Introduction to Radio Interferometry: What you need to know to apply to ALMA

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Resolution of Observations

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

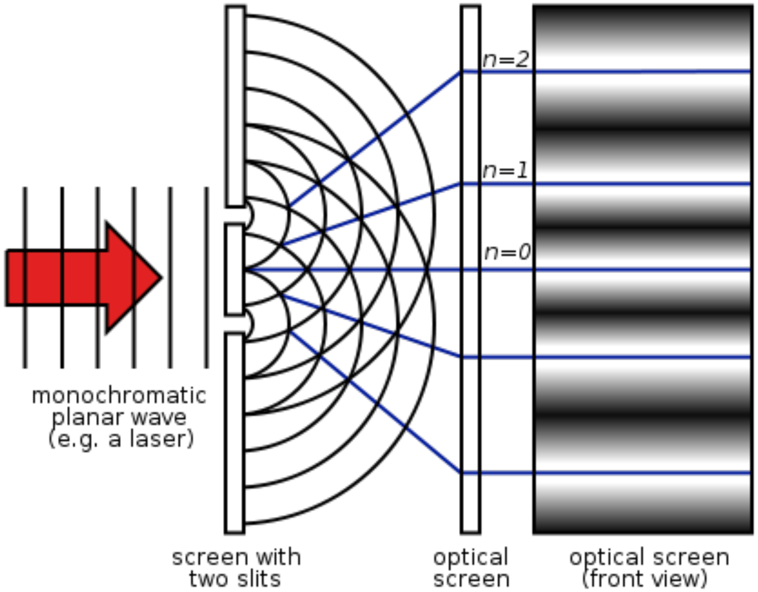
To reach that resolution at λ ~1mm, we would need a 2 km-diameter dish!

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

This is interferometry!

What is an interferometer?

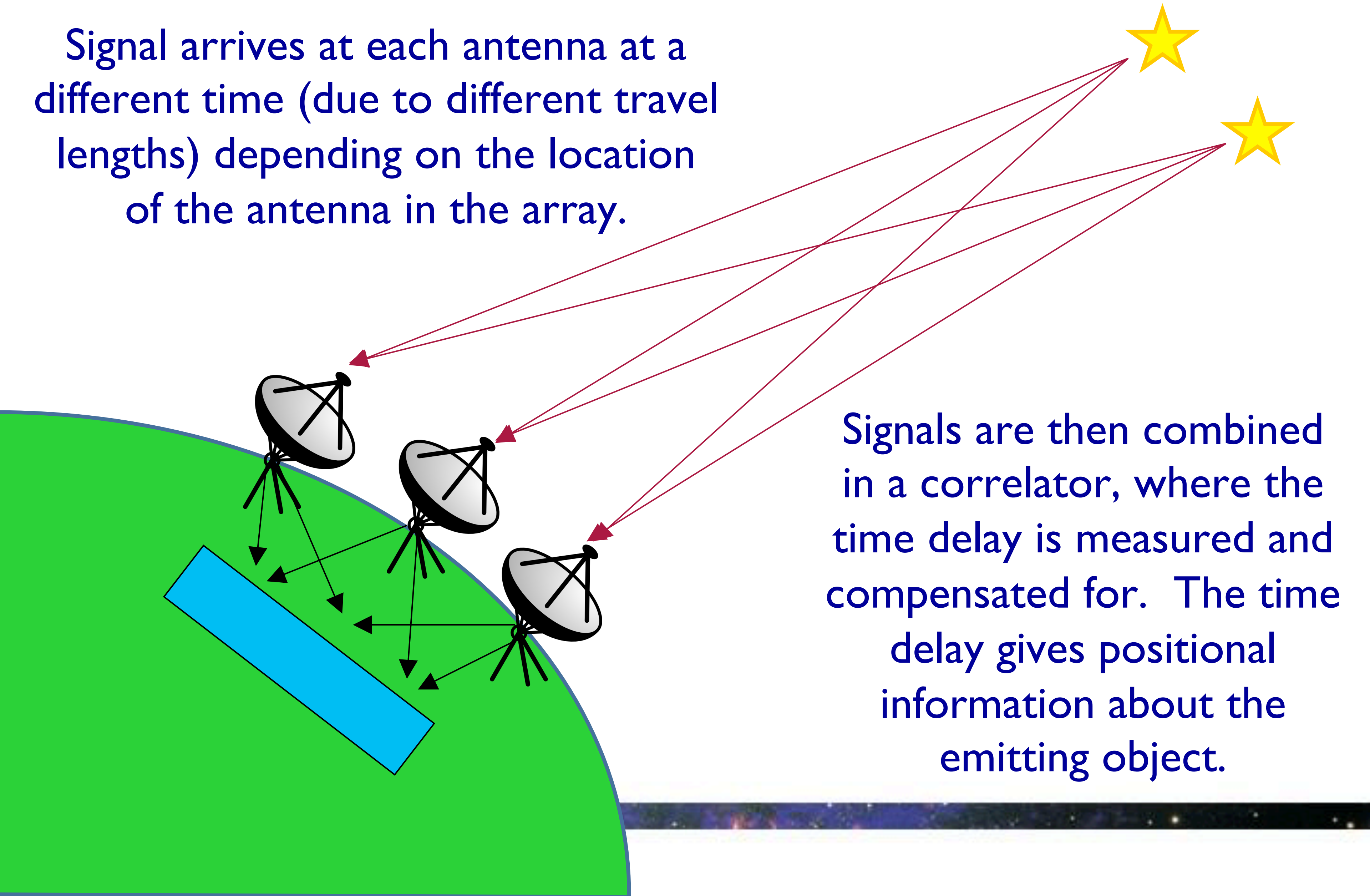
An *interferometer* measures the interference pattern produced by multiple apertures, much like a 2-slit experiment.



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

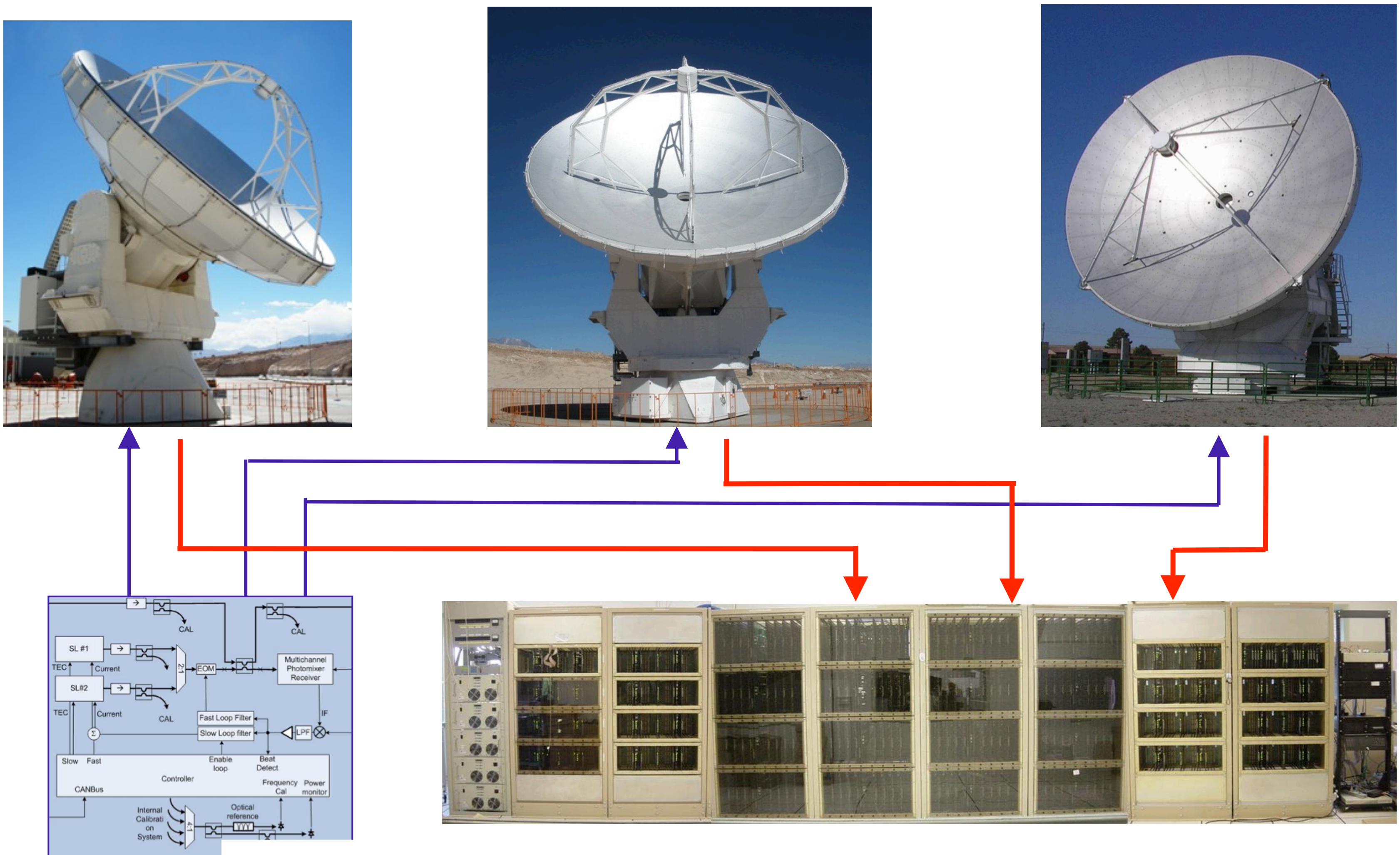
How Do We Use Interferometry?

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



Signals are then combined in a correlator, where the time delay is measured and compensated for. The time delay gives positional information about the emitting object.

Some Instrument Details



Outgoing signals: pointing and tracking, tuning receivers, timing reference

Incoming signals: device health, fiber length, astronomical signal (to the correlator for multiplication and averaging)

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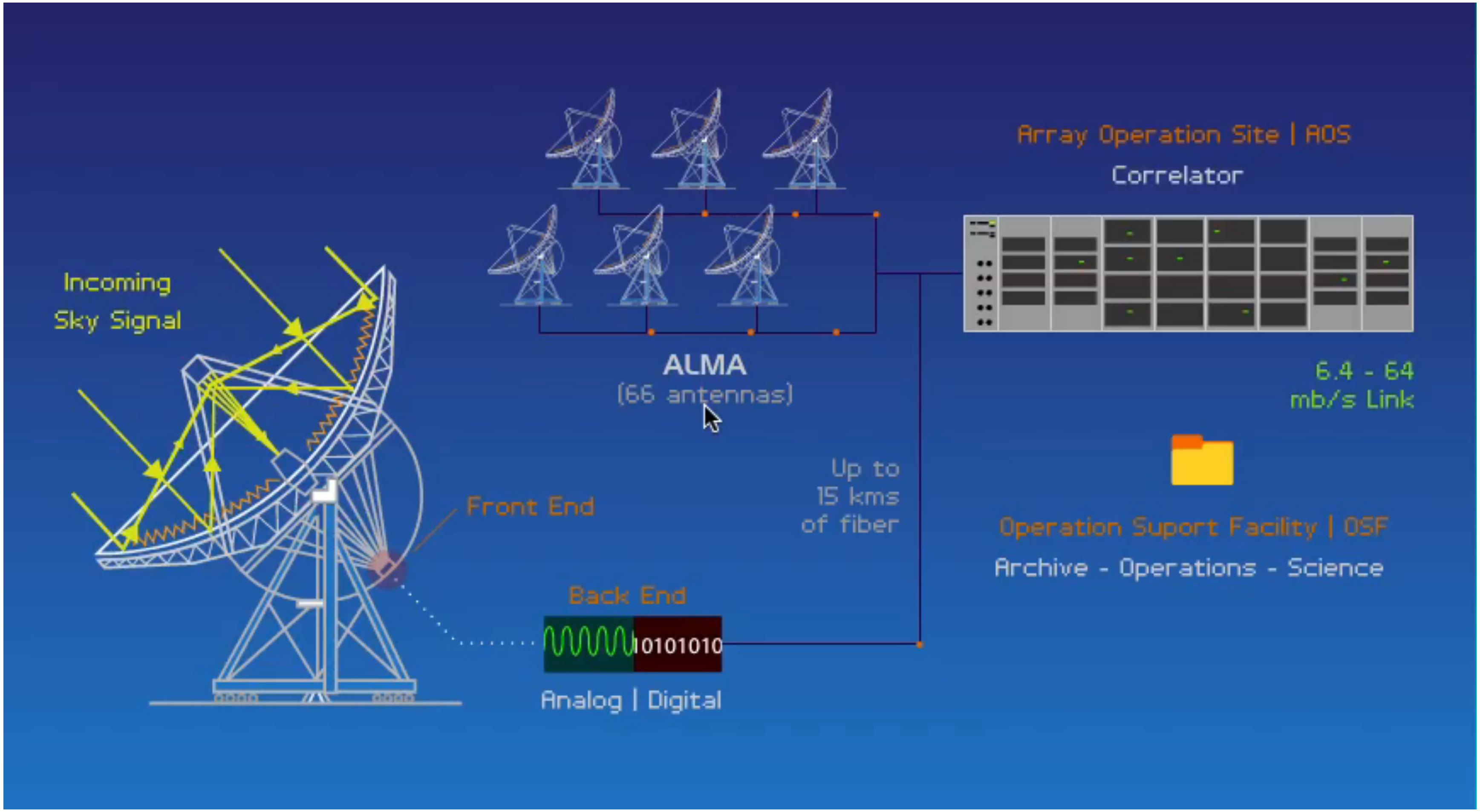
An Interferometer In Action



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Interferometry and Fourier Transforms

- An interferometer measures the interference pattern produced by pairs of apertures.
- Interferometer data are termed "**visibilities**"
- The interference pattern is directly related to the source brightness:
  - For small fields-of-view: the complex ***visibility***, V(u,v), is the 2D **Fourier transform** of the brightness on the sky, T(l,m)

$$V(u,v) \xrightarrow{\textbf{FT}} T(l,m)$$

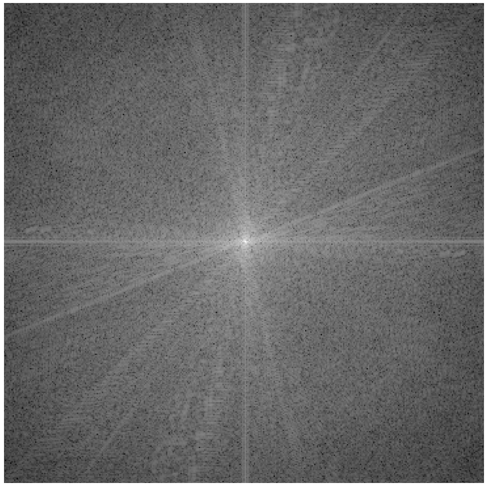
What Are Visibilities?

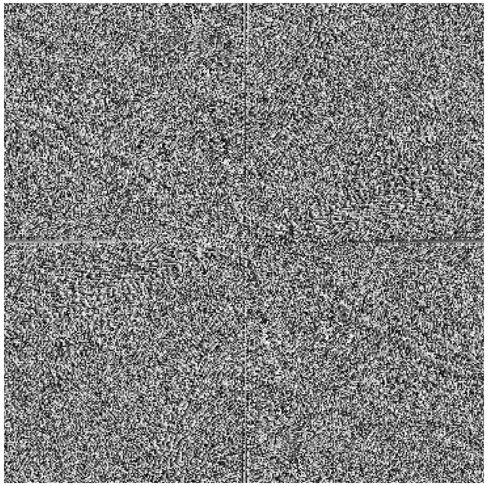
Each V(u,v) contains information on T(l,m) everywhere

Each V(u,v) is a complex quantity

Expressed as (real, imaginary) or (amplitude, phase)

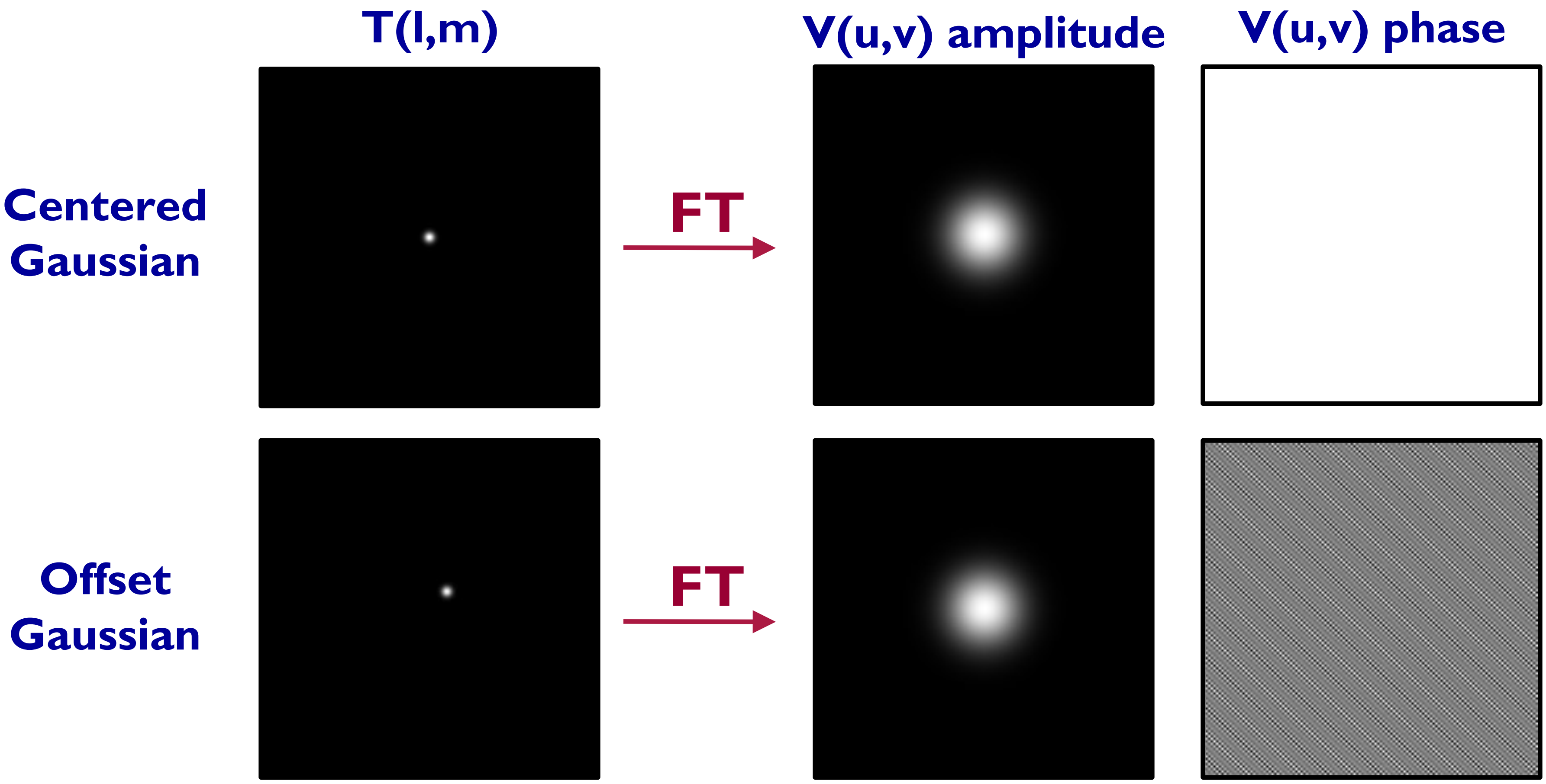
FT →





T(l,m) V(u,v) amplitude V(u,v) phase

Examples of 2D Fourier Transforms

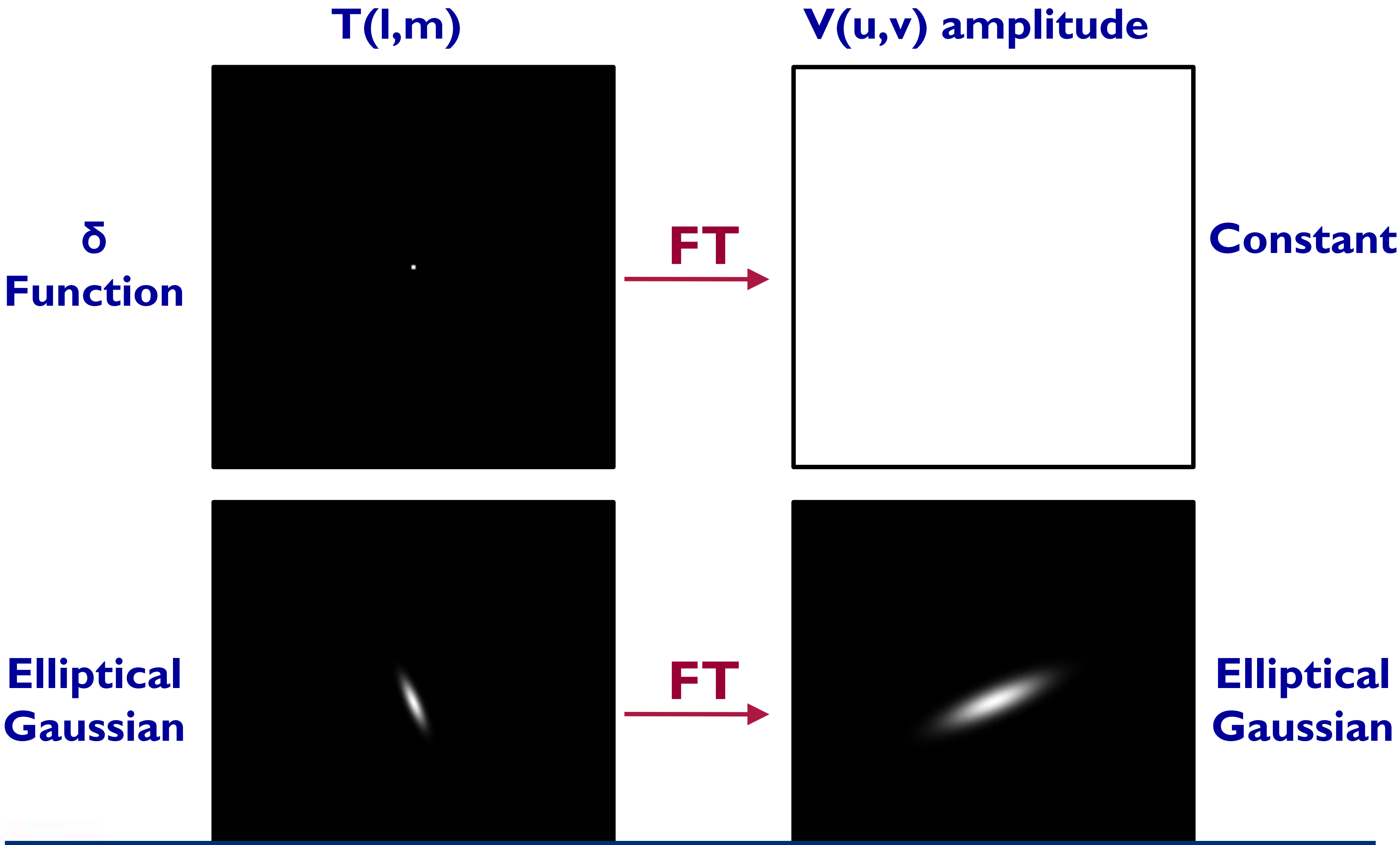


Rules of the Fourier Transform:

Amplitude tells you 'how much' of a spatial frequency

Phase tells you 'where' the spatial frequency is

Examples of 2D Fourier Transforms



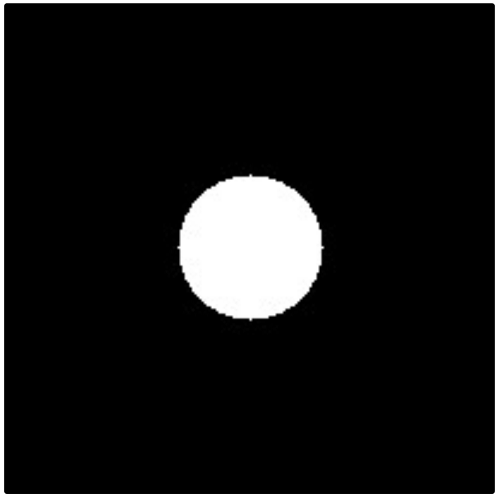
Rules of the Fourier Transform:

Narrow features transform to wide features (and vice versa)

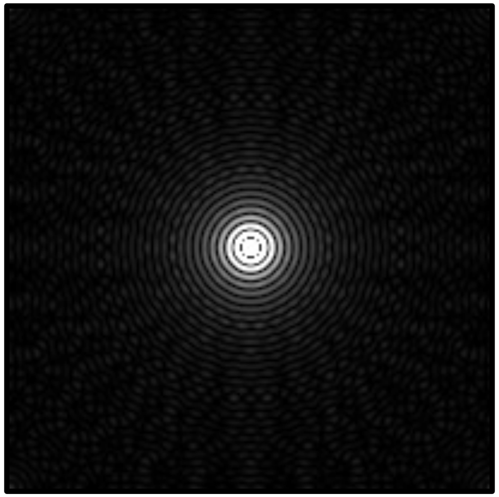
Examples of 2D Fourier Transforms

T(l,m) | **V(u,v) amplitude**

Uniform Disk

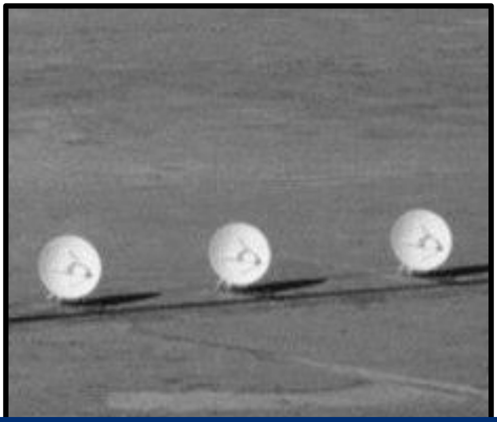


FT →



Bessel Function

VLA Antennas



FT →

Bessel Function!

Rules of the Fourier Transform:

Sharp features (edges) result in many high spatial features

Basics of Aperture Synthesis

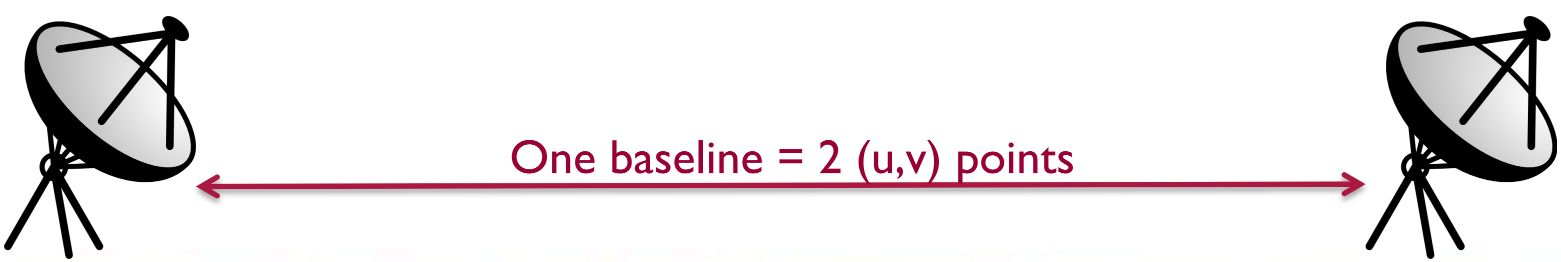
Idea: Sample V(u,v) at a enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{max}, v_{max})

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. Earth's rotation
2. Reconfigure physical layout of N antennas



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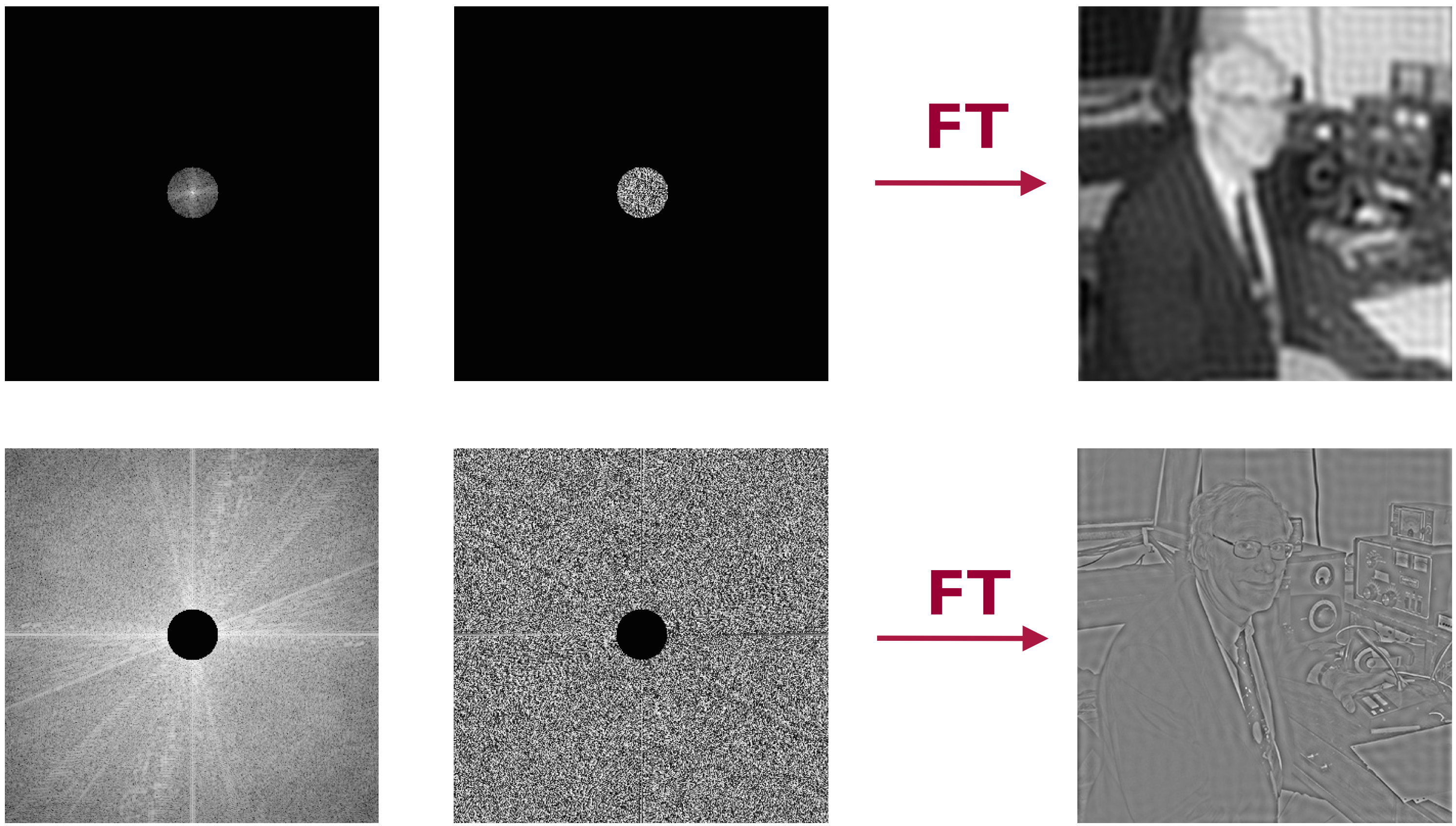
Implications of (u,v) Coverage

What does it mean if our (u,v) coverage is not complete?

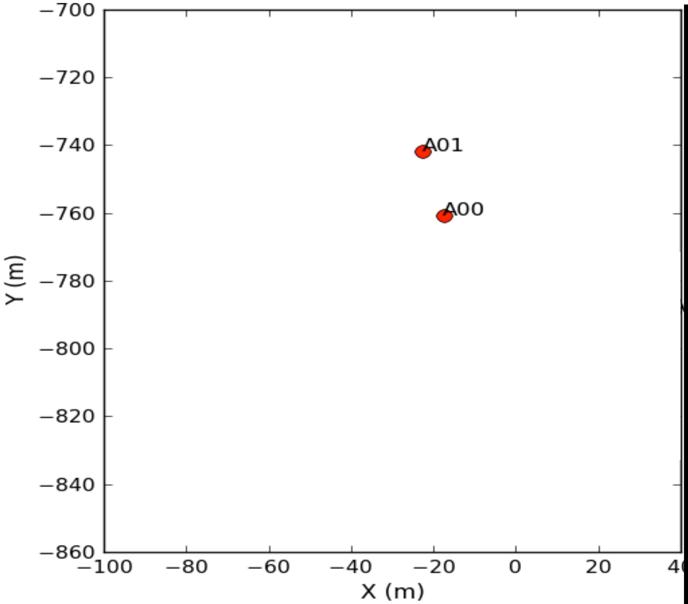
V(u,v) amplitude | V(u,v) phase | T(l.m)

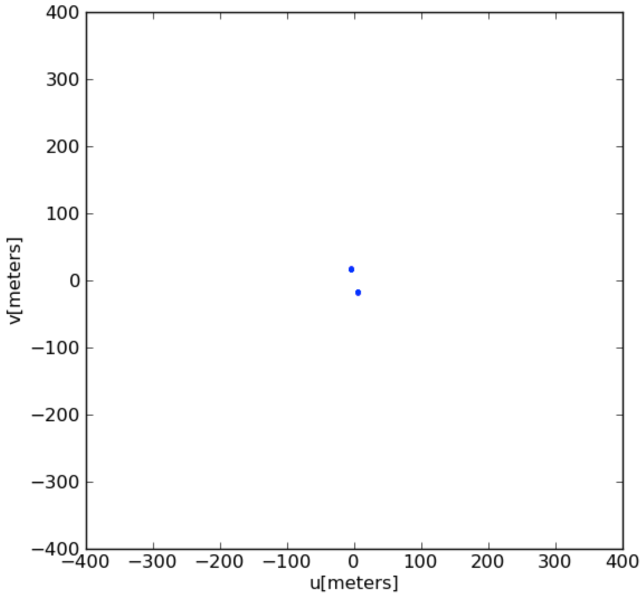
Missing High Spatial Frequencies

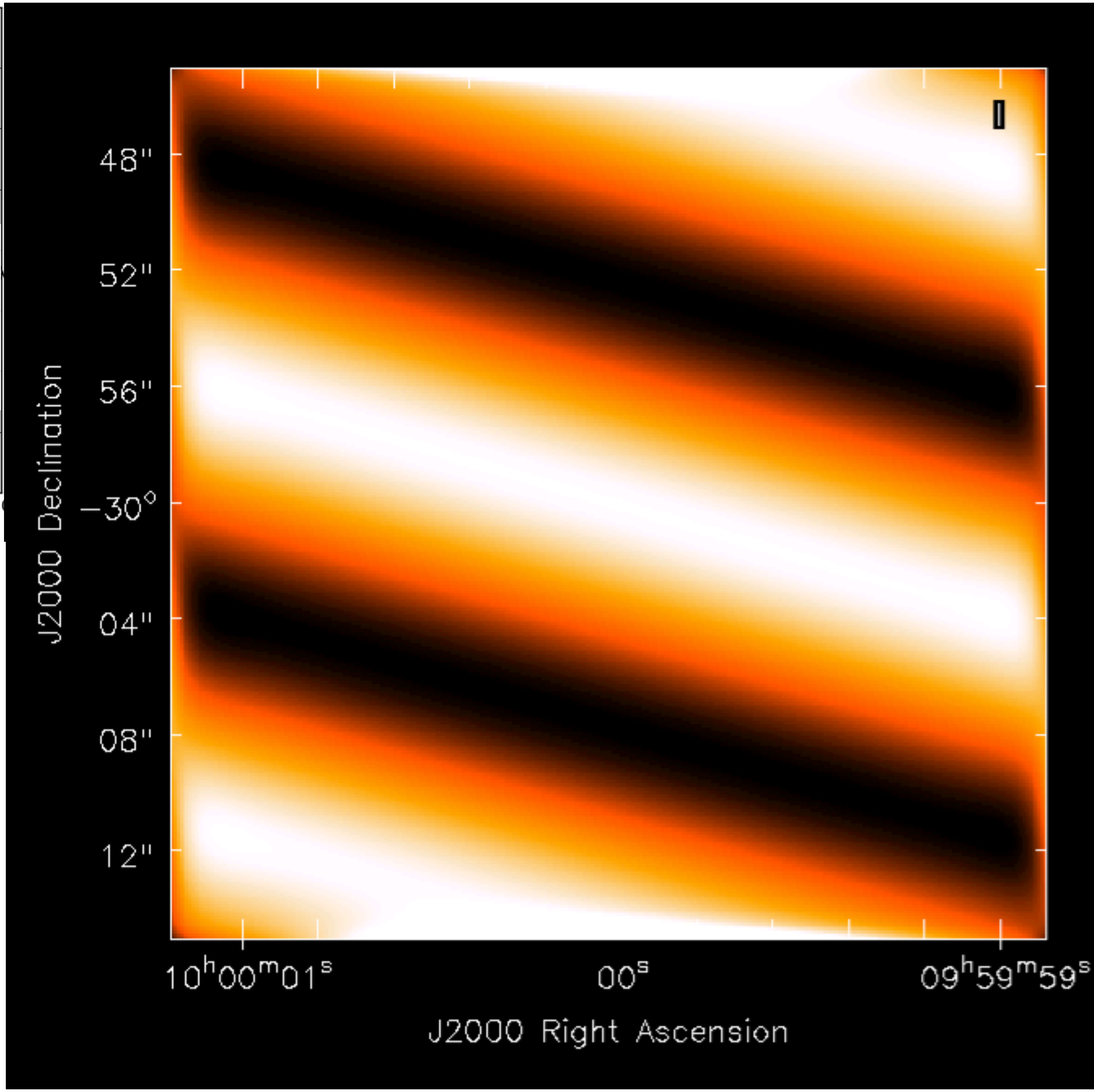
Missing Low Spatial Frequencies



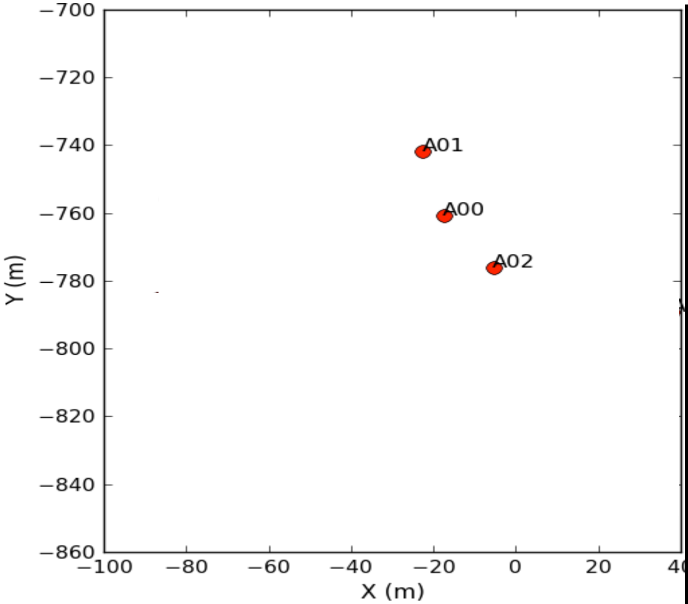
Example: Fringe pattern with 2 Antennas

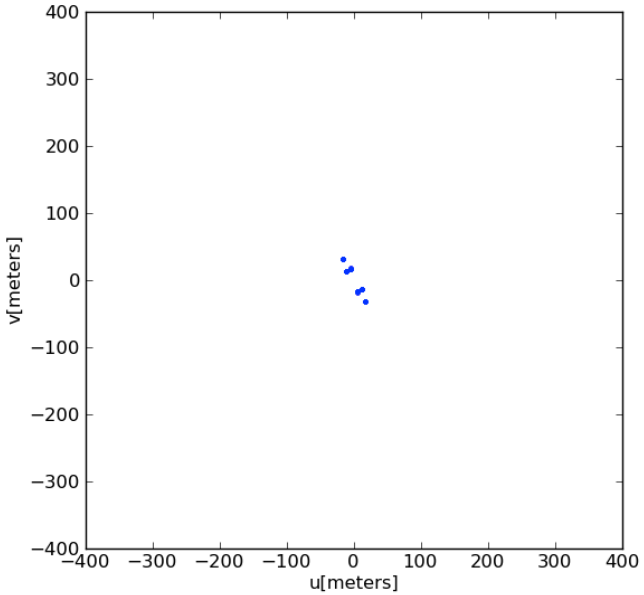


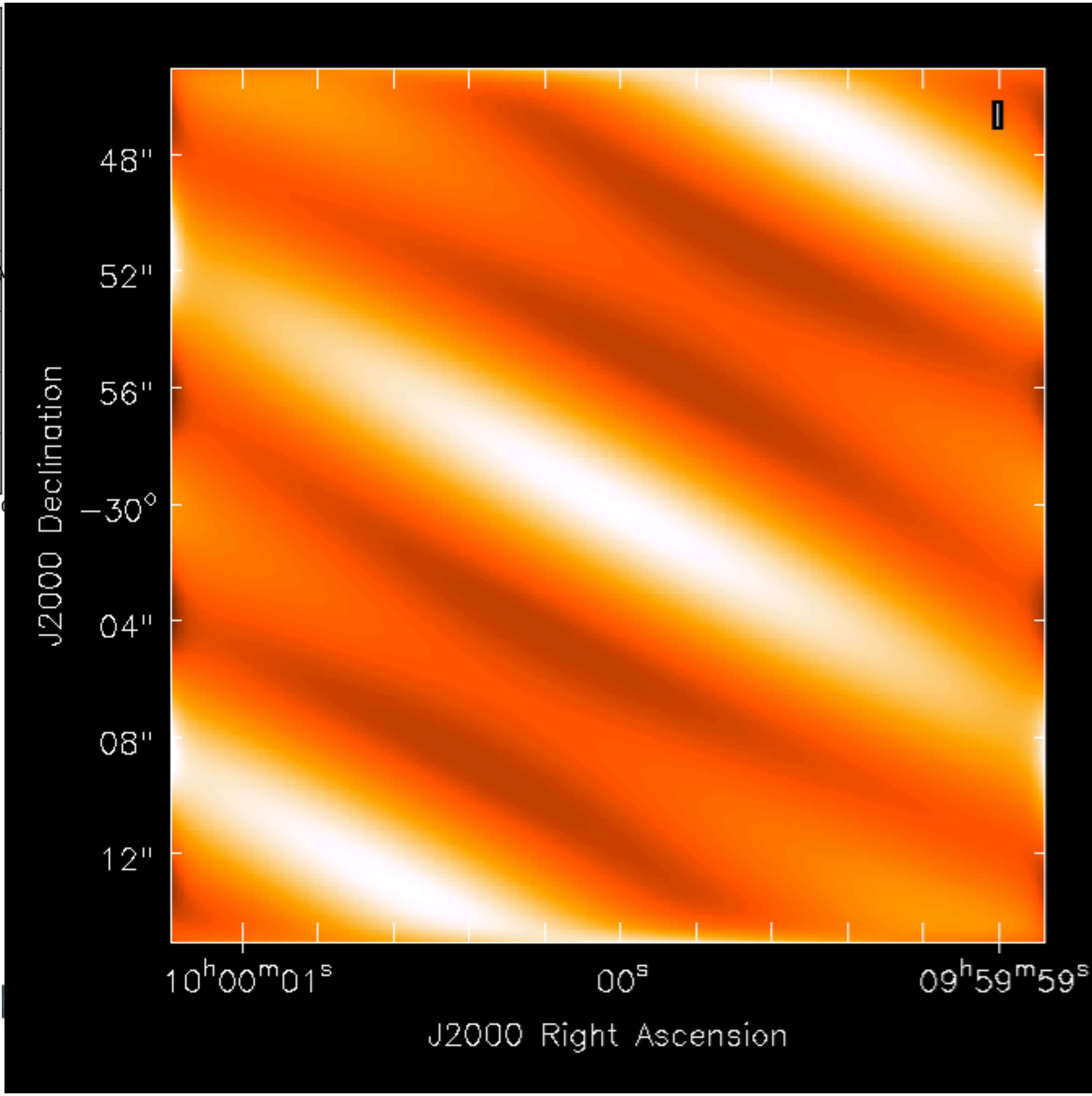




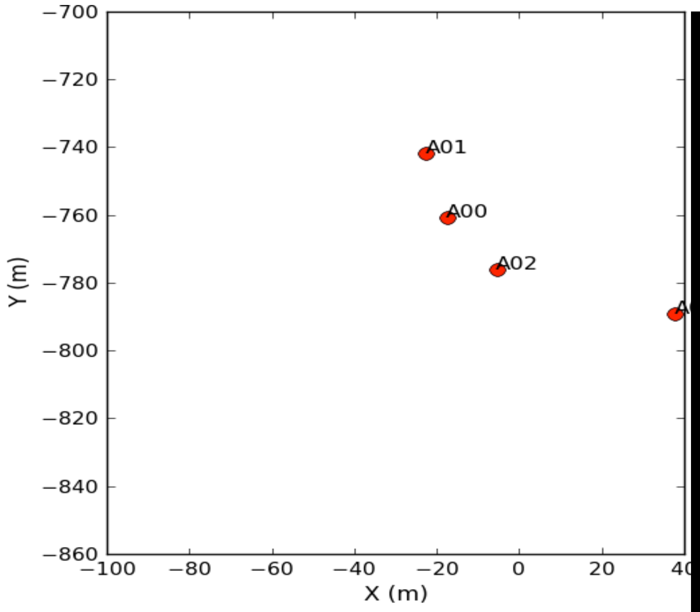
Example: Fringe pattern with 3 Antennas

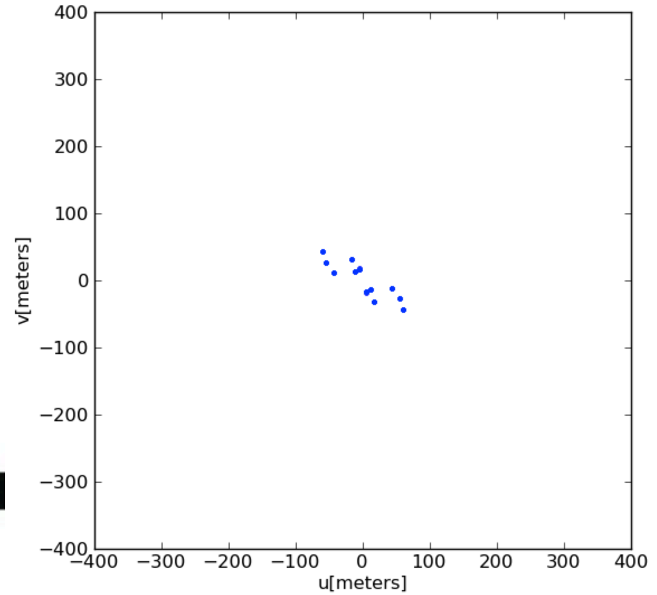


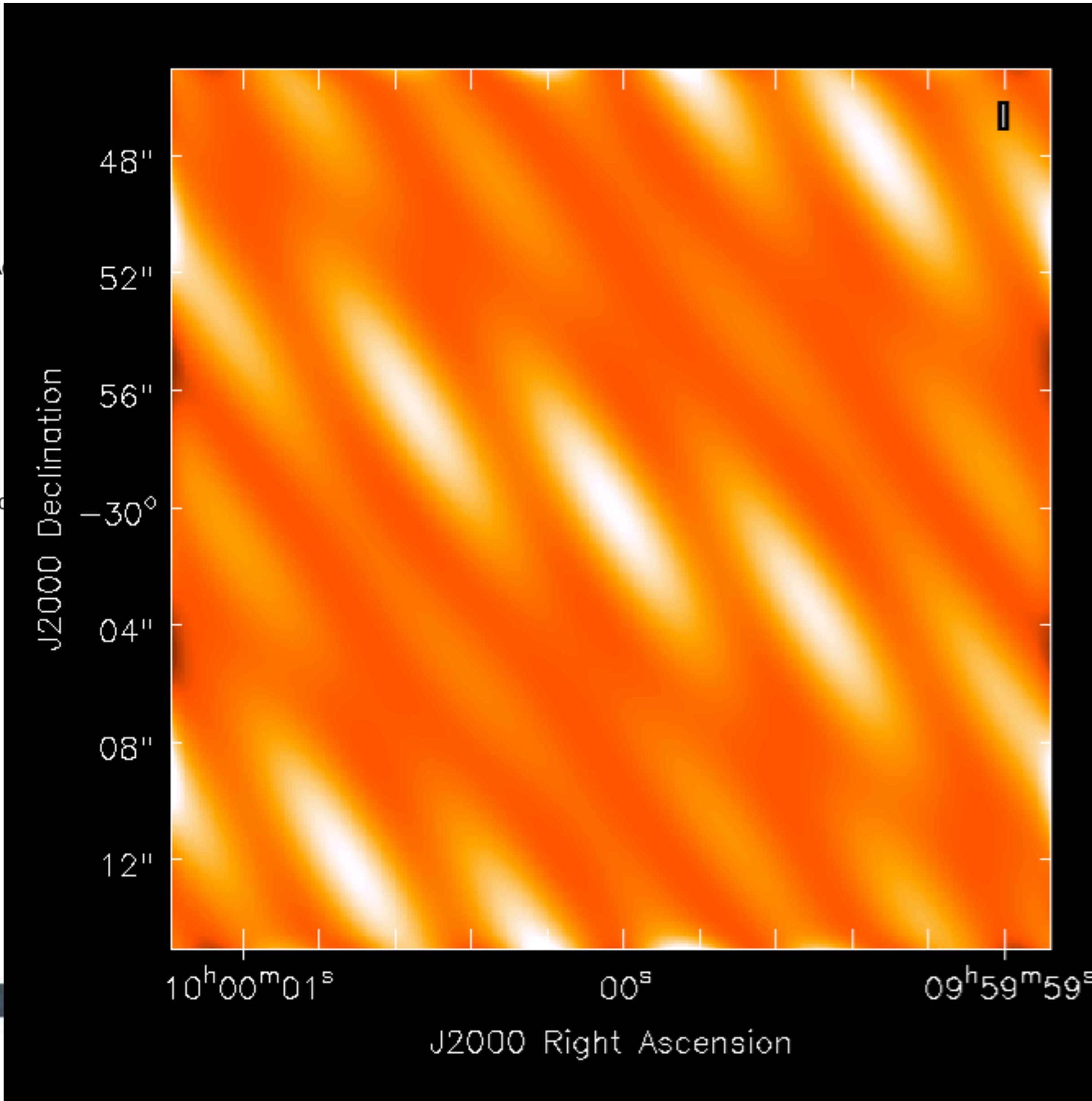




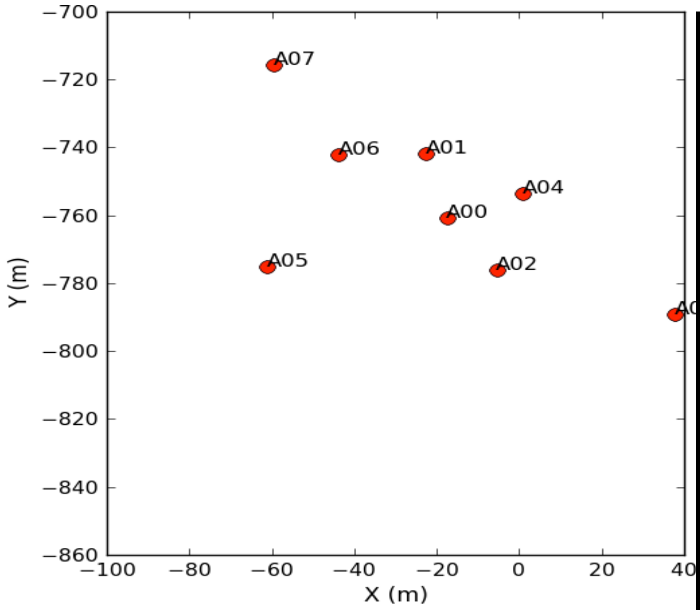
Example: Fringe pattern with 4 Antennas

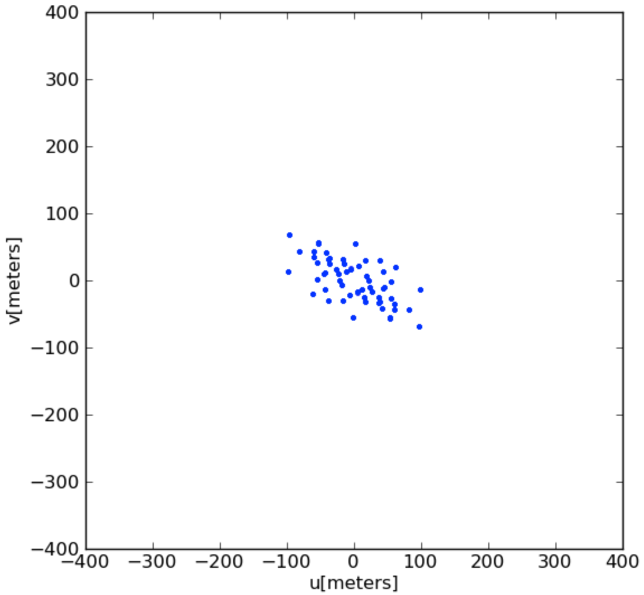


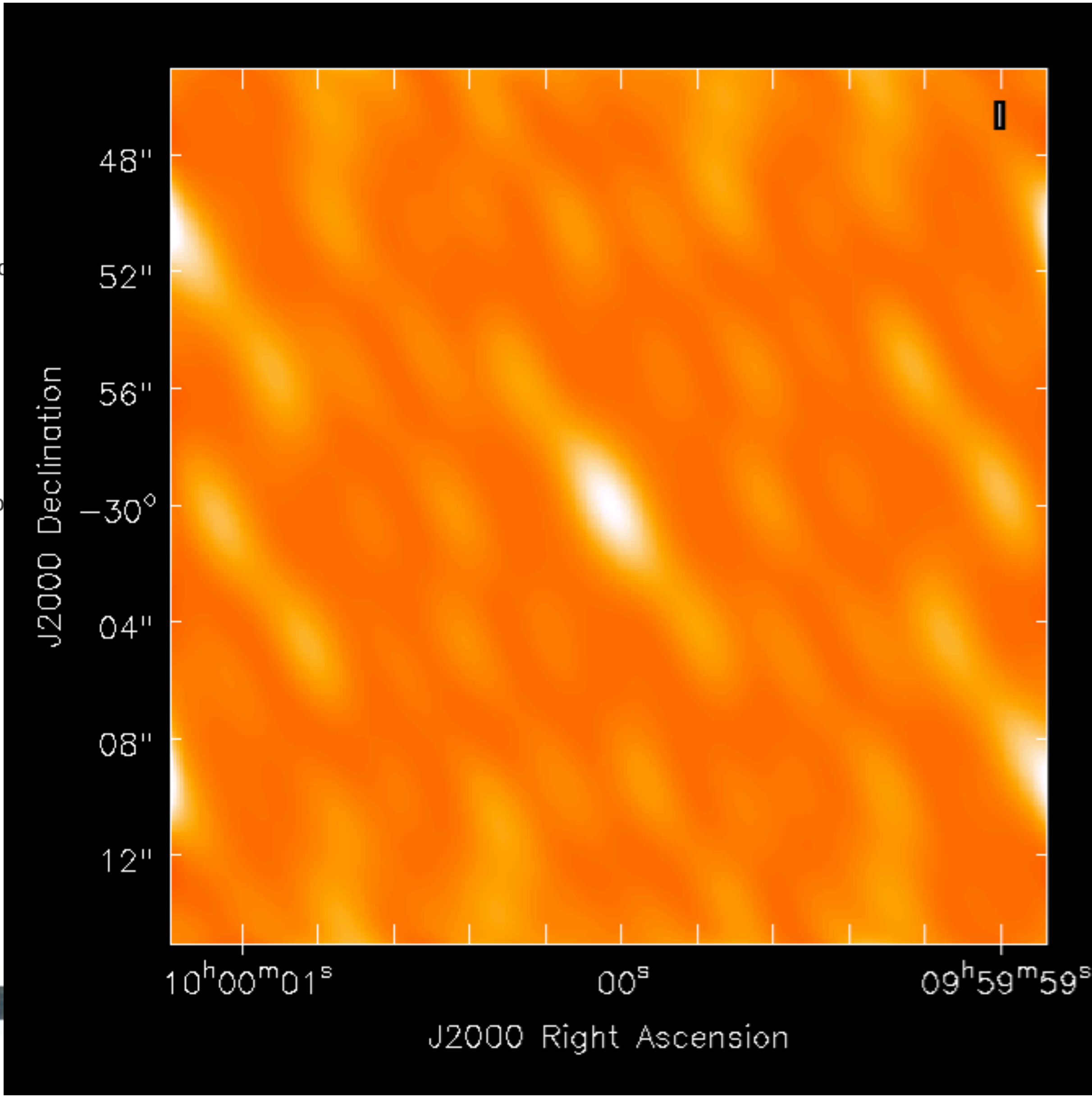




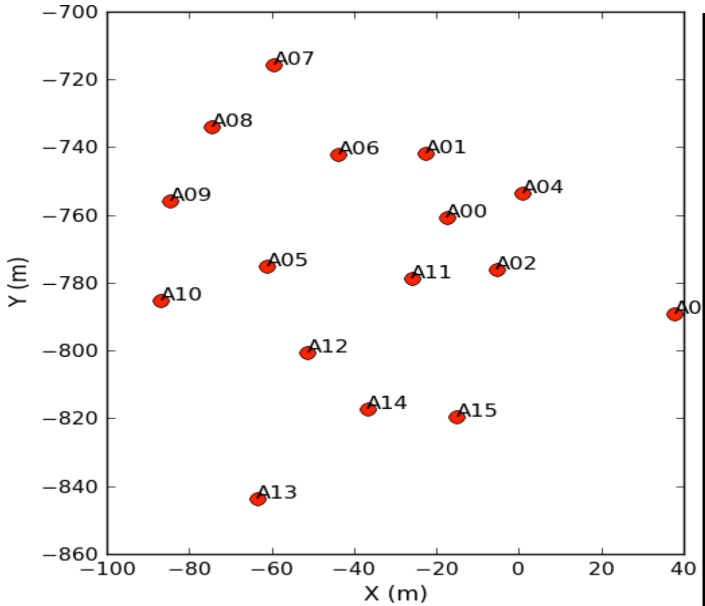
Example: Fringe pattern with 8 Antennas

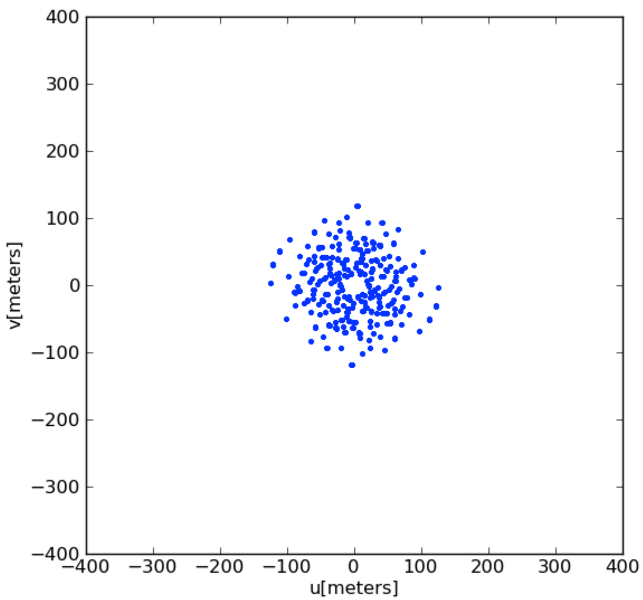


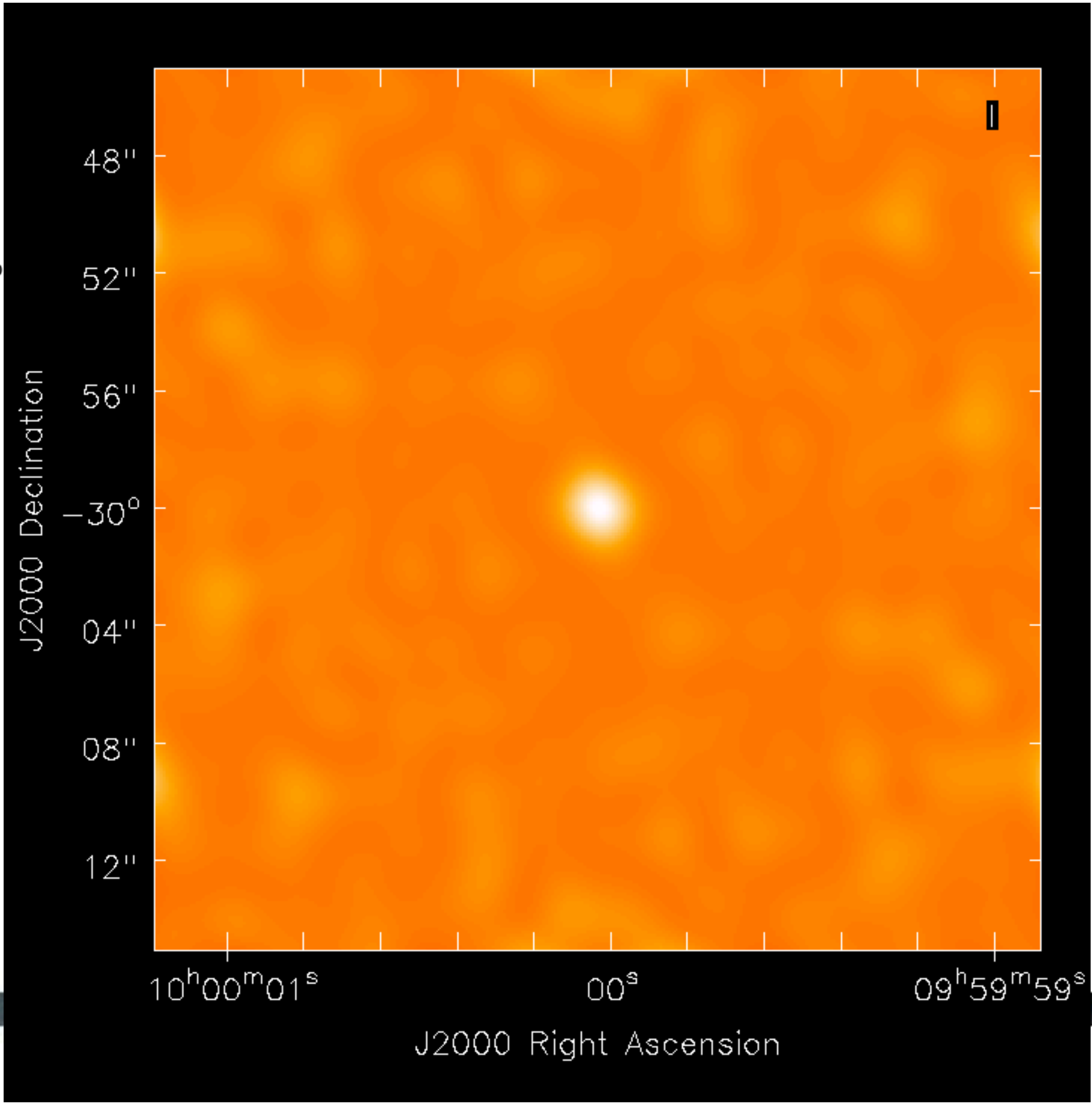




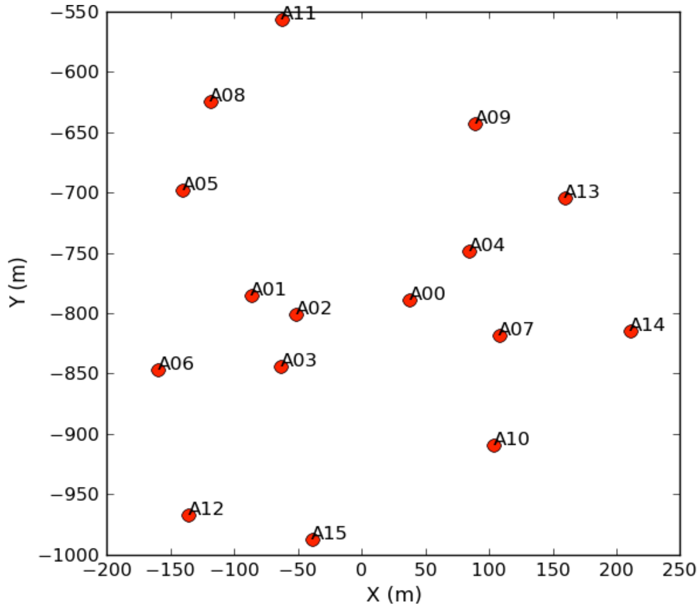
16 Antennas – Compact Configuration

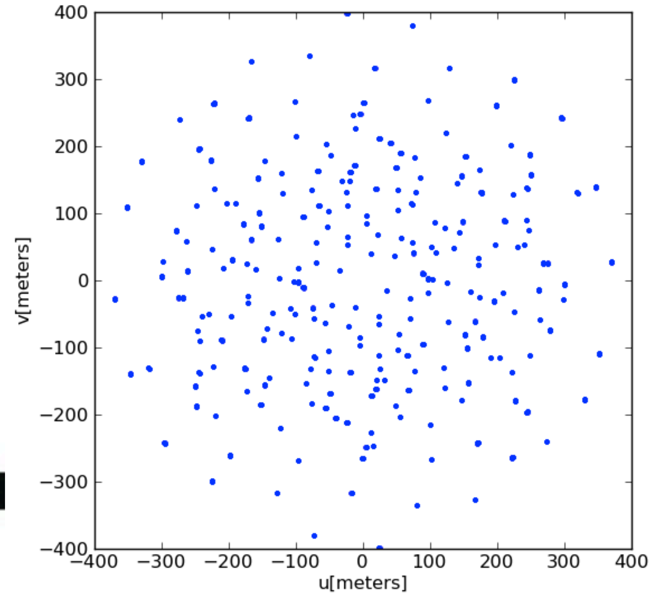


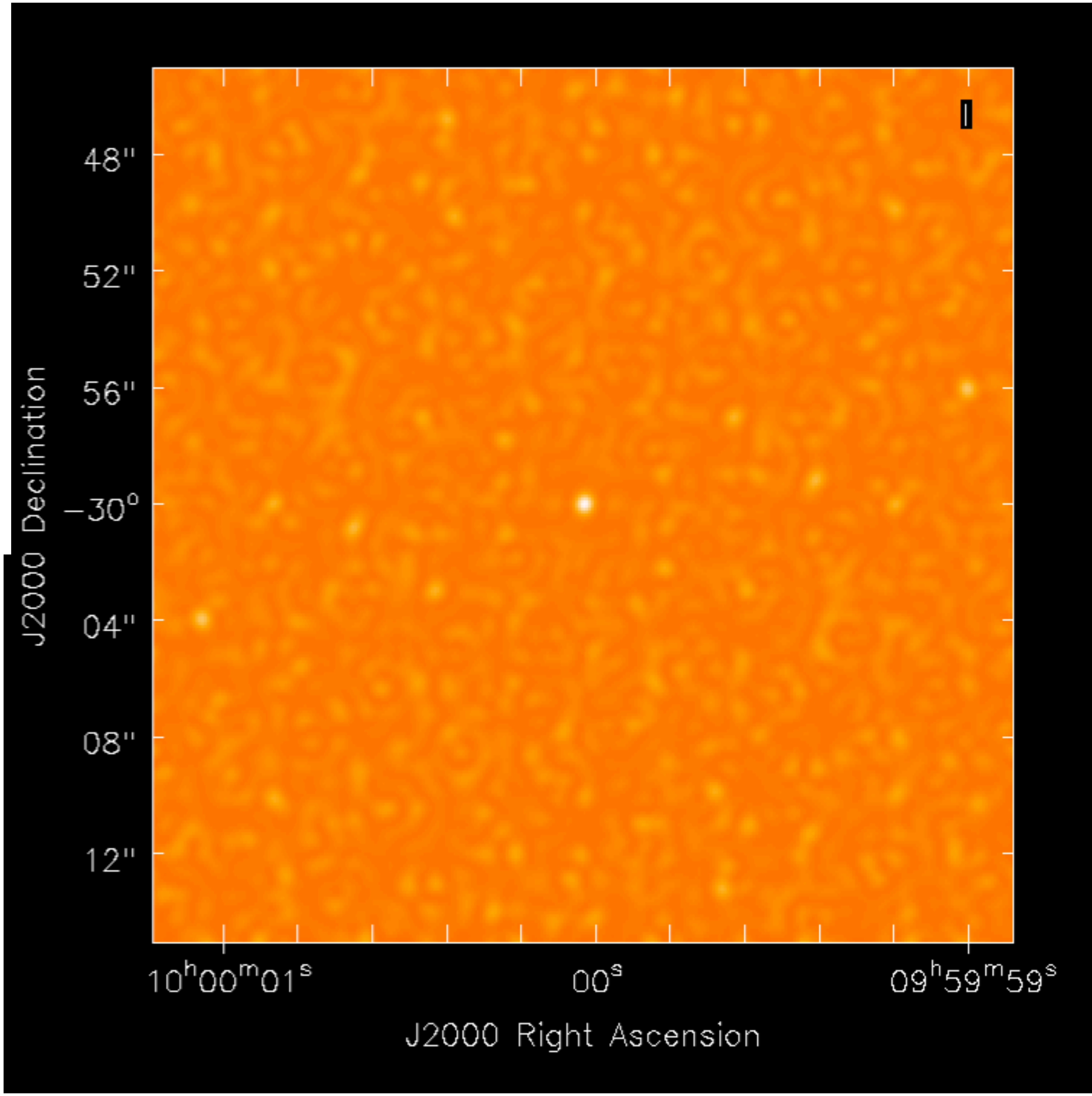




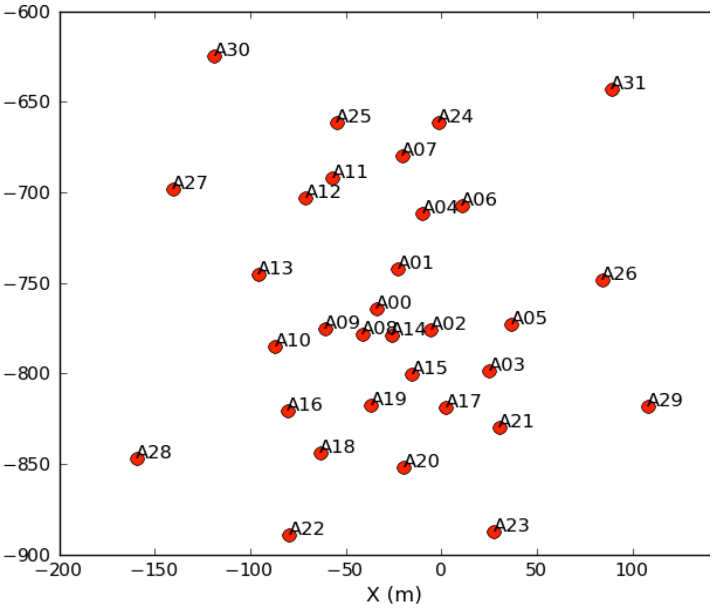
16 Antennas – Extended Configuration

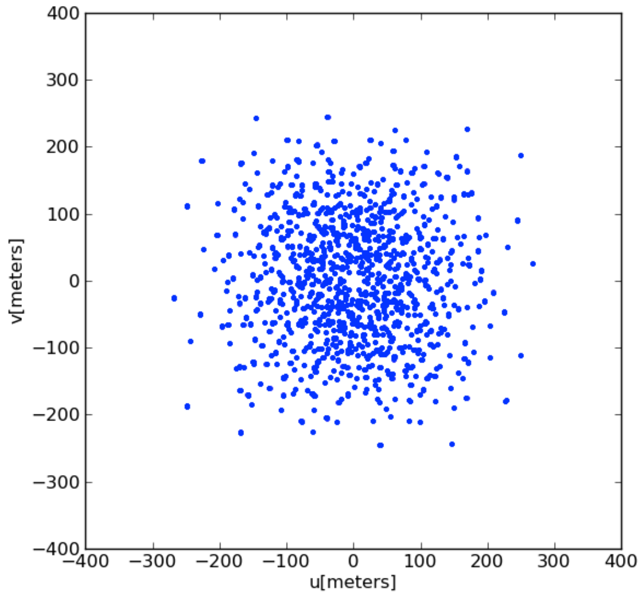


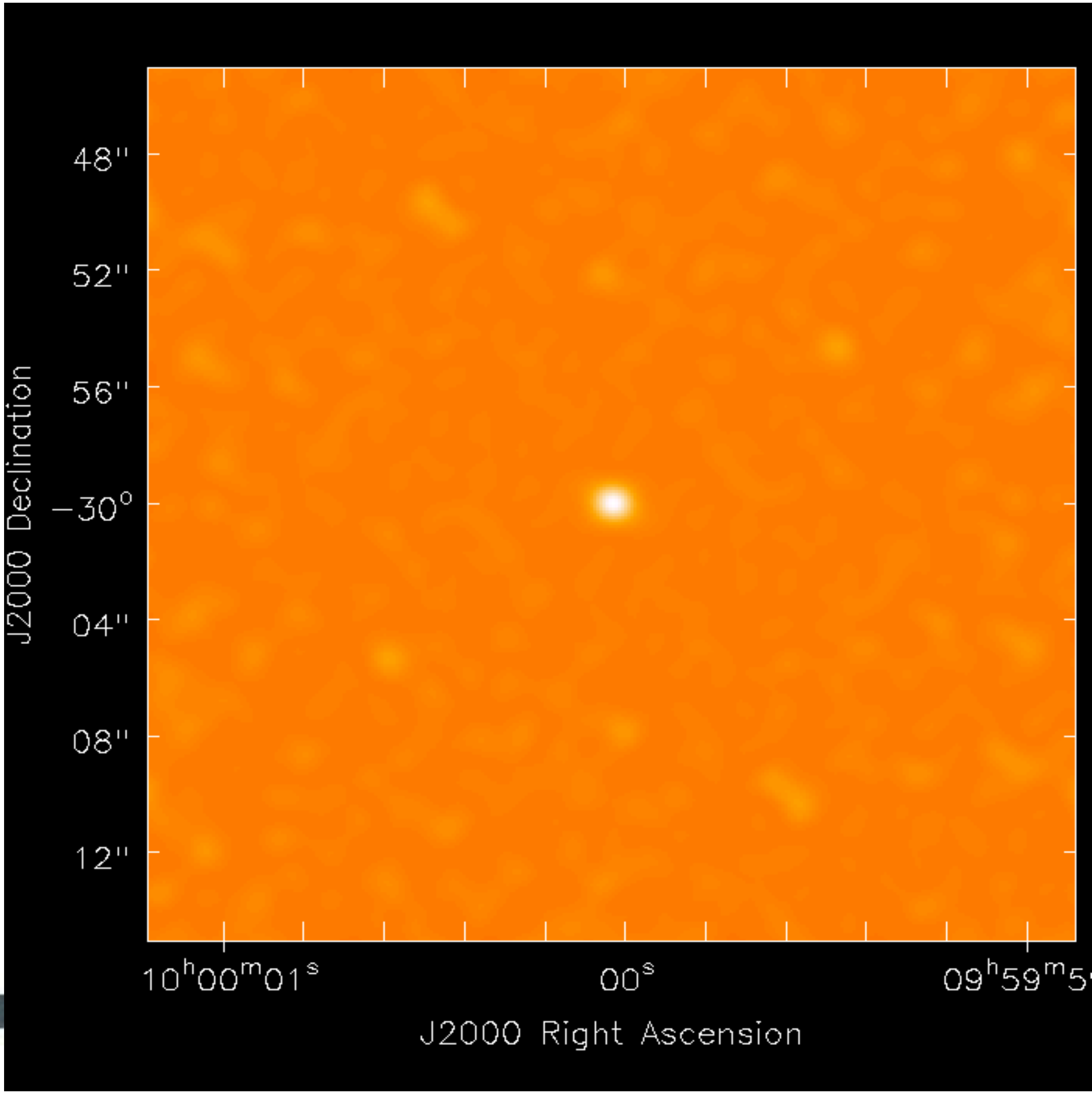




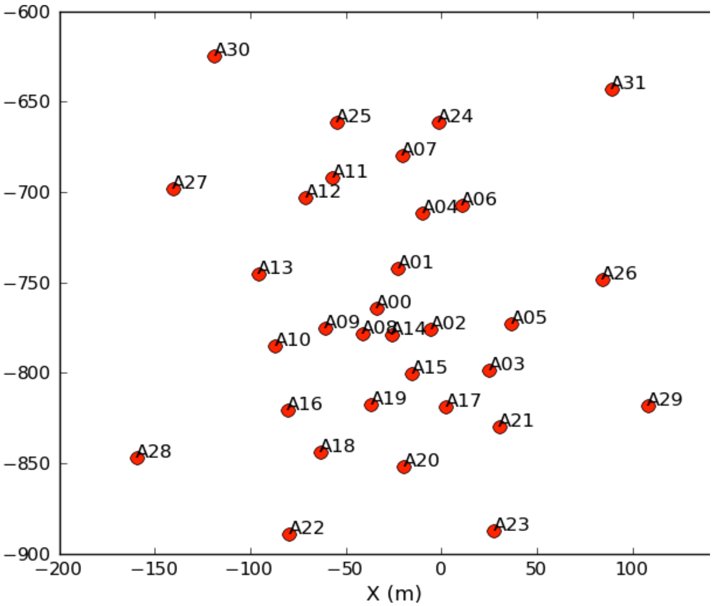
32 Antennas – Instantaneous

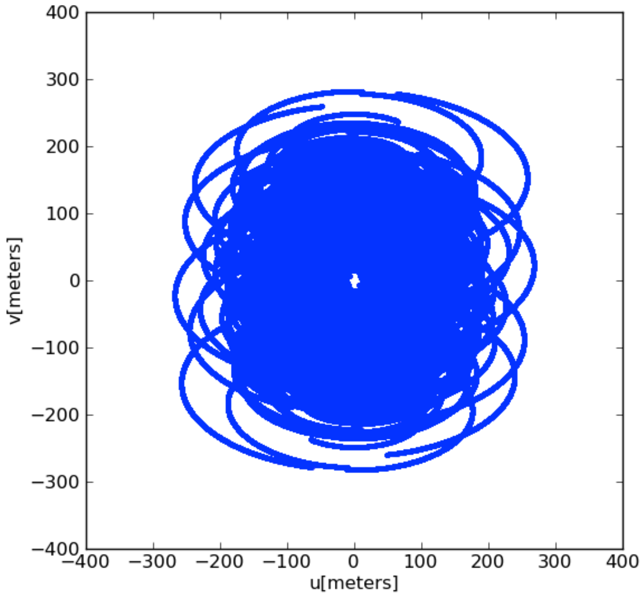


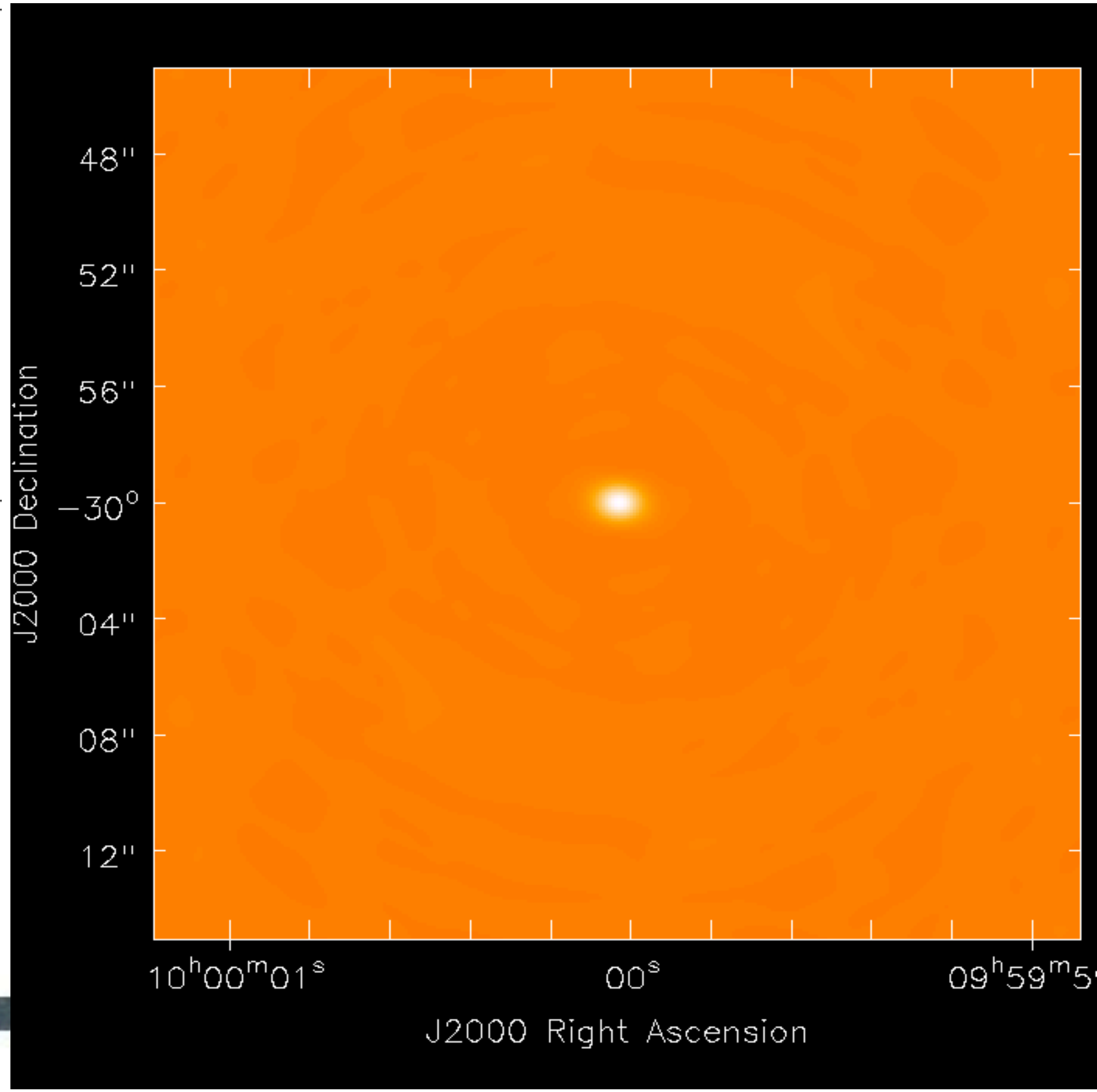




32 Antennas – 8 hours







Characteristic Angular Scales

Angular resolution of telescope array:

$\sim \lambda/B_{max}$ (B_{max} = longest baseline)

Maximum angular scale:

$\sim \lambda/B_{min}$ (B_{min} = shortest distance between antennas)

Field of view (FOV):

$\sim \lambda/D$ (D = antenna diameter)

*Sources more extended than the FOV can be observed using multiple pointing centers in a mosaic

An interferometer is sensitive to a range of angular sizes: $\lambda/B_{max} < \theta < \lambda/B_{min}$

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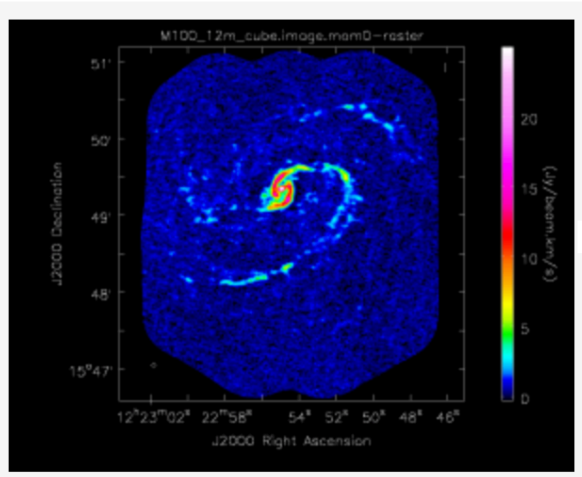
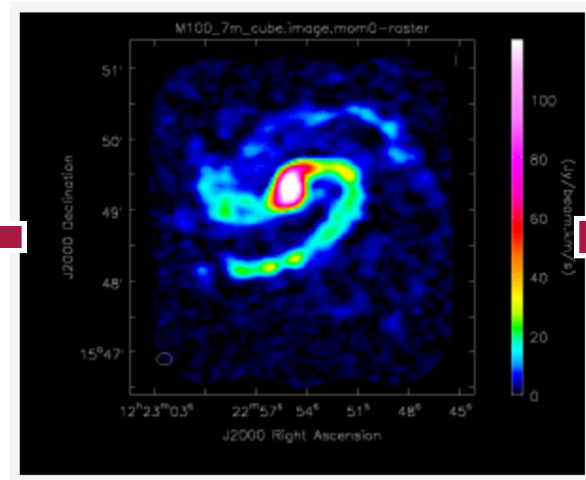
Characteristic Angular Scales: M100

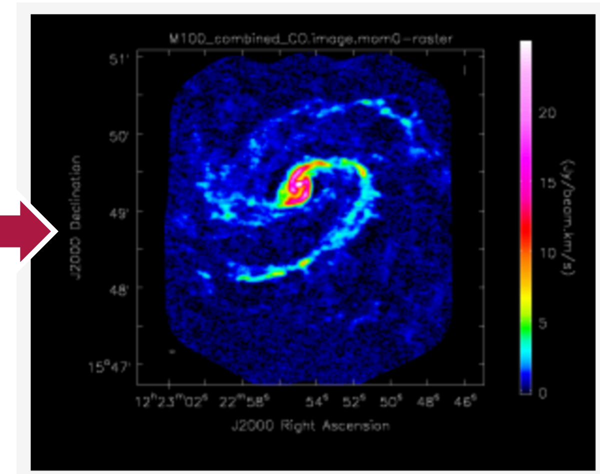
ALMA 12m



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!

Angular Scales — A Proposal Tip!

Most Extended configuration	Allowed Compact configuration pairings	Extended 12-m Array Multiplier	Multiplier if compact 12-m Array needed	Multiplier if 7-m Array needed	Multiplier if TP Array needed and allowed
7-m Array	TP			1	1.7
C43-1	7-m Array & TP	1		7.0	11.9
C43-2	7-m Array & TP	1		4.7	8.0
C43-3	7-m Array & TP	1		2.4	4.1
C43-4	C43-1 & 7-m Array & TP	1	0.34	2.4	4.0
C43-5	C43-2 & 7-m Array & TP	1	0.26	1.2	2.1
C43-6	C43-3 & 7-m Array & TP	1	0.25	0.6	1.0
C43-7	C43-4	1	0.23		
C43-8	C43-5	1	0.22		
C43-9	C43-6	1	0.21		
C43-10	-	1			

From the ALMA Cycle 6 Proposal Guide

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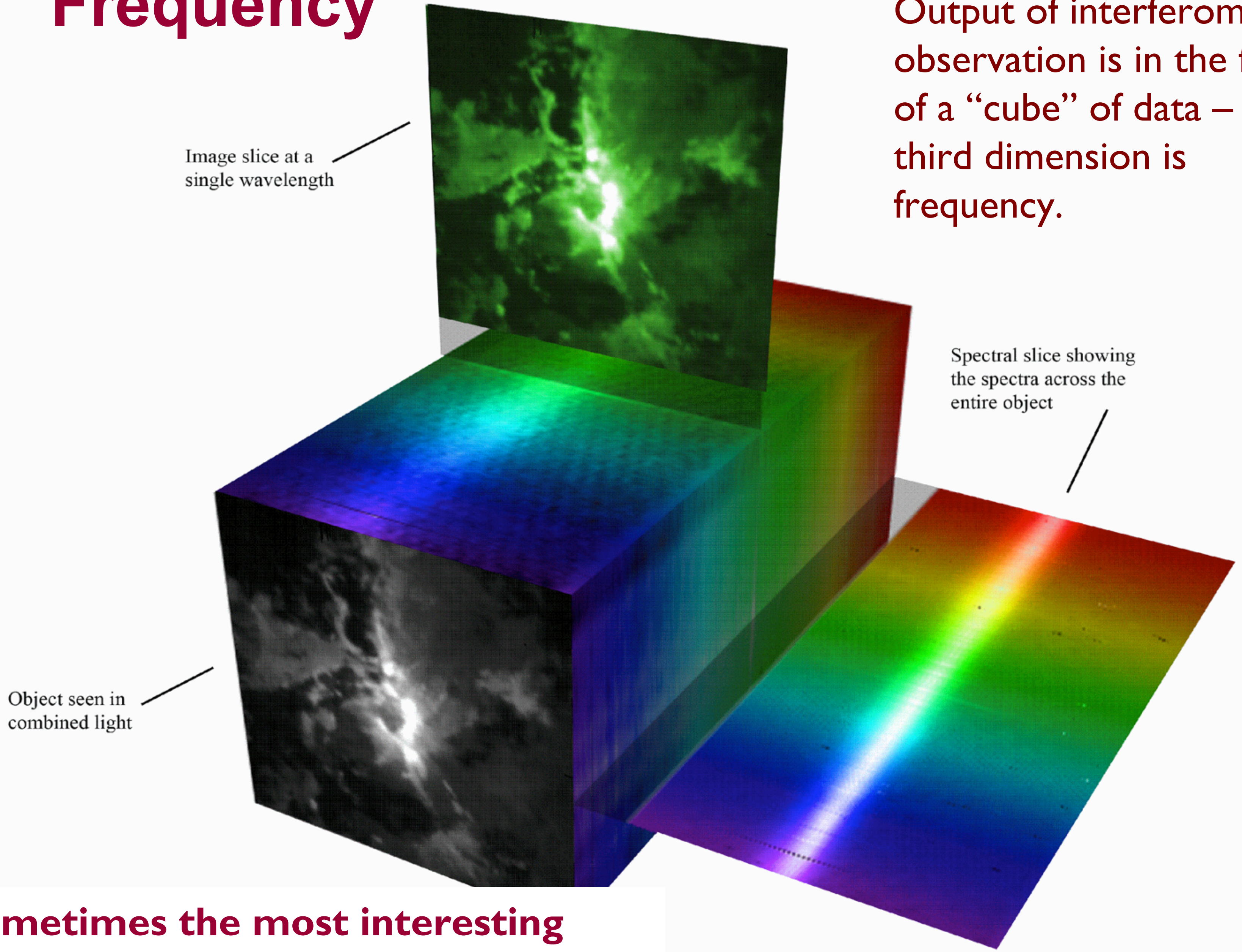
Interferometry: Spatial Considerations (Summary)

- The **sensitivity** is given by the number of antennas times their area
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam)
- The **resolution** is given by the largest distance between antennas (called the synthesized beam)
- The **largest angular scale** that can be imaged is given by the shortest distance between antennas

Frequency

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!

Radio Astronomy uses *Heterodyne Technology*

Observed sky frequencies are converted to lower frequency signals (IF output) by mixing with a signal created by a Local Oscillator. The output can then be amplified and analyzed more easily while retaining the original phase and amplitude information.

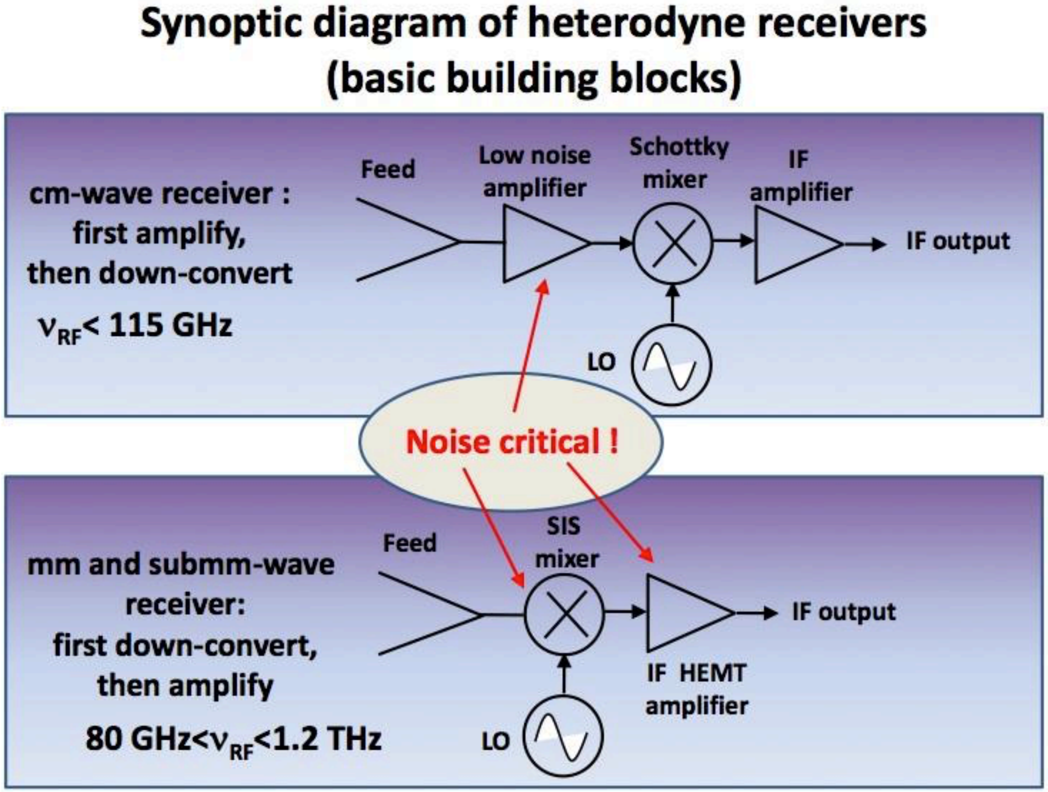
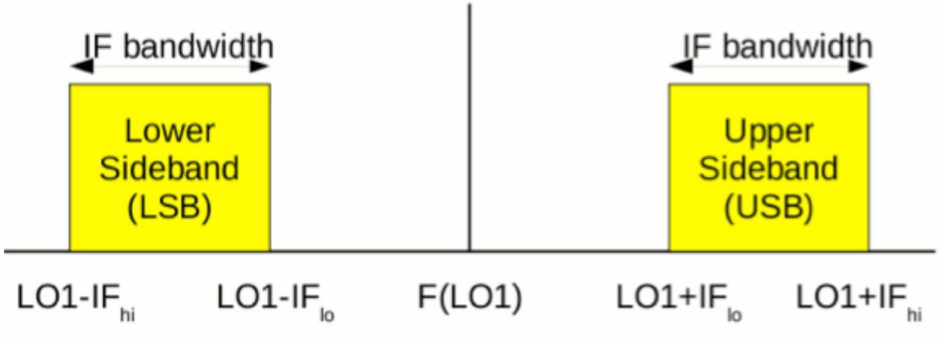


Image from Alessandro Navarrini (IRAM)

ALMA's Correlator

ALMA's correlator can be configured in many ways, allowing for great flexibility in spectral resolution and coverage!



**Expanded in Band 6*

- Four 2 GHz-wide, tunable* basebands in each polarization. Total bandwidth up to 7.5 GHz (x2 polarizations)
- IF range is 4-8 GHz* in Bands 3-8 and 4-12 GHz in Bands 9&10
- Choose fine (down to 15 kHz) up to broad spectral resolution, split baseband into 2-4 spectral windows as needed

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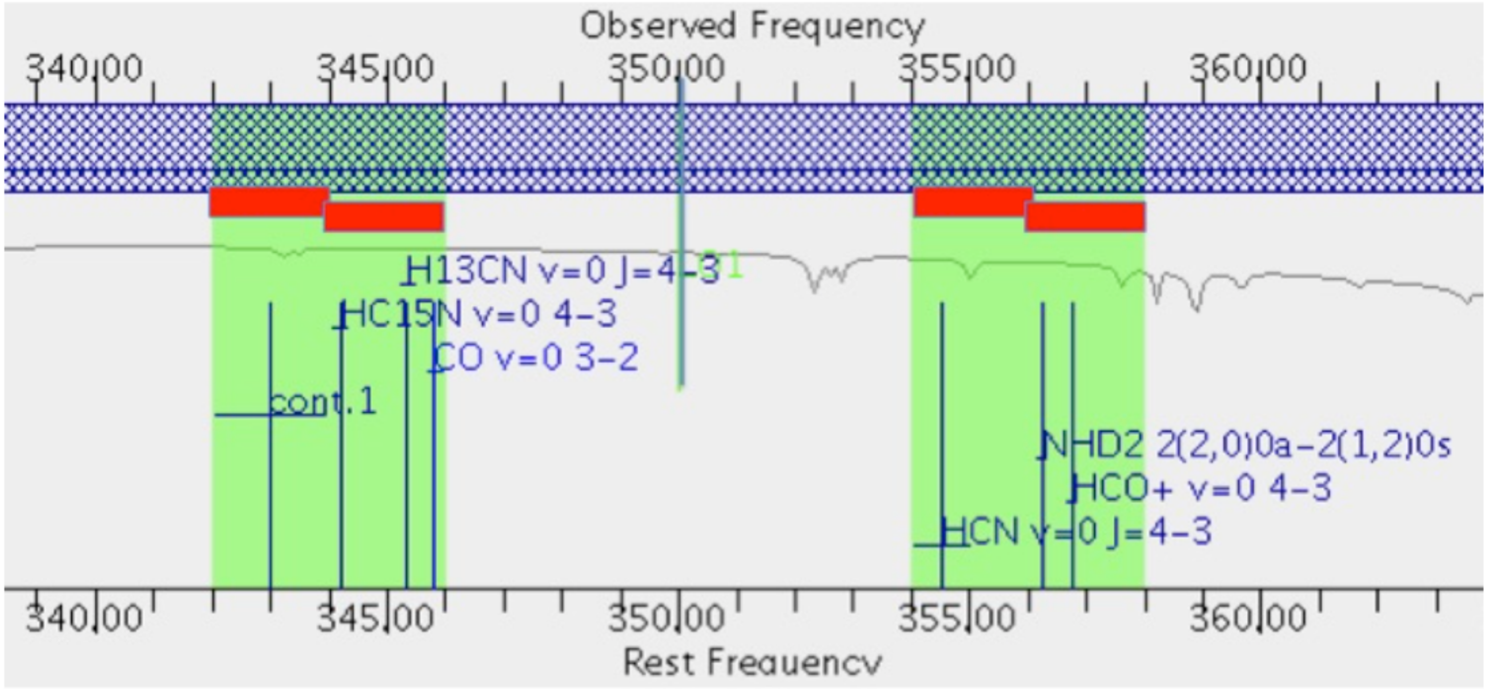
ALMA's Correlator



Example of a Frequency Setup

Green areas: IF ranges

Red bars: basebands

Horizontal lines: spectral windows

Blue hashed: tuning range

Curved line: atmospheric transmission

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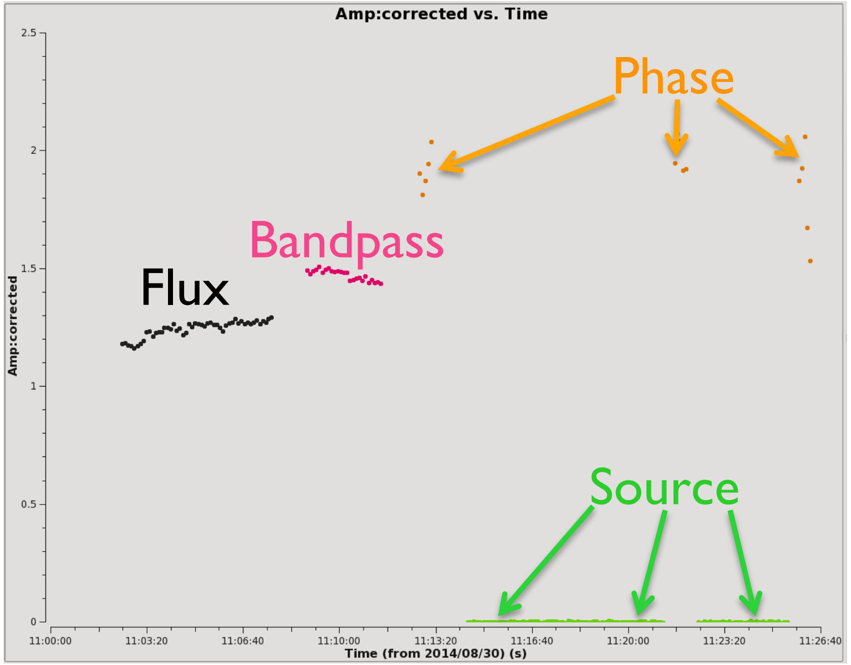
Calibration

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

Gain calibrator
Bright quasar near science target
Solves for atmospheric and instrumental variations with time

Bandpass calibrator
Bright quasar
Fixes instrumental effects and variations vs. frequency

Absolute flux calibrator
Solar system object or quasar
Used to scale relative amplitudes to absolute value



- ***In most cases, ALMA will handle calibration***
- ***Calibration results in overhead: sharing calibration is therefore good!***

Key Takeaways/Considerations

- Interferometry samples the Fourier components of the sky brightness: visibilities
    - To make an image in the sky place, we have to Fourier transform our sampled visibilities
    - *uv* coverage will be incomplete (the more complete the better). With ALMA, high fidelity should be achieved in a short time, but simulations can test this
- Different baselines (array configurations!) sample different spatial scales
    - Angular resolution is given by ~λ/Bmax→ long baselines for high resolution
    - Maximum angular scale ~ λ/Bmin → resolve out large-scale structure
- If your mapping area exceeds 1/3 the primary beam: mosaic
- Spectral considerations: ALMA's correlator is highly flexible, but there are restrictions on what you can do!

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Good Future References

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

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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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