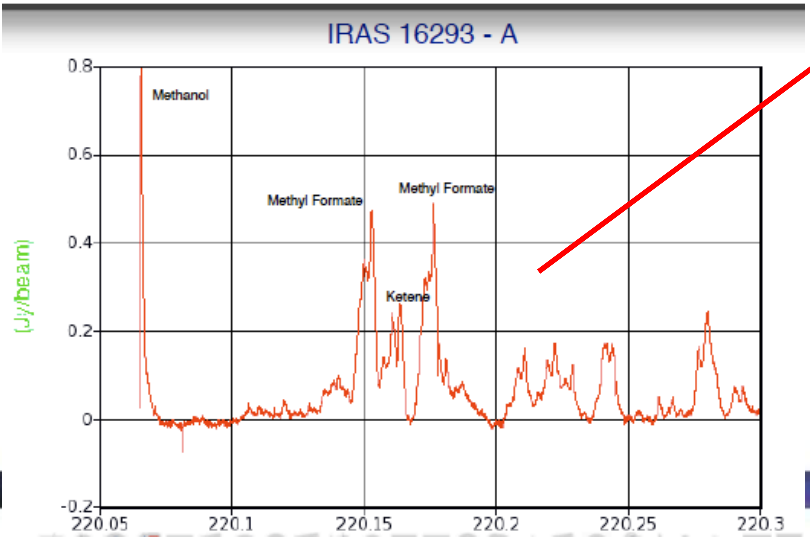
Not only 2D imaging, but 3D

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

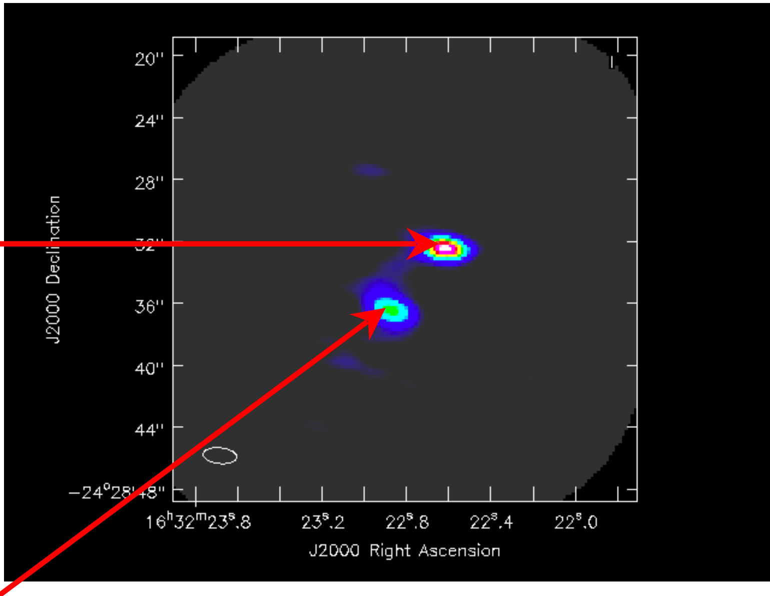


Sometimes the most interesting science lies in the third dimension


IRAS 16293 - B


IRAS 16293 - A

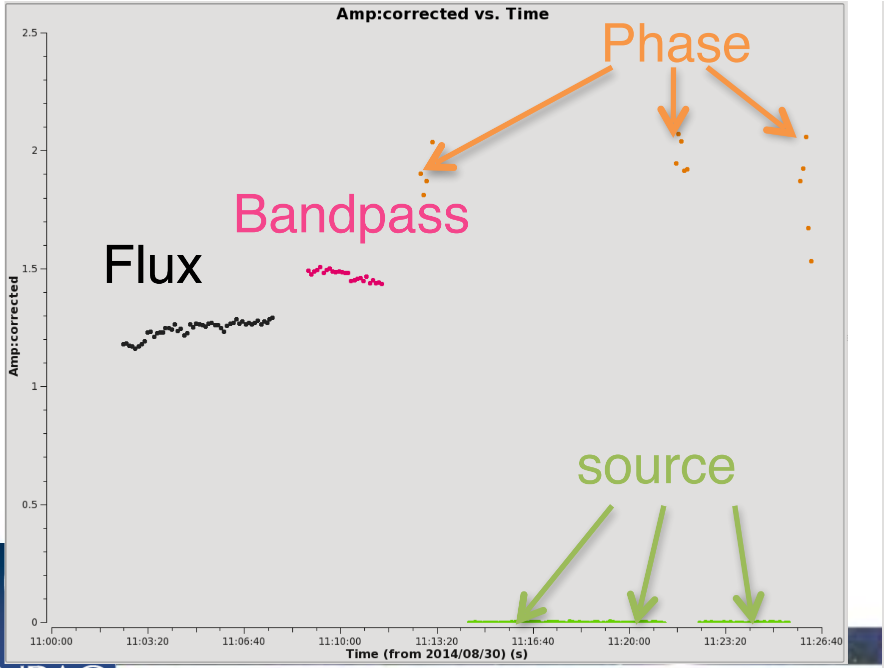
Band 6

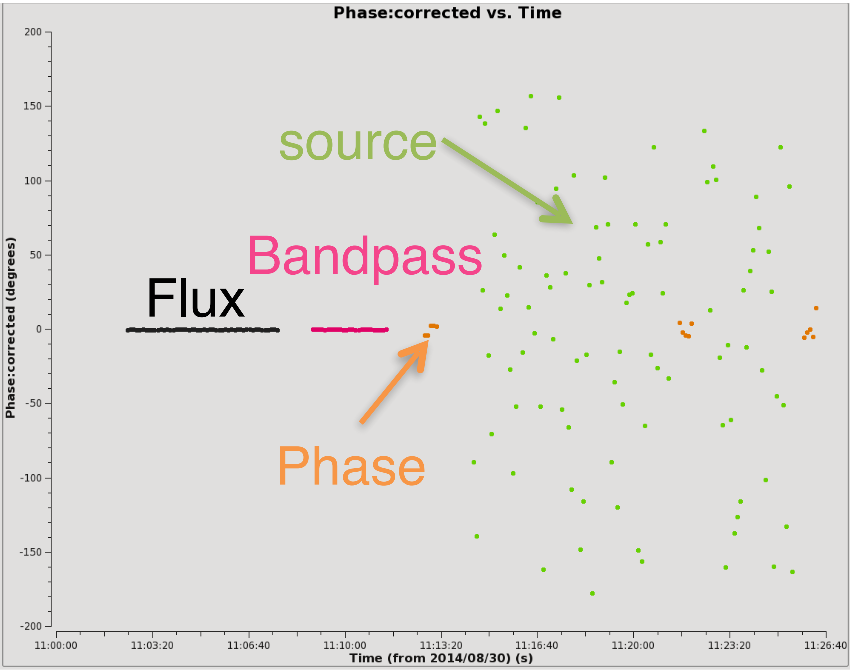


J. Turner & ALMA CSV team

A Brief Word on Calibration

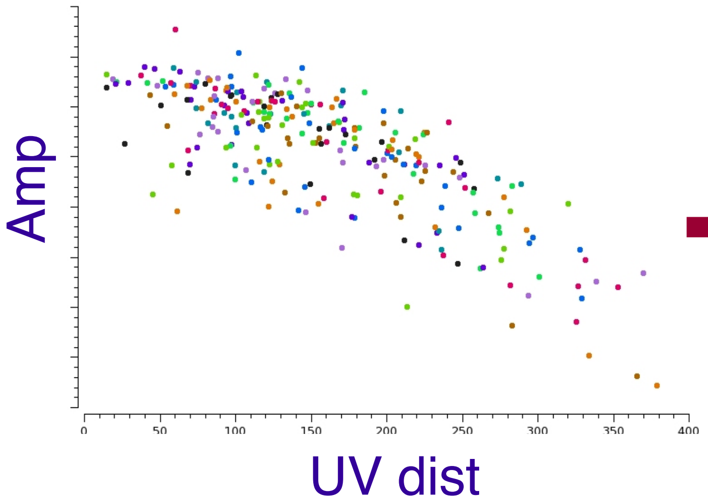
- Interferometers measure visibilities of real telescopes as a function of time and frequency.
- We need to take into account instrument differences between antennas, changing weather conditions, etc.





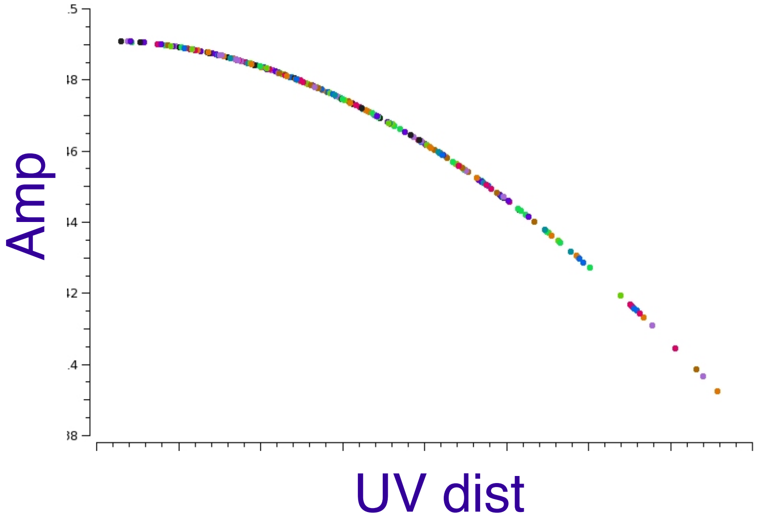
Flux (or Amplitude) Calibration

Flux calibration takes into account your absolute scaling



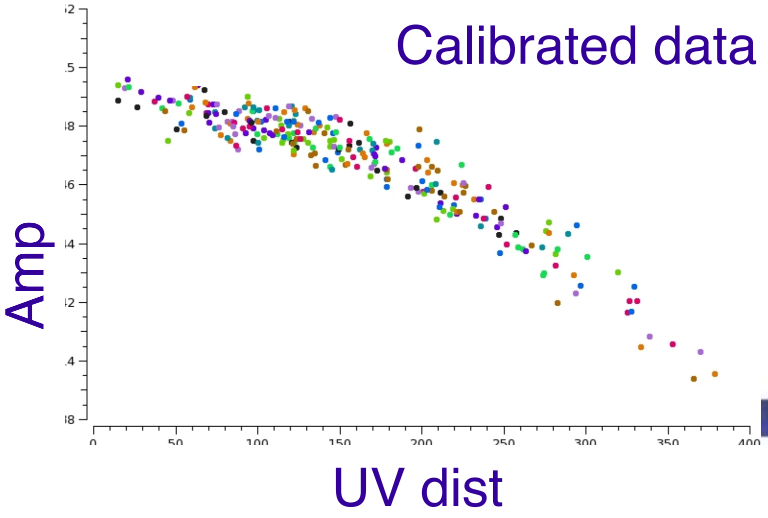
Uncalibrated data

+

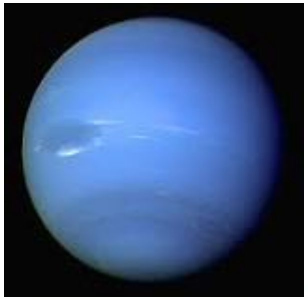


UV model

=

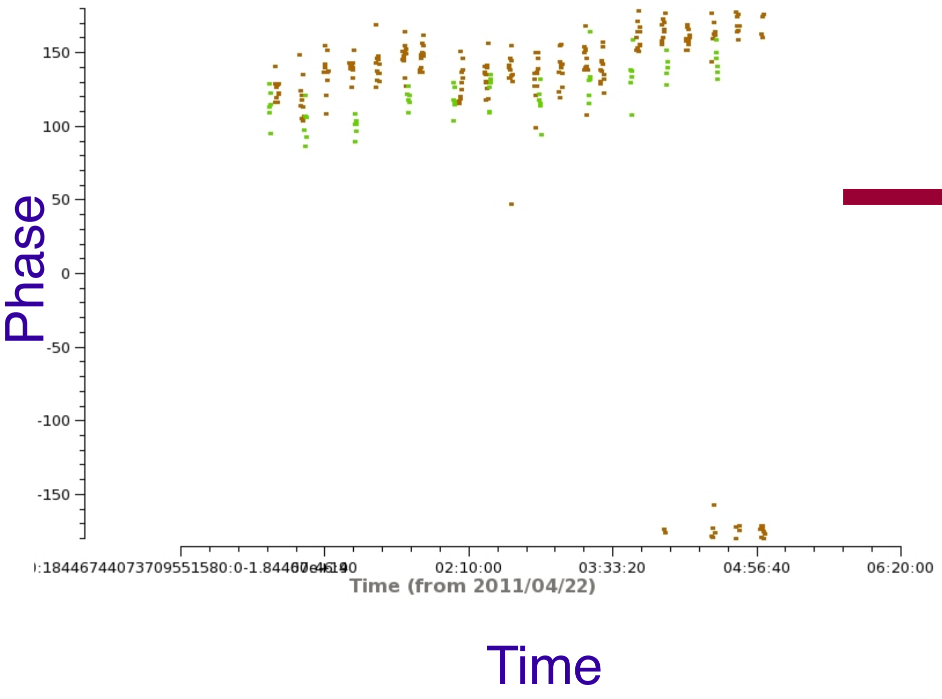


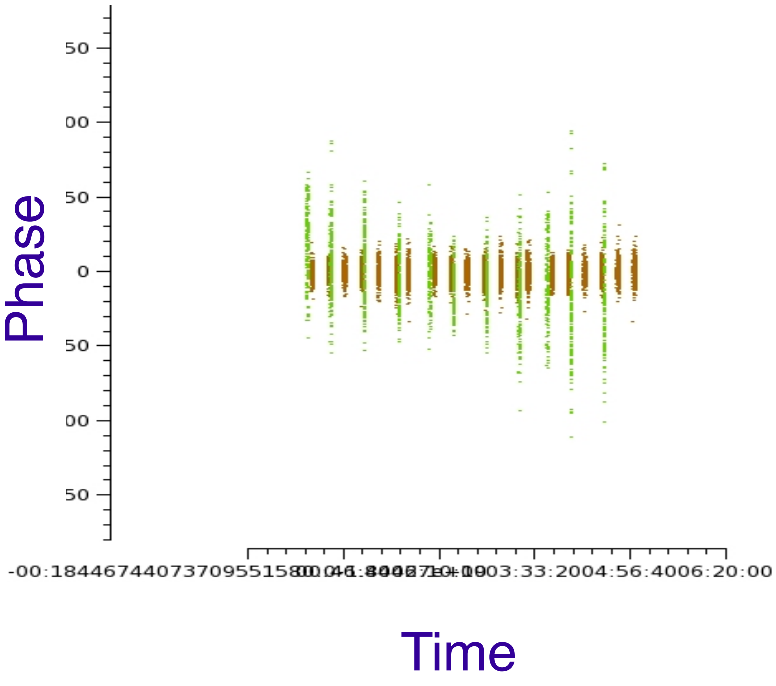
Calibrated data



Phase Calibration

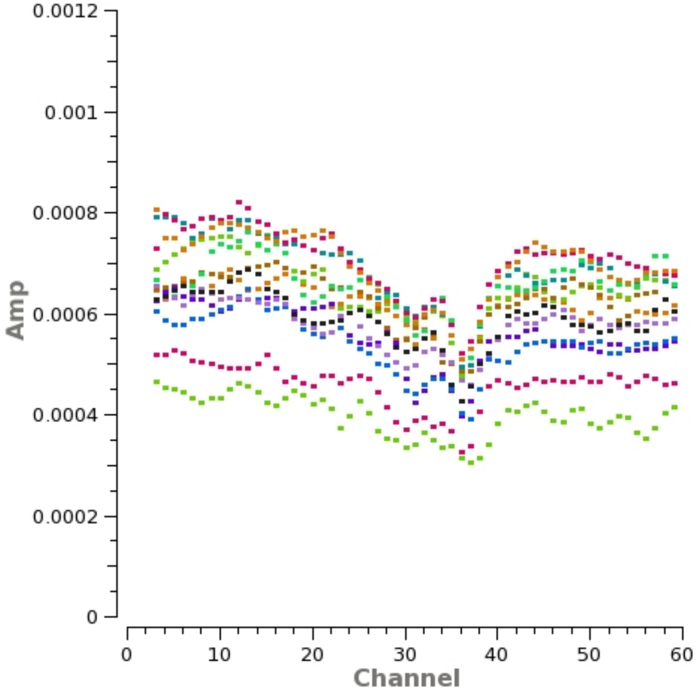
Phase calibration takes into account how your flux varies throughout your observation



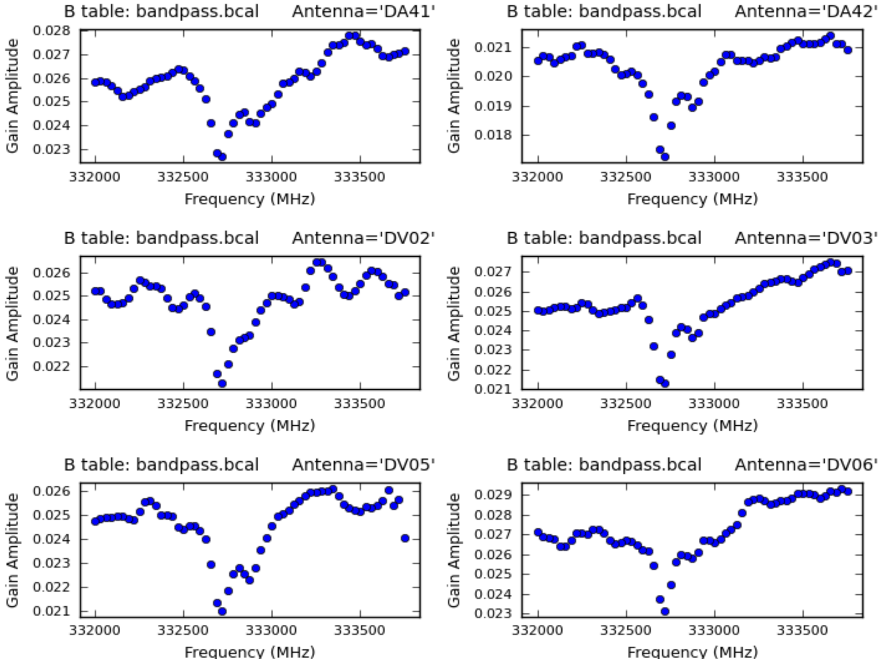


Bandpass Calibration (Amplitude)

Primarily correcting for frequency dependent telescope response (i.e. in the correlator/spectral windows)



Before calibration

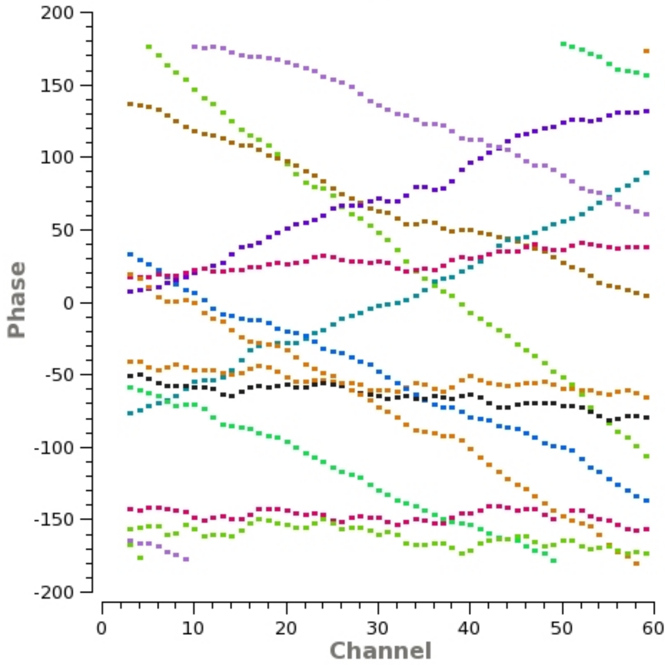


Solutions for individual antennas

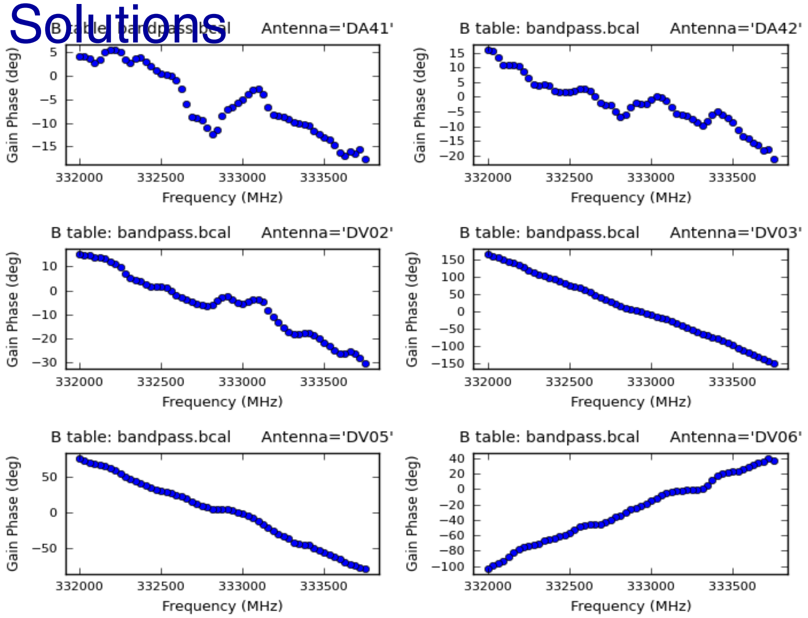
Bandpass Calibration (Phase)

Primarily correcting for frequency dependent telescope response (i.e. in the correlator/spectral windows)

Baselines to one antenna



Antenna-based Bandpass Solutions



Good Future References

Thompson, A.R., Moran, J.M., Swensen, G.W. 2017 “Interferometry and Synthesis in Radio Astronomy”, 3rd edition (Springer)

http://www.springer.com/us/book/9783319444291

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

www.nrao.edu
science.nrao.edu

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Back up slides

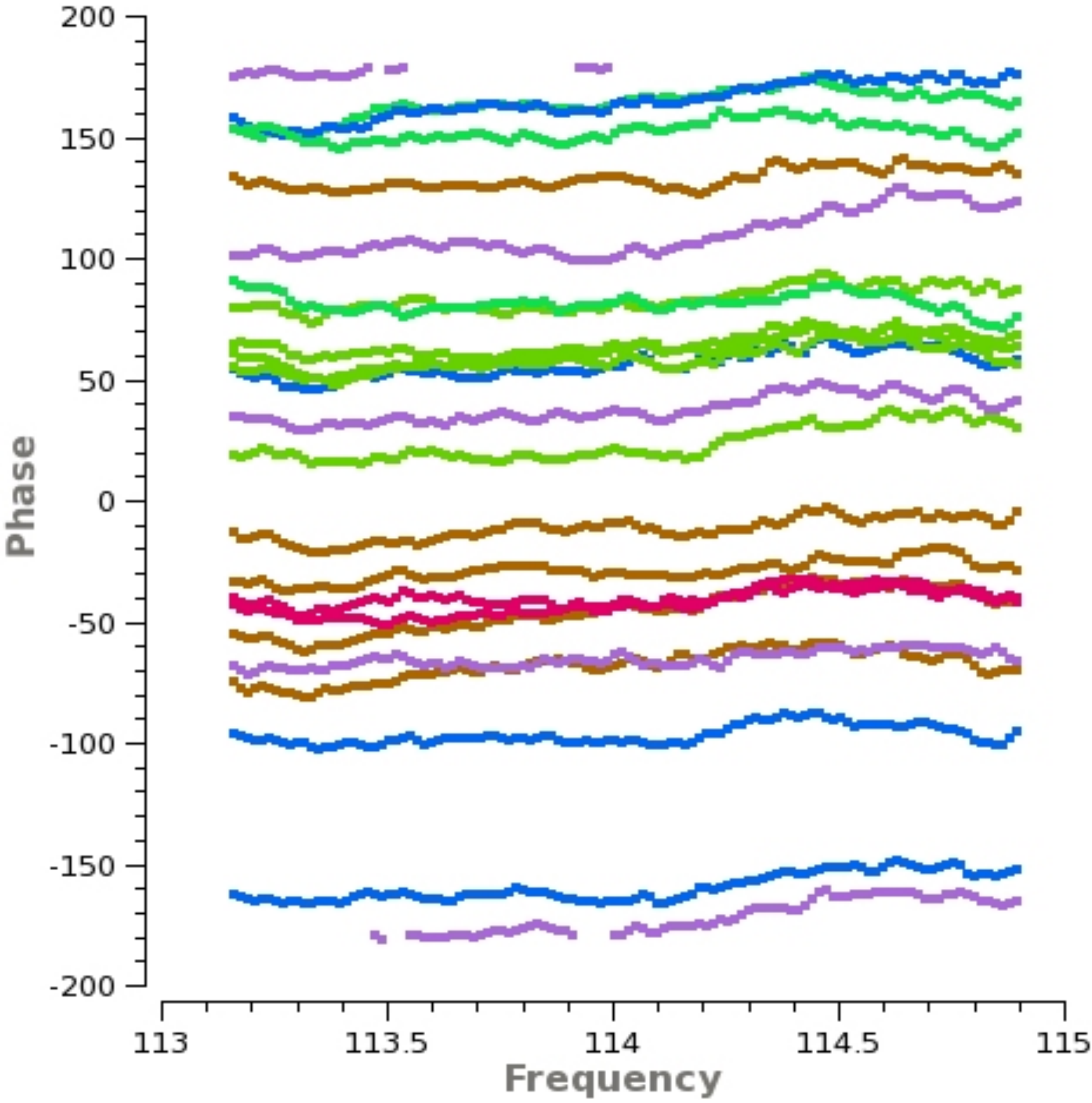
Calibration Process

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

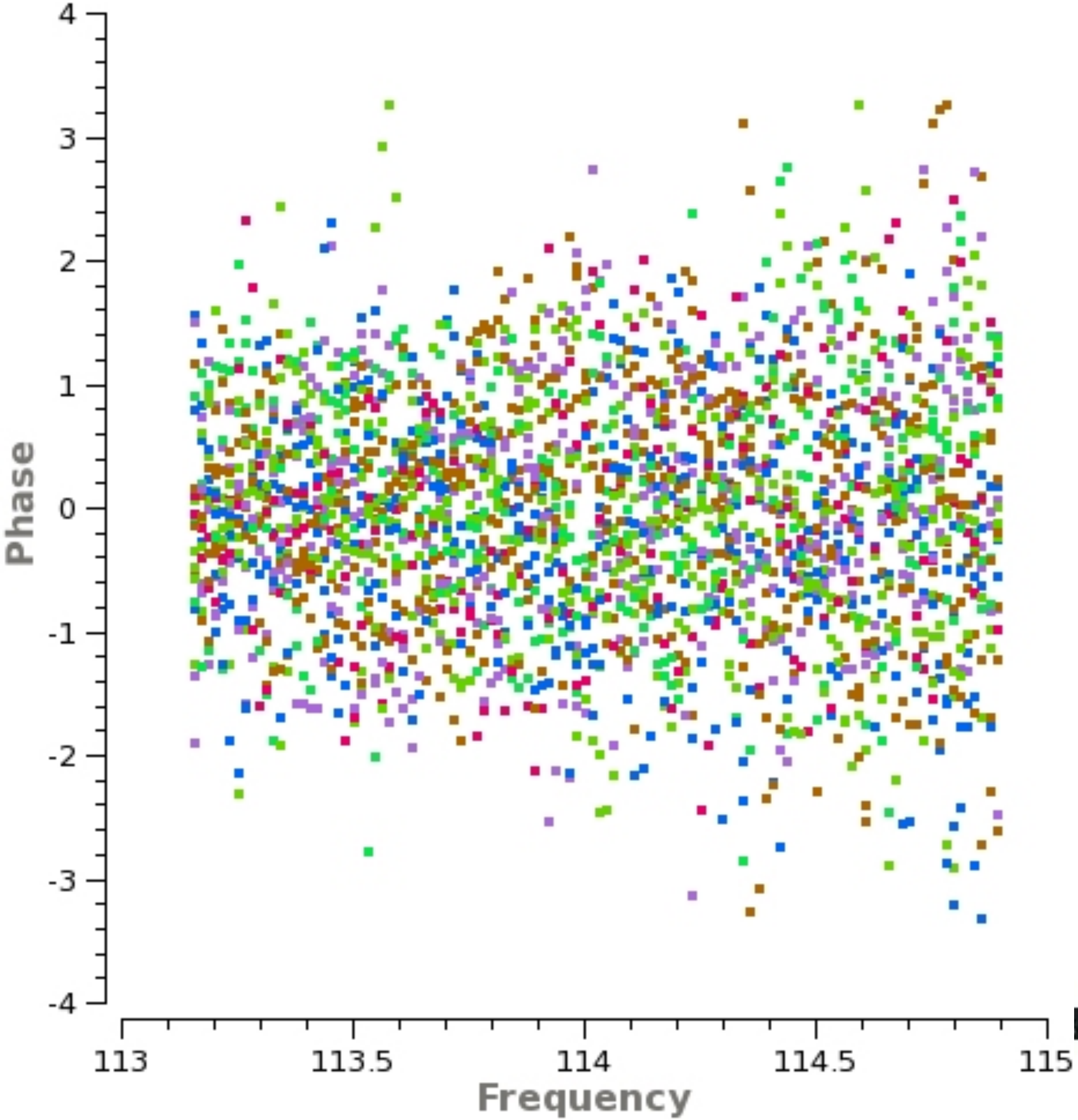
Steps in calibrating interferometric data:
(Note: You don't have to worry about these in your observational set up!)

- 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 Phase vs. Frequency (Before)



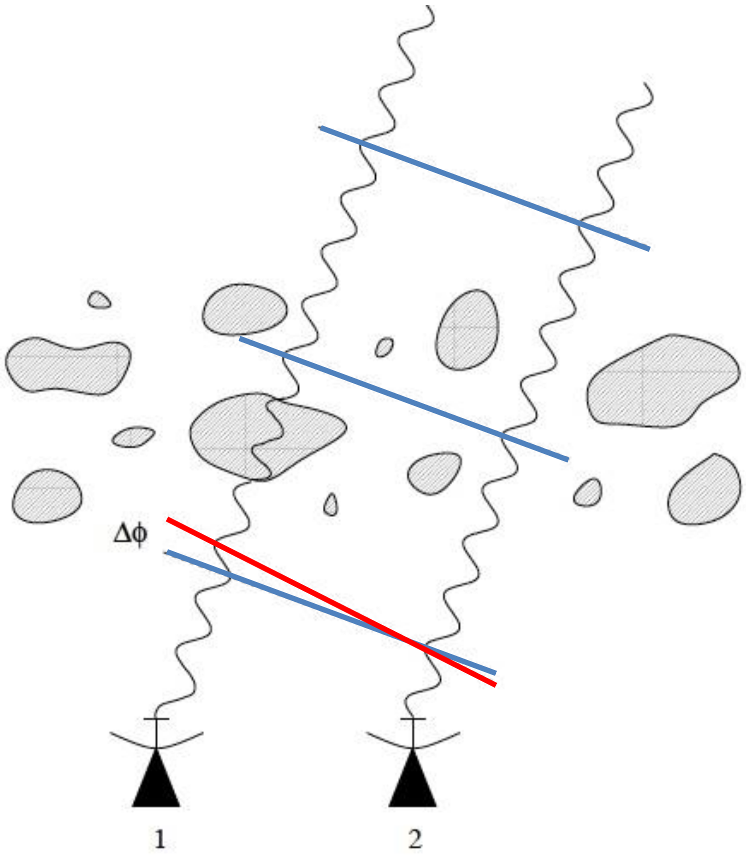
Bandpass Phase vs. Frequency (After)



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.

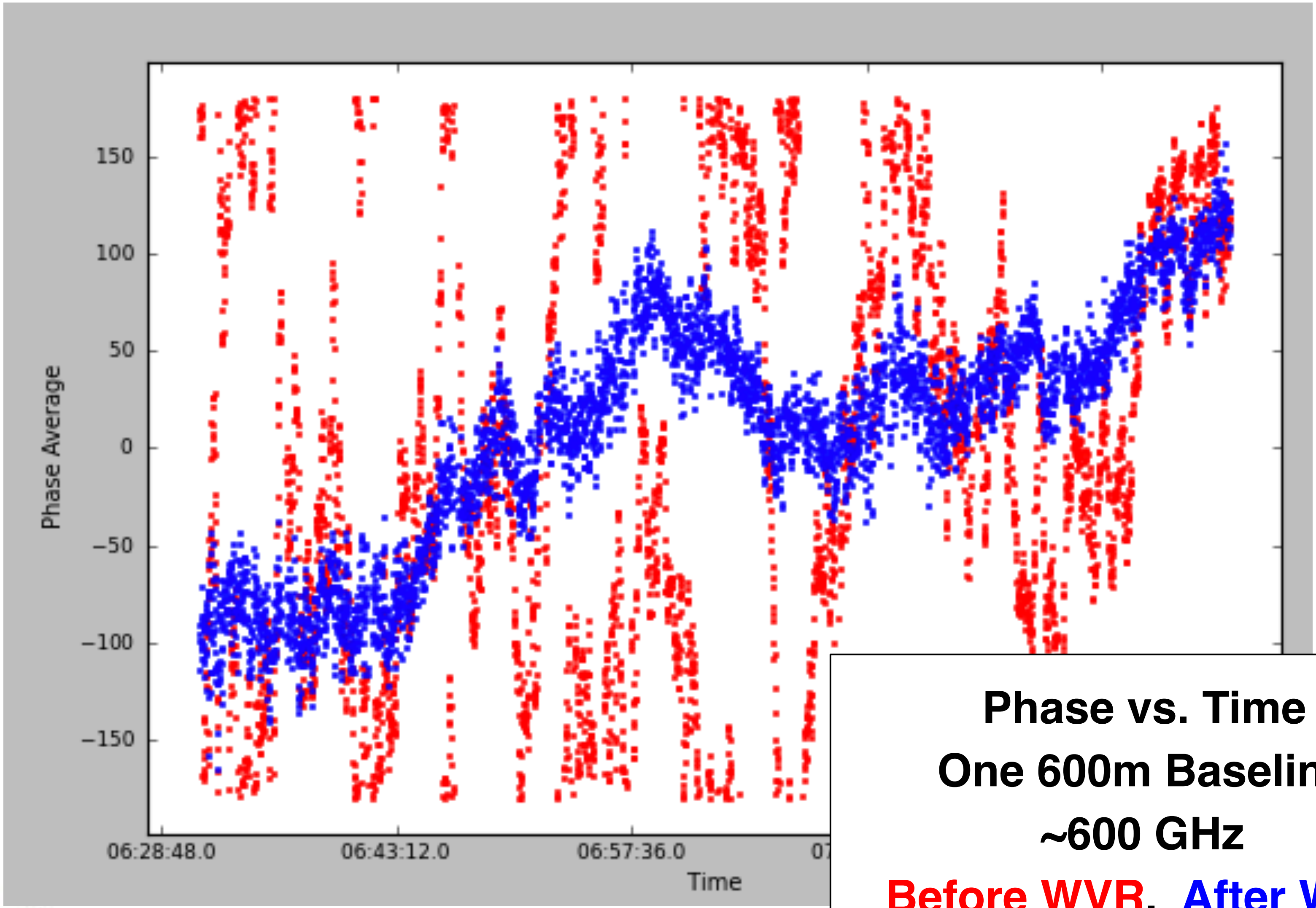


Phase & Amplitude Gain Calibration

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

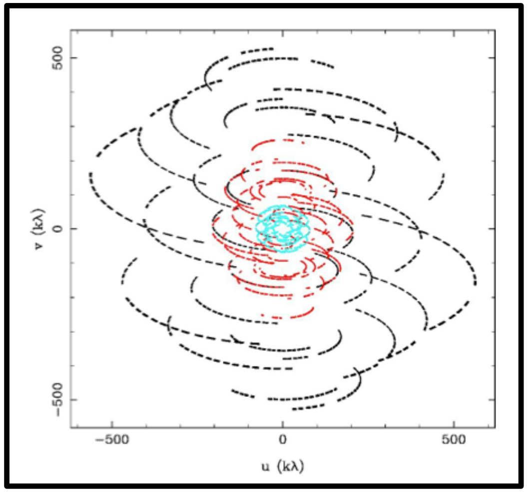
One 600m Baseline

~600 GHz

Before WVR, After WVR

The Dirty Beam

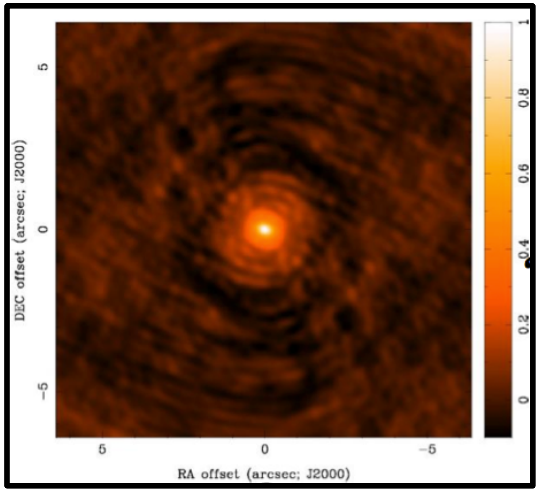
$S(u,v)$



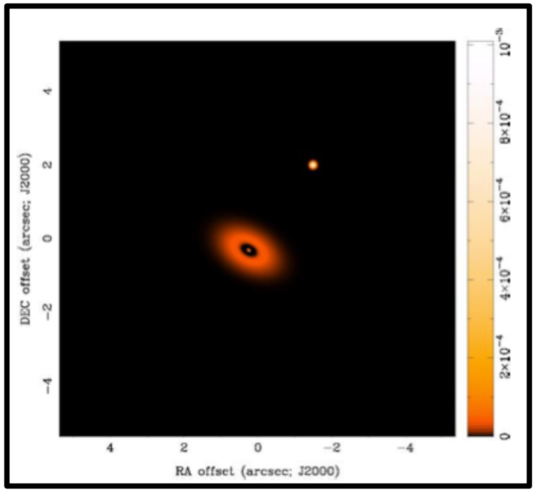
FT →

$s(x,y)$

“Dirty Beam”

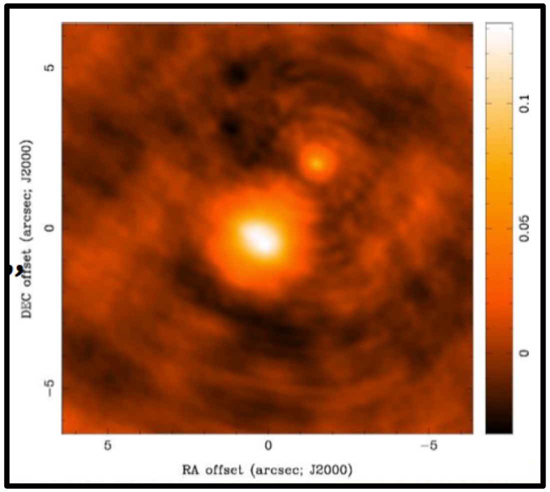


***(Convolution)**



$T(x,y)$

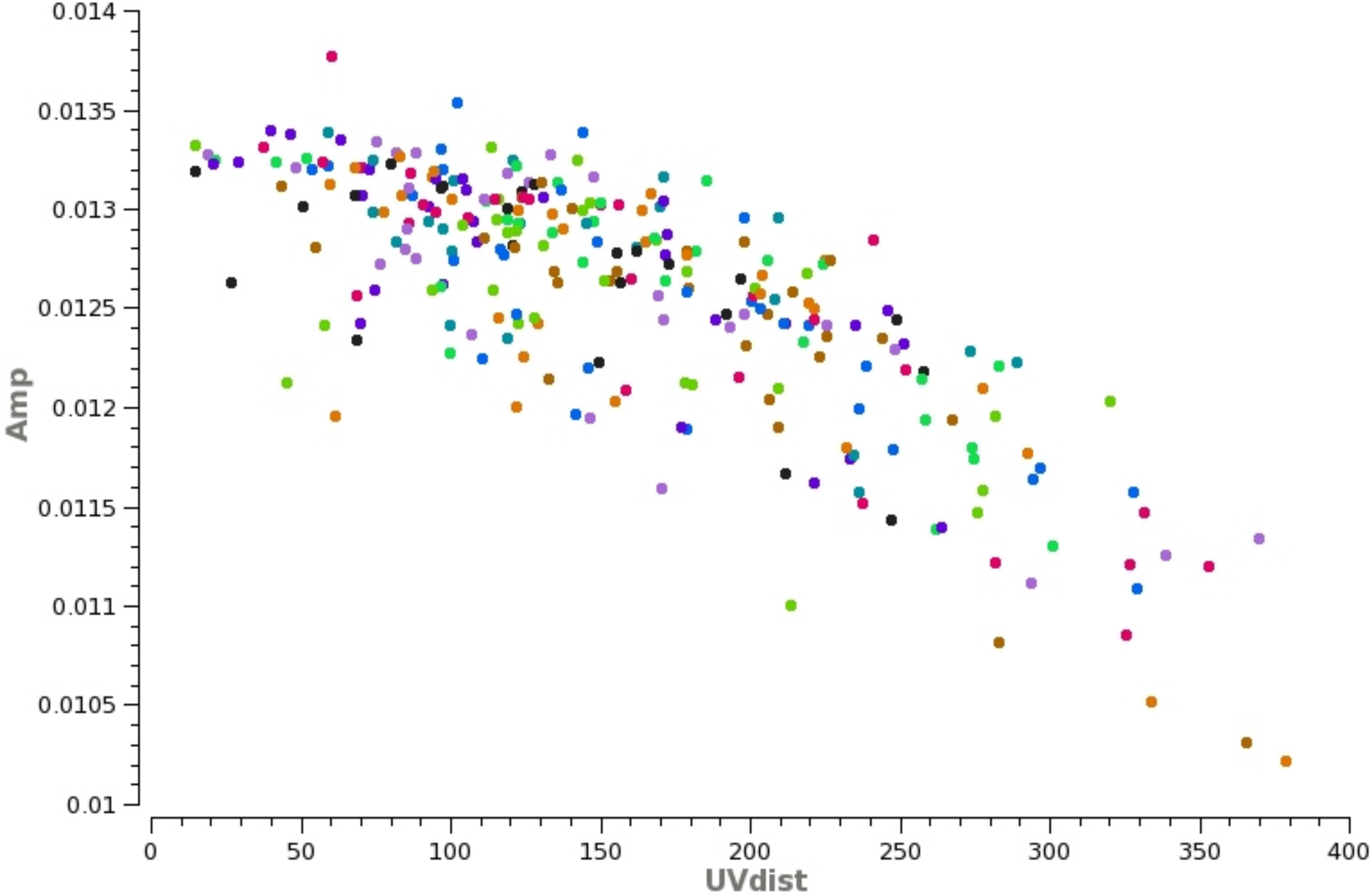
←



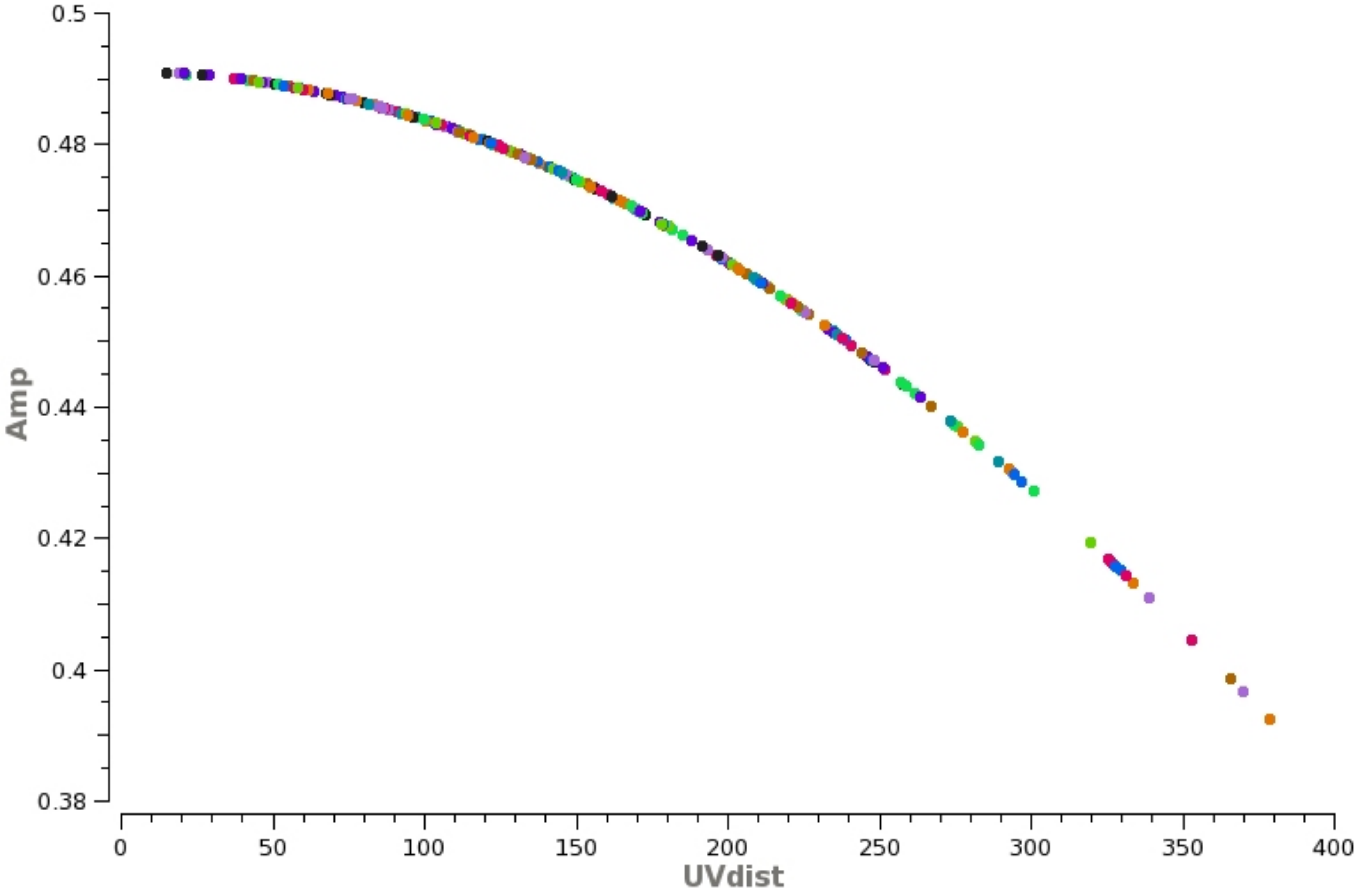
$T_D(x,y)$

“Dirty Image”

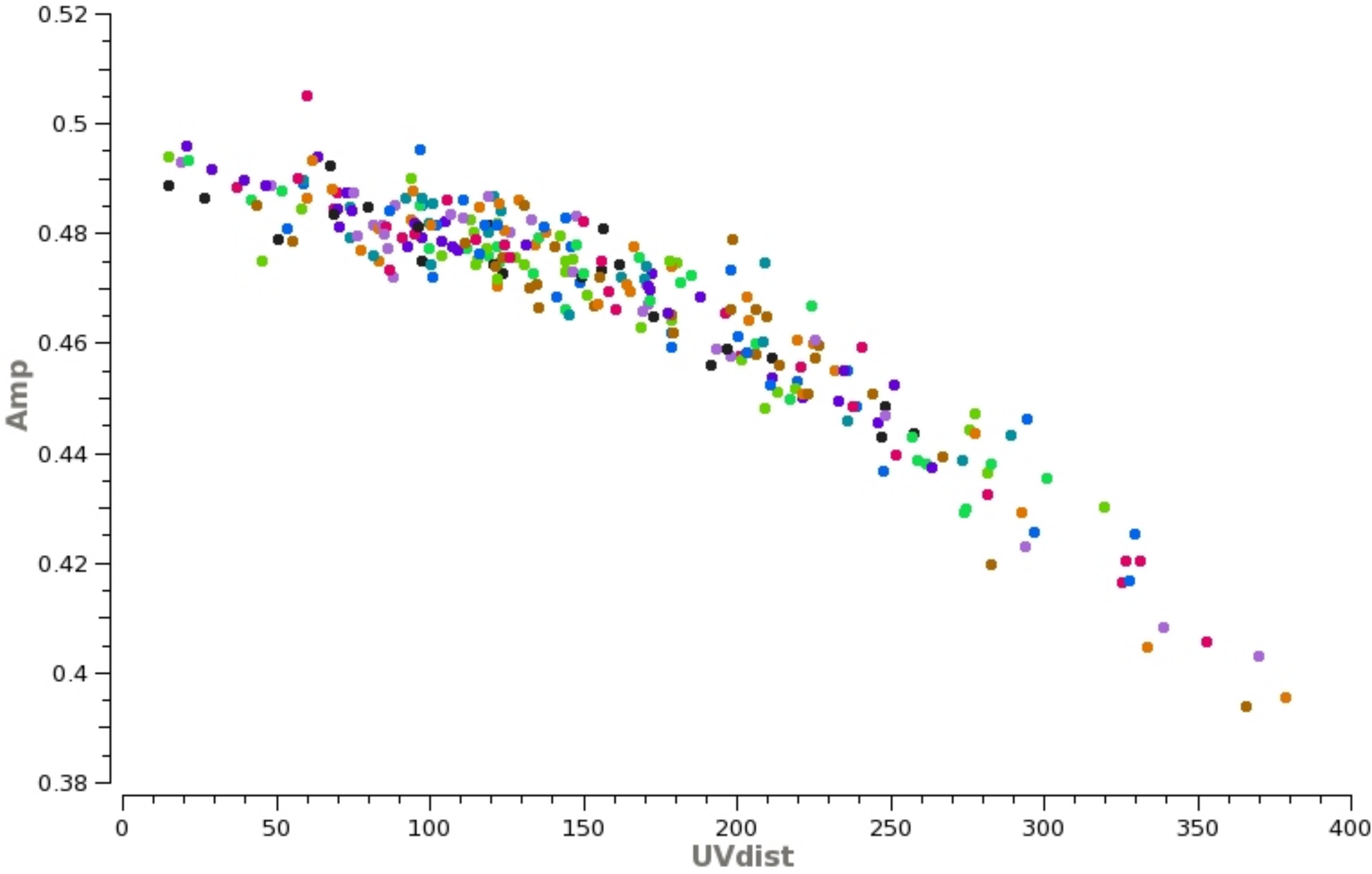
Amp-Calibrators Amp vs. uv-distance (Before)

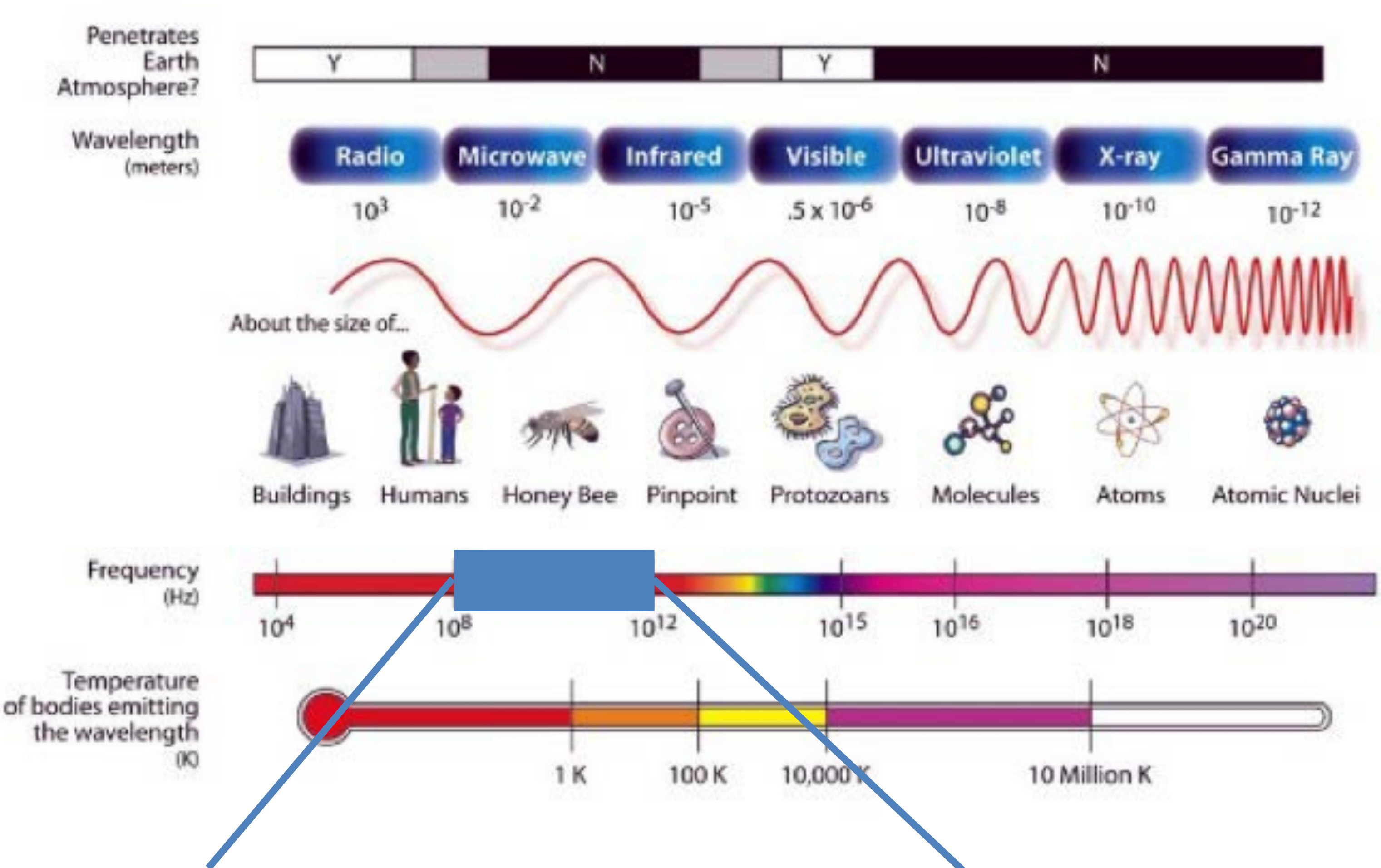


Amp-Calibrators Amp vs. uv-distance (Model)



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





VLA
~1 - 50 GHz
~300 - 6 mm

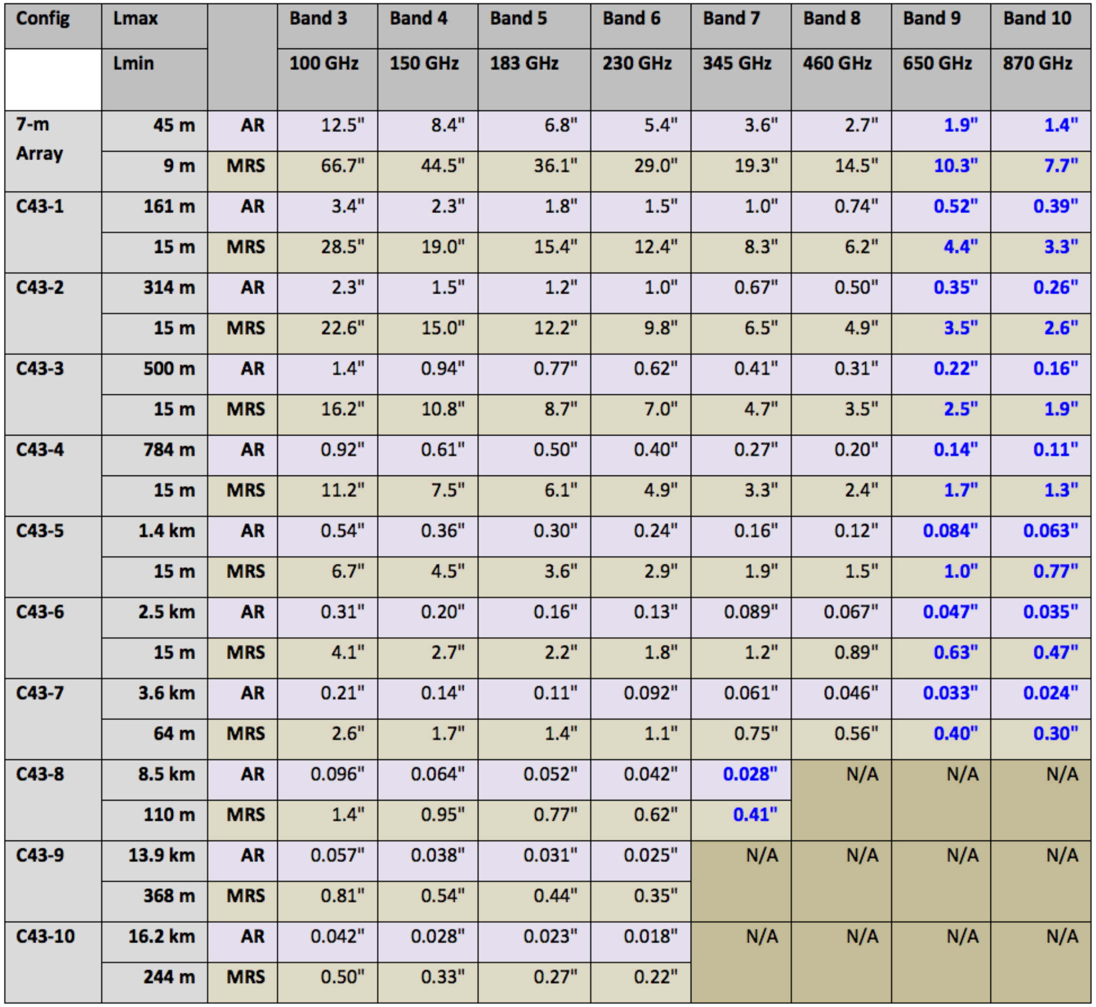
ALMA
~84 - 950 GHz
~3 - 0.3 mm

Angular Scales — A Proposal Tip!

Interferometers act as spatial filters - shorter baselines are sensitive to larger targets, so remember …

Spatial scales larger than the smallest baseline cannot be imaged

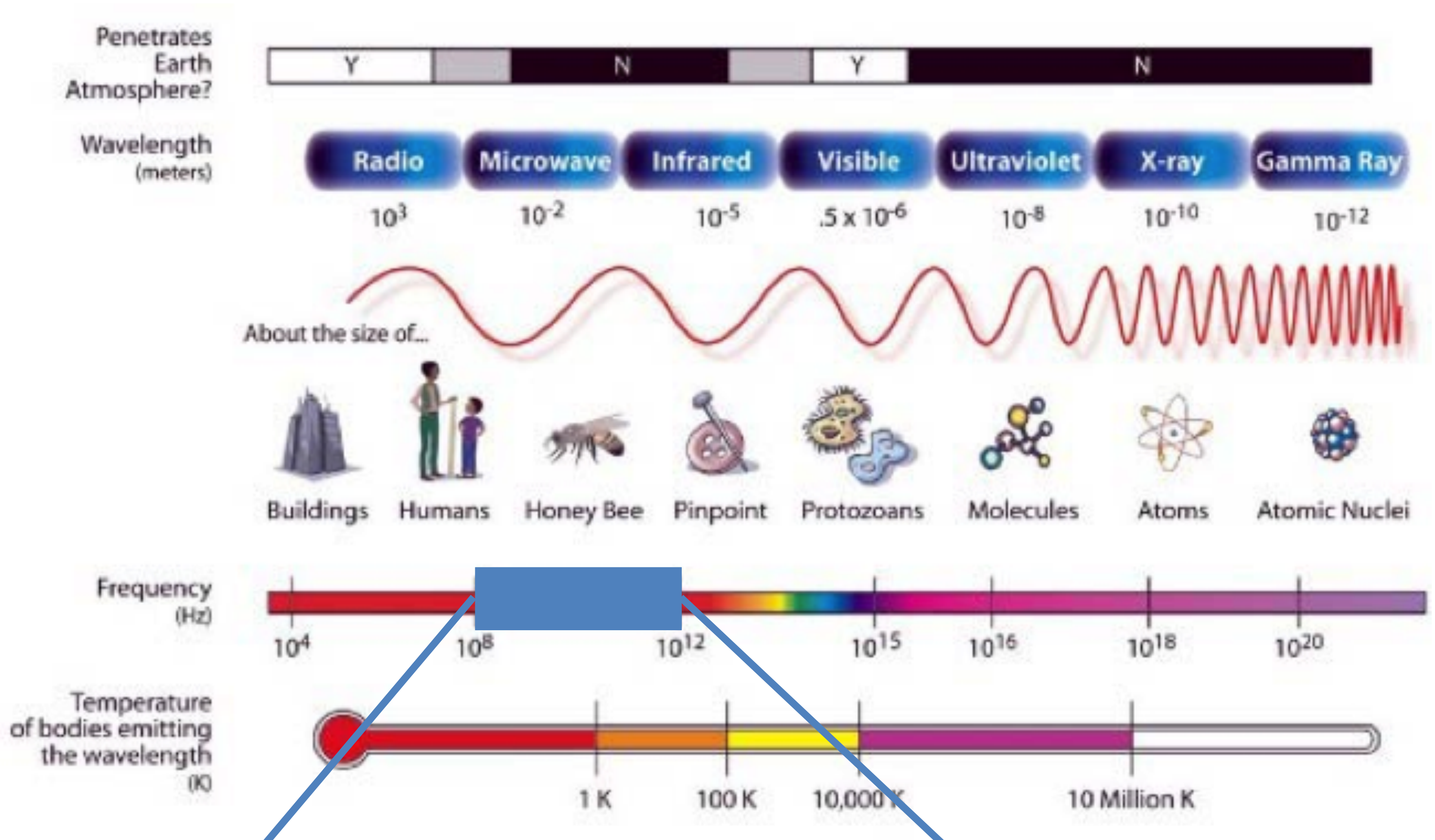
Spatial scales smaller than the largest baseline cannot be resolved

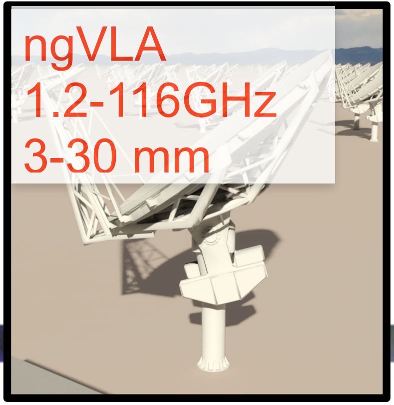


Config	Lmax		Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin		100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m Array	45 m	AR	12.5"	8.4"	6.8"	5.4"	3.6"	2.7"	1.9"	1.4"
	9 m	MRS	66.7"	44.5"	36.1"	29.0"	19.3"	14.5"	10.3"	7.7"
C43-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	28.5"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C43-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C43-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C43-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C43-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C43-6	2.5 km	AR	0.31"	0.20"	0.16"	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"	2.2"	1.8"	1.2"	0.89"	0.63"	0.47"
C43-7	3.6 km	AR	0.21"	0.14"	0.11"	0.092"	0.061"	0.046"	0.033"	0.024"
	64 m	MRS	2.6"	1.7"	1.4"	1.1"	0.75"	0.56"	0.40"	0.30"
C43-8	8.5 km	AR	0.096"	0.064"	0.052"	0.042"	0.028"	N/A	N/A	N/A
	110 m	MRS	1.4"	0.95"	0.77"	0.62"	0.41"			
C43-9	13.9 km	AR	0.057"	0.038"	0.031"	0.025"	N/A	N/A	N/A	N/A
	368 m	MRS	0.81"	0.54"	0.44"	0.35"				
C43-10	16.2 km	AR	0.042"	0.028"	0.023"	0.018"	N/A	N/A	N/A	N/A
	244 m	MRS	0.50"	0.33"	0.27"	0.22"				

From the ALMA Cycle 6 Proposal Guide

NRAO





ngVLA
1.2-116GHz
3-30 mm

ALMA
~84 - 950 GHz
~3 - 0.3 mm