Introduction to Radio Interferometry

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With help from Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt

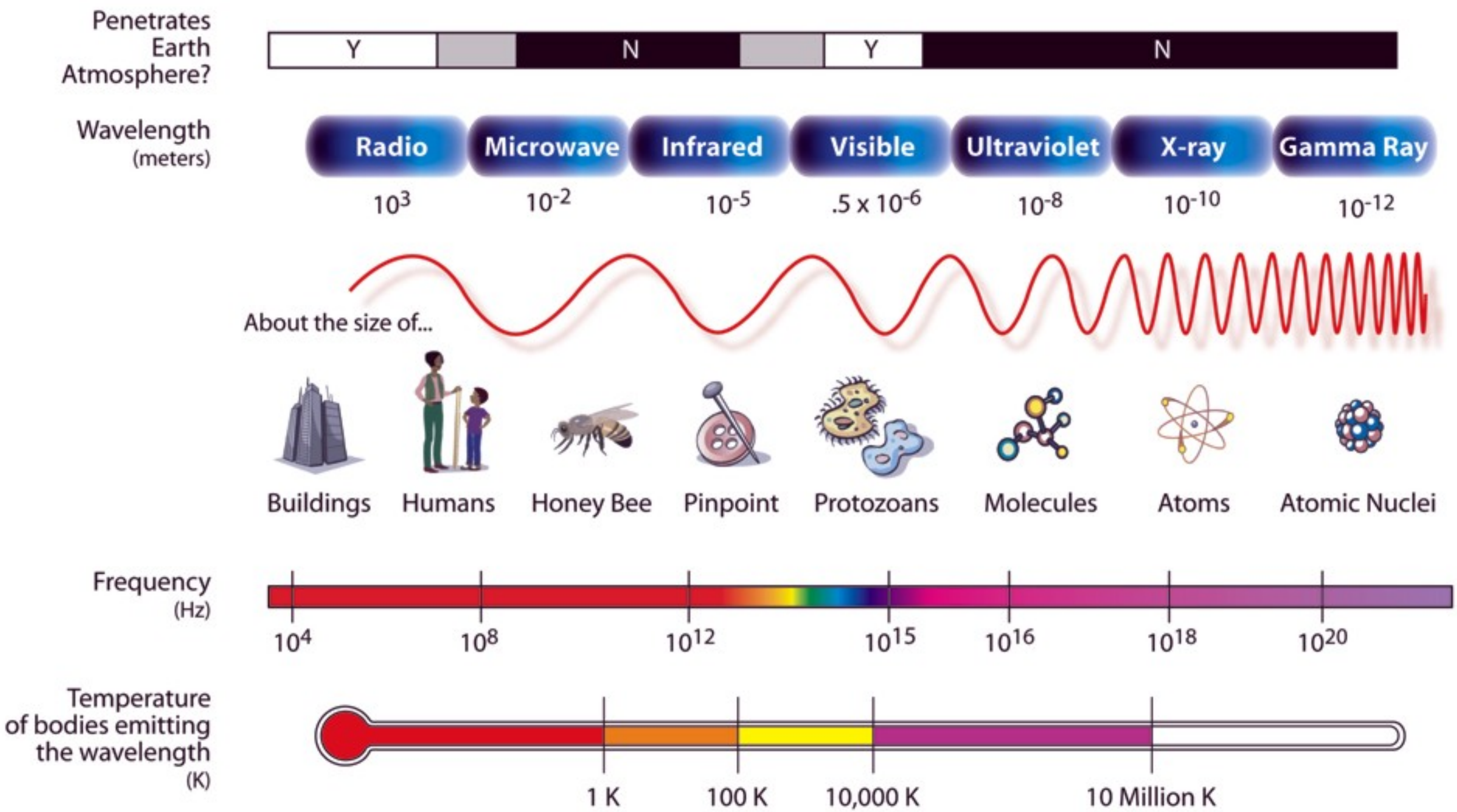
Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array

NRAO

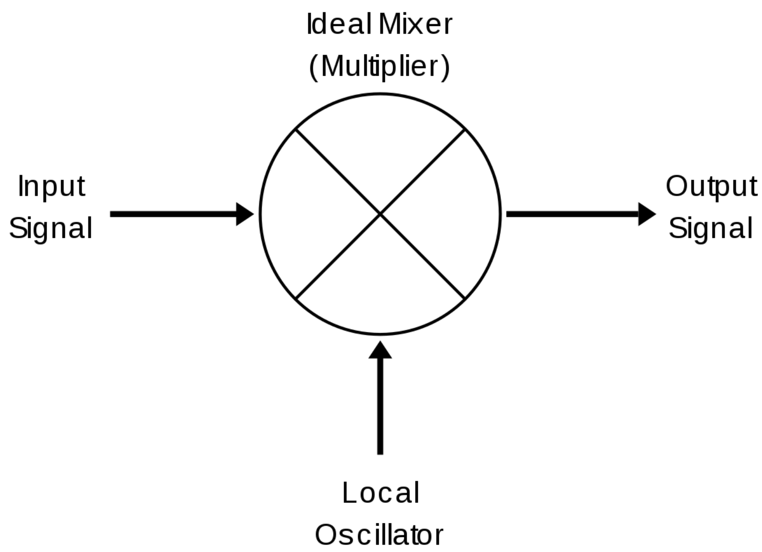
Introduction to Radio Interferometry

- ☐ Quick background on radio astronomy
- ☐ Radio interferometry: how does it work?
- ☐ (u,v) visibilities & aperture synthesis
- ☐ Turning visibilities into images
- ☐ Brief note on calibration
- ☐ Useful radio interferometry references

Radio astronomy: (sub-)mm to cm wavelengths



Radio astronomy uses heterodyne receivers



Heterodyne receivers down-convert observed signals to lower frequencies by mixing them with artificially created **Local Oscillator [LO]** signal

The output can then be amplified and analyzed more easily (e.g., by the correlator) while retaining the original phase and amplitude information

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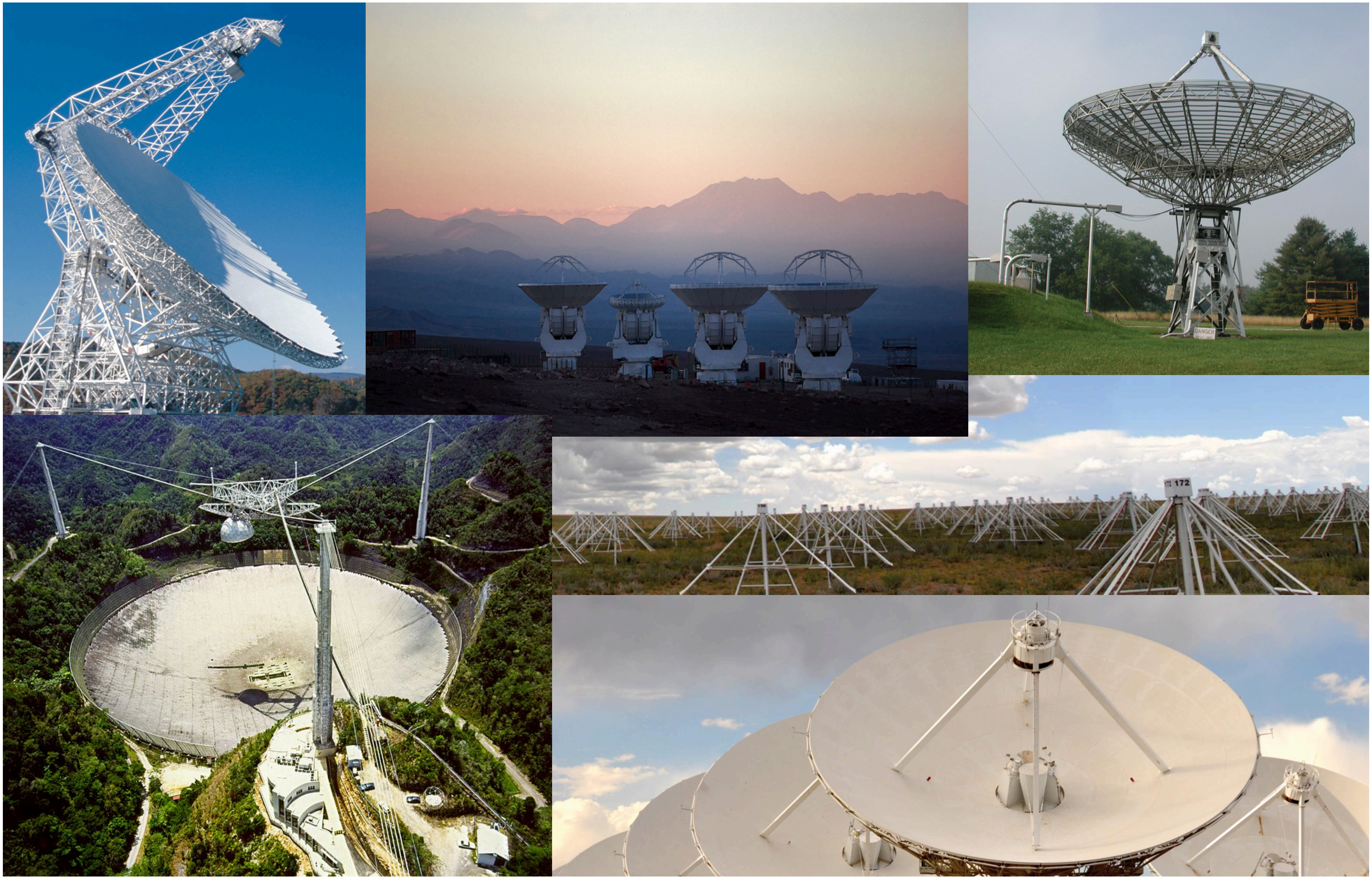
Long wavelengths mean no glass mirrors



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Interferometry lets us achieve high angular resolution at radio wavelengths

Angular resolution for most telescopes is ~ λ/D

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

For the Hubble Space Telescope:

λ ~ 1μm & D ~ 2.4m ➔ resolution ~ 0.13"

2km dishes would be needed for HST resolution at λ ~1mm

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

This is interferometry!

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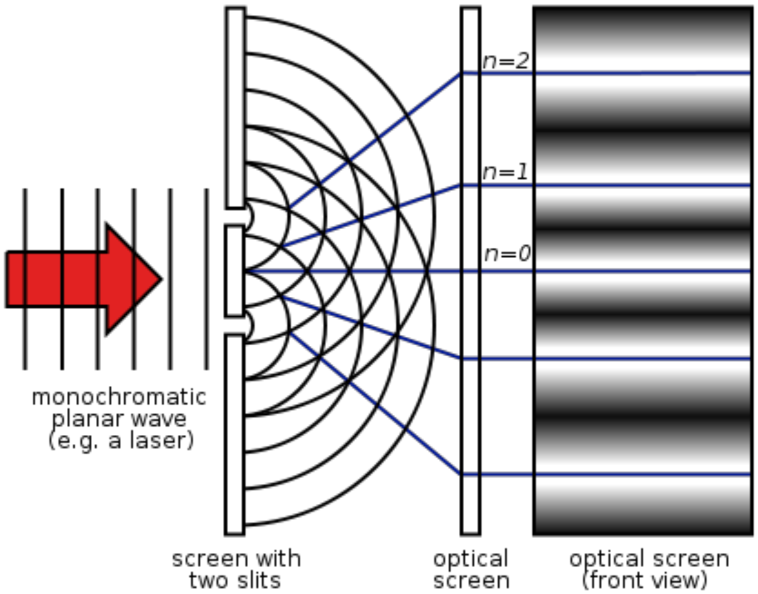
Radio interferometers measure interference patterns between pairs of antennas

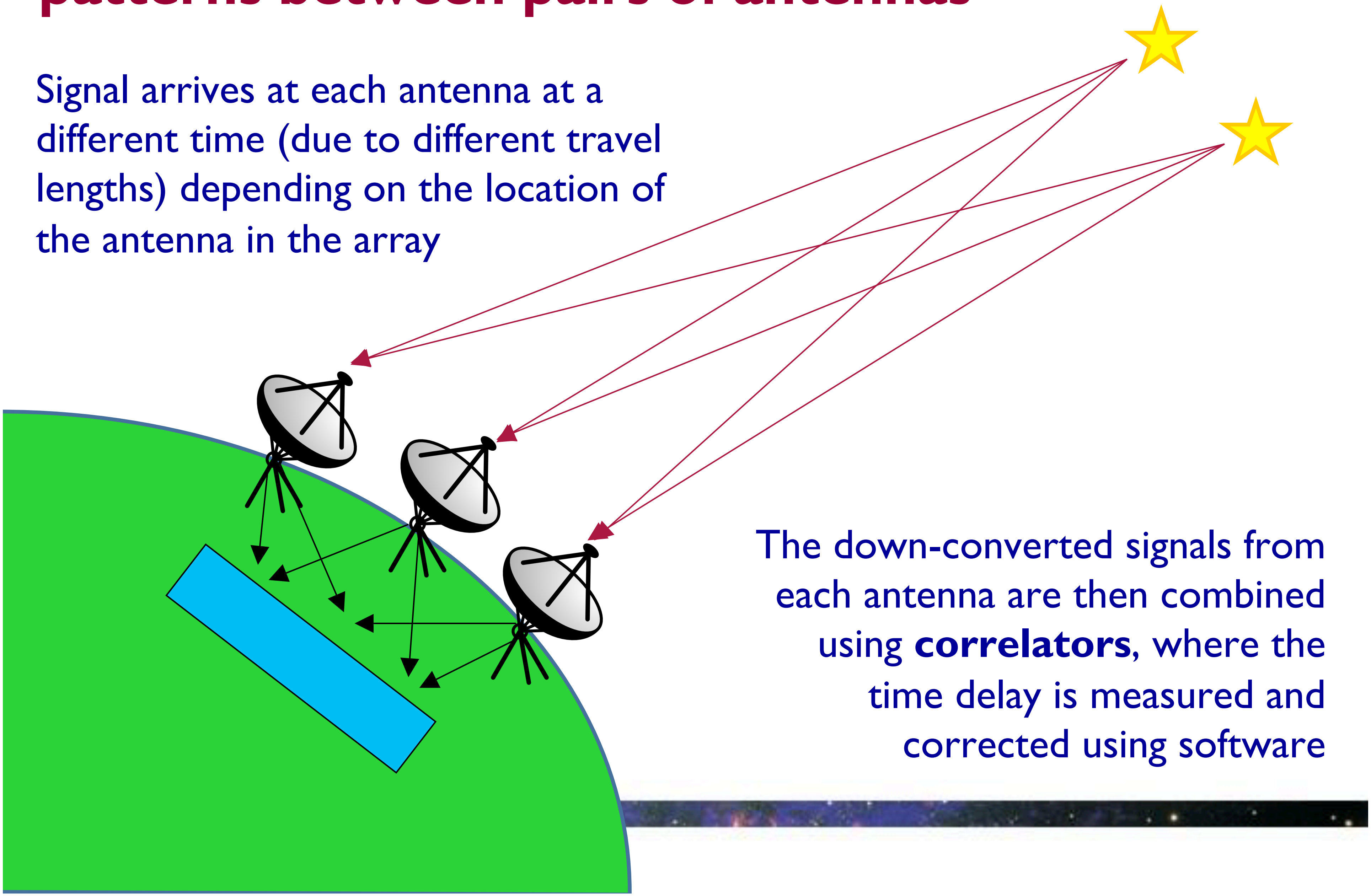
An **interferometer** measures the interference pattern produced by multiple apertures, much like a two-slit experiment



In radio astronomy, the apertures are the individual radio **antennas** and the signals are multiplied (not added)

Radio interferometers measure interference patterns between pairs of antennas

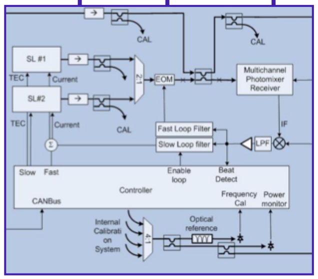
Signal arrives at each antenna at a different time (due to different travel lengths) depending on the location of the antenna in the array



The down-converted signals from each antenna are then combined using **correlators**, where the time delay is measured and corrected using software

Radio interferometry is complicated

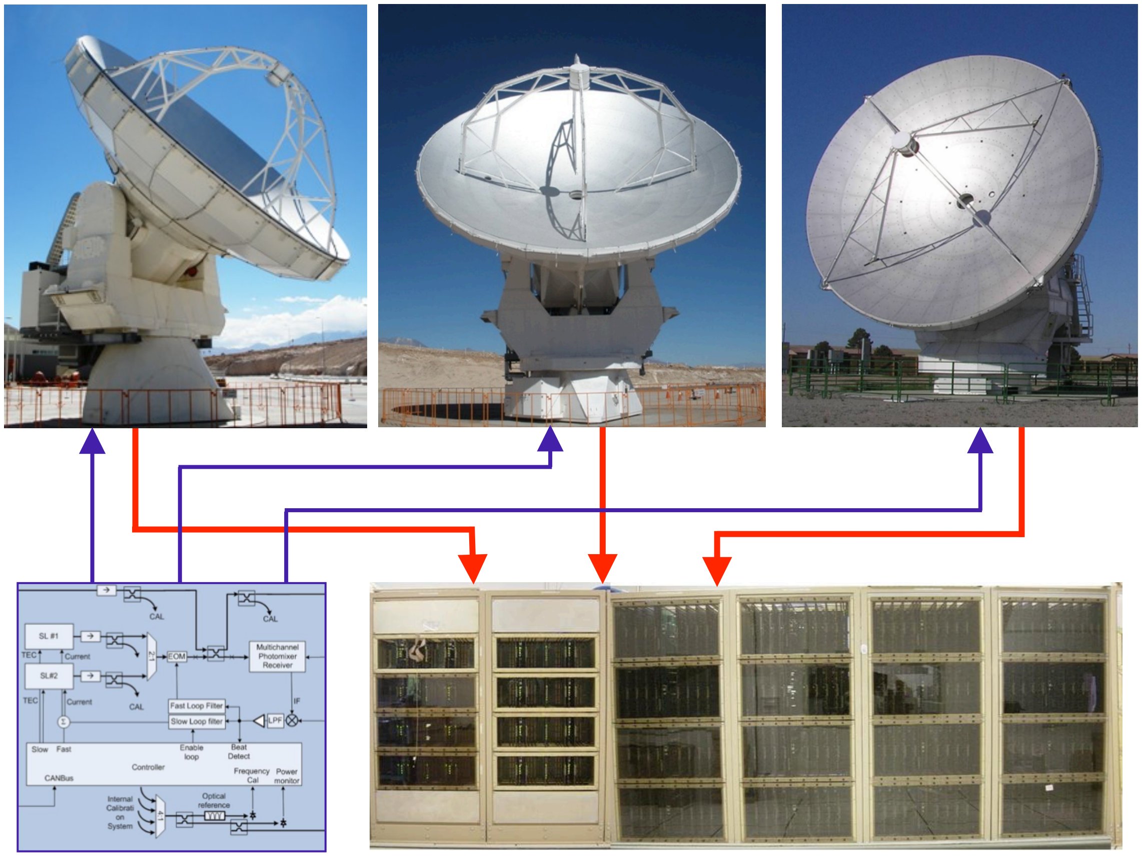
Signals **going out** to antennas control pointing/tracking, receiver tuning, timing reference, etc.



Need accurate clocks to precisely measure arrival times

Band 10 wavelength error = 1 picosecond & need << wavelength timing precision
Each antenna has on-board clock with high sampling rates

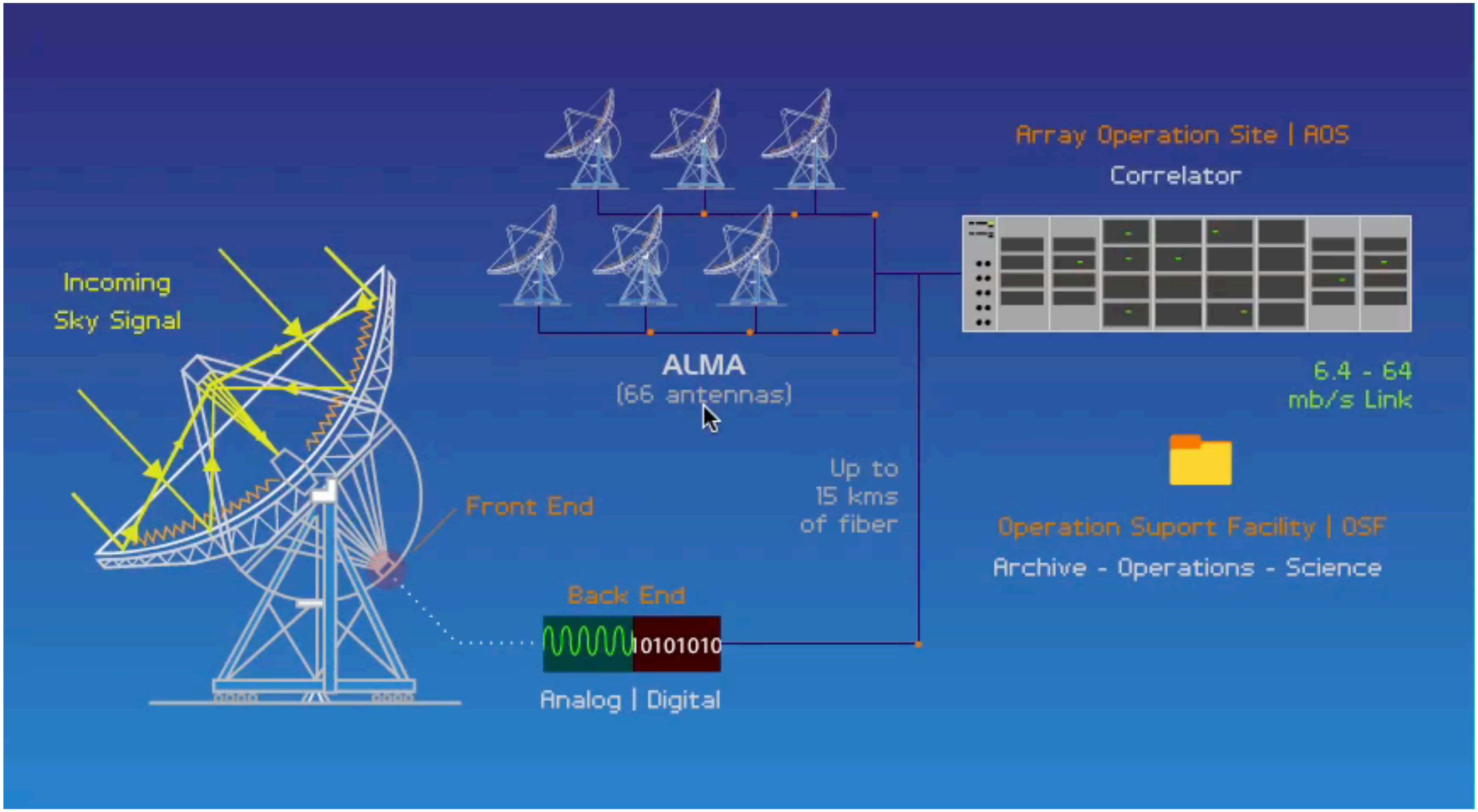
Radio interferometry is complicated



Signals **going out** to antennas control pointing/tracking, receiver tuning, timing reference, etc.

Astronomical signals coming **back** are sent to correlator (total array = 600 GB/s to process)

A radio interferometer in action...



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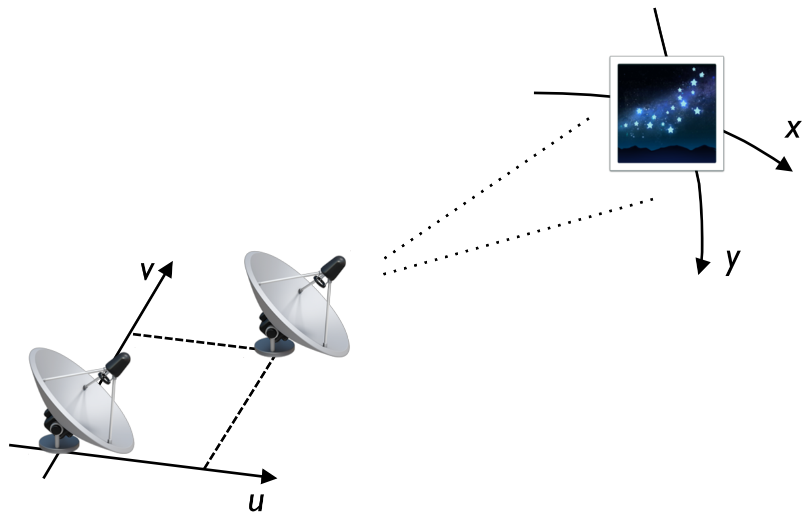
Fourier transforms [FT] allow us to translate interference pattern measured at telescope into radio brightness on the sky

$$V(u,v) \overset{\text{FT}}{\rightleftarrows} T(x,y)$$

Complex visibilities
(what we measure at telescope; Fourier space)

Sky brightness distribution
(what we want to know; image space)



What is the complex visibility *V(u,v)*?

Real component = **amplitude**

Brightness of a certain frequency component

Imaginary component = **phase**

Where that frequency component is located

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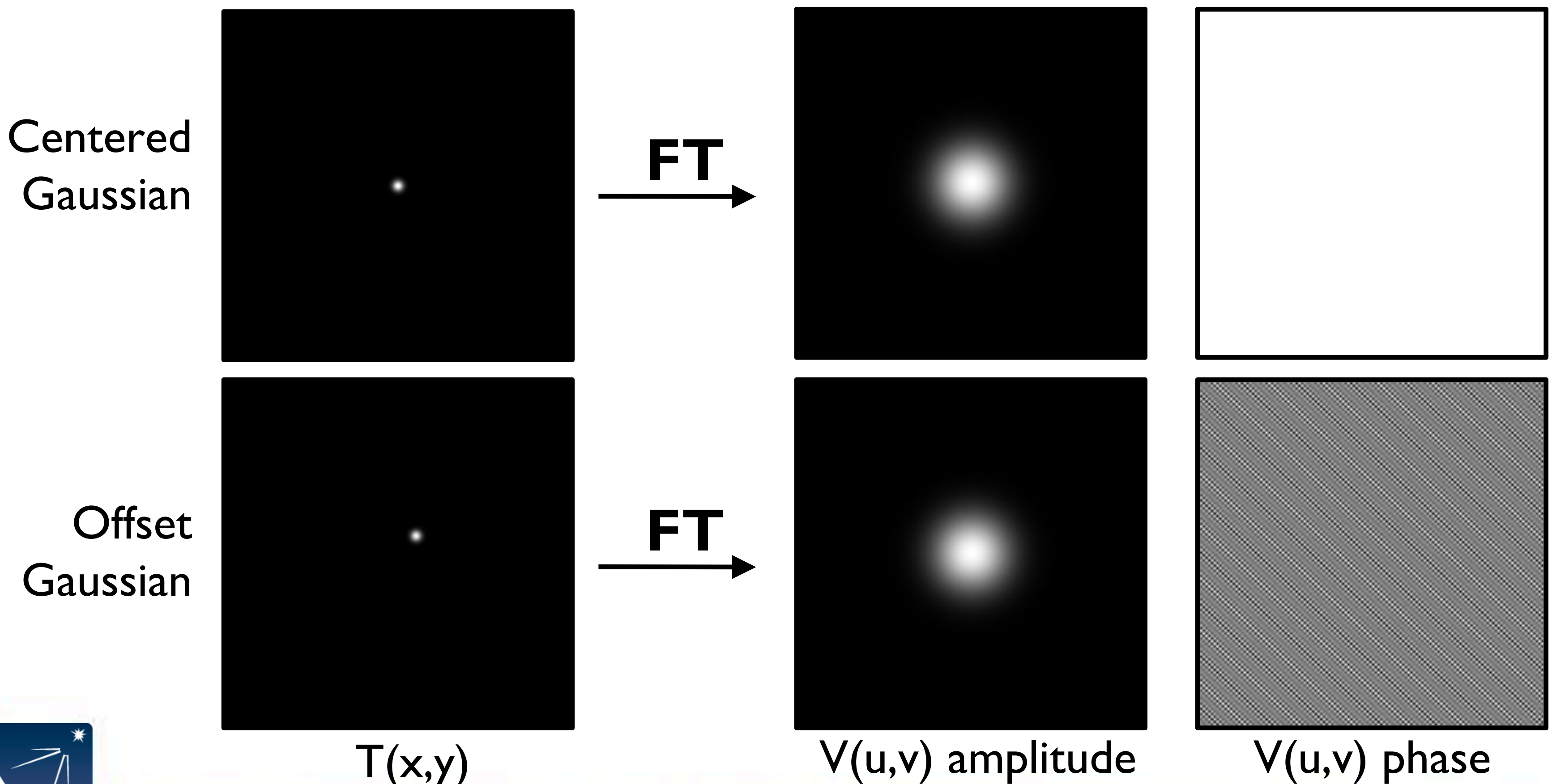
Real component = **amplitude**
Brightness of a certain frequency component

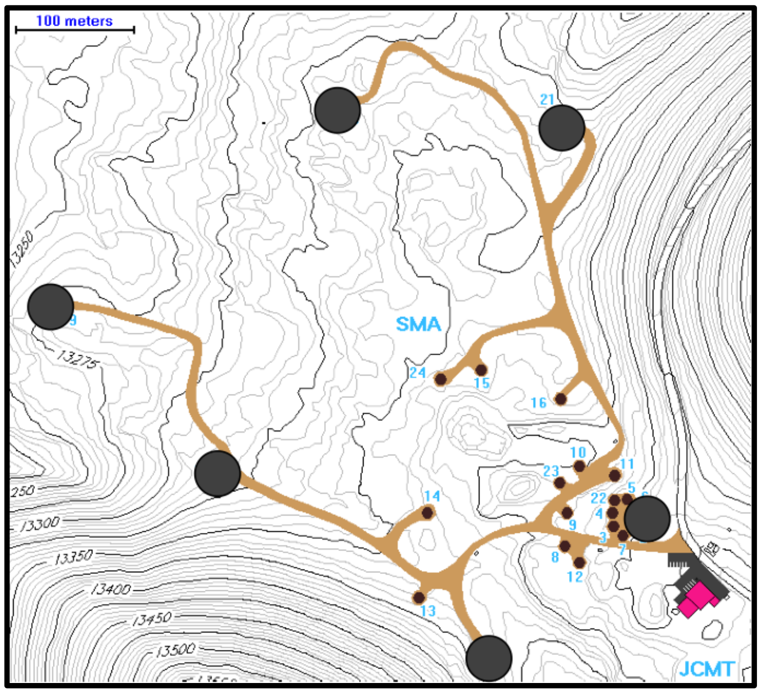
Imaginary component = **phase**
Where that component is located

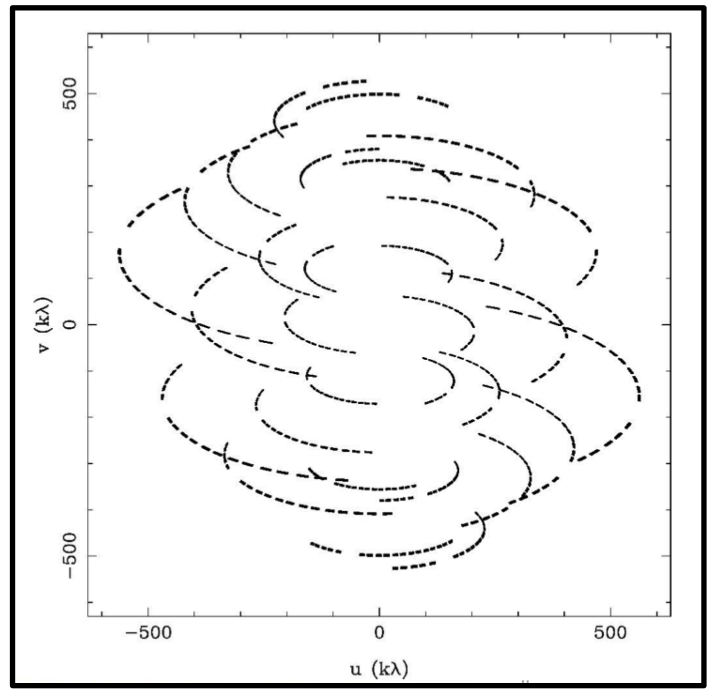


Problem of finite (u,v) plane sampling

Problem of finite (u,v) plane sampling

1 antenna pair = 1 baseline = 2 (u,v) points

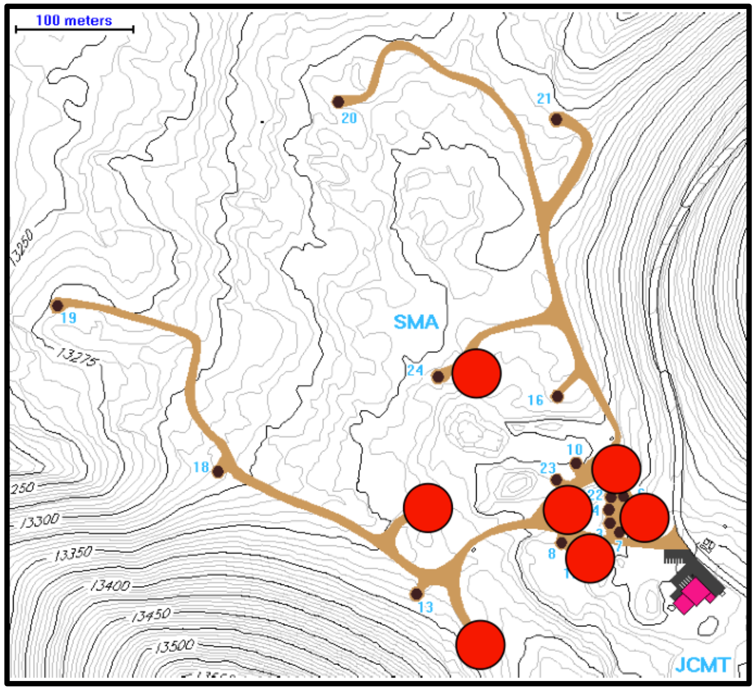


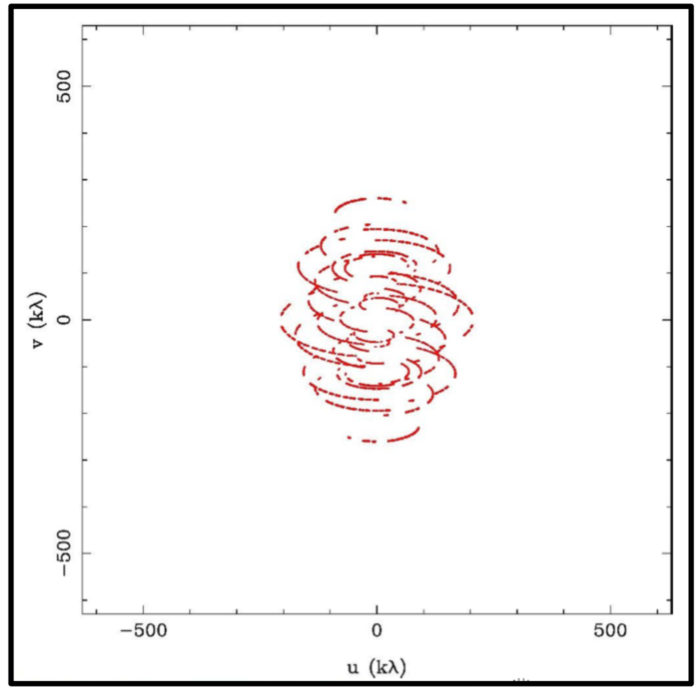


Very Extended SMA configuration

Problem of finite (u,v) plane sampling

1 antenna pair = 1 baseline = 2 (u,v) points





Extended SMA configuration

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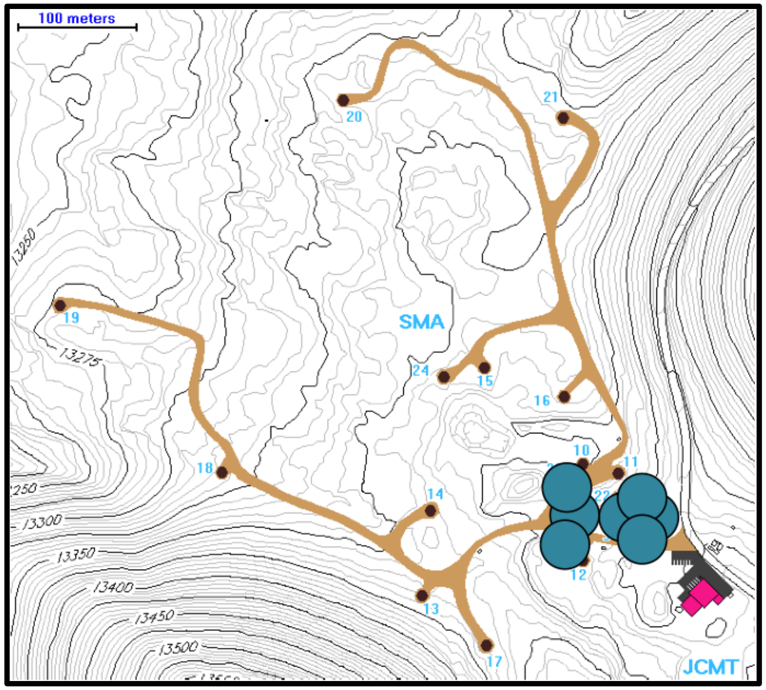
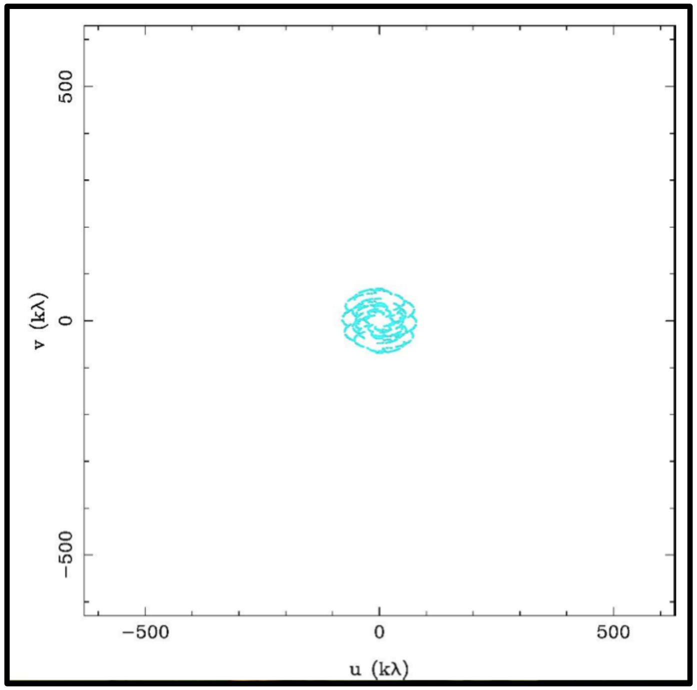
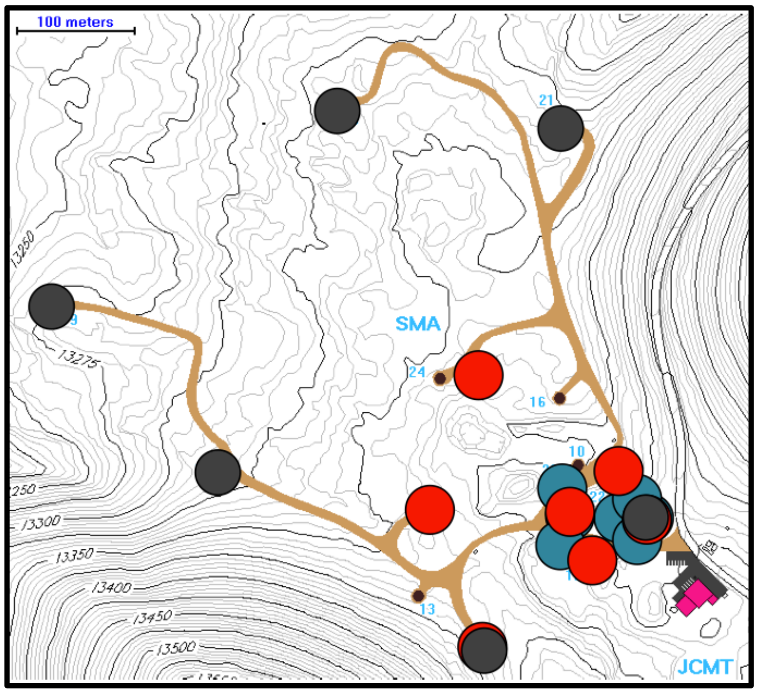


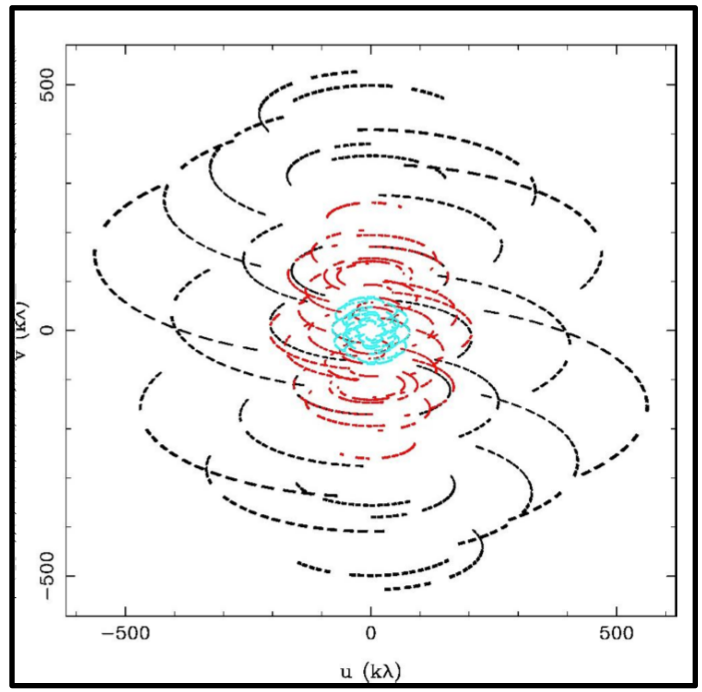


Compact SMA configuration

Problem of finite (u,v) plane sampling

1 antenna pair = 1 baseline = 2 (u,v) points





Combine configurations to get most "(u,v) plane coverage"

Problem of (u,v) plane sampling

What happens if our (u,v) coverage is not complete?

Problem of (u,v) plane sampling

What happens if our (u,v) coverage is not complete?

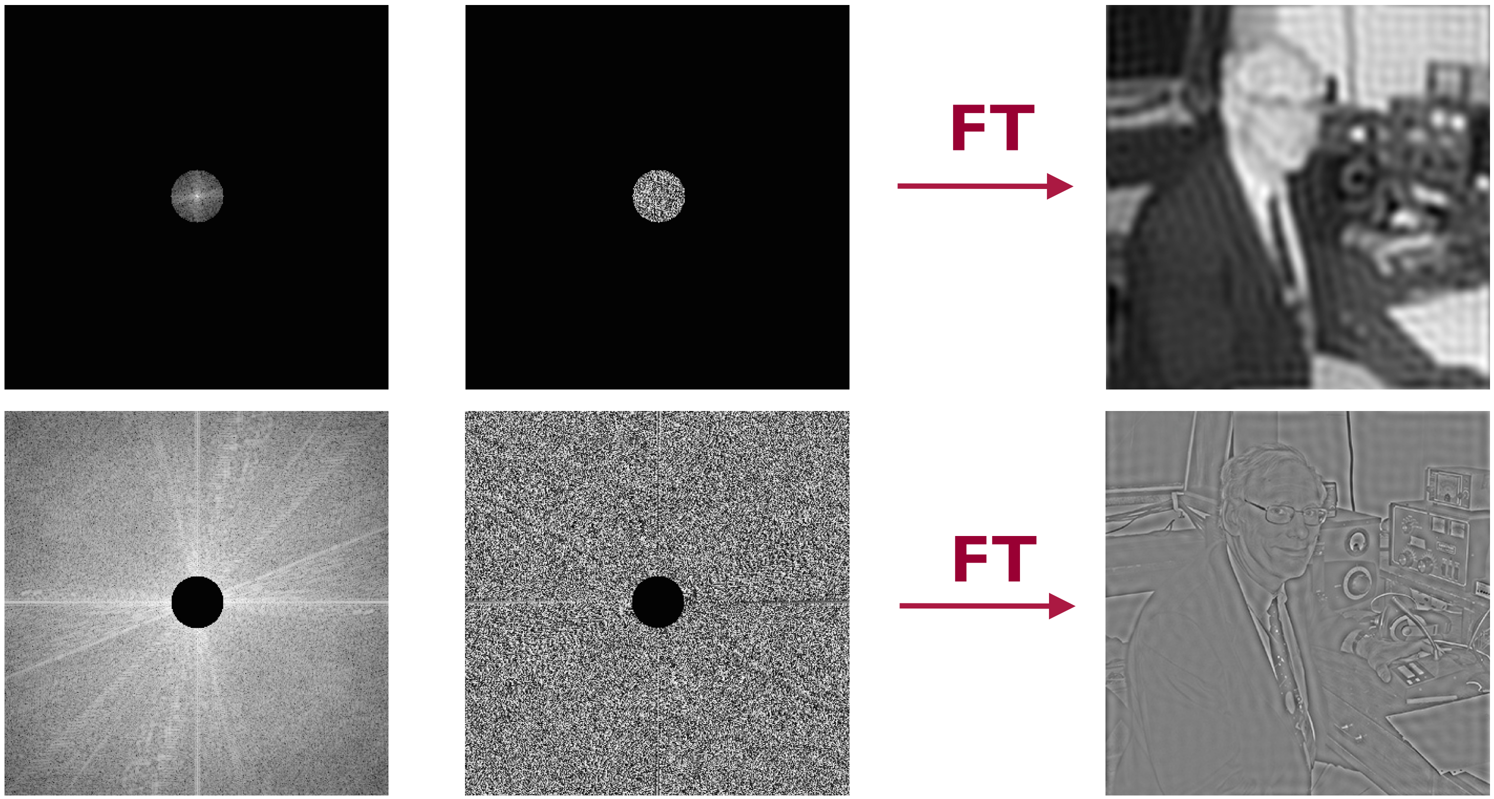
V(u,v) amplitude **V(u,v) phase** **T(x,y)**

Missing <u>high</u> spatial freq.

(compact arrays)

Missing <u>low</u> spatial freq.

(extended arrays)



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Sampling (u,v) plane = "aperture synthesis"

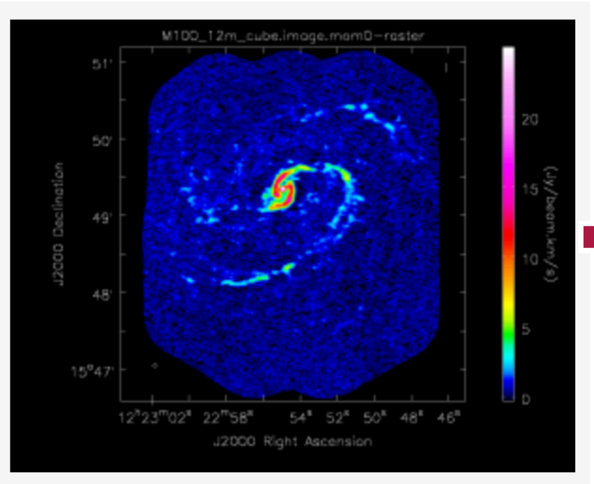
Sample V(u,v) at a enough (u,v) points using distributed small antennas to synthesize large antenna of size (u_{max},v_{max})

For **N antennas**, we get **N(N-1) samples** at each observation

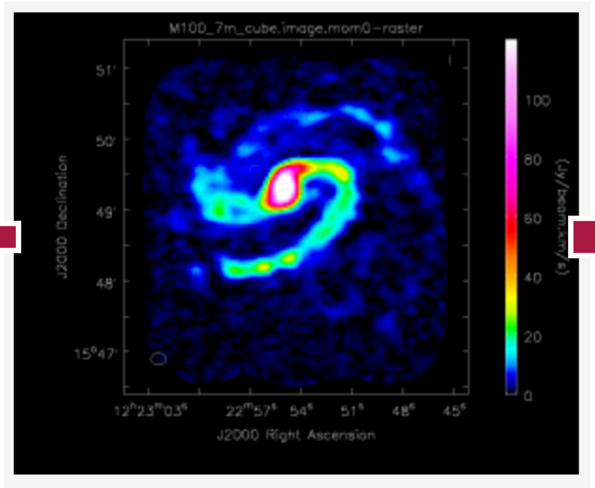
Fill out the rest of the (u,v) plane using 1) Earth's rotation and 2) physically reconfiguring antennas

Aperture synthesis example: M100

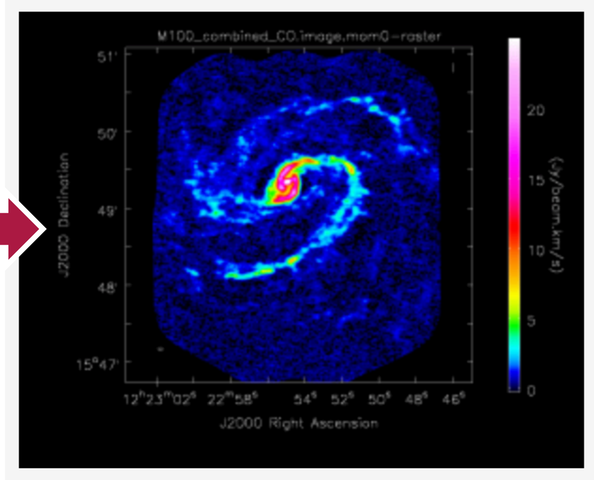
ALMA 12m



ACA 7m



Combined



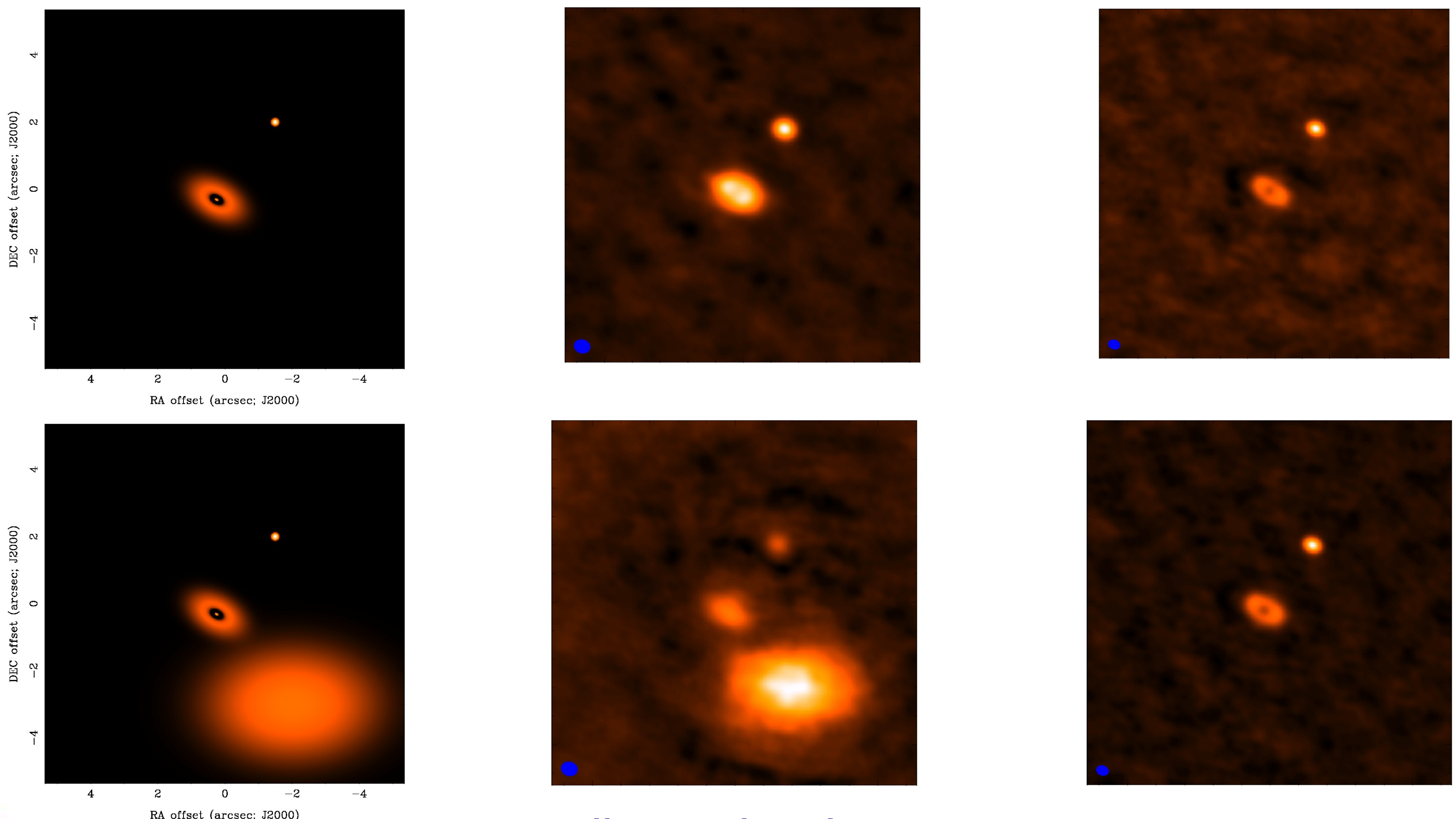
ALMA 12m shows smaller spatial scales (denser, clumpier emission)
ACA 7m data shows larger spatial scales (diffuse, extended emission)

To get both — you need a combined image!

Beware: more arrays adds time to your proposal & affects available scheduling!

Aperture synthesis example: short spacings

You can miss (big!) things if the (u,v) plane is insufficiently sampled (not always a bad thing!)



sky model

all spatial scales
(full uv coverage)

missing short spacings
(central hole)

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Characteristic angular scales in interferometry

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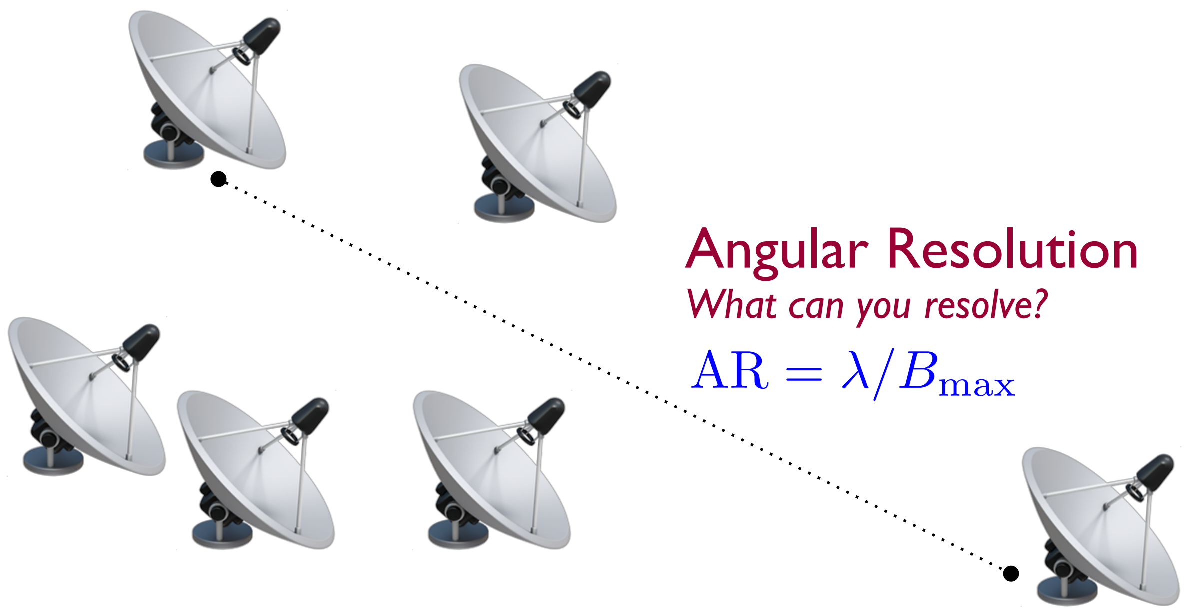
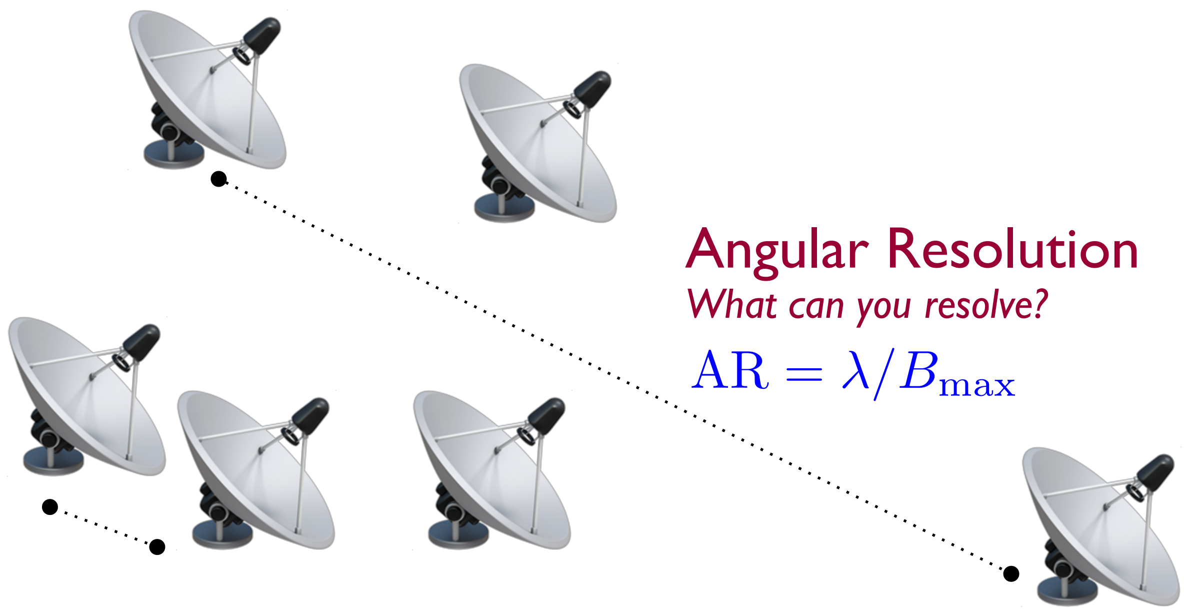


$$\mathrm{AR} = \lambda / B_{\mathrm{max}}$$

Characteristic angular scales in interferometry



Angular Resolution

What can you resolve?

$$\mathrm{AR} = \lambda / B_{\mathrm{max}}$$

Maximum Recoverable Scale

What's the biggest structure you can see?

$$\mathrm{MRS} = \lambda / B_{\mathrm{min}}$$

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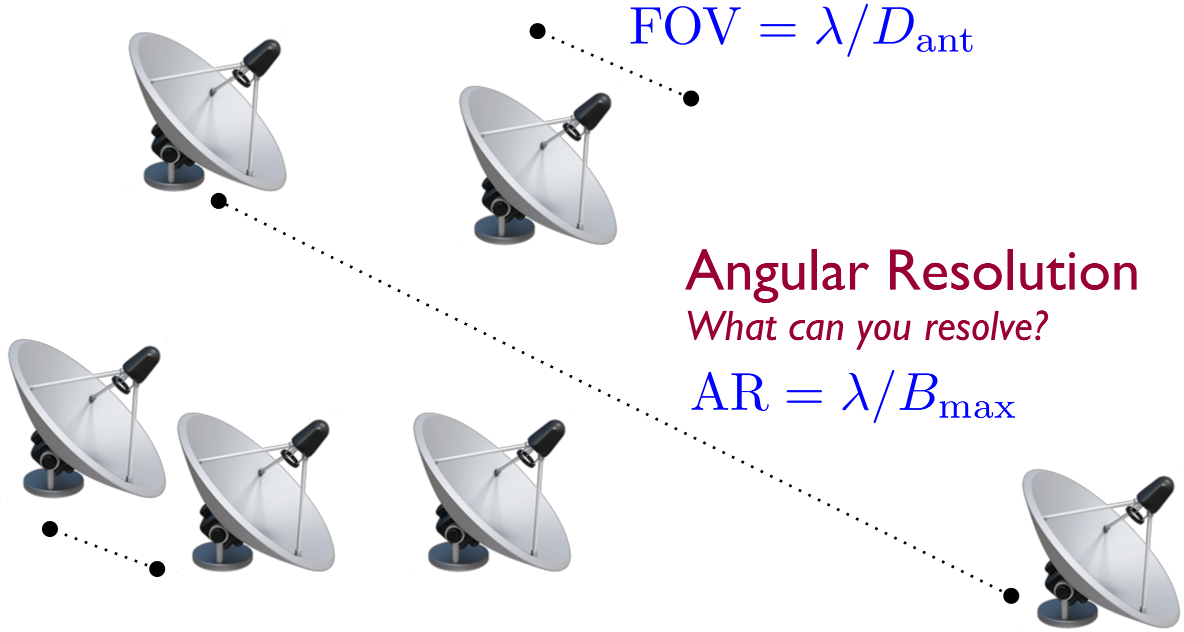
Characteristic angular scales in interferometry



Field of View

How big is your image?

$$\mathrm{FOV} = \lambda / D_{\mathrm{ant}}$$

Angular Resolution

What can you resolve?

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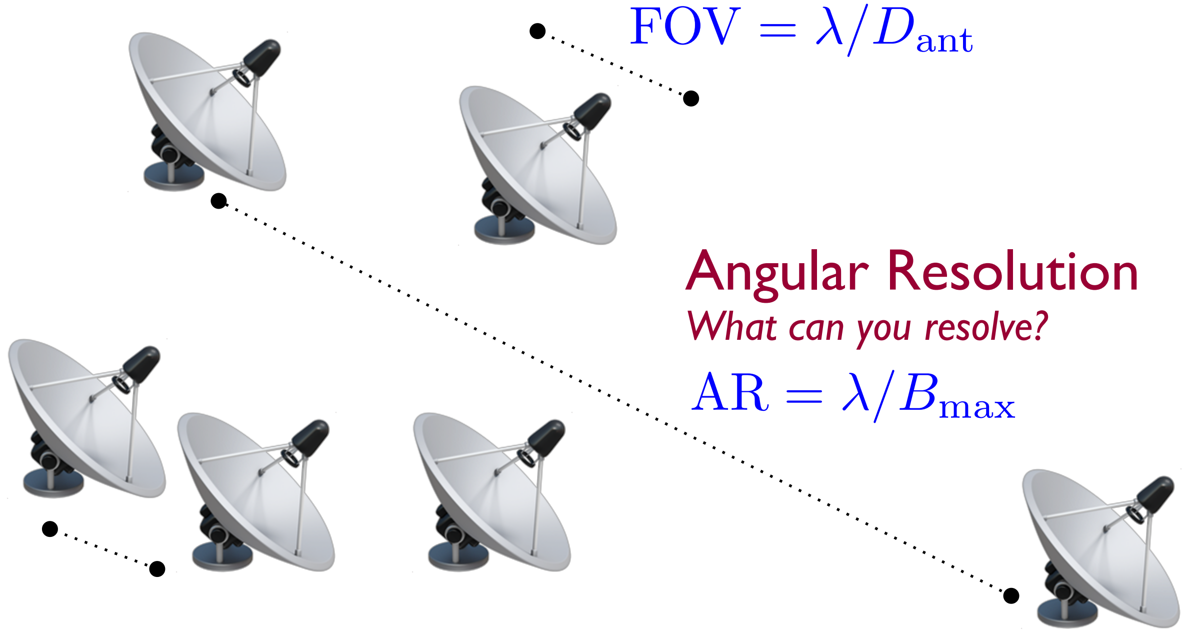
Characteristic angular scales in interferometry



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Angular Resolution

What can you resolve?

$$\mathrm{AR} = \lambda / B_{\mathrm{max}}$$

Maximum Recoverable Scale

What's the biggest structure you can see?

$$\mathrm{MRS} = \lambda / B_{\mathrm{min}}$$

Need to make sure the AR & MRS are sufficient for your science, and that your object will fit in the FOV!

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Characteristic angular scales in interferometry

Interferometers act as **spatial filters**

Spatial scales > smallest baseline cannot be imaged

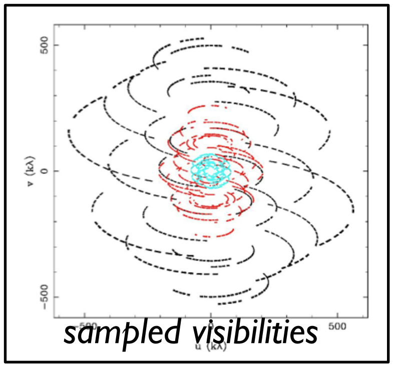
Spatial scales < largest baseline cannot be resolved

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.735	0.52	0.389
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C43-2	θ_{res} (arcsec)	2.3	1.53	1.24	0.999	0.666	0.499	0.353	0.264
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.9	3.47	2.59
C43-3	θ_{res} (arcsec)	1.42	0.943	0.765	0.615	0.41	0.308	0.218	0.163
	θ_{MRS} (arcsec)	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C43-4	θ_{res} (arcsec)	0.918	0.612	0.496	0.399	0.266	0.2	0.141	0.106
	θ_{MRS} (arcsec)	11.2	7.5	6.08	4.89	3.26	2.44	1.73	1.29
C43-5	θ_{res} (arcsec)	0.545	0.363	0.295	0.237	0.158	0.118	0.0838	0.0626
	θ_{MRS} (arcsec)	6.7	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C43-6	θ_{res} (arcsec)	0.306	0.204	0.165	0.133	0.0887	0.0665	0.0471	0.0352
	θ_{MRS} (arcsec)	4.11	2.74	2.22	1.78	1.19	0.892	0.632	0.472
C43-7	θ_{res} (arcsec)	0.211	0.141	0.114	0.0917	0.0612	0.0459	0.0325	0.0243
	θ_{MRS} (arcsec)	2.58	1.72	1.4	1.12	0.749	0.562	0.398	0.297
C43-8	θ_{res} (arcsec)	0.096	0.064	0.0519	0.0417	0.0278	-	-	-
	θ_{MRS} (arcsec)	1.42	0.947	0.768	0.618	0.412	-	-	-
C43-9	θ_{res} (arcsec)	0.057	0.038	0.0308	0.0248	0.0165	-	-	-
	θ_{MRS} (arcsec)	0.814	0.543	0.44	0.354	0.236	-	-	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.0227	0.0183	0.0122	-	-	-
	θ_{MRS} (arcsec)	0.496	0.331	0.268	0.216	0.144	-	-	-

Table 7.1: Resolution (θ_{res}) and maximum recoverable scale (θ_{MRS}) for the 7-m Array and 12-m Array configurations available during Cycle 7 as a function of a representative frequency in a band. The value of θ_{MRS} is computed using the 5$^{\text{th}}$ percentile baseline (L05) from Table 7.2 and Equation 7.7. The value of θ_{res} is the mean size of the interferometric beam obtained through simulation with CASA, using Briggs (u, v) plane weighting with *robust=0.5*. The computations were done for a source at zenith; for sources transiting at lower elevations, the North-South angular measures will increase proportional to 1/sin(ELEVATION).

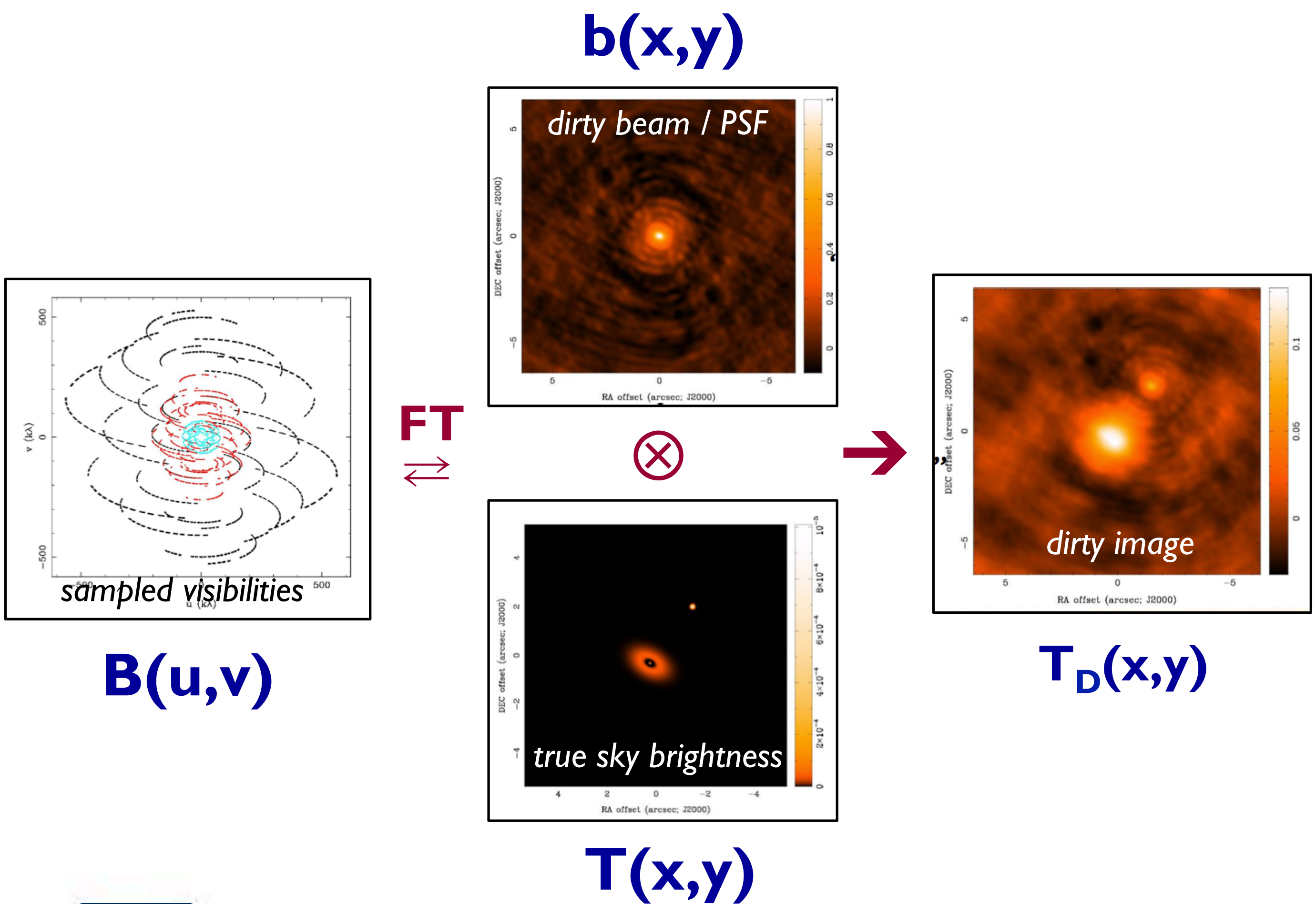
NRAO

Observed ("dirty") images are the true sky brightness convolved with the interferometer's PSF ("dirty beam")



B(u,v)

Observed ("dirty") images are the true sky brightness convolved with the interferometer's PSF ("dirty beam")



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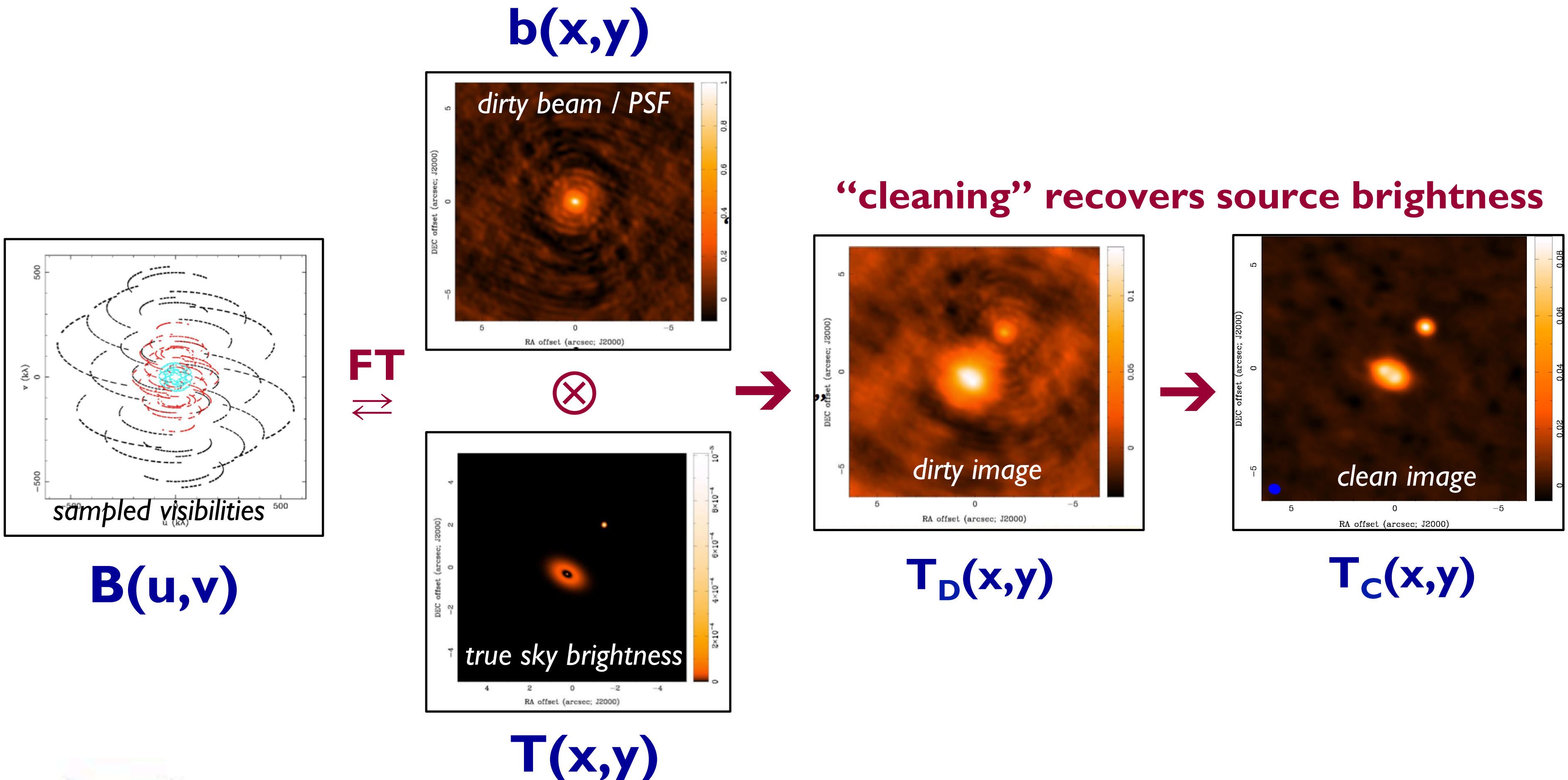
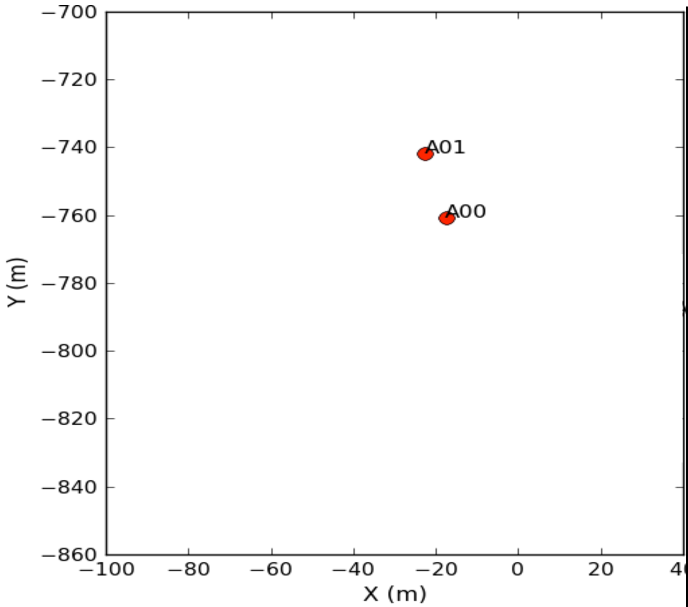
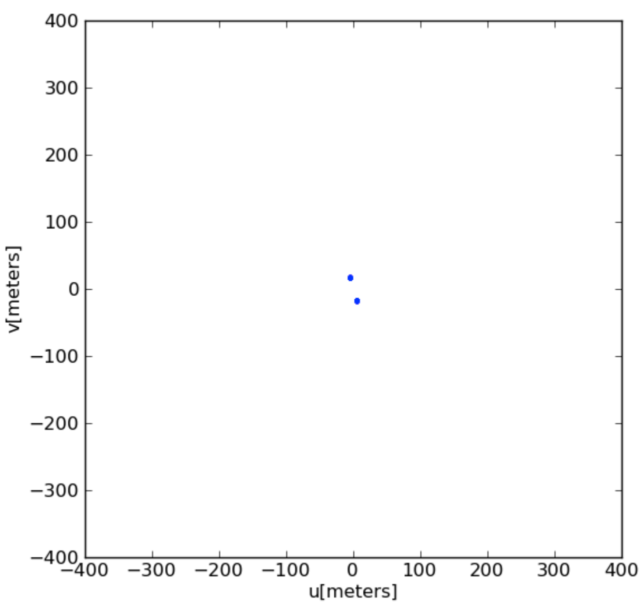
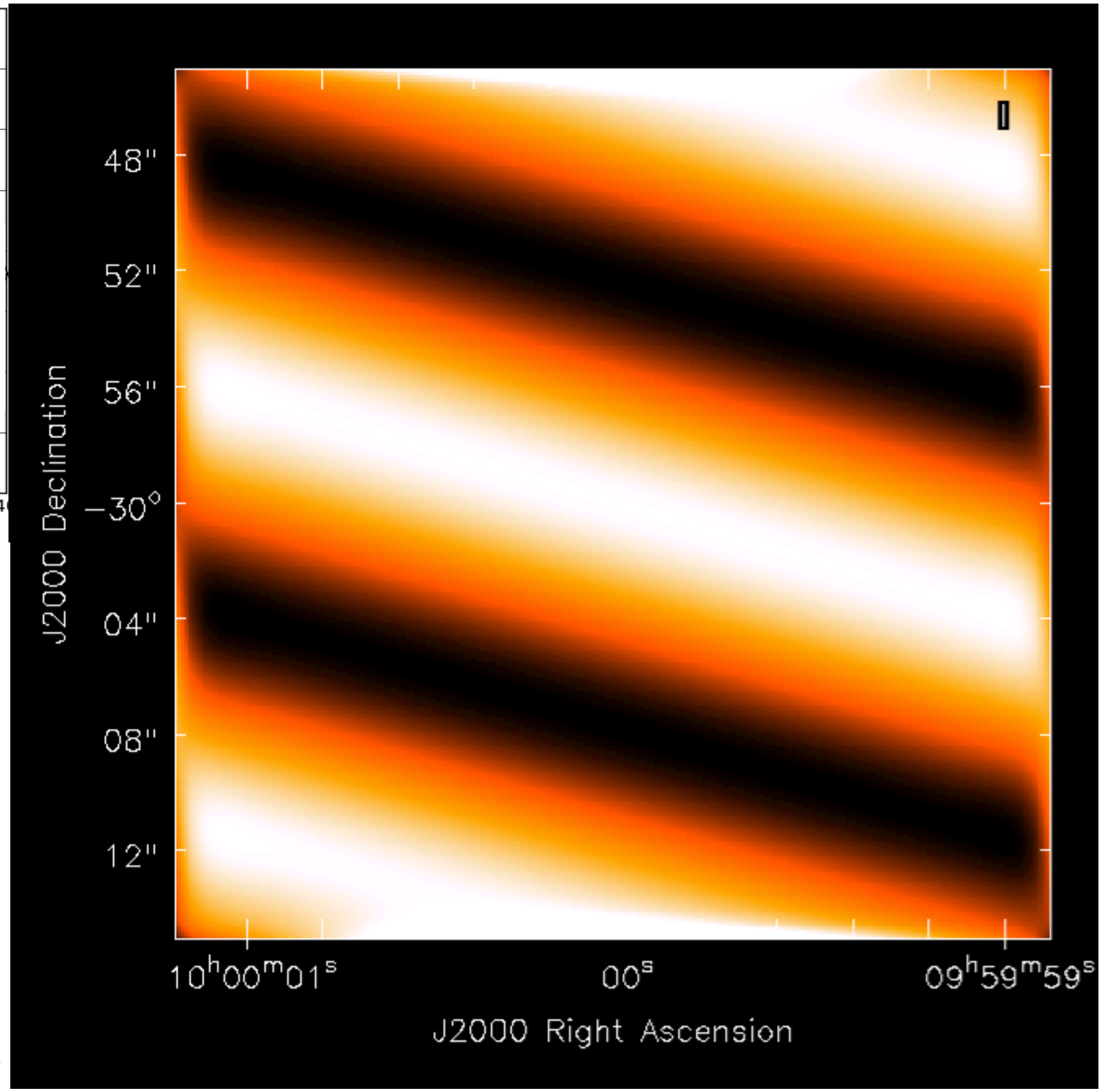


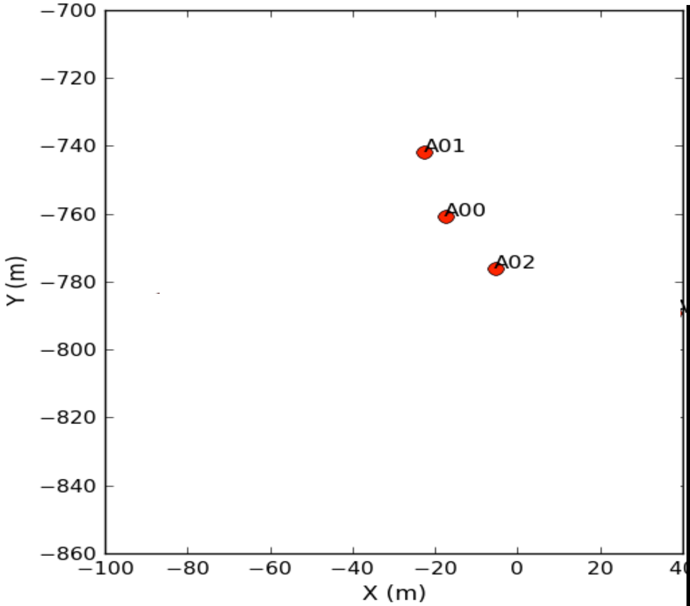
Fringe pattern with 2 antennas (1 baseline)

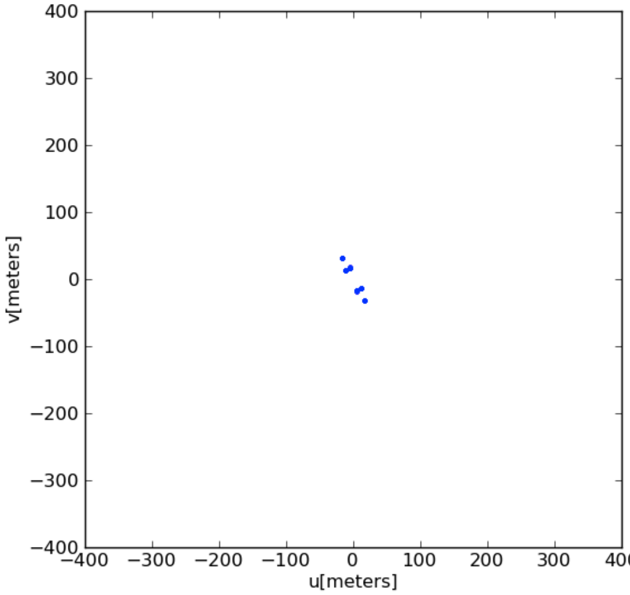


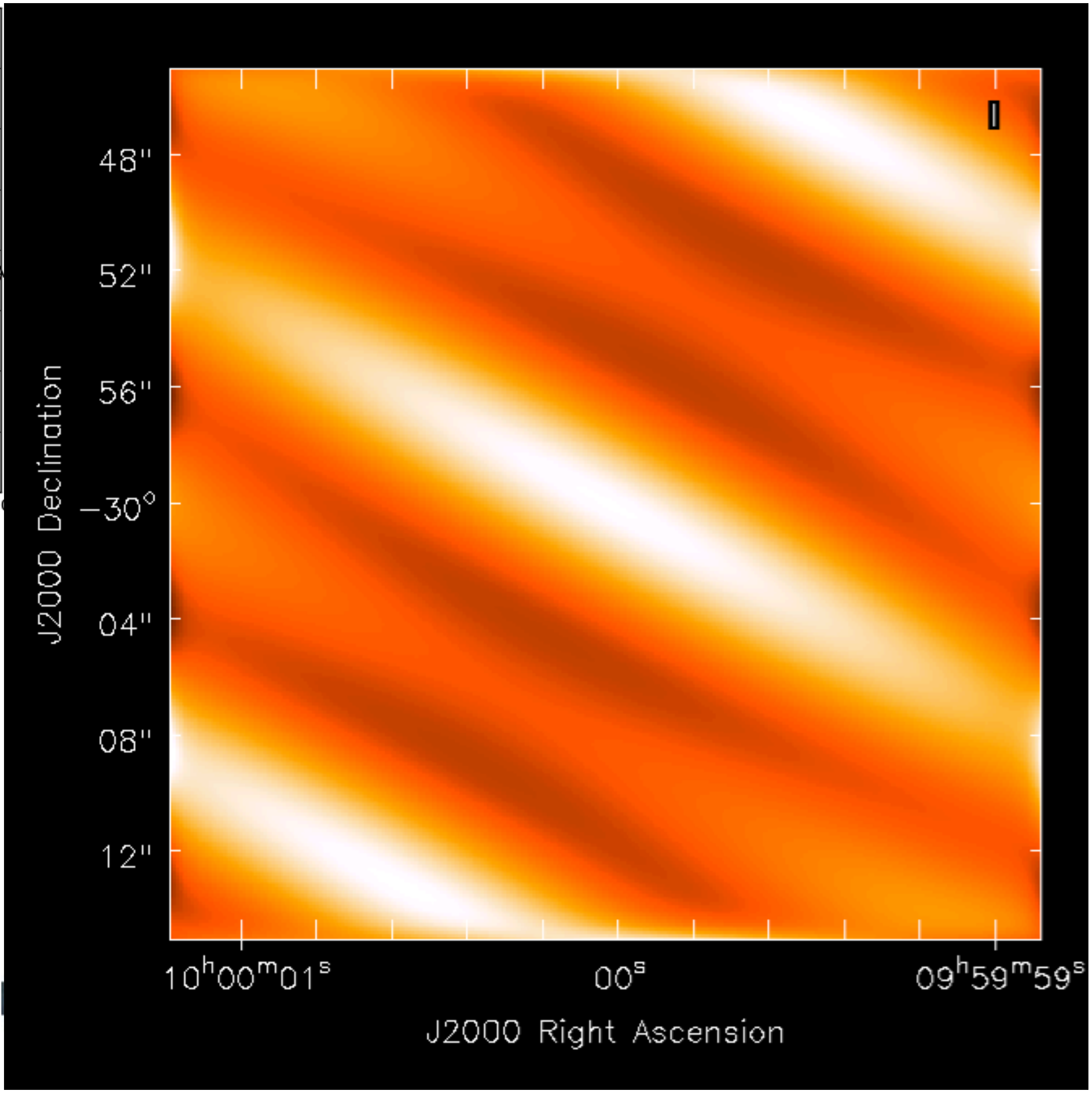




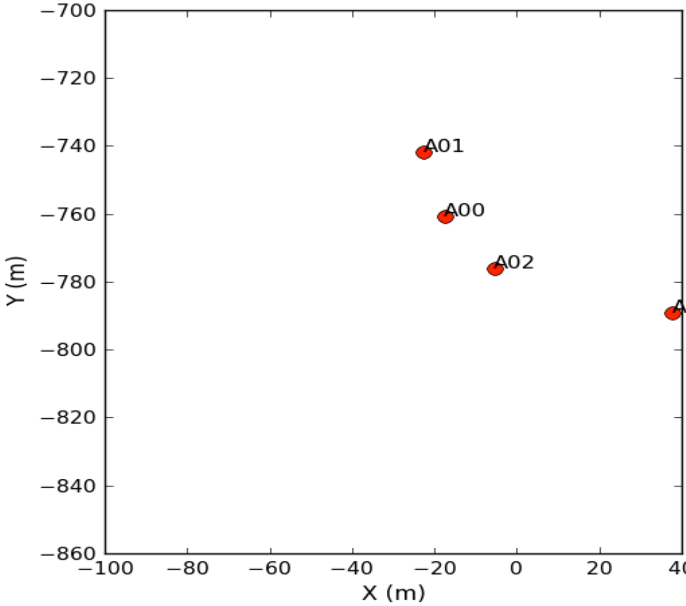
Fringe pattern with 3 antennas (3 baselines)

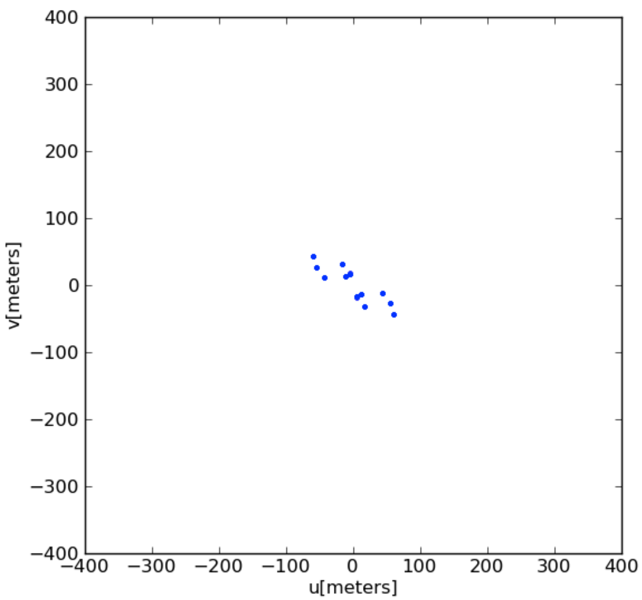


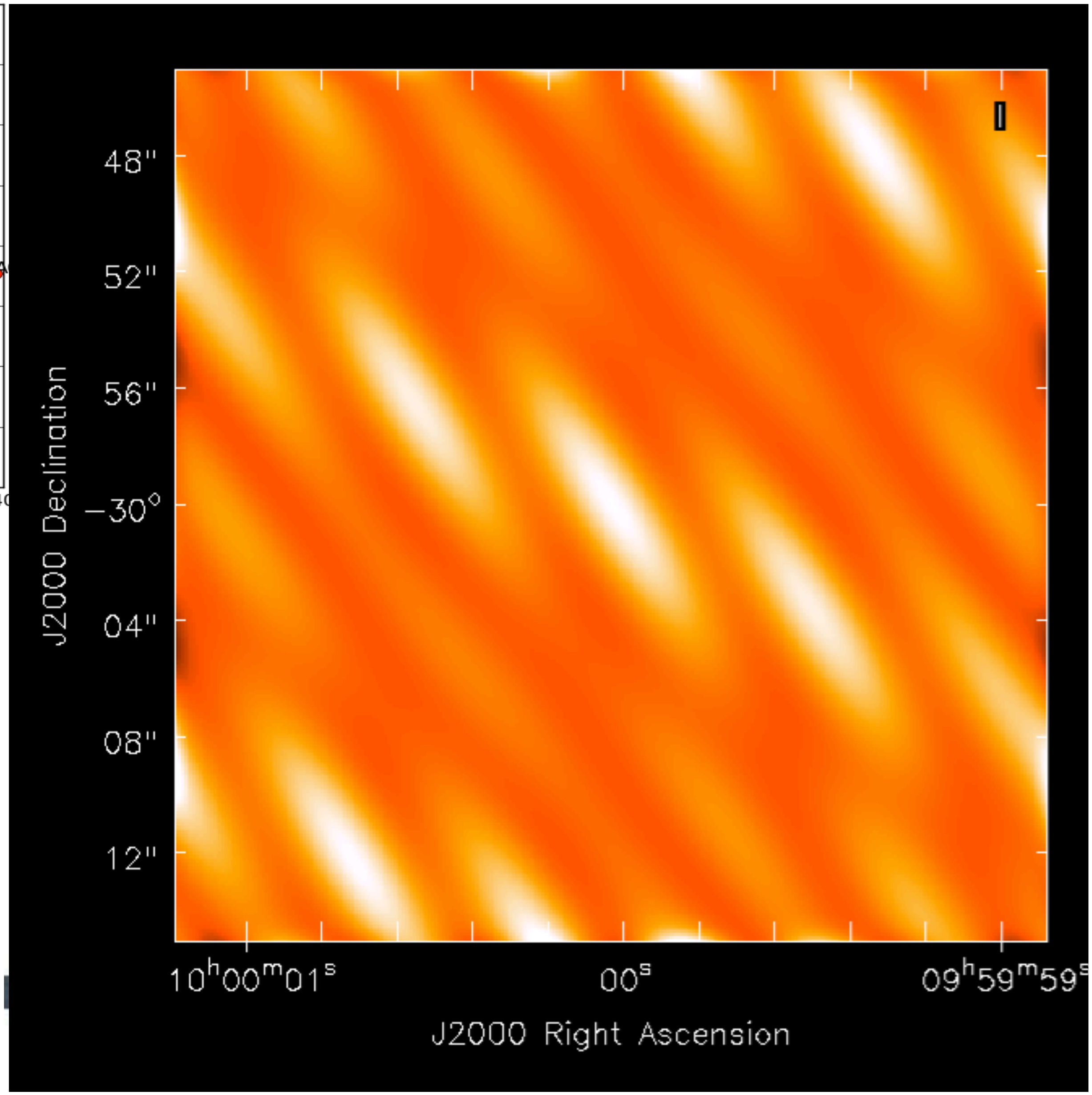




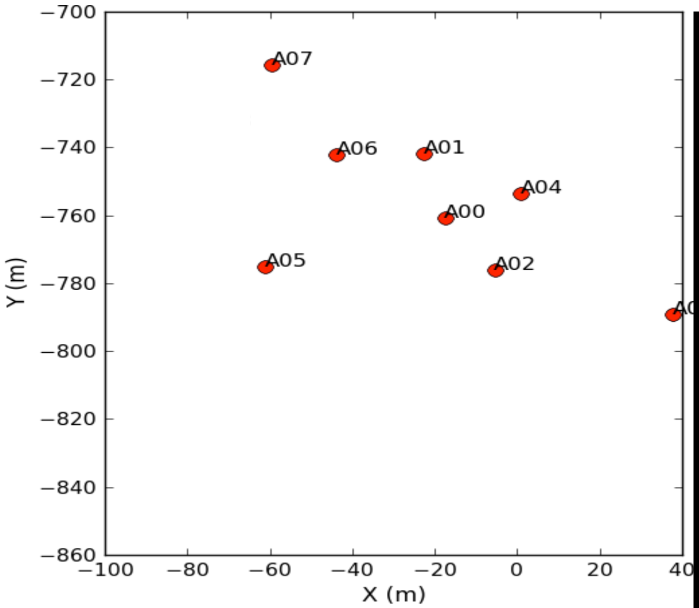
Fringe pattern with 4 antennas (6 baselines)

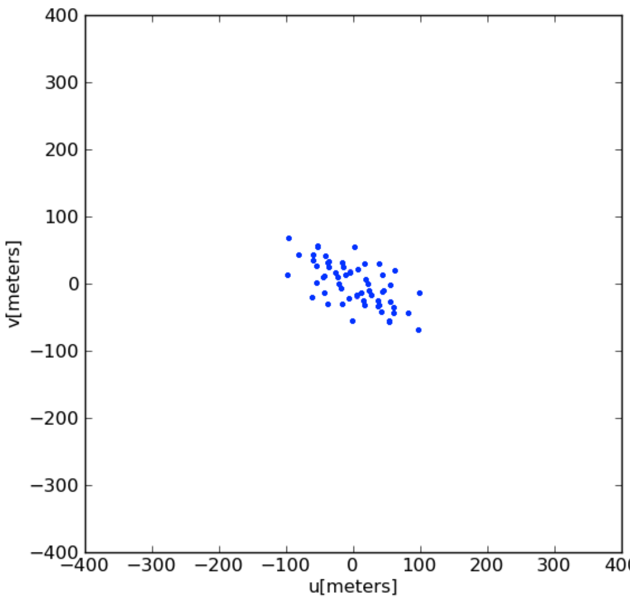


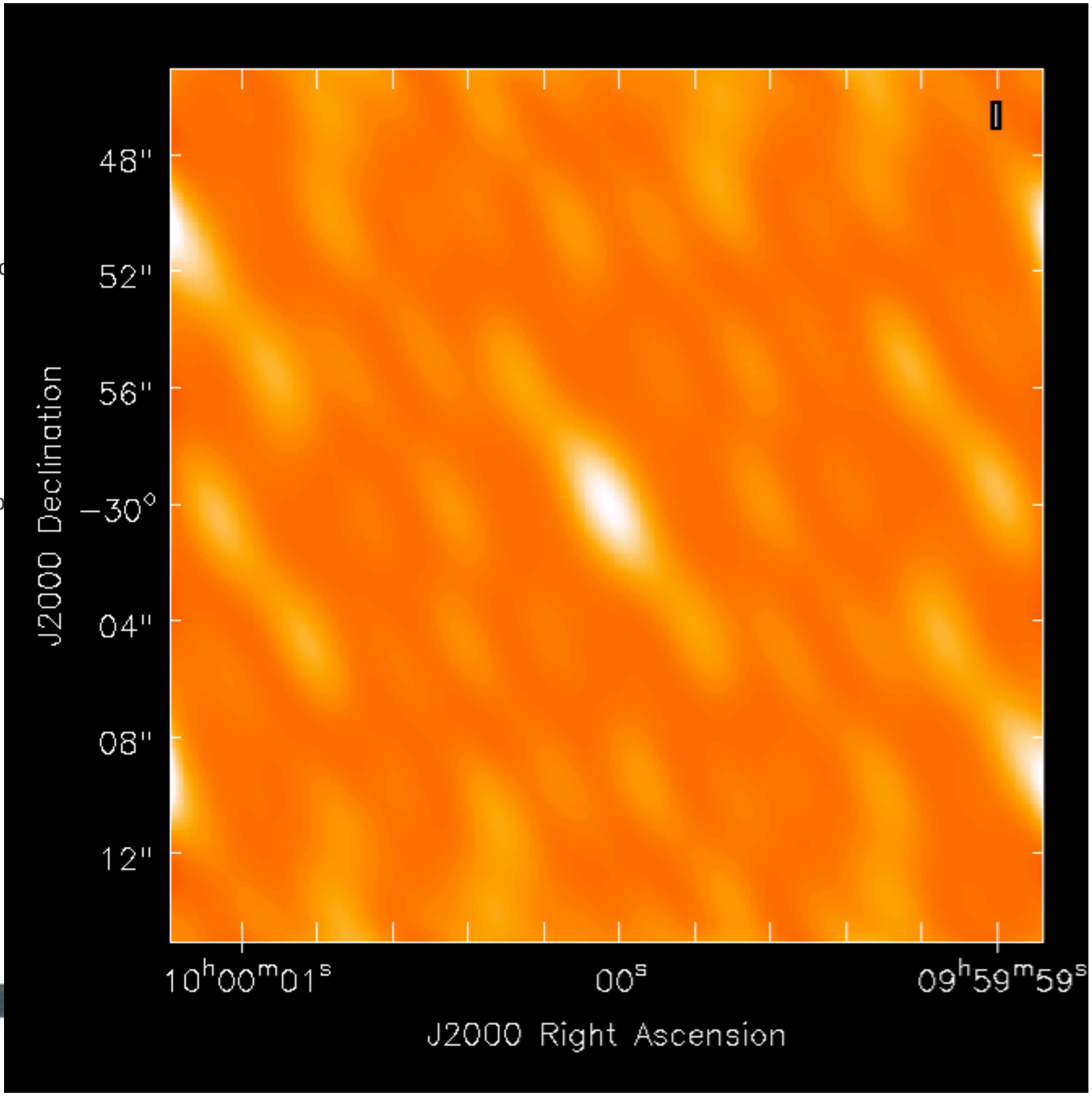




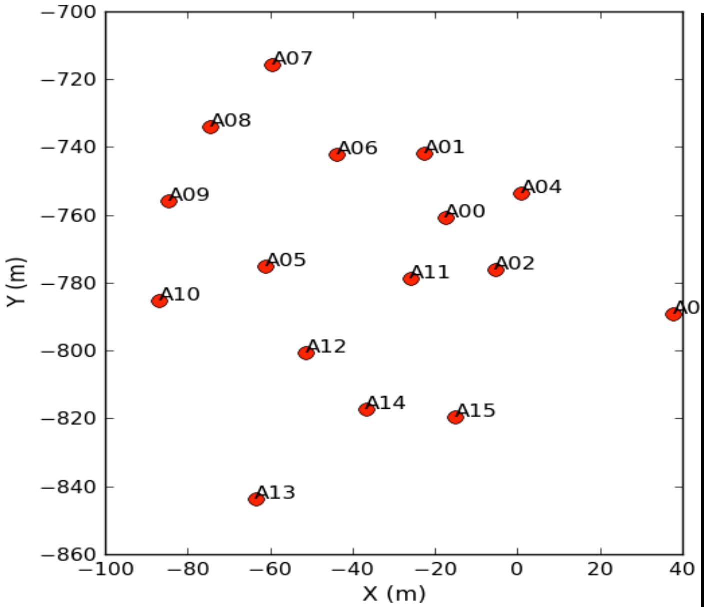
Fringe pattern with 8 antennas (28 baselines)

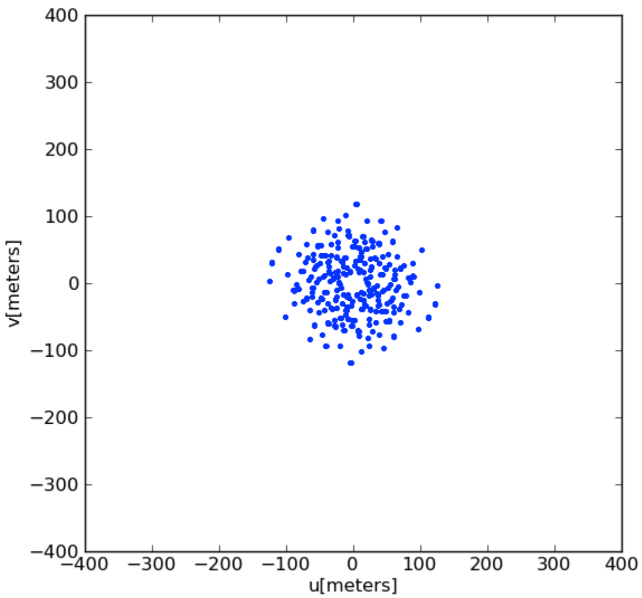


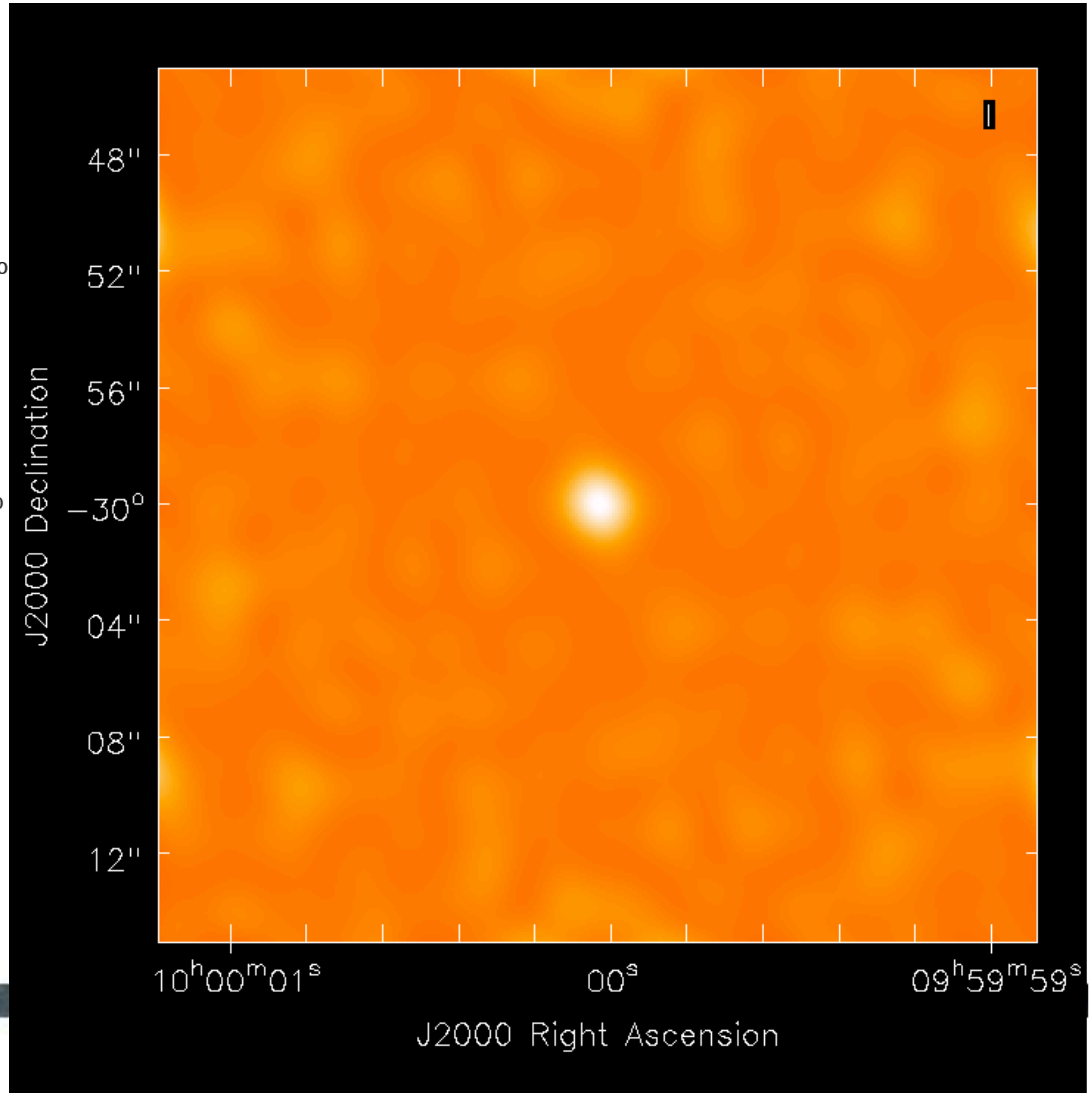




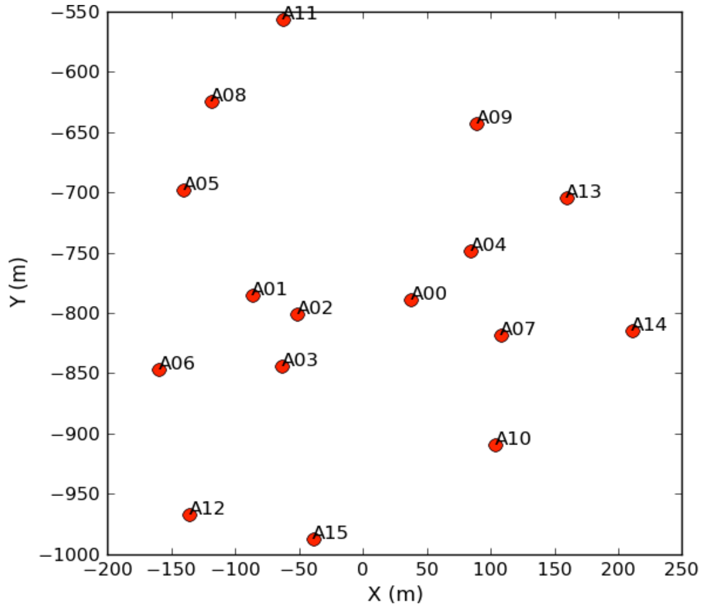
Fringe pattern with 16 antennas (compact)

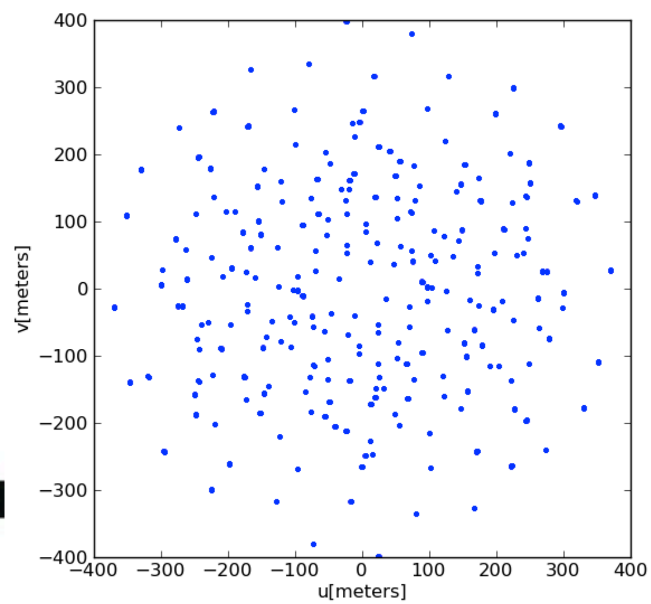


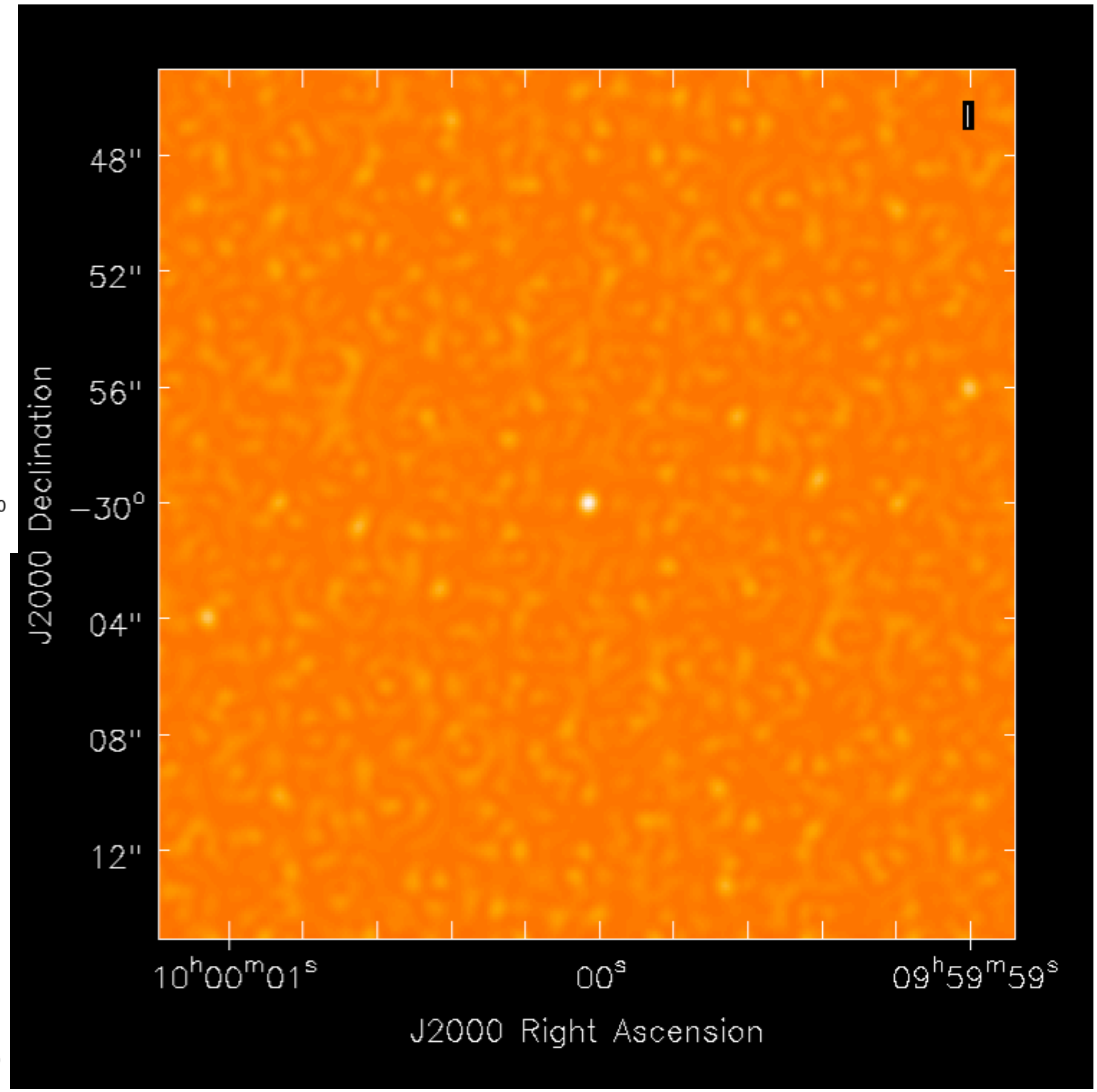




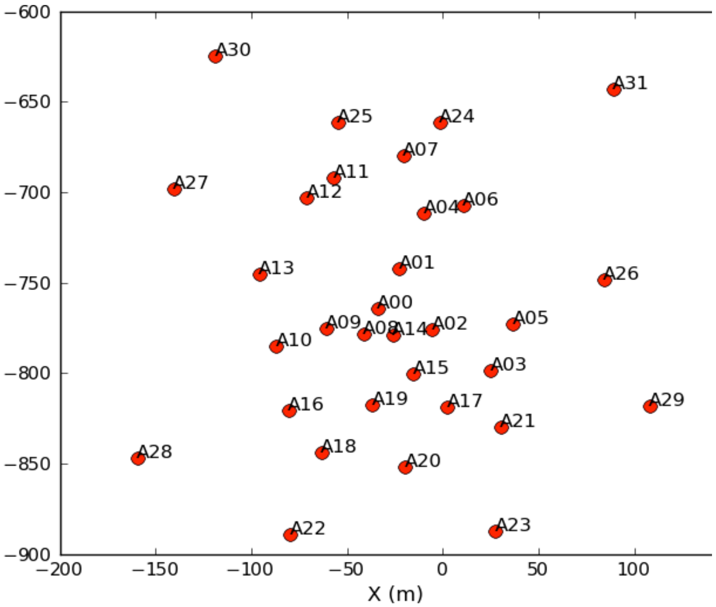
Fringe pattern with 16 antennas (extended)

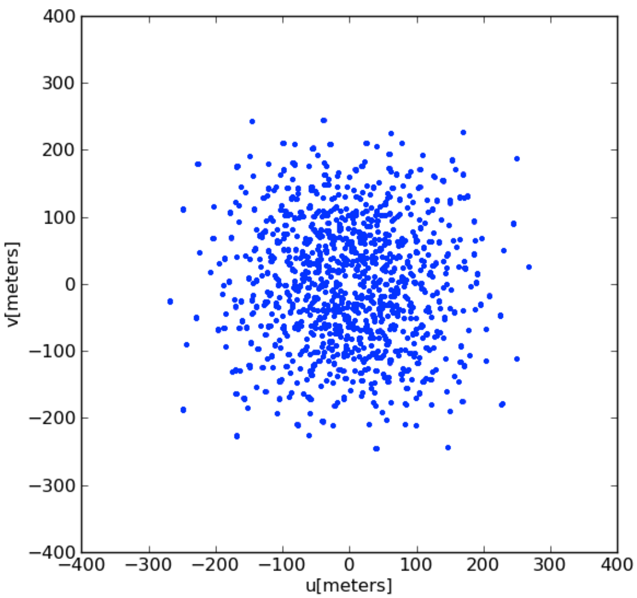


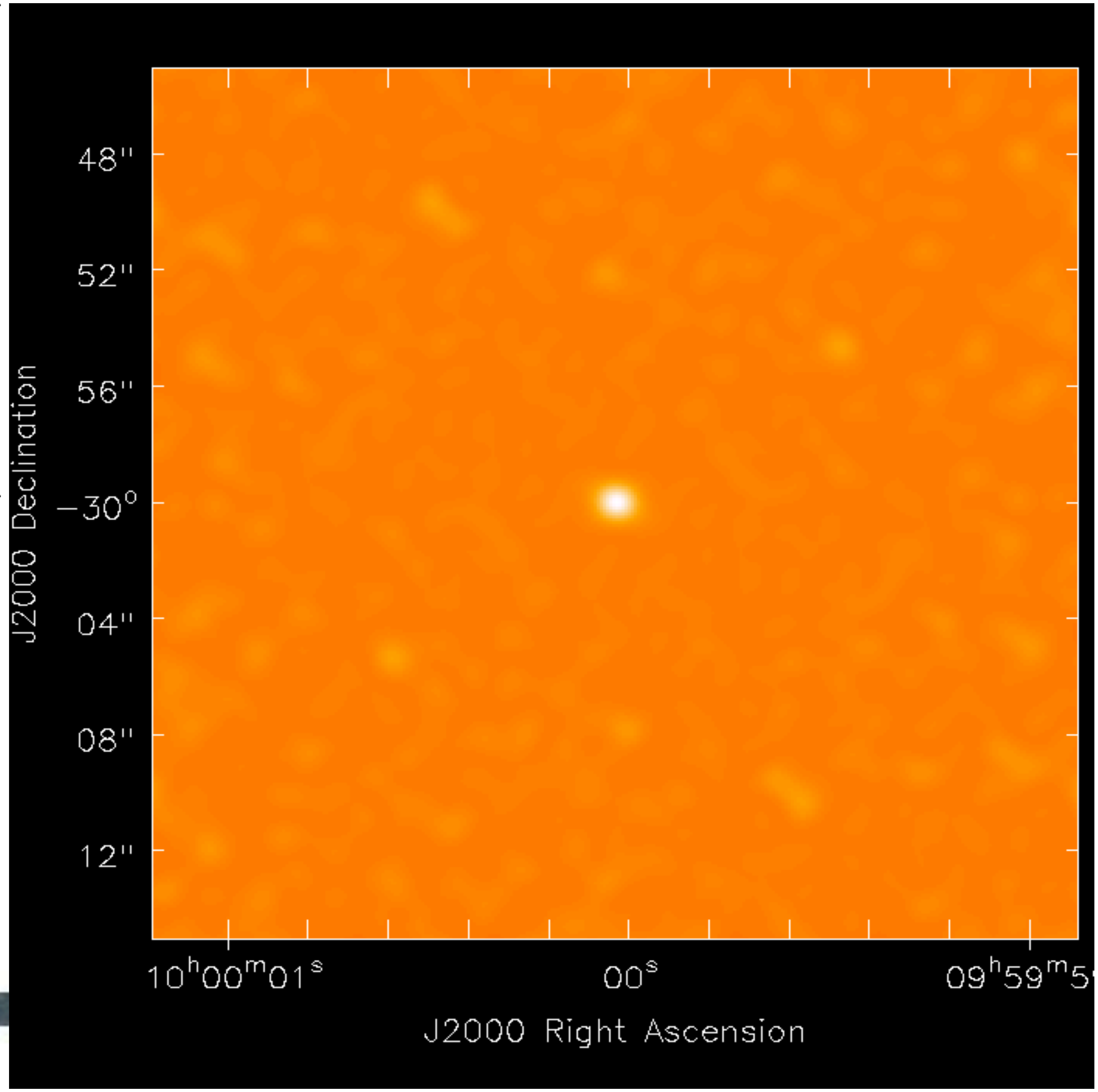




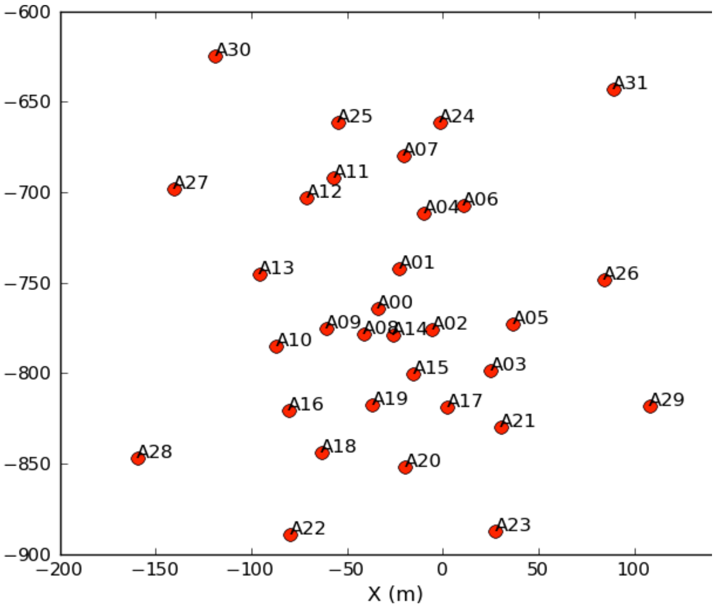
Fringe pattern with 32 antennas (instantaneous)

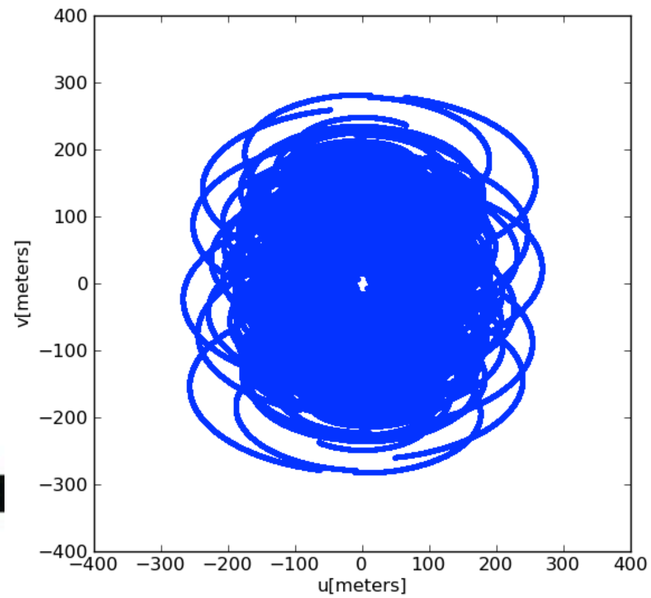


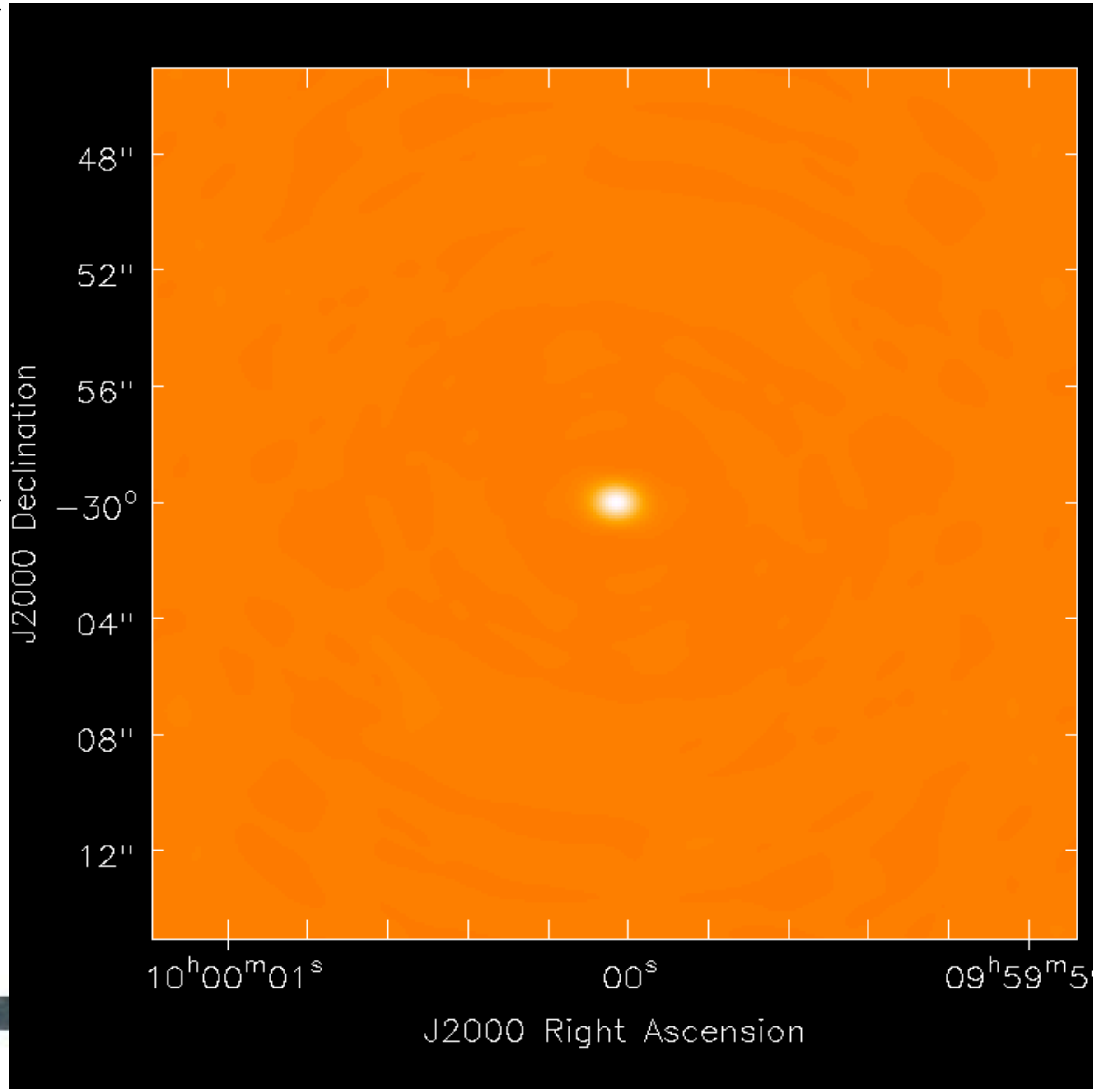




Fringe pattern with 32 antennas (8 hours)

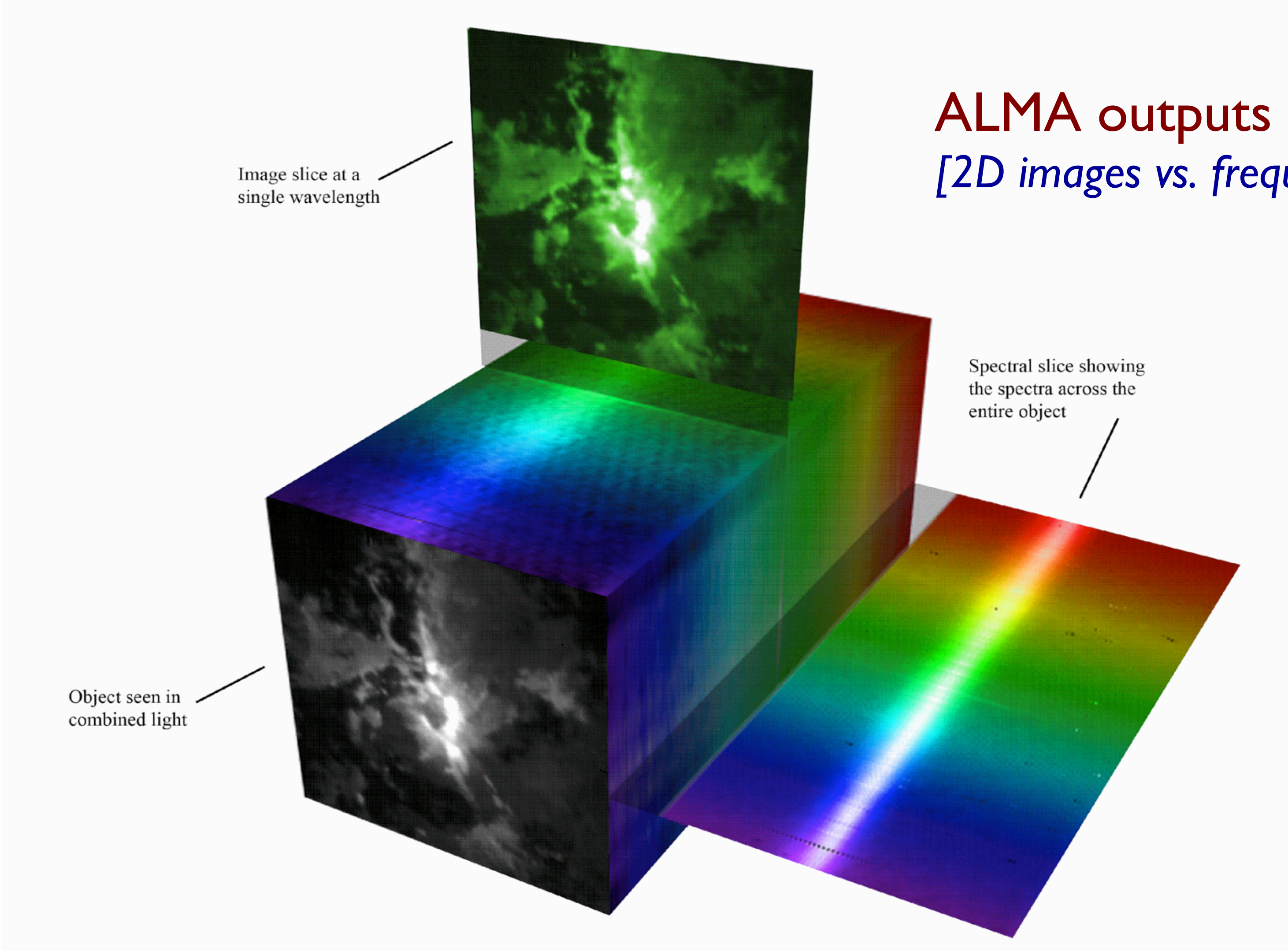






ALMA outputs a **data cube**

[2D images vs. frequency]



Introduction to Radio Interferometry

- ☑ Quick background on radio astronomy
- ☑ Radio interferometry: how does it work?
- ☑ (u,v) visibilities & aperture synthesis
- ☑ Turning visibilities into images
- ☐ Brief note on calibration
- ☐ Useful radio interferometry references

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Brief note on calibration

Interferometers measure visibilities (i.e., amplitude and phase of cross-correlated signals between pairs of antennas) whose variations in time and frequency due to the atmosphere/instrument need to be corrected for during post processing.

*ALMA projects are divided into **Scheduling Blocks [SBs]**. Calibrators are observed before, after, and during each SB to correct for variations.*

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Calibration requirements (handled by ALMA OT):

Gain/Phase calibrator

Bright quasar near science target

Solves for atmospheric and instrumental variations with time

Bandpass calibrator

Bright quasar

Fixes frequency-dependent variations from instrument

Flux calibrator

Solar system object or quasar

Scale relative amplitudes to absolute values

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Useful Radio Interferometry 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

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