Introduction to Radio Interferometry

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National Science Foundation

Associated Universities, Inc.

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

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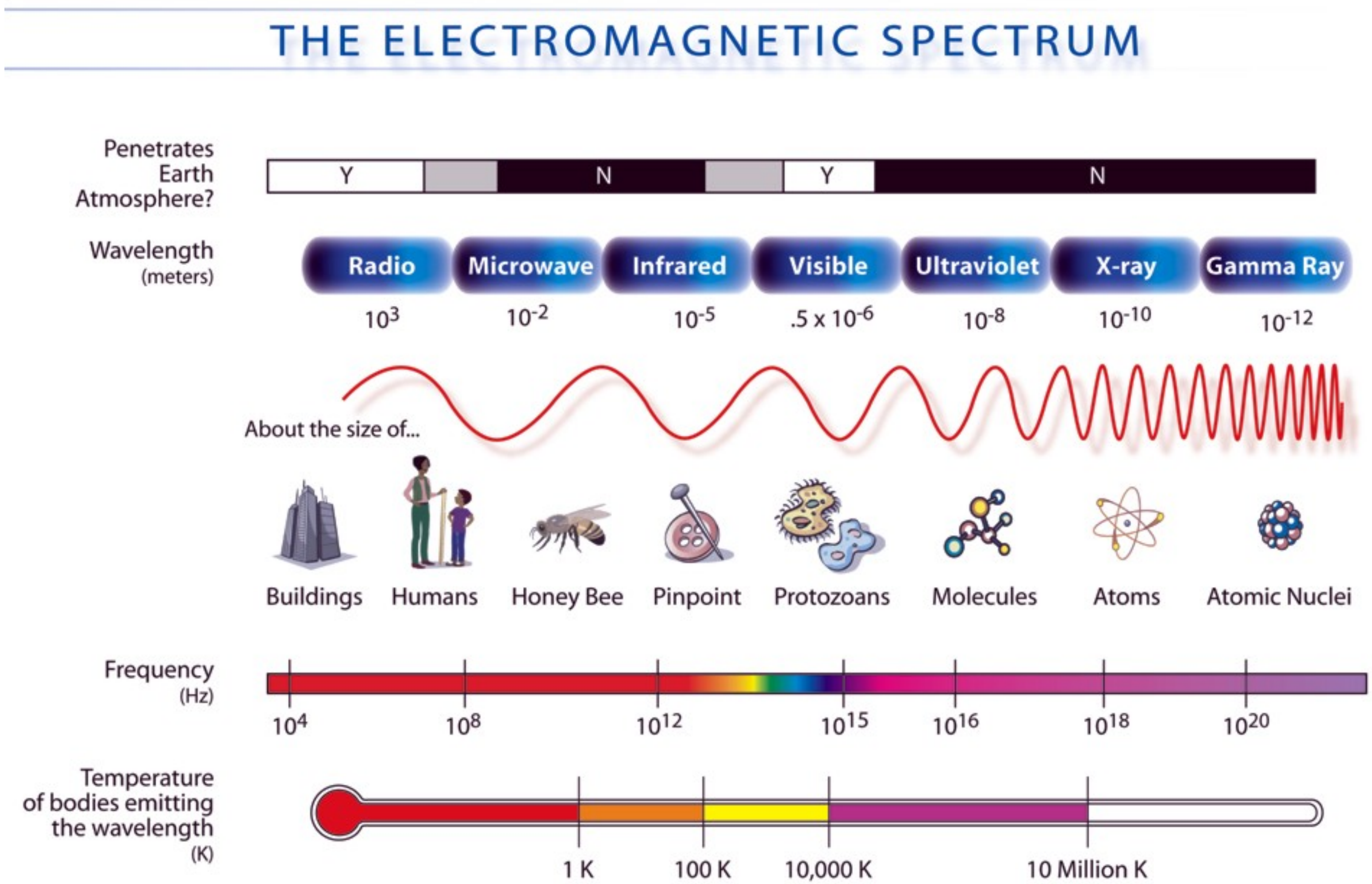
Radio Astronomy

Now used to refer to most telescopes using heterodyne technology



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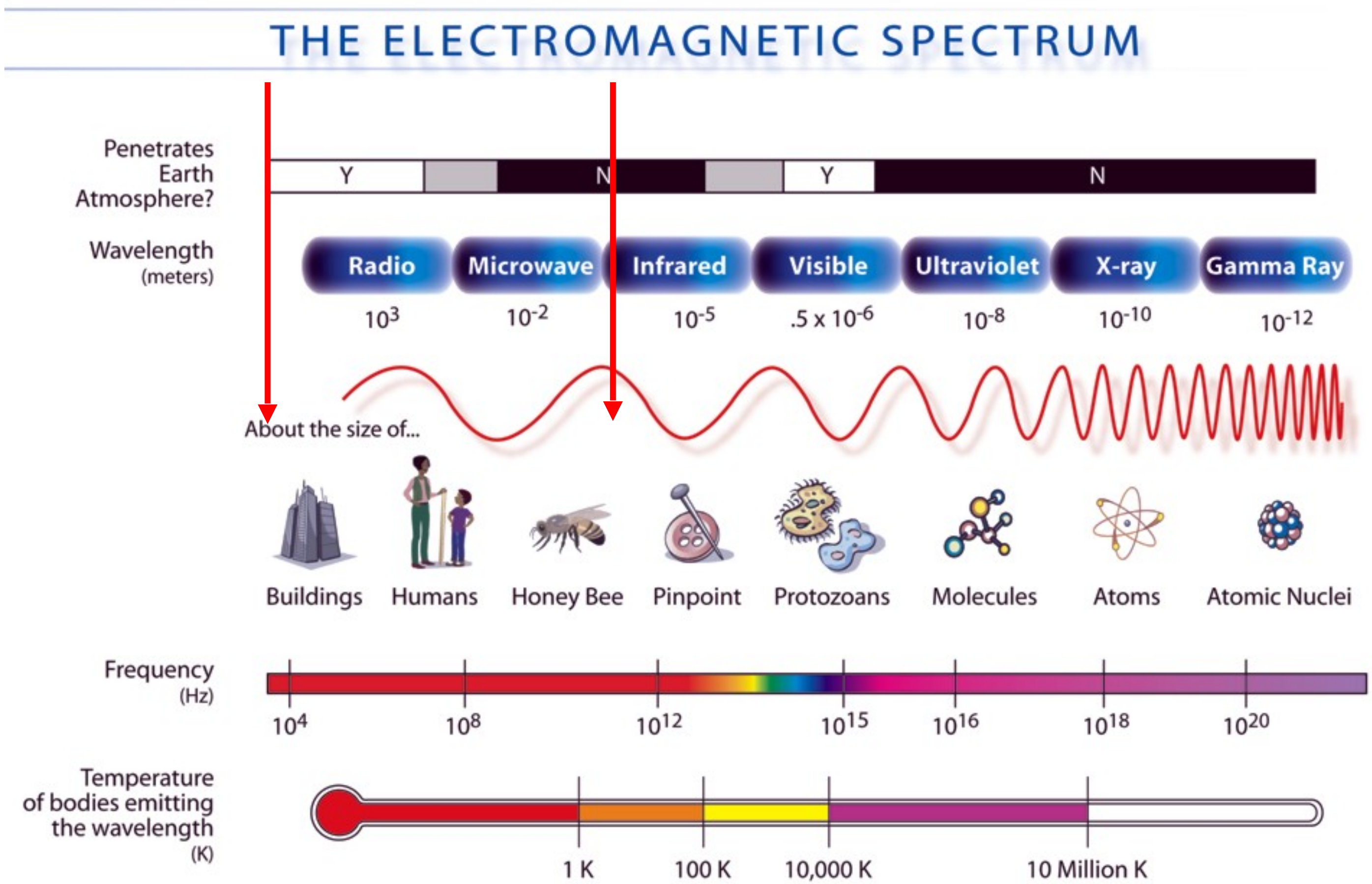


What is heterodyne?

In a heterodyne receiver, 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 while retaining the original phase and amplitude information.

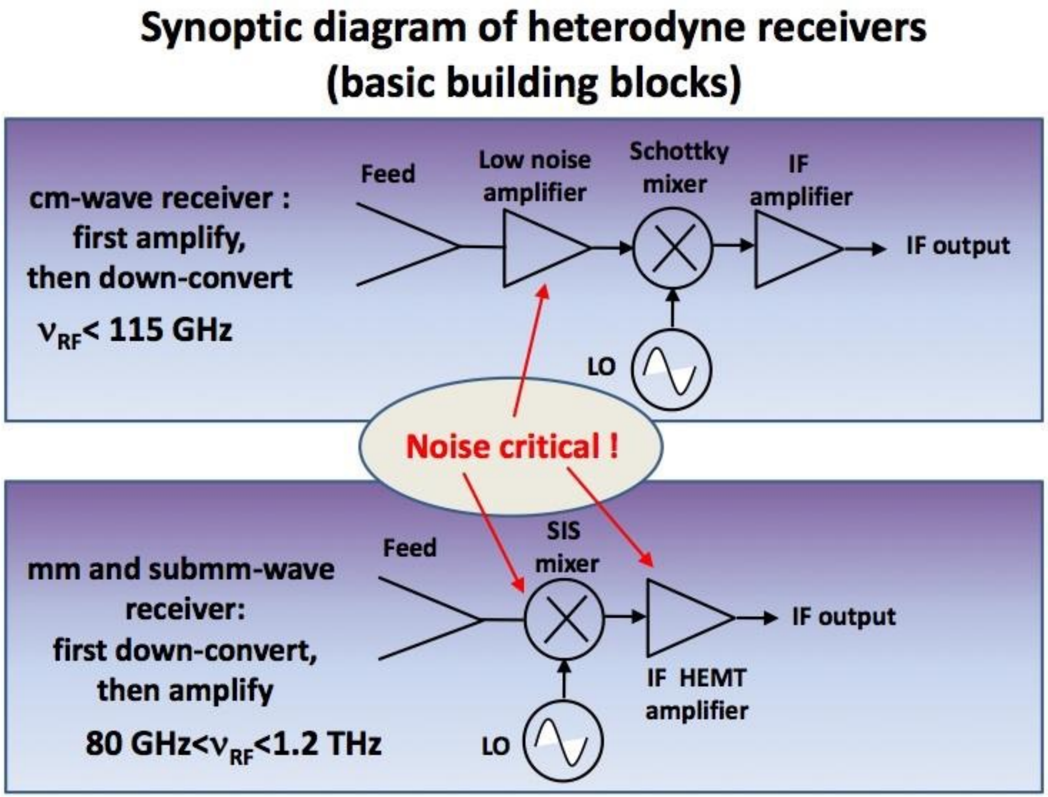
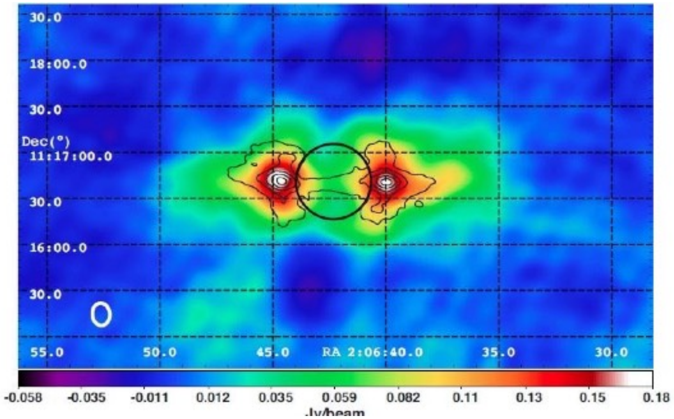


Image from Alessandro Navarrini (IRAM)

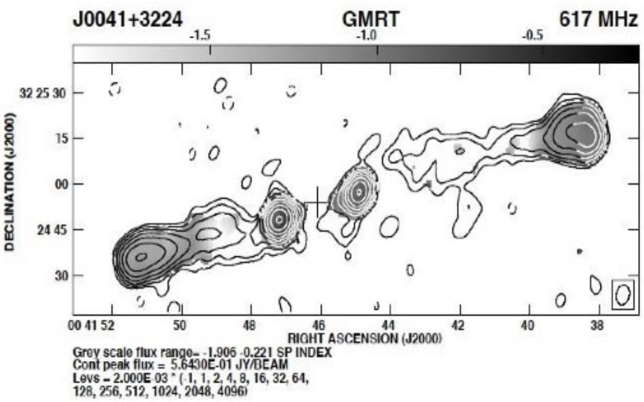
Long wavelength means no glass mirrors

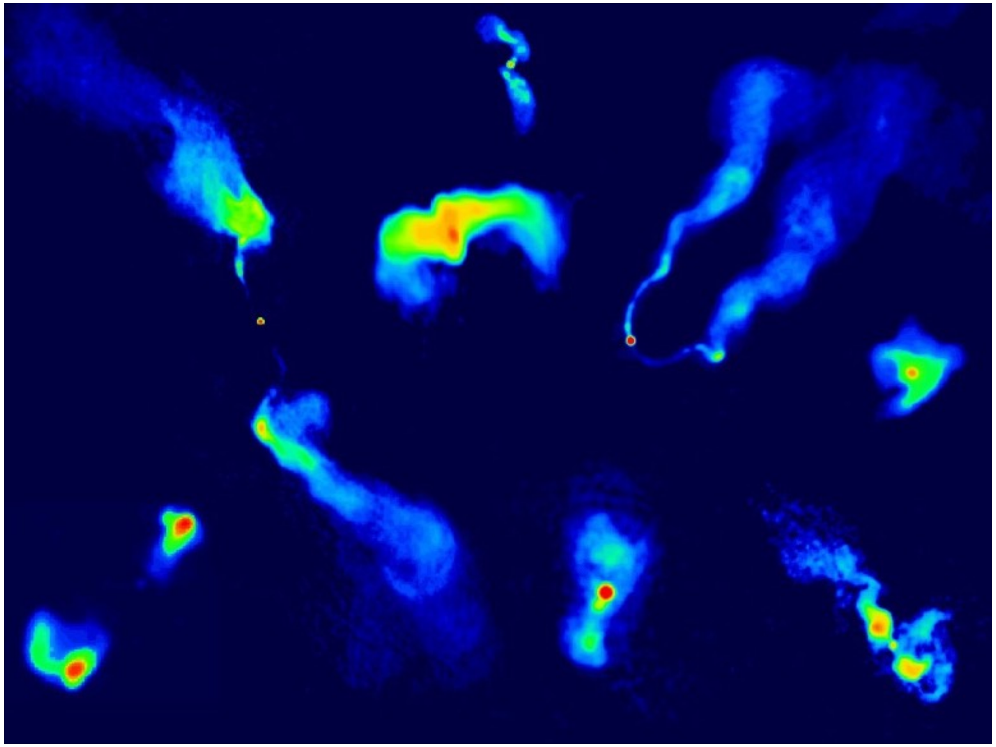
What can we observe? (MHz-GHz range)

Jupiter's radiation belt at 100MHz



Relic emission from old radio galaxies





Synchrotron emission from extended radio galaxies (5 GHz)

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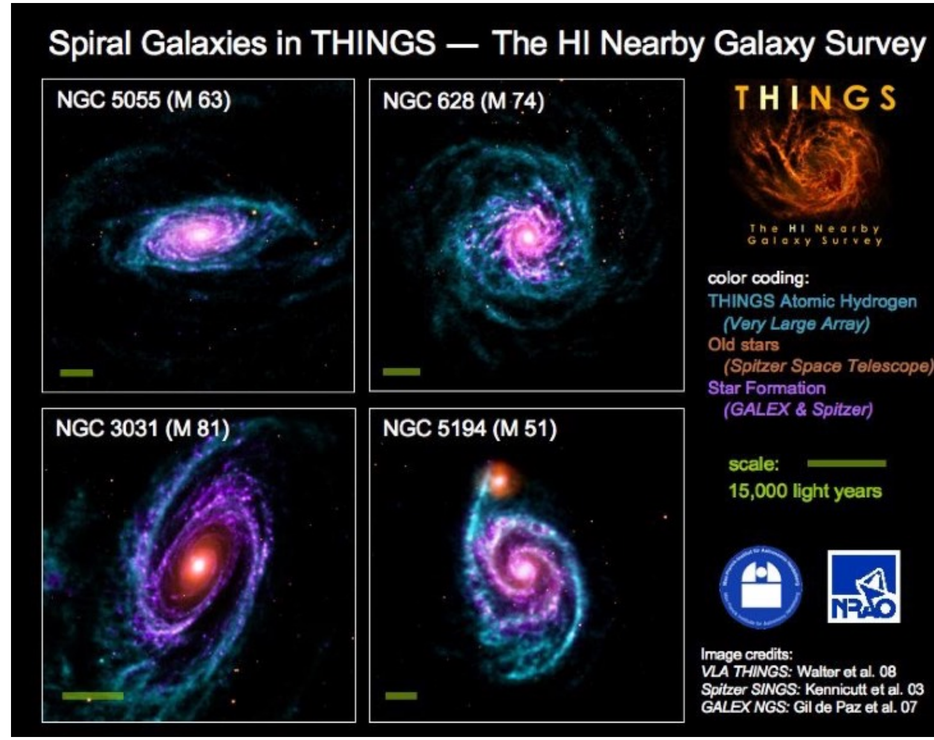
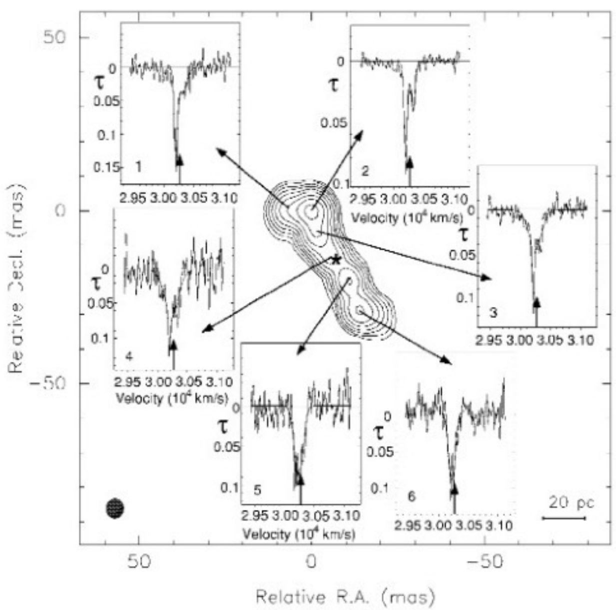
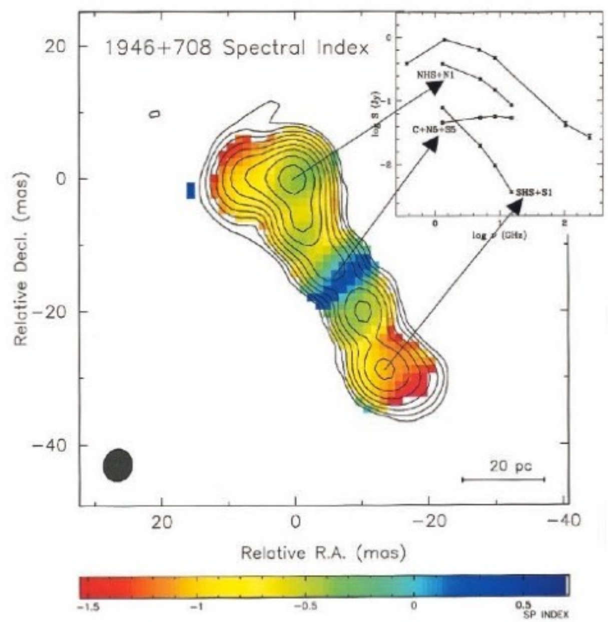
Images from NRAO Image Gallery: http://images.nrao.edu/

At low frequencies (MHz-GHz):



HI emission and absorption, free-free absorption in galaxies

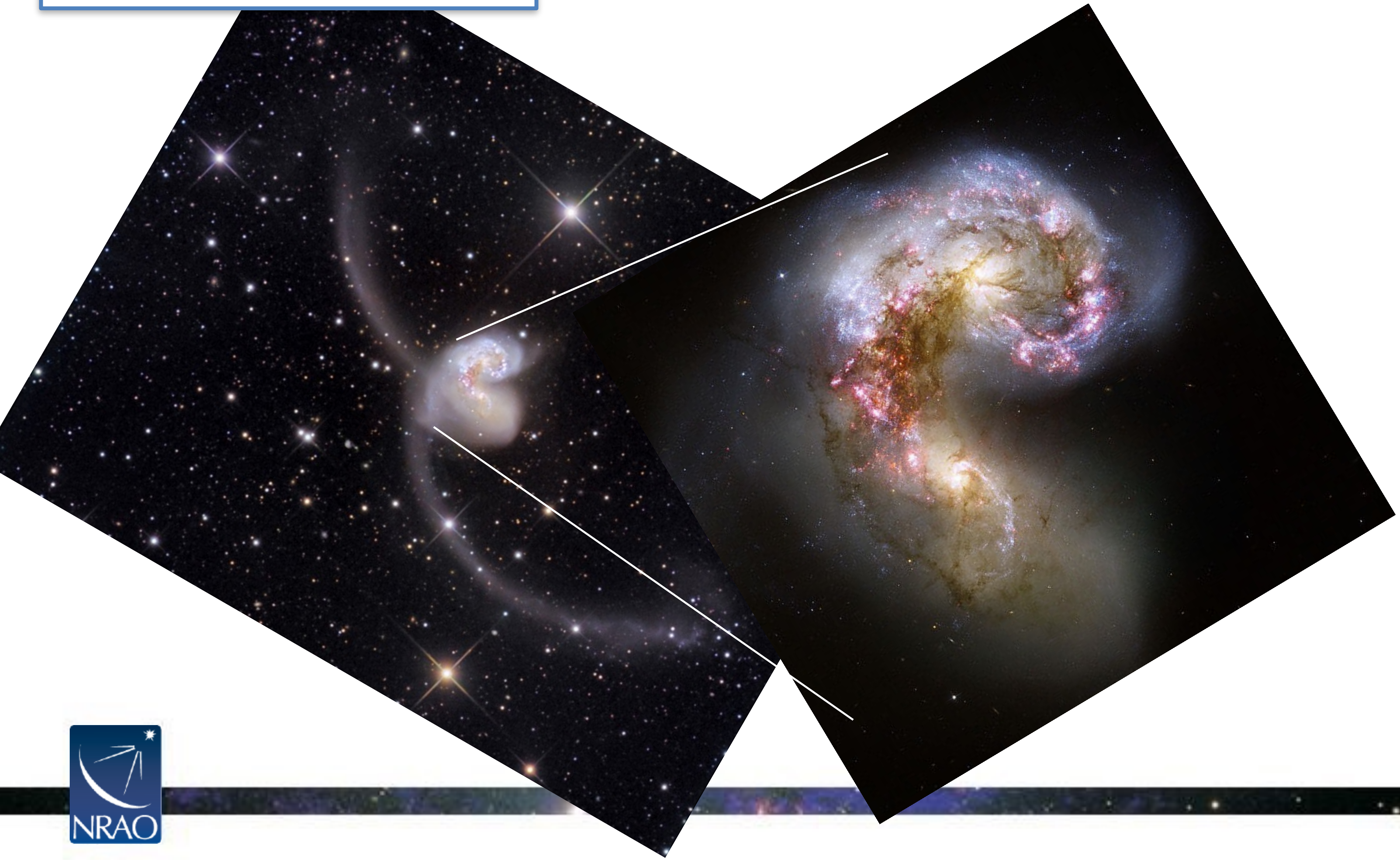




At high frequencies (>> GHz):

Antennae Galaxies

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



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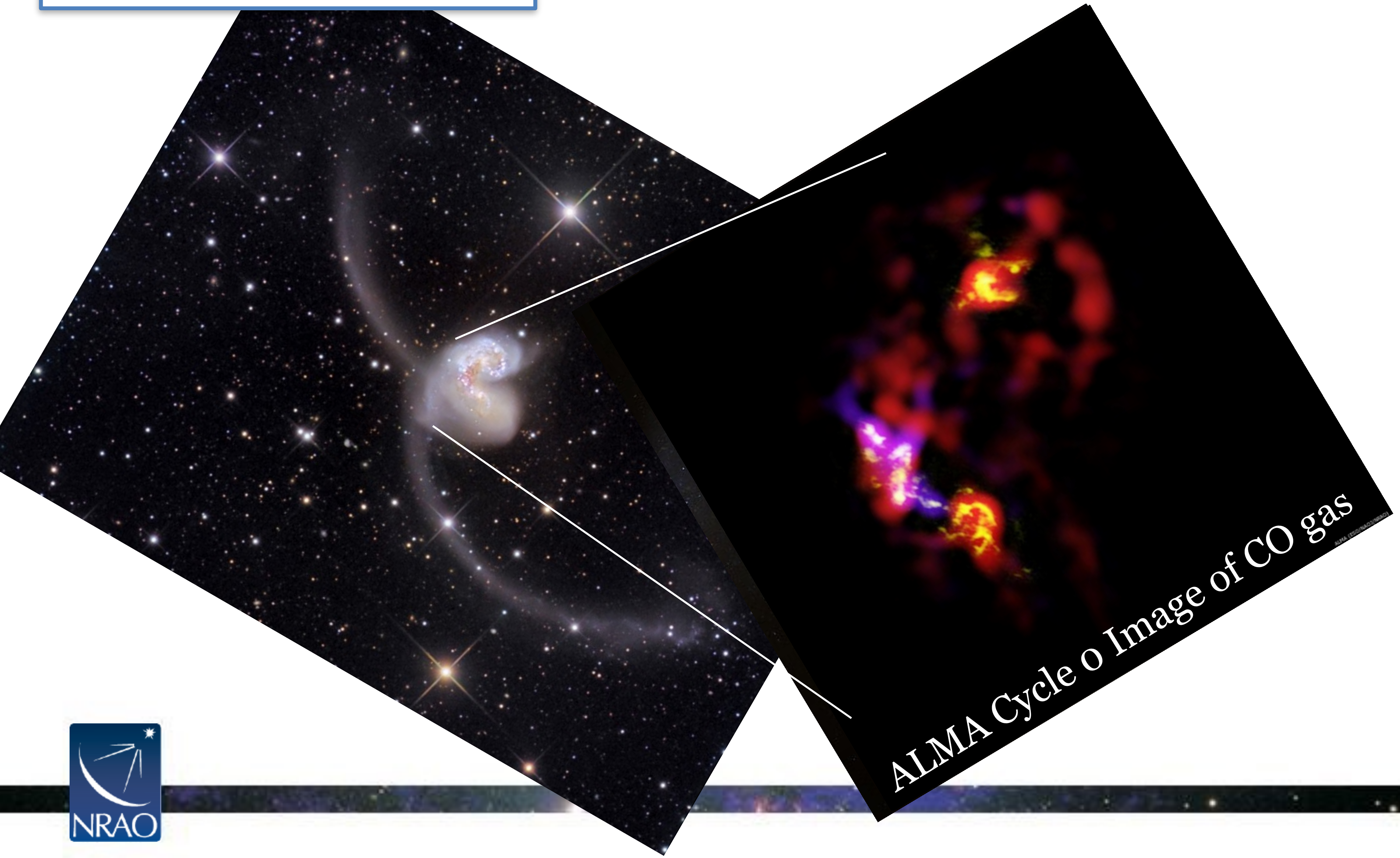

At high frequencies (>> GHz):

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

Antennae Galaxies

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

Effelsberg 100-m dish at cm wavelength is ~ 2 arcmin which is similar to the human eye

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!

Resolution of Observations

Angular resoluti

D is the diameter of ... of

Effelsberg 100-m ... nin

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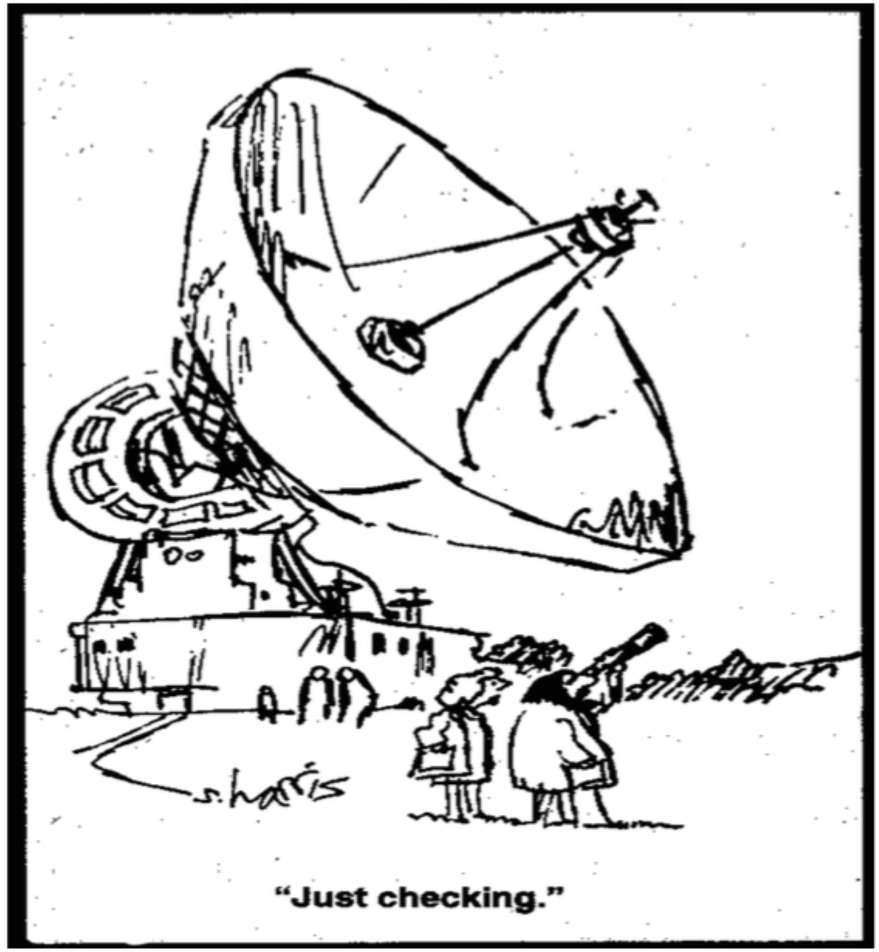
λ ~ 1um / L

To reach that resolut ... a 2

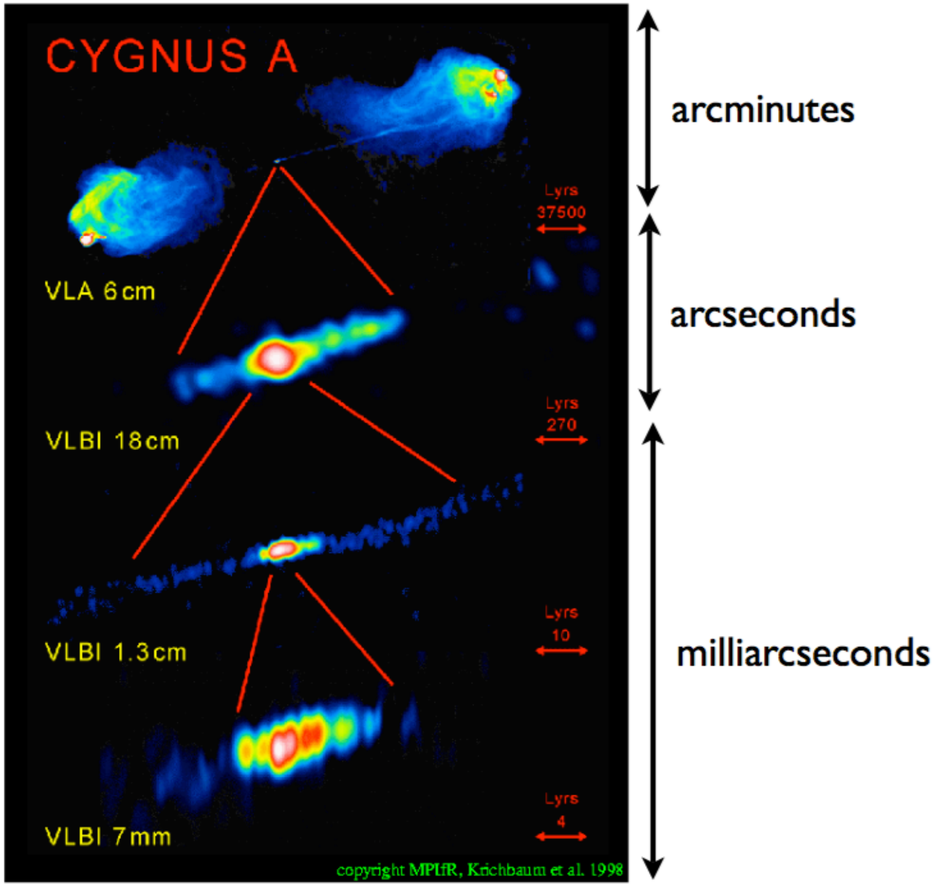
kn

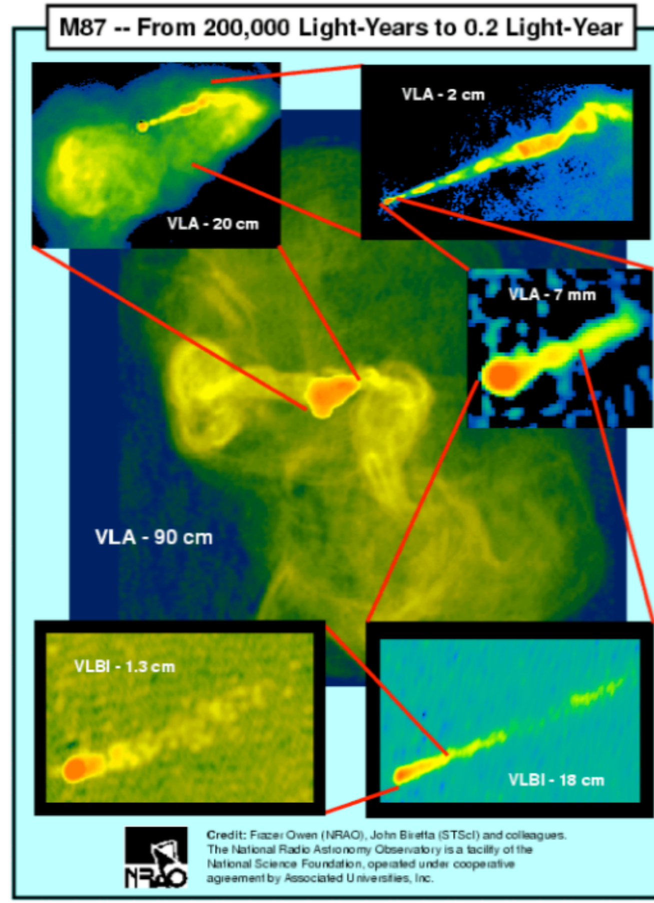


"Just checking."

Resolution of Observations

Radio sources can show emission on scales of arcminutes --> arcseconds --> milliarcseconds...





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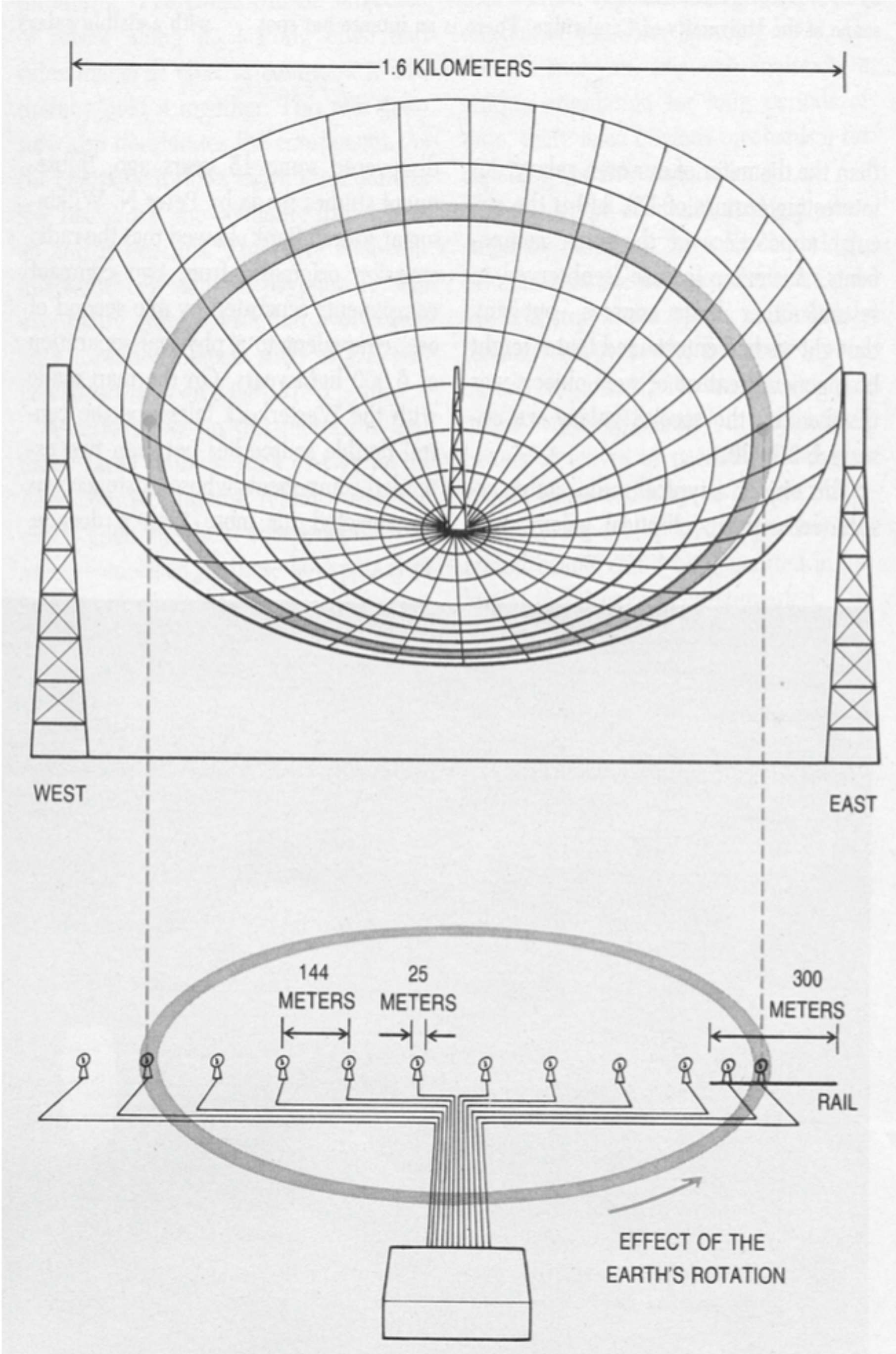
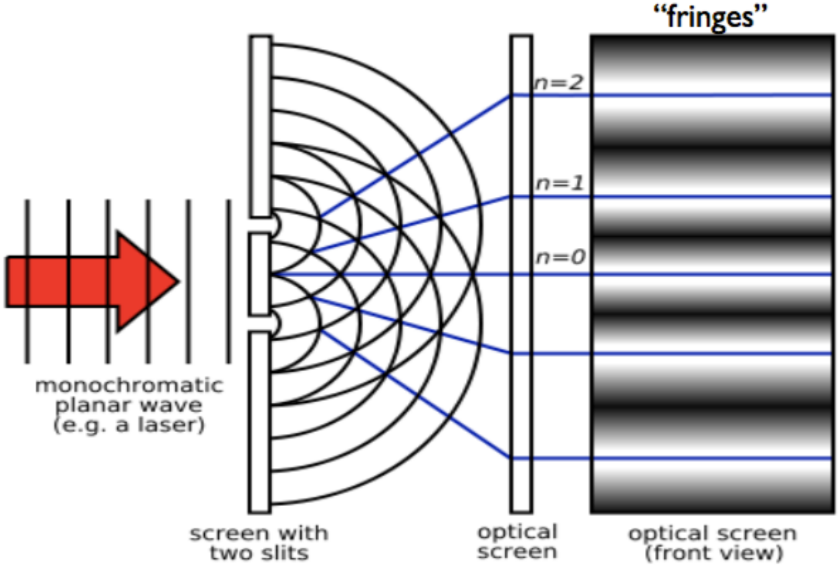


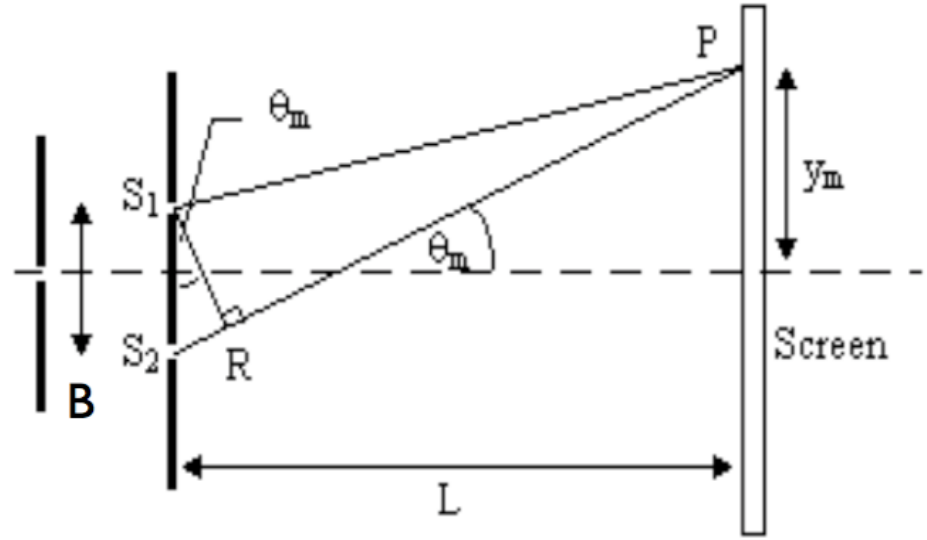
Instead, we use arrays of smaller dishes to achieve the same high angular resolution at radio frequencies

"Aperture Synthesis"

This is interferometry!

What is an interferometer?





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

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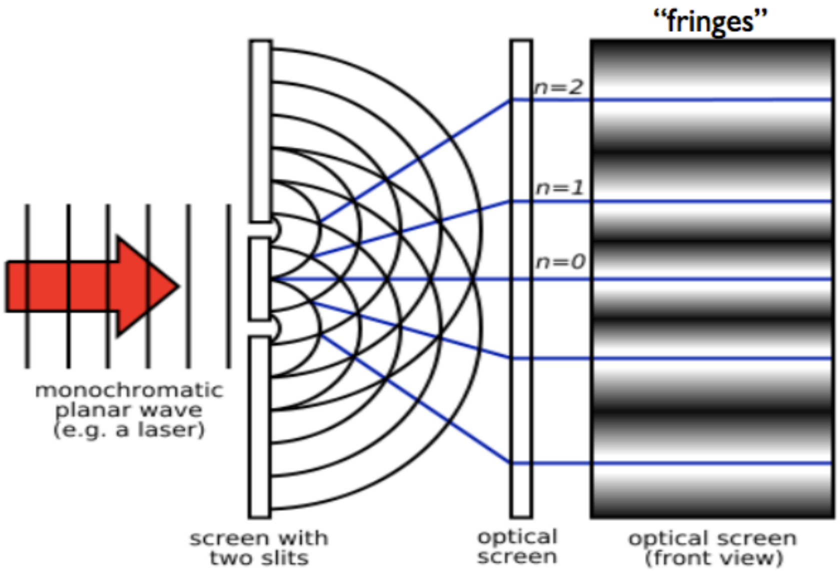
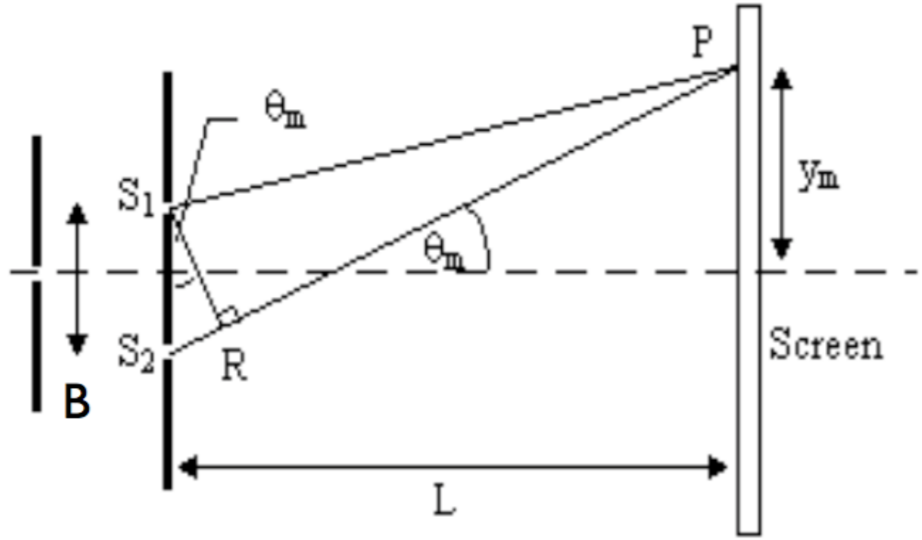
What is an interferometer?





$$B sin(\theta) = m\lambda$$ where m is any +ve or -ve integer

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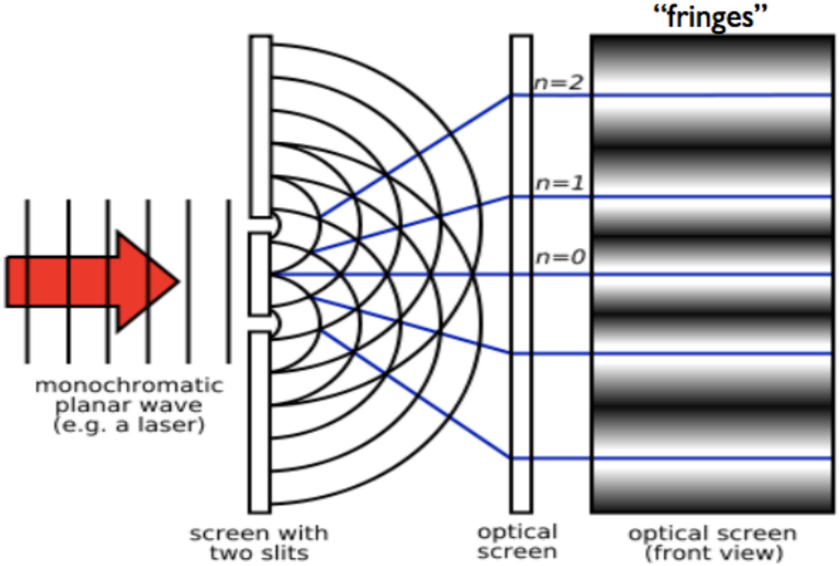

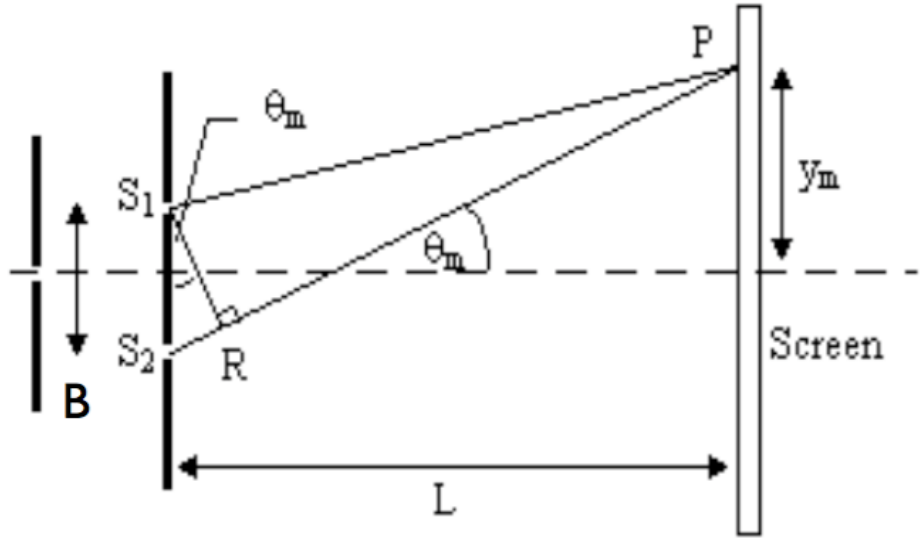

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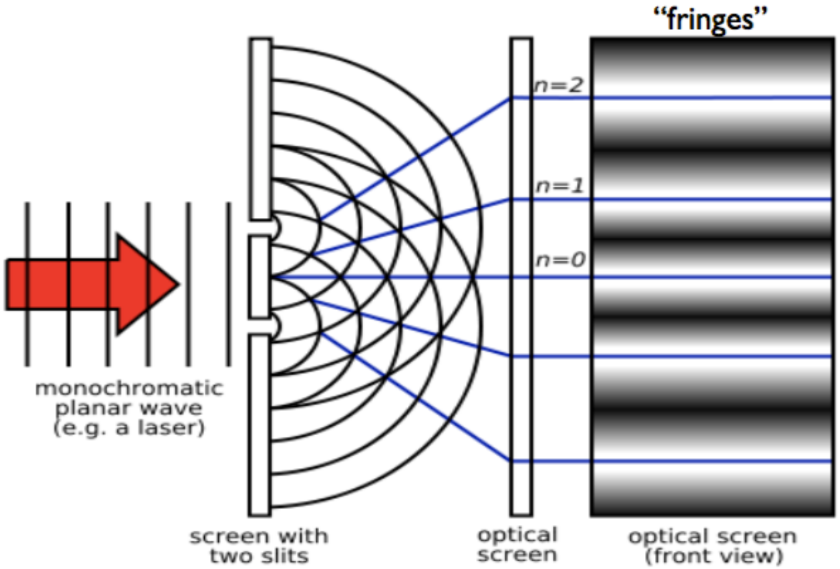
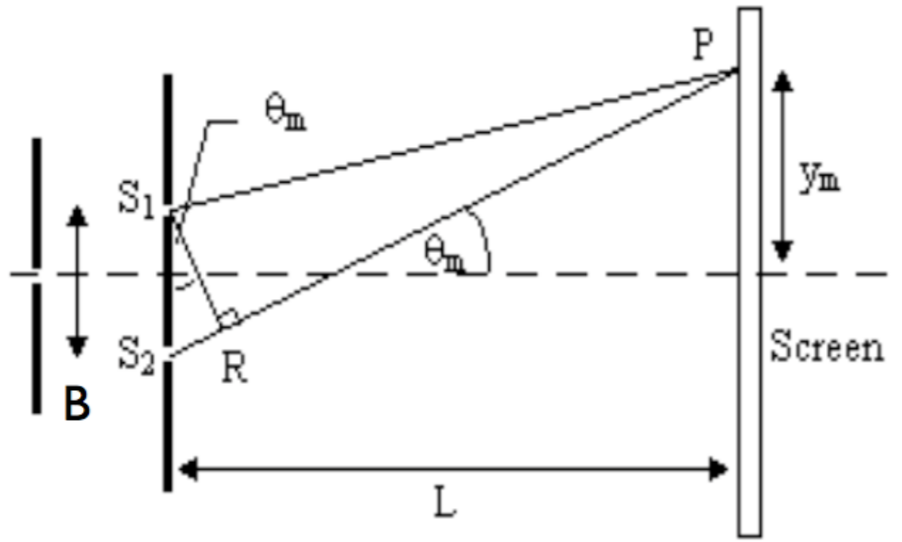
Space between two consecutive constructive interference

$$\Delta y = \frac{\lambda L}{B}$$

$$\theta \sim \frac{\lambda}{B}$$

What is an interferometer?





$$B sin(\theta) = m\lambda$$ where m is any +ve or -ve integer

Space between two consecutive constructive interference

$$\Delta y = \frac{\lambda L}{B} \Rightarrow \theta \sim \frac{\lambda}{B}$$

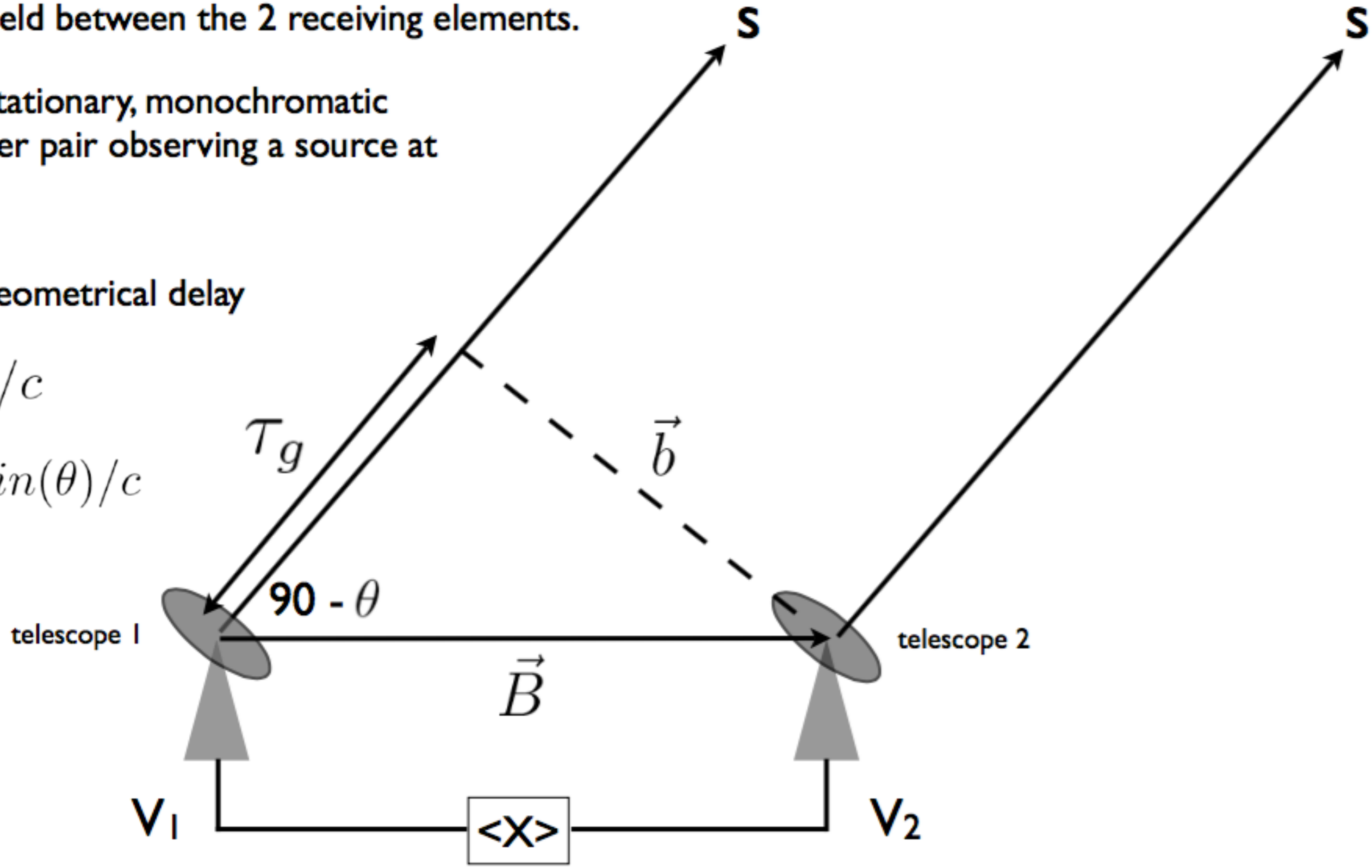
A radio interferometer measures the coherence of the electric field between the 2 receiving elements.

Consider a stationary, monochromatic interferometer pair observing a source at infinity.

τ_g is the geometrical delay

$$\tau_g = \vec{B}.\hat{s}/c$$

$$|\tau_g| = Bsin(\theta)/c$$



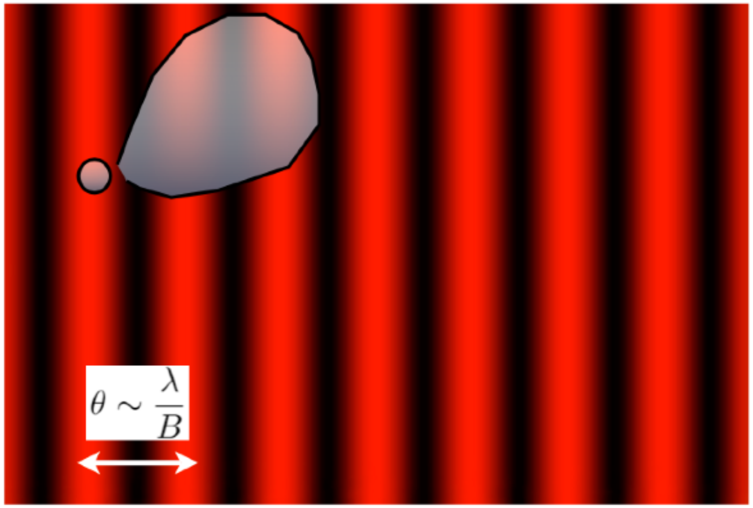
Correlator - multiplies signal and averages

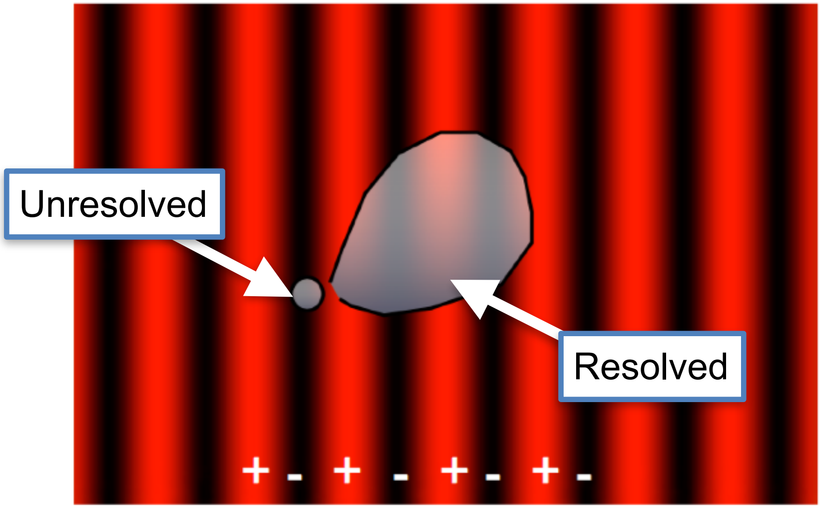
$$m\lambda = Bsin(\theta)$$ where m is a +ve or -ve integer:

Analogous to the Young's two slit experiment!

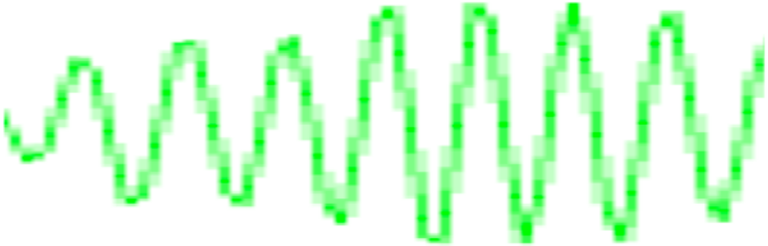
We can imagine that a radio interferometer casts fringes on the sky.

Consider a fixed 2-element interferometer orientated east-west and pointing at one particular position on the sky:

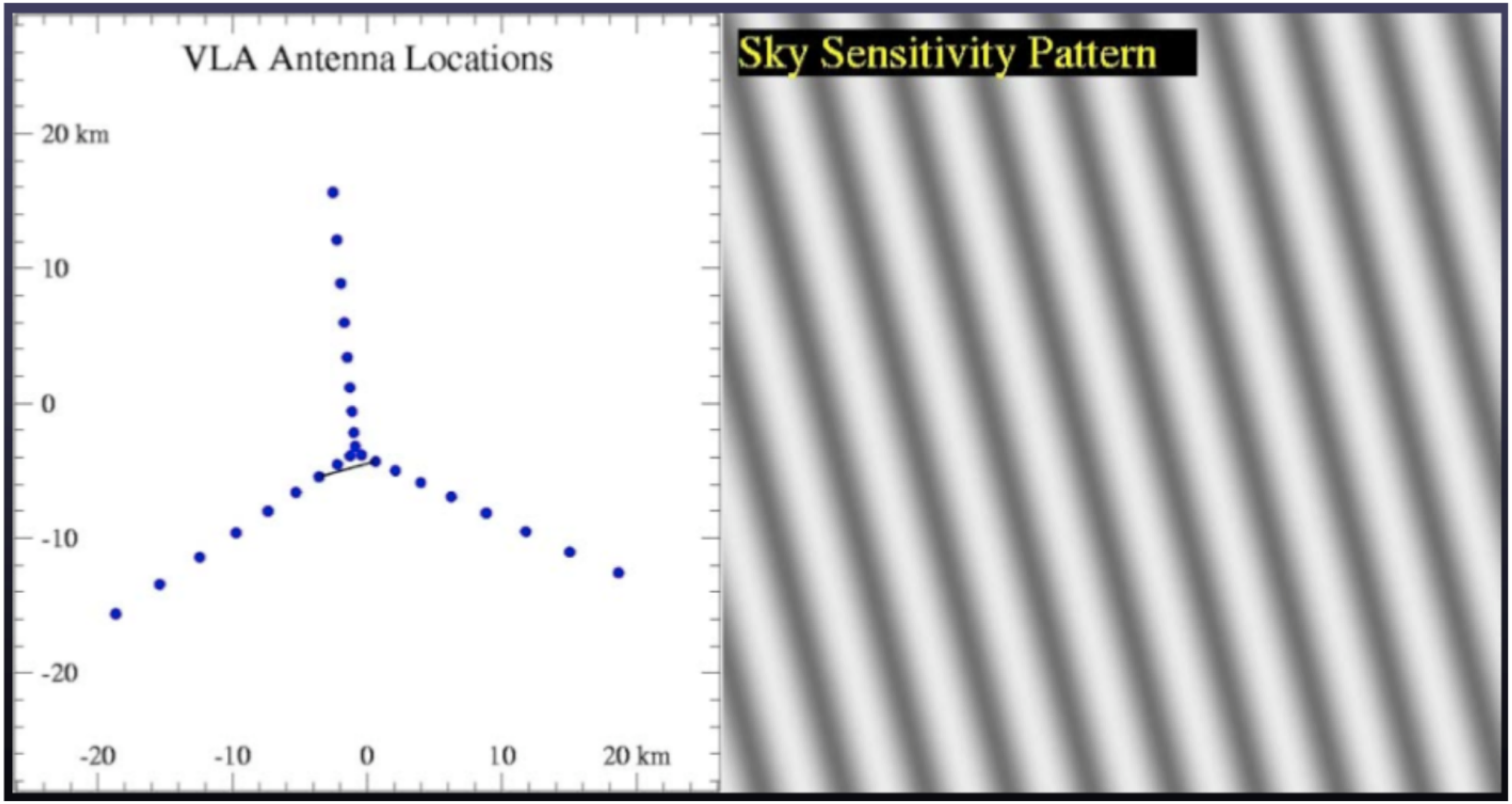




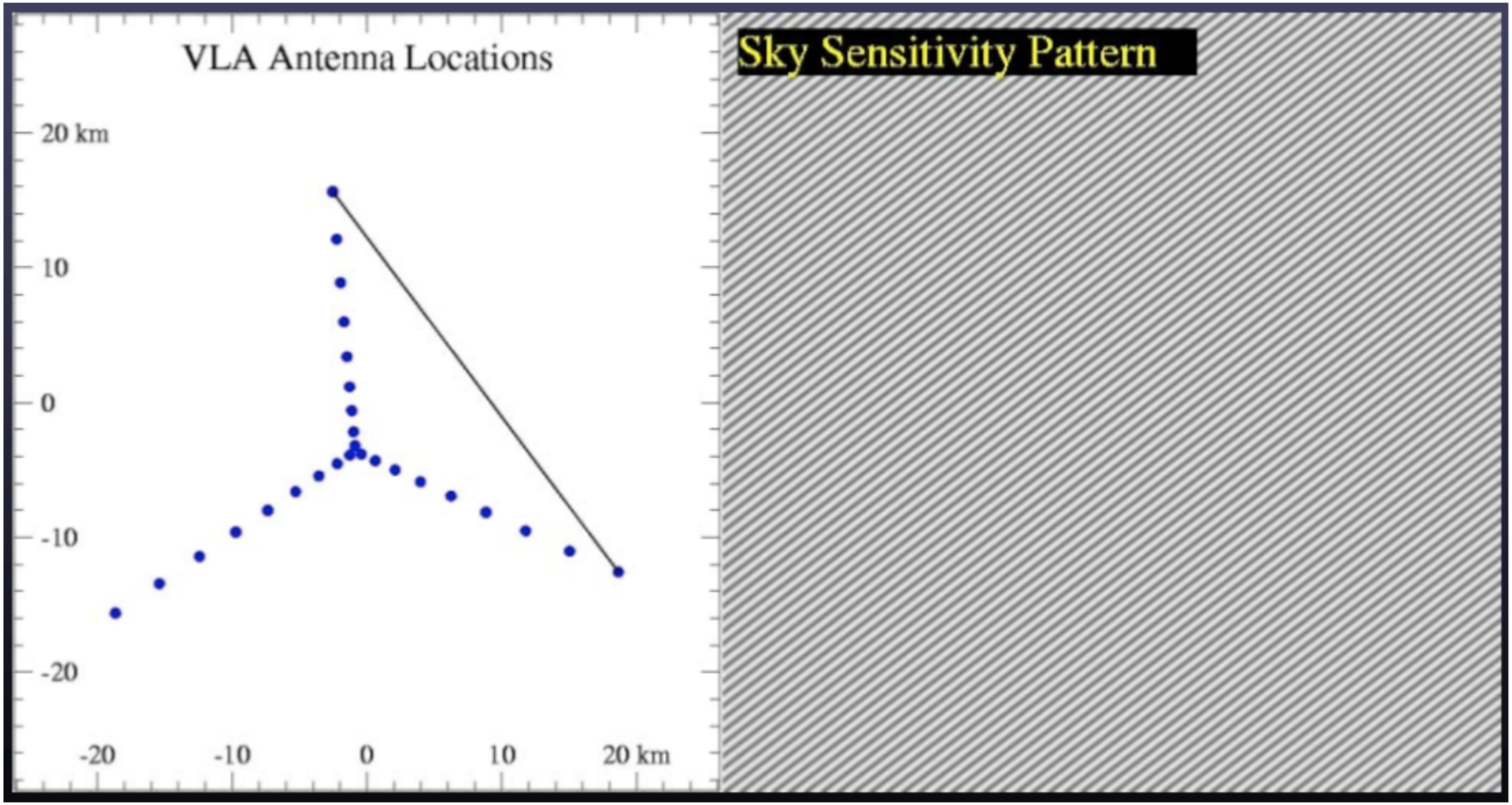
The Earth's rotation moves the source across the sky with the output of the interferometer depending on the alignment between the source structure and the fringes at any given time.

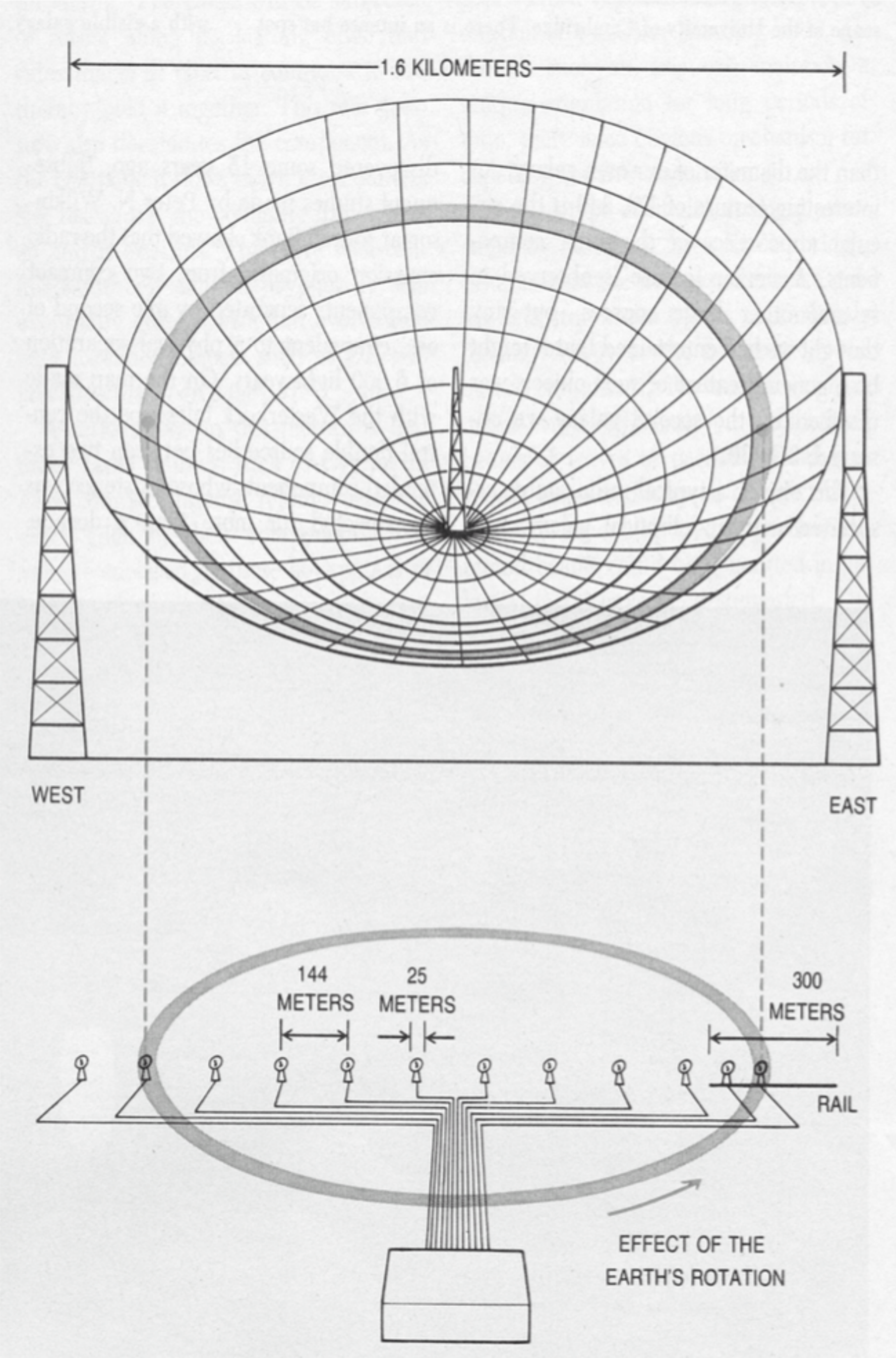


Fringes projected on the sky produced by short VLA baseline



Fringes projected on the sky produced by long VLA baseline





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

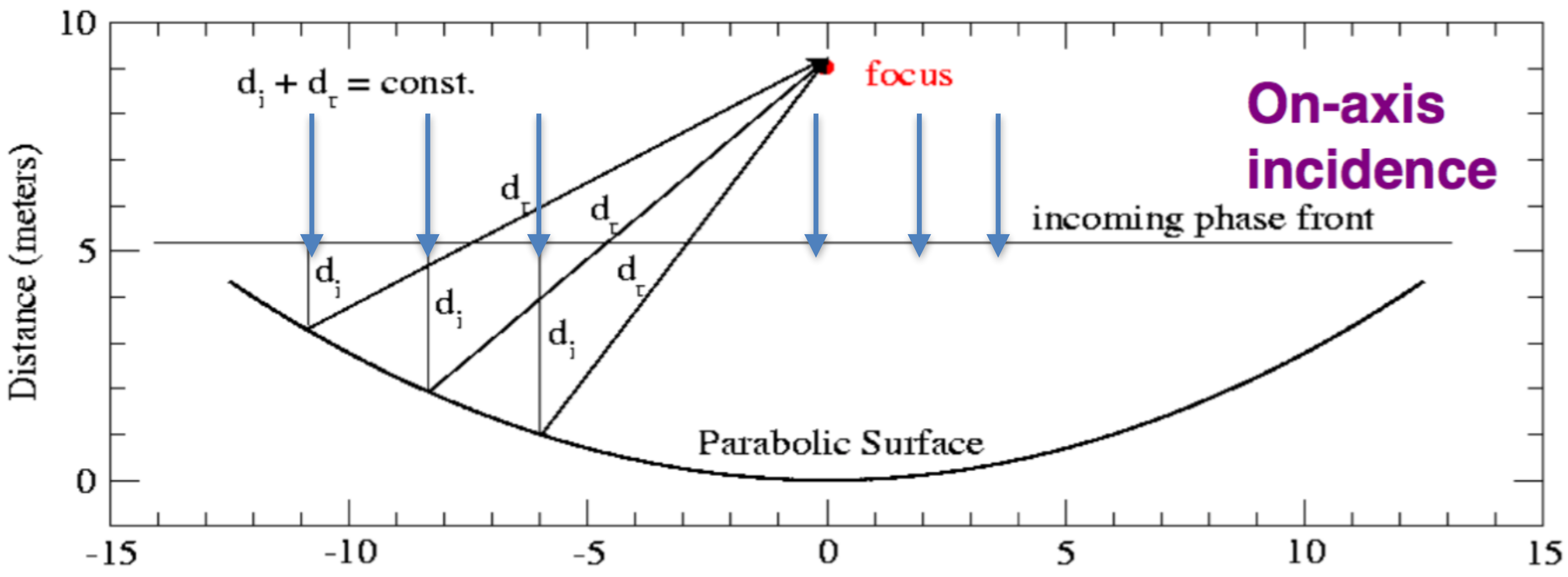
"Aperture Synthesis"

This is interferometry!

Aperture Synthesis

The methodology of synthesizing a continuous aperture through summations of separated pairs of antennas is called 'aperture synthesis'.

Distance from incoming phase front to focal point is the same for all the arrays. The E-fields will be in phase at the focus.



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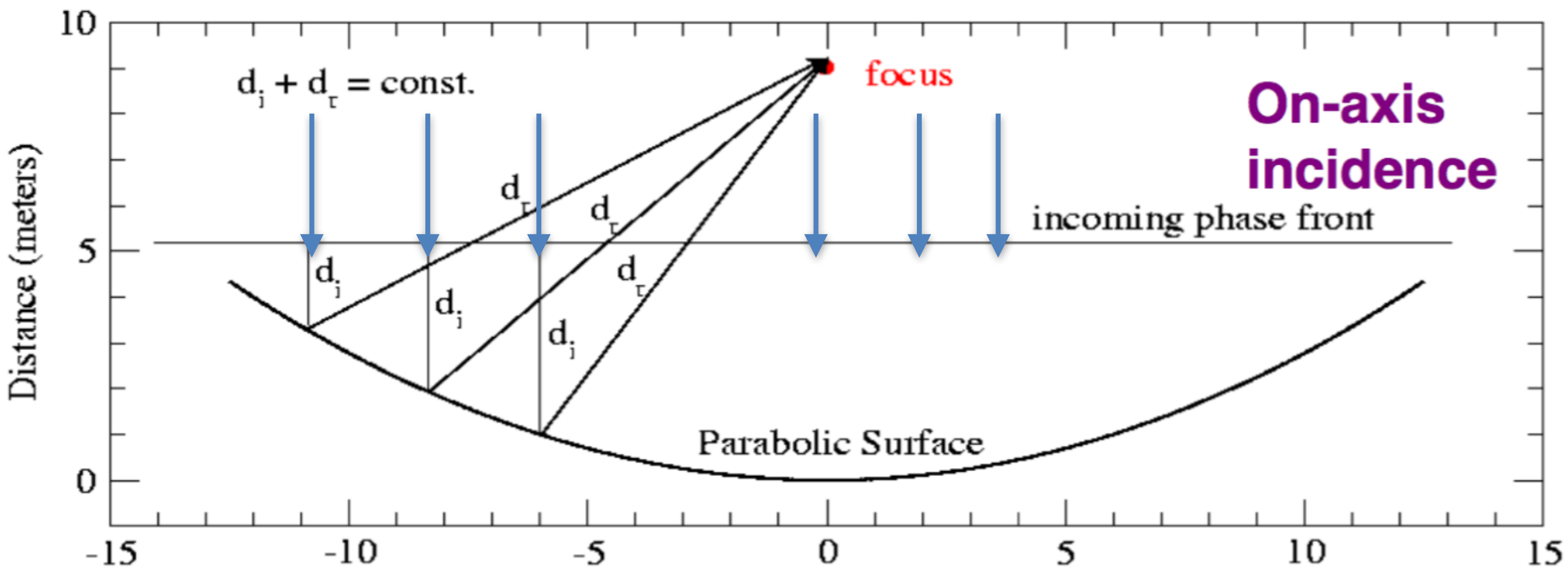
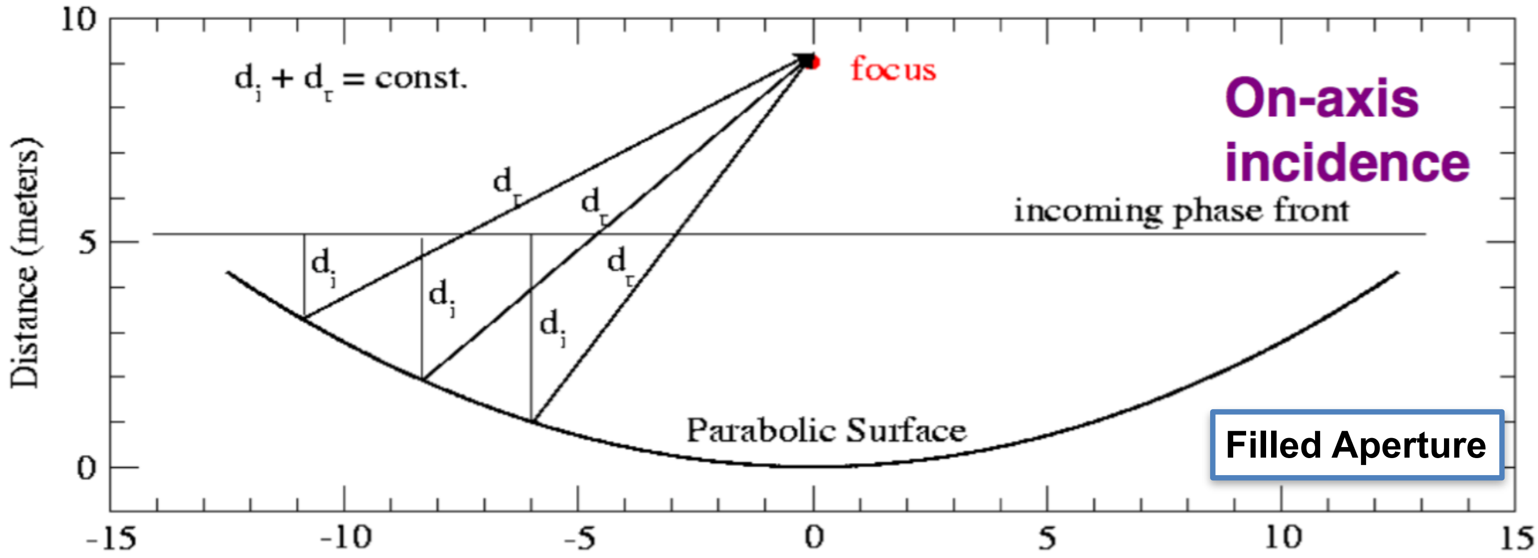
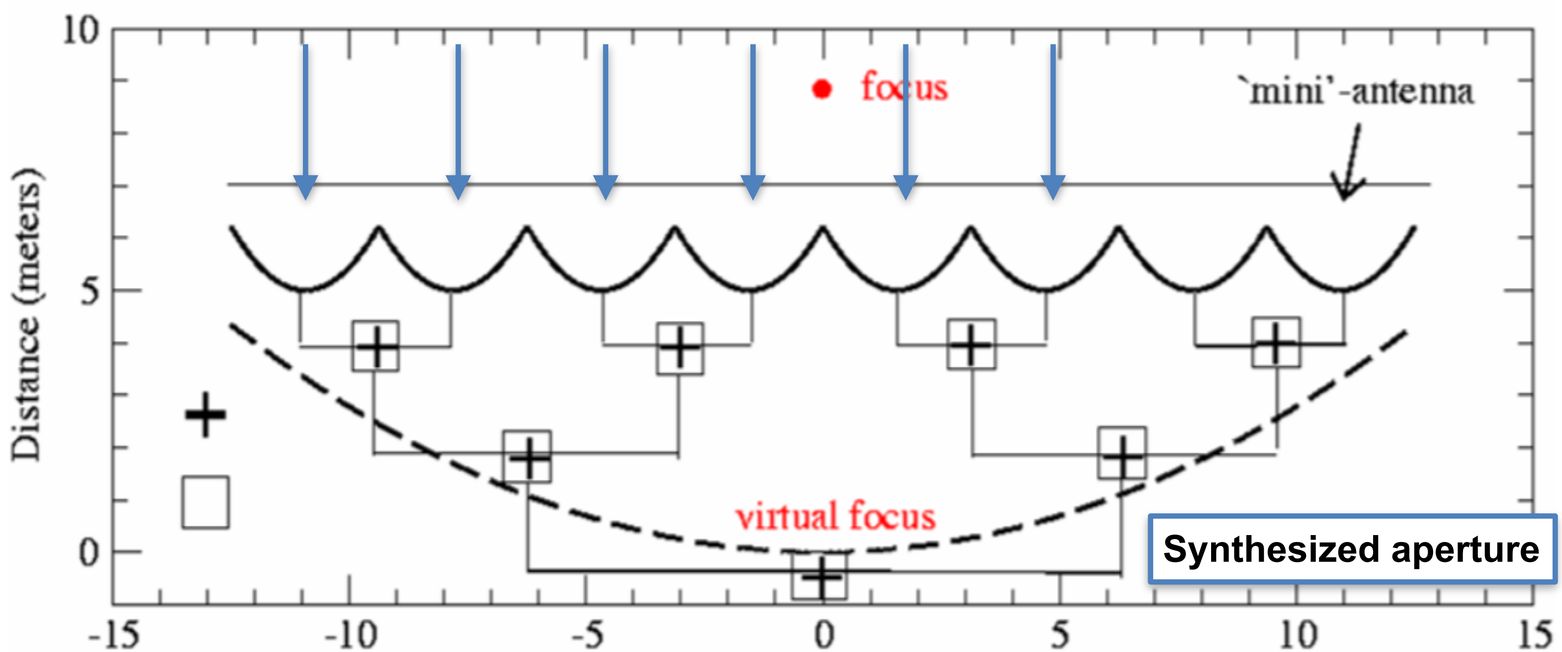
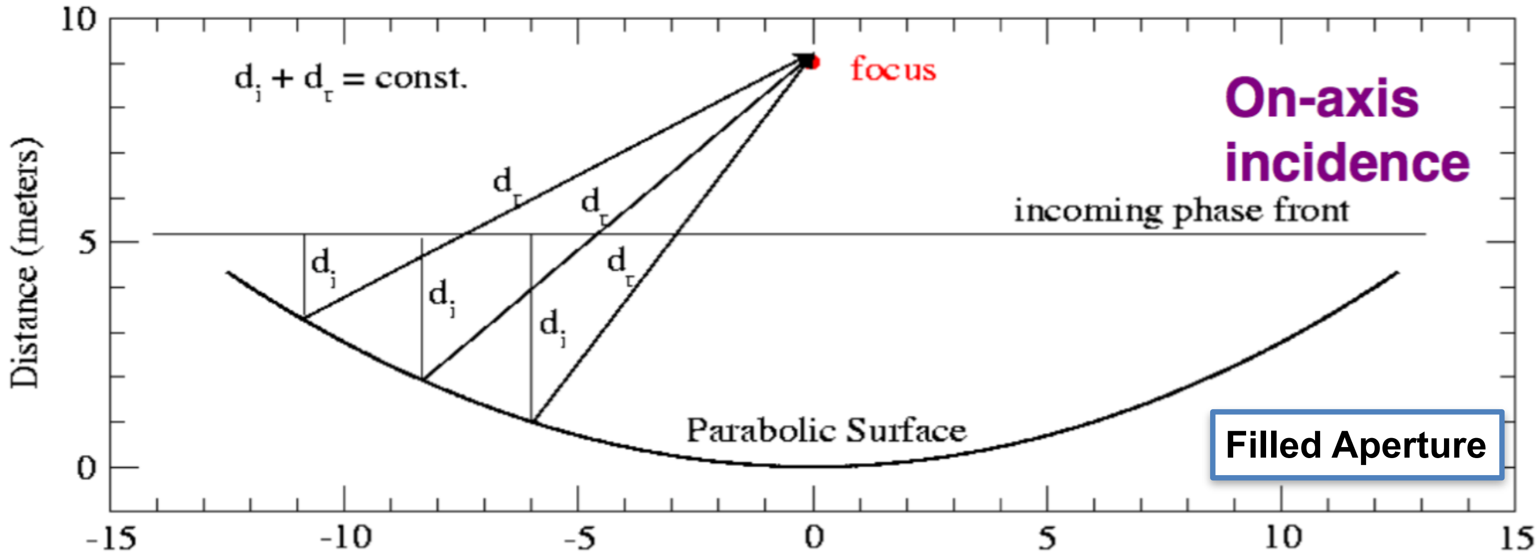




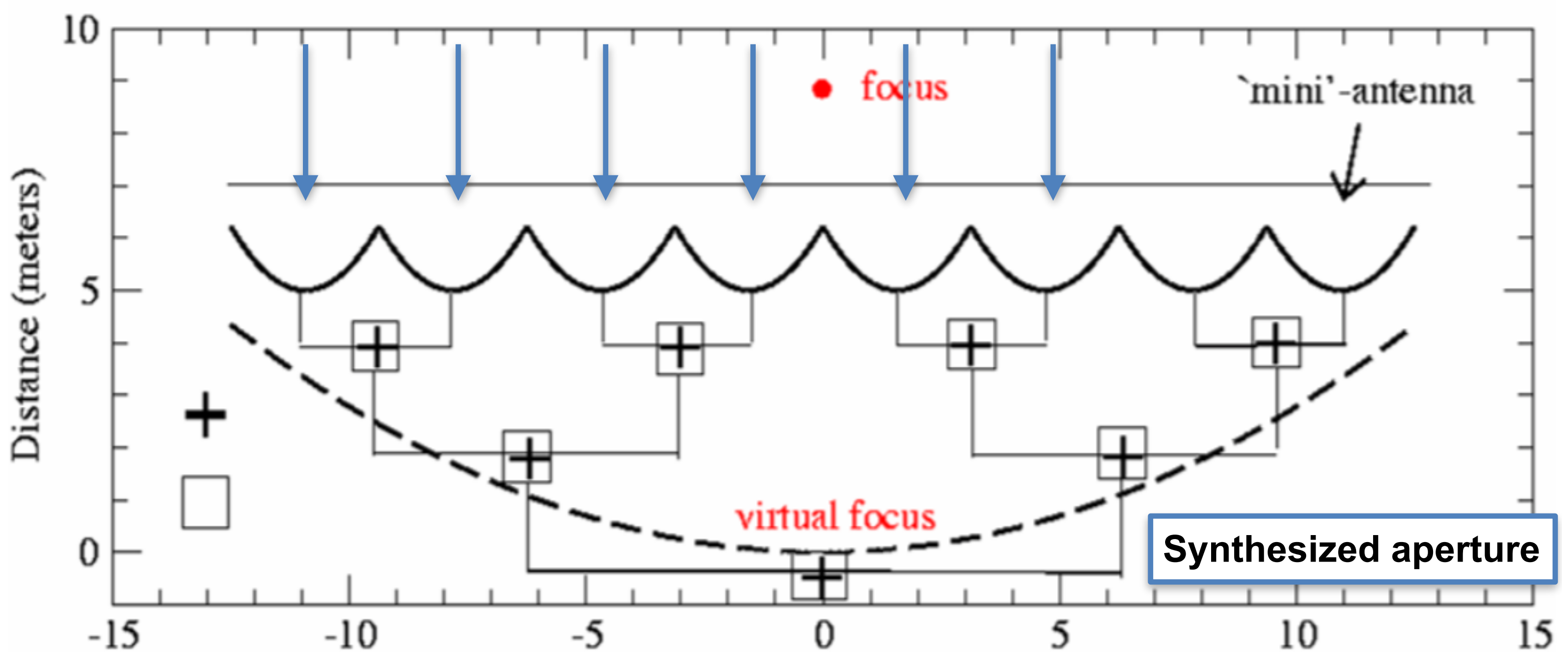
Distance (meters)
$d_i + d_r$ = const.
focus
On-axis incidence
incoming phase front
Parabolic Surface
Filled Aperture



Distance (meters)
focus
`mini'-antenna
virtual focus
Synthesized aperture



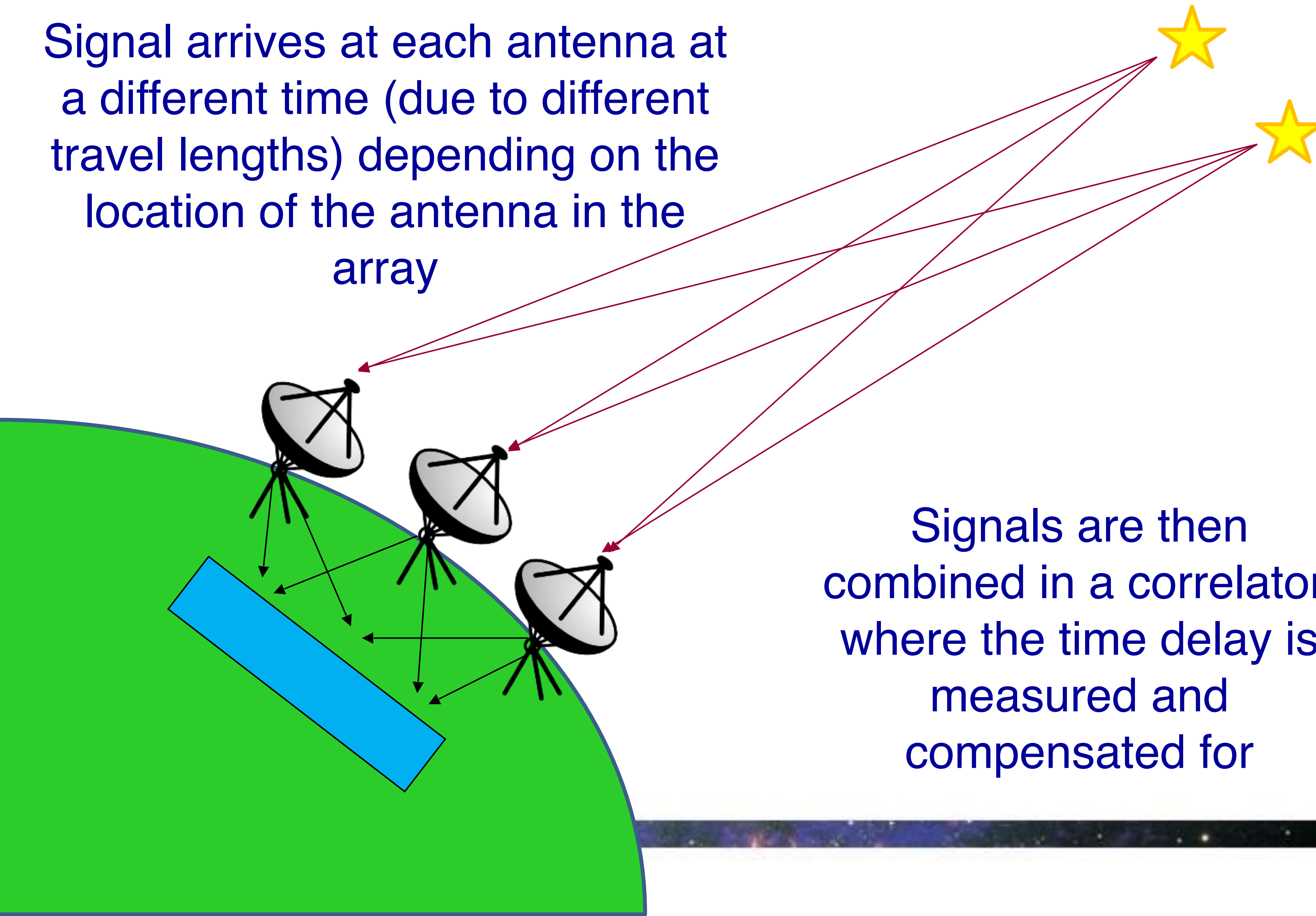
On-axis incidence
$d_i + d_r$ = const.
focus
incoming phase front
Parabolic Surface
Distance (meters)
Filled Aperture



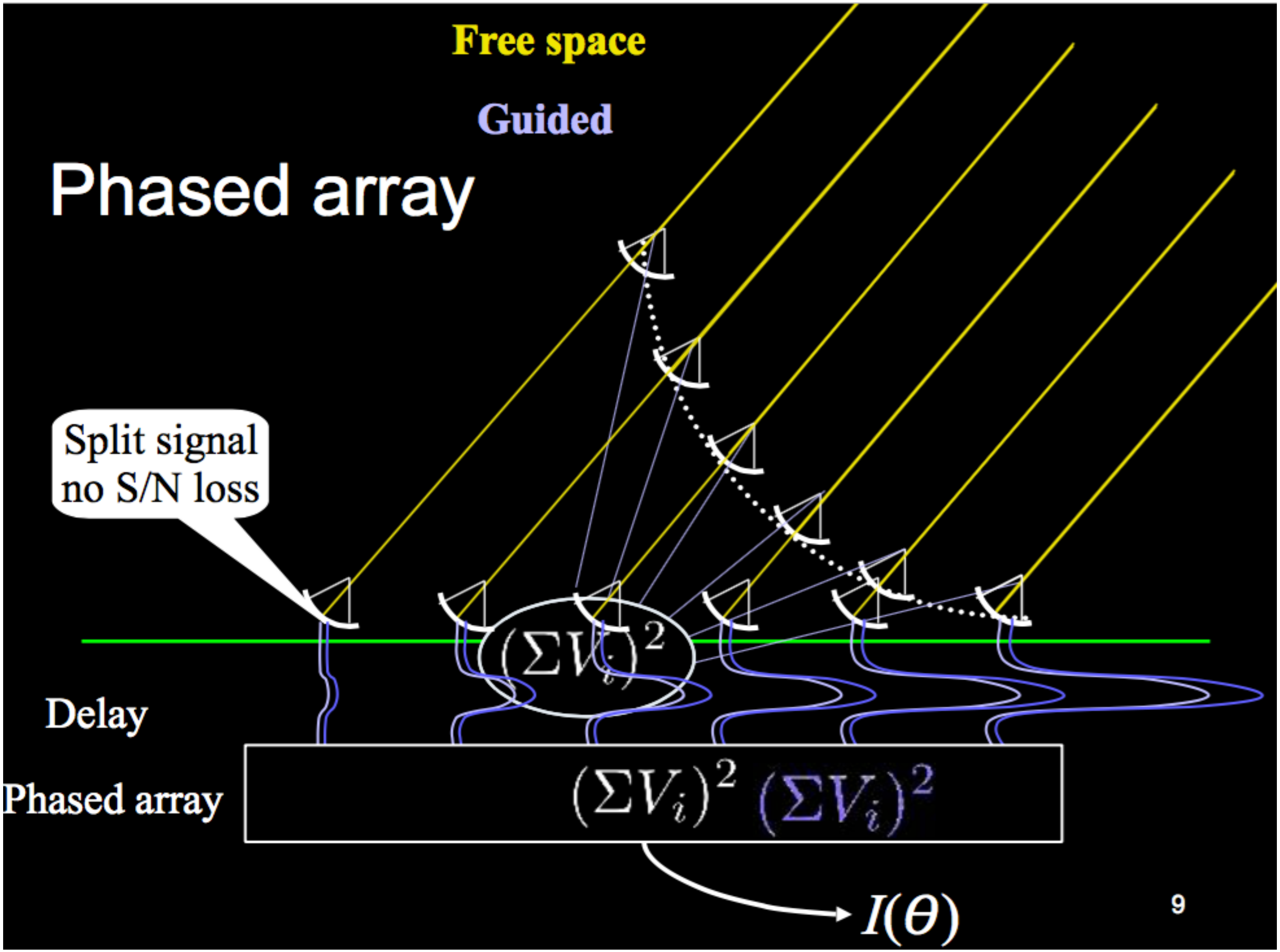
focus
`mini'-antenna
virtual focus
Distance (meters)
Synthesized aperture

How Do We Use Interferometry?

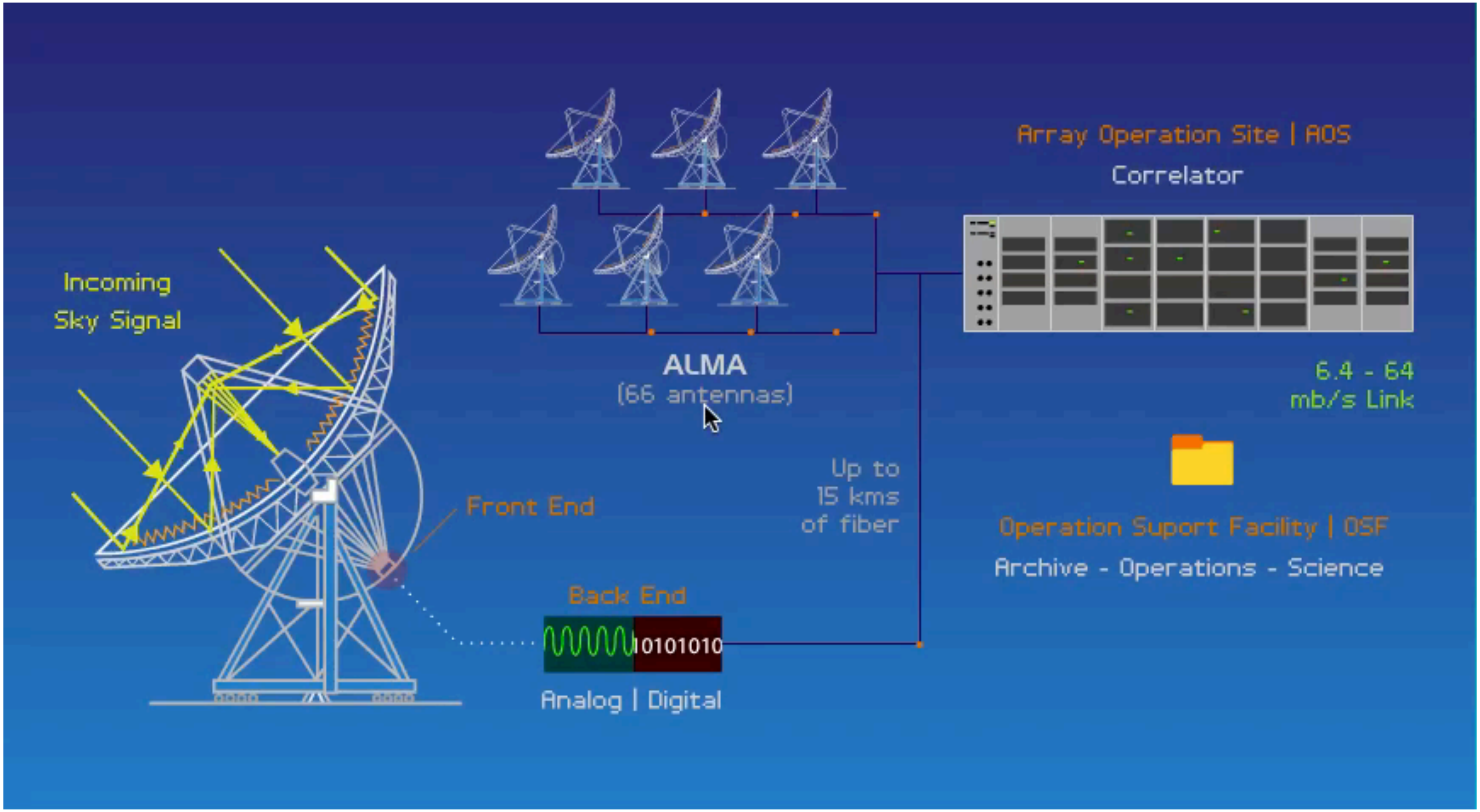
Signal arrives at each antenna at a different time (due to different travel lengths) depending on the location of the antenna in the array



Signals are then combined in a correlator, where the time delay is measured and compensated for


Free space
Guided
Phased array
Split signal
no S/N loss
$(\Sigma V_i)^2$
Delay
Phased array
$(\Sigma V_i)^2$ $(\Sigma V_i)^2$
$I(\theta)$

An Interferometer In Action



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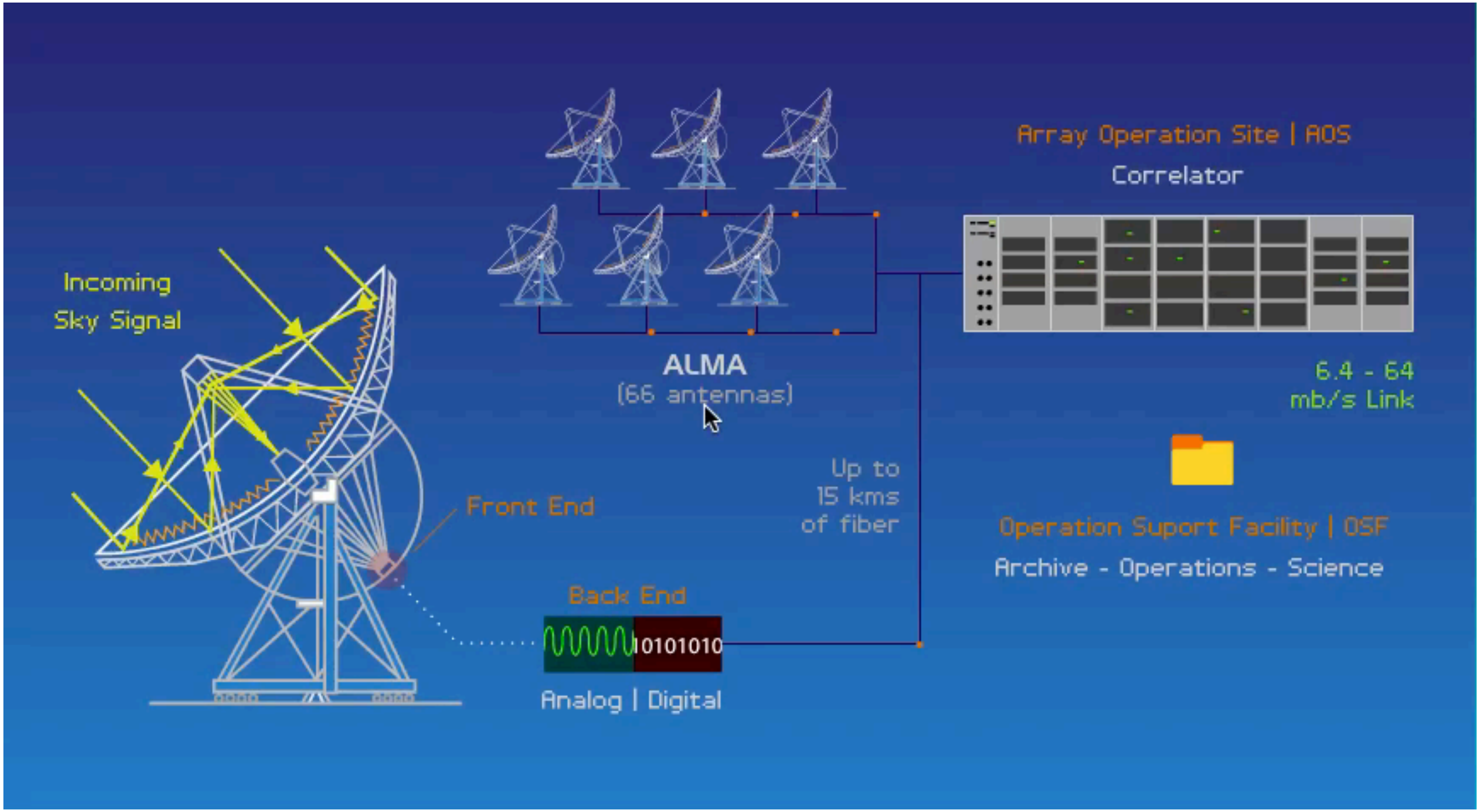

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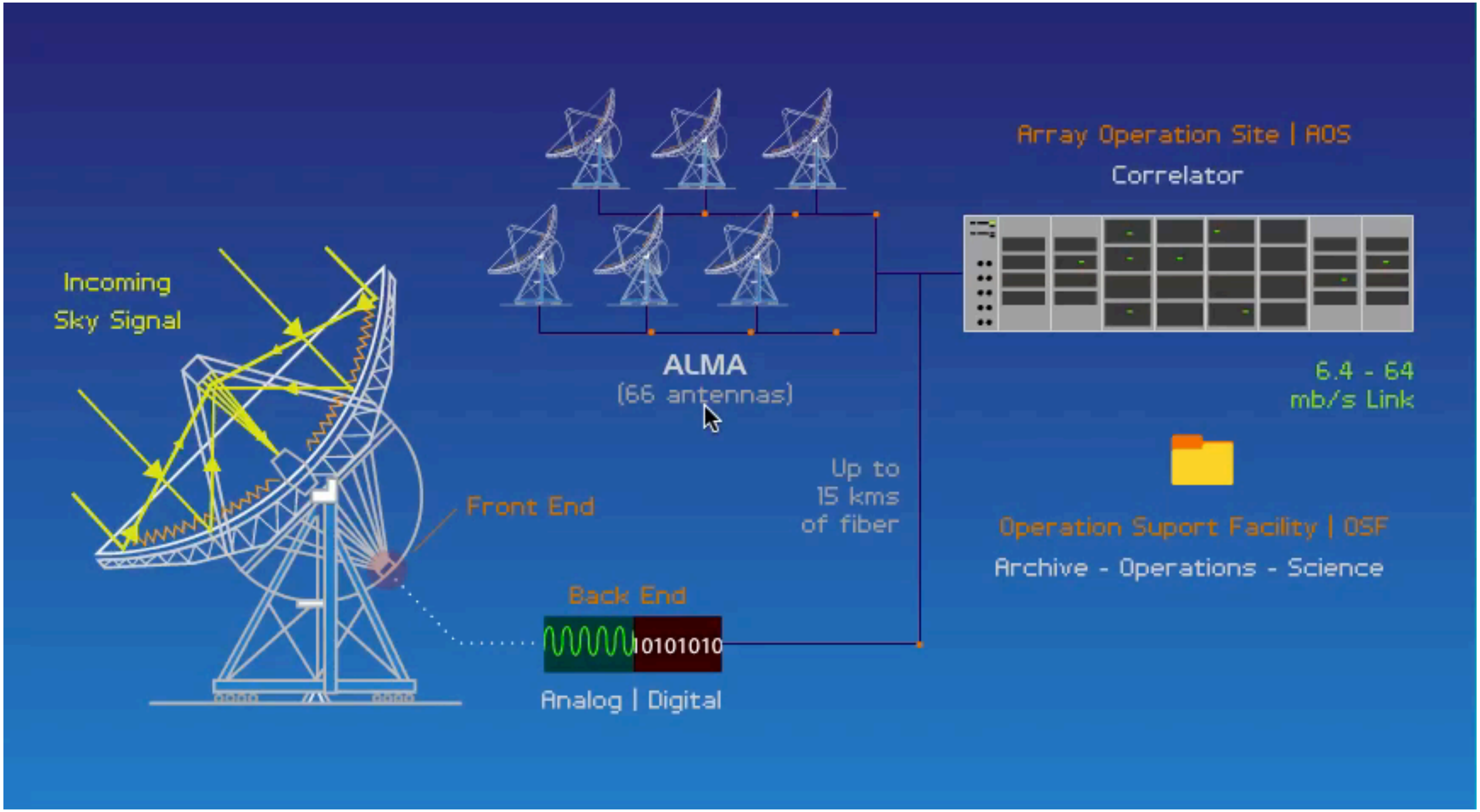


What have we learnt so far?

1. **Angular resolution for most telescopes is ~ λ/D**
   D is the diameter of the telescope and λ is the wavelength of observation

2. **For radio waves, we need km-size dishes in order to get similar angular resolution images. Technically difficult.**

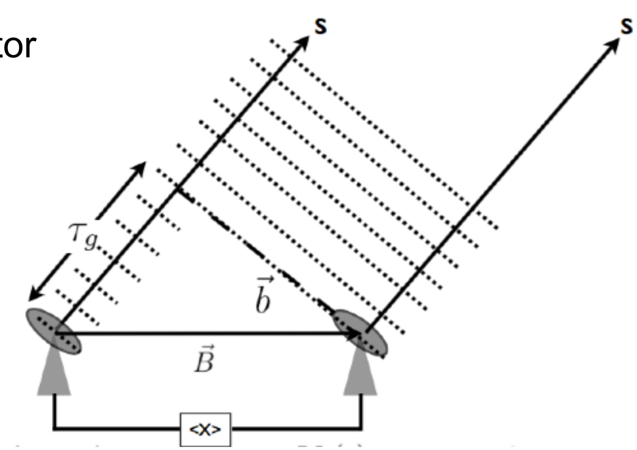
3. **Analogous to the double slit experiment, two antennas response can be seen as fringes in the sky.** Sources smaller than ~ λ/B are unresolved.

4. **Aperture Synthesize is a technique that allows us to use the correlated signal of smaller dishes in order to "synthesize" apertures much larger than can be constructed as a filled aperture, giving very good spatial resolution.**

Let's back to the two element interferometer:

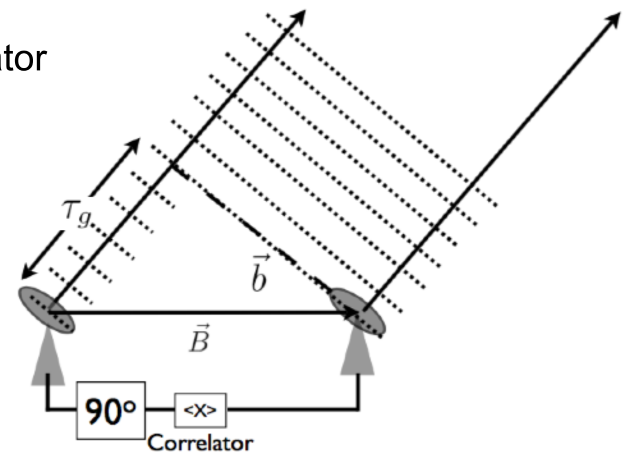
Cosine correlator

$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$



$V_1(t) = v_1 \cos 2\pi\nu(t - \tau_g)$ Correlator $V_2(t) = v_2 \cos 2\pi\nu t$

Sine correlator



$V_1(t) = v_1 \cos 2\pi\nu(t - \tau_g - \pi/2)$ $V_2(t) = v_2 \cos 2\pi\nu t$

$$r(\tau_g) =< V_1 V_2 >= \frac{1}{2} V^2 (\cos(2\pi\nu\tau_g))$$

Complex correlator

$$r_{sin}(\tau_g) = \frac{1}{2} V^2 \sin(2\pi\nu\tau_g)$$

Both, cosine and sine correlations are needed to recover the flux density of the source

We define the complex visibility

$$V = R_C - iR_S = Ae^{-i\phi}$$

$$A = \sqrt{R_C^2 + R_S^2}$$

$$\phi = \tan^{-1}\left(\frac{R_S}{R_C}\right)$$

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If we integrate over an extended source:

Visibility

$$V_\upsilon(\mathbf{b}) = R_C - iR_S = \iint I_\nu(s)\, e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c}\, d\Omega$$

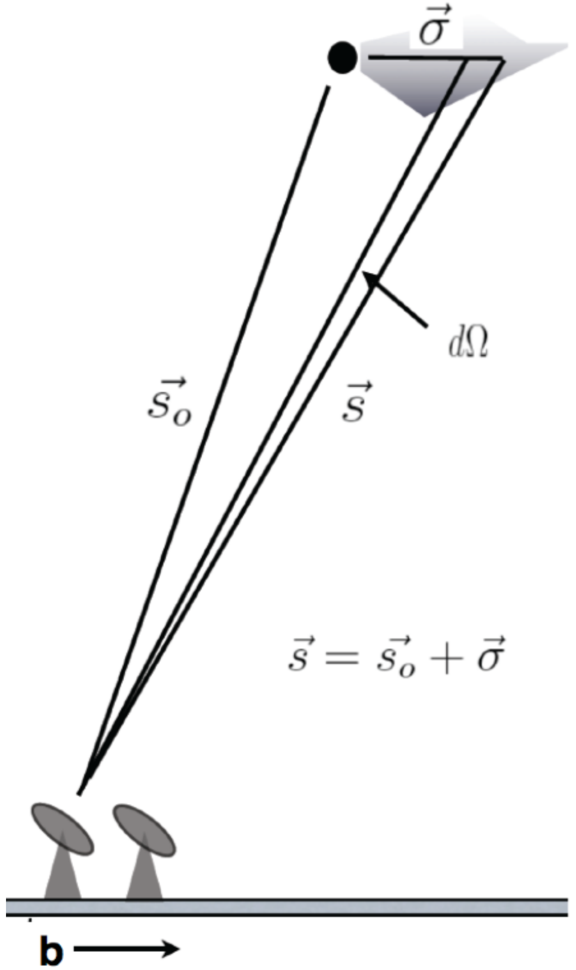
$\mathbf{s_o}$ = phase tracking center

$\boldsymbol{\sigma}$ = source spatial distribution

$\mathbf{s}$ = source direction
$= \mathbf{s_o} + \boldsymbol{\sigma}$

Delay $= \mathbf{b} \cdot \mathbf{s}$
$= \underbrace{\mathbf{b}\cdot\mathbf{s_o}} + \mathbf{b}\cdot\boldsymbol{\sigma}$

Geometric delay for phase center



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If we integrate over an extended source:

Total response obtained by integrating over solid angle subtended by the source

$$R_C(\mathbf{b}) = \int A(\boldsymbol{\sigma})\, I(\boldsymbol{\sigma})\, e^{-i2\pi \mathbf{b}\cdot\mathbf{s}/\lambda}\, d\Omega \qquad \mathbf{b}\cdot\mathbf{s} = \mathbf{b}\cdot\mathbf{s}_o + \mathbf{b}\cdot\boldsymbol{\sigma}$$

$$= \int A'(\boldsymbol{\sigma})\, I(\boldsymbol{\sigma})\, e^{-i2\pi \mathbf{b}\cdot\boldsymbol{\sigma}/\lambda}\, d\Omega \quad A_o\, e^{-i2\pi \mathbf{b}\cdot\mathbf{s}_o/\lambda}$$

$$\equiv V(\mathbf{b}) = \text{visibility function}$$

We have introduce the beam pattern response of the antenna $A'(\vec{\sigma})$ into the equation

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image plane

orthogonal coordinates in plane of sky (direction cosines)

l : east-west

m: north-south

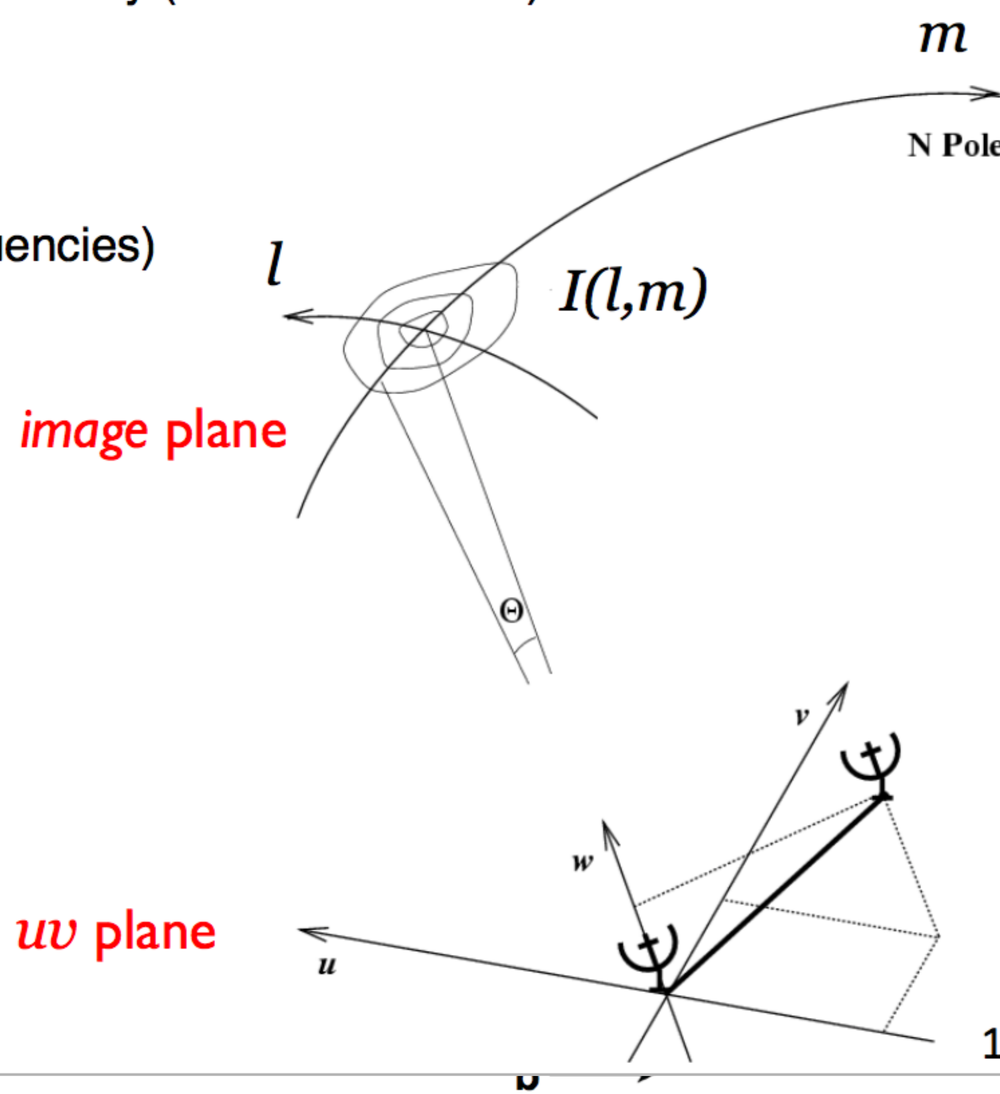
uv plane

array coordinates (spatial frequencies)

u: east-west

v: north-south

w: towards the source



Finally!

van Cittert - Zernicke relation

$$\mathcal{V}(u,v) = \iint I(l,m) e^{-2\pi i(ul+vm)} dl\,dm$$

$$I(l,m) = \iint \mathcal{V}(u,v) e^{2\pi i(ul+vm)} du\,dv$$

$I(l,m)$ can be recovered from $V(u,v)$ via Fourier Transform

$V(u,v)$ expressed as (real, imaginary) or (amplitude, phase)

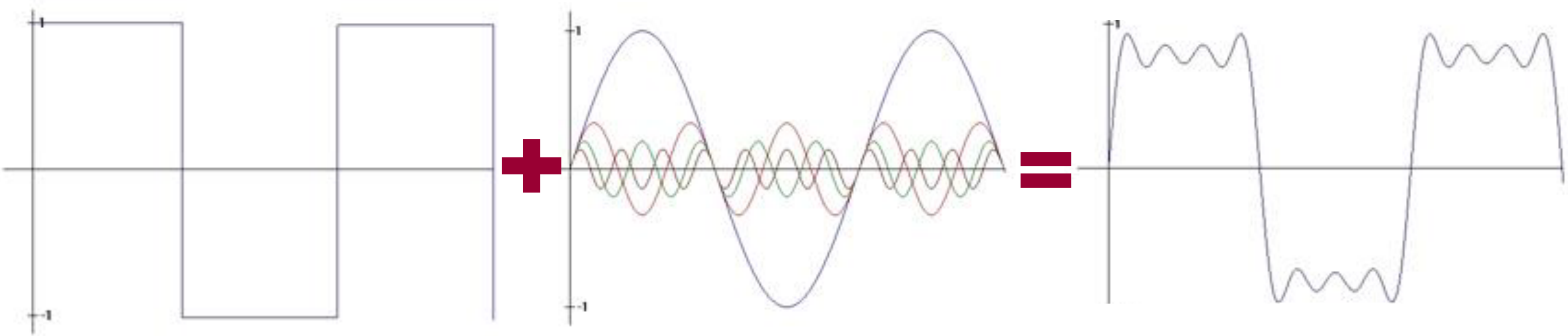
$$A = \sqrt{\Re^2 + \Im^2}$$

$$\phi = \tan^{-1}\left(\frac{\Im}{\Re}\right)$$

$\Im$

Introducing 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 & signal

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

What Are Visibilities?

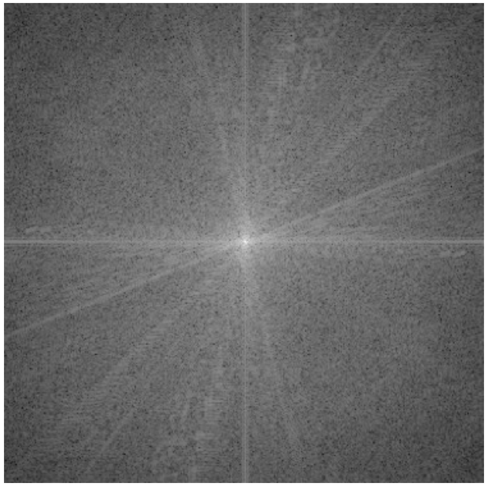
Each V(u,v) contains information on I(x,y) everywhere

Each V(u,v) is a complex quantity

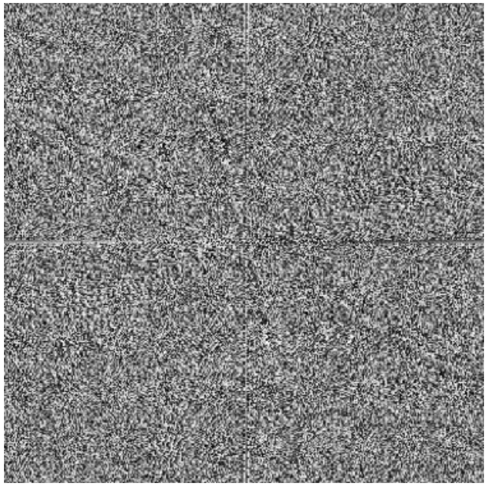
Expressed as (real, imaginary) or (amplitude, phase)

I(x,y)

FT →

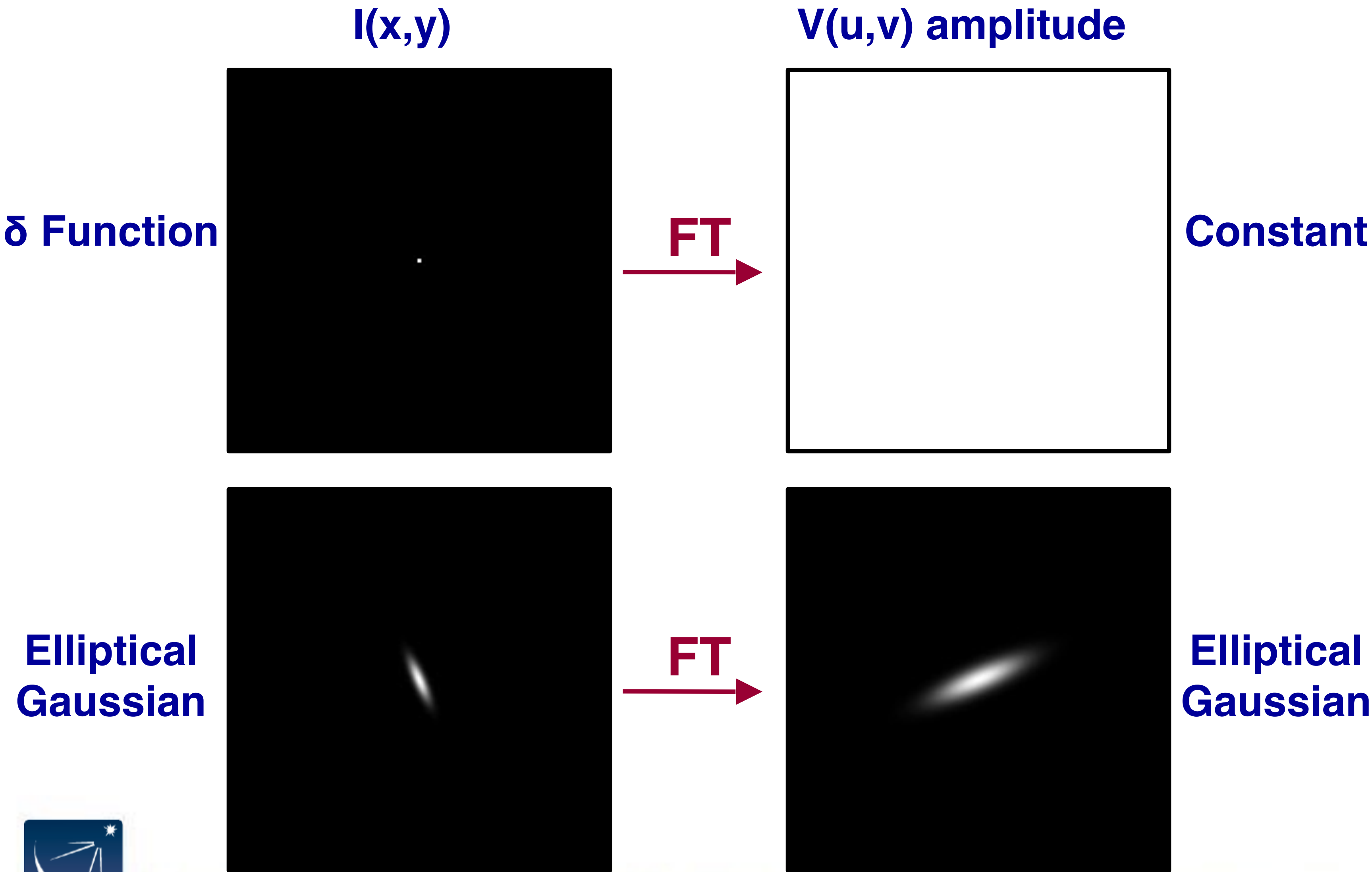


V(u,v) amplitude

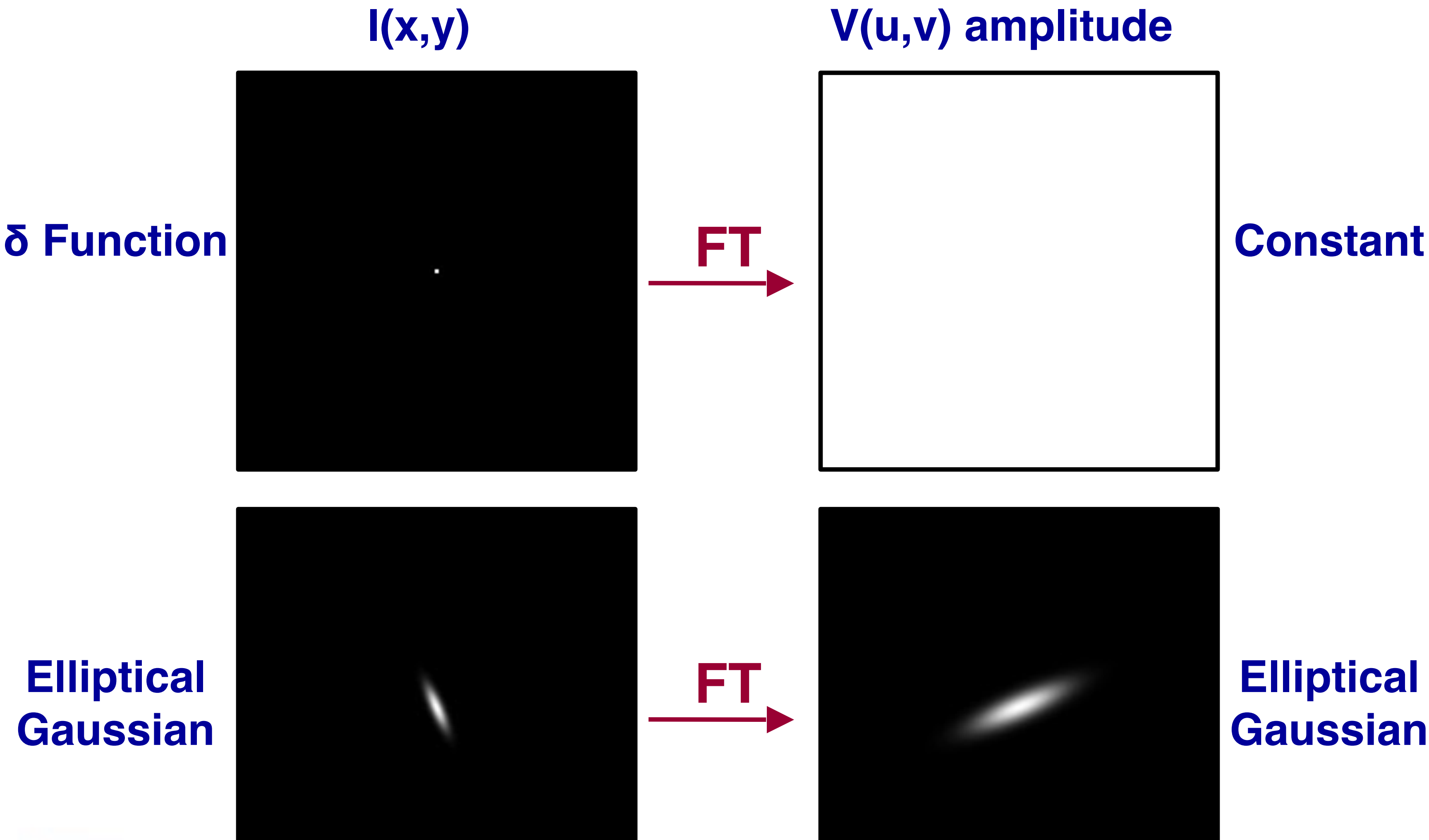


V(u,v) phase

Examples of 2D Fourier Transforms



Examples of 2D Fourier Transforms



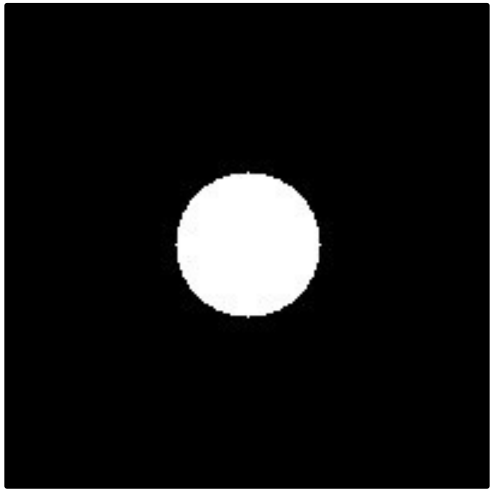
Rules of the Fourier Transform:

Narrow features transform to wide features (and vice versa)

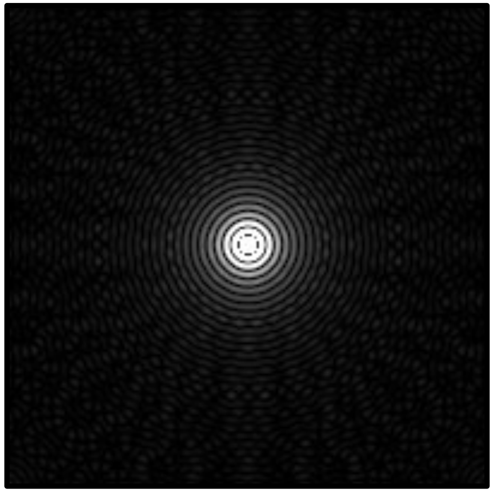
Examples of 2D Fourier Transforms

I(x,y) | **V(u,v) amplitude**

Uniform Disk

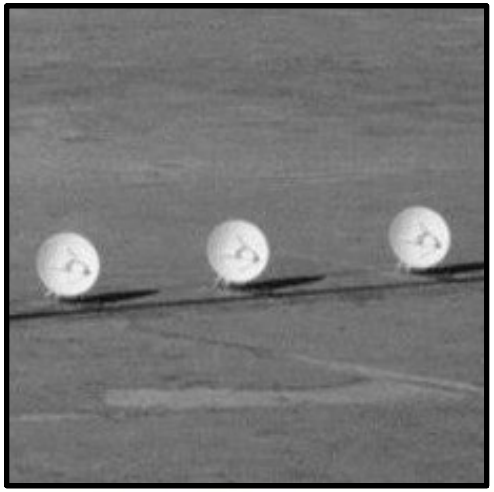


FT →

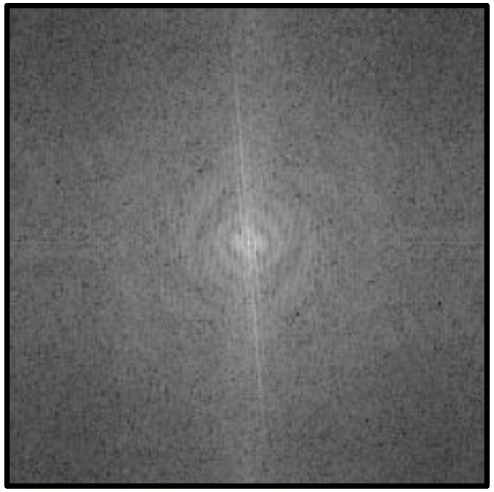


Bessel Function

VLA Antennas



FT →

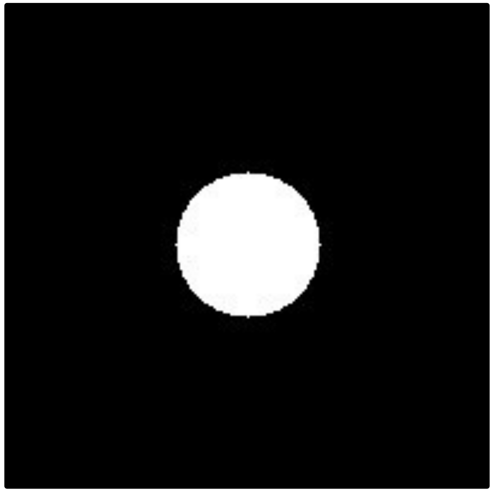


Bessel Function!

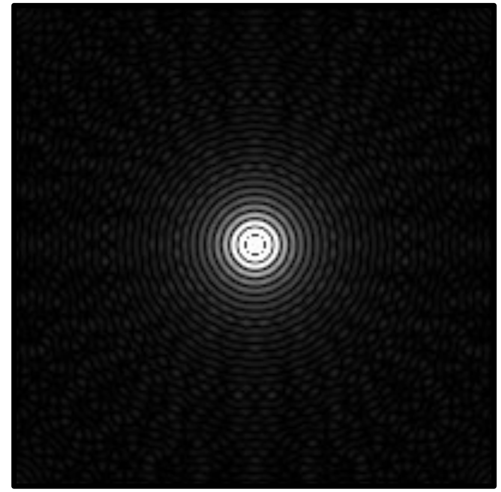
Examples of 2D Fourier Transforms

I(x,y) | V(u,v) amplitude

Uniform Disk

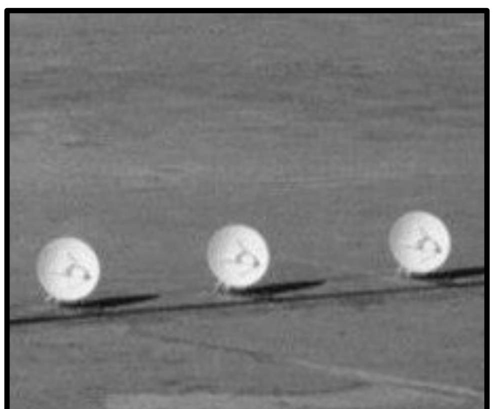


FT →



Bessel Function

VLA Antennas



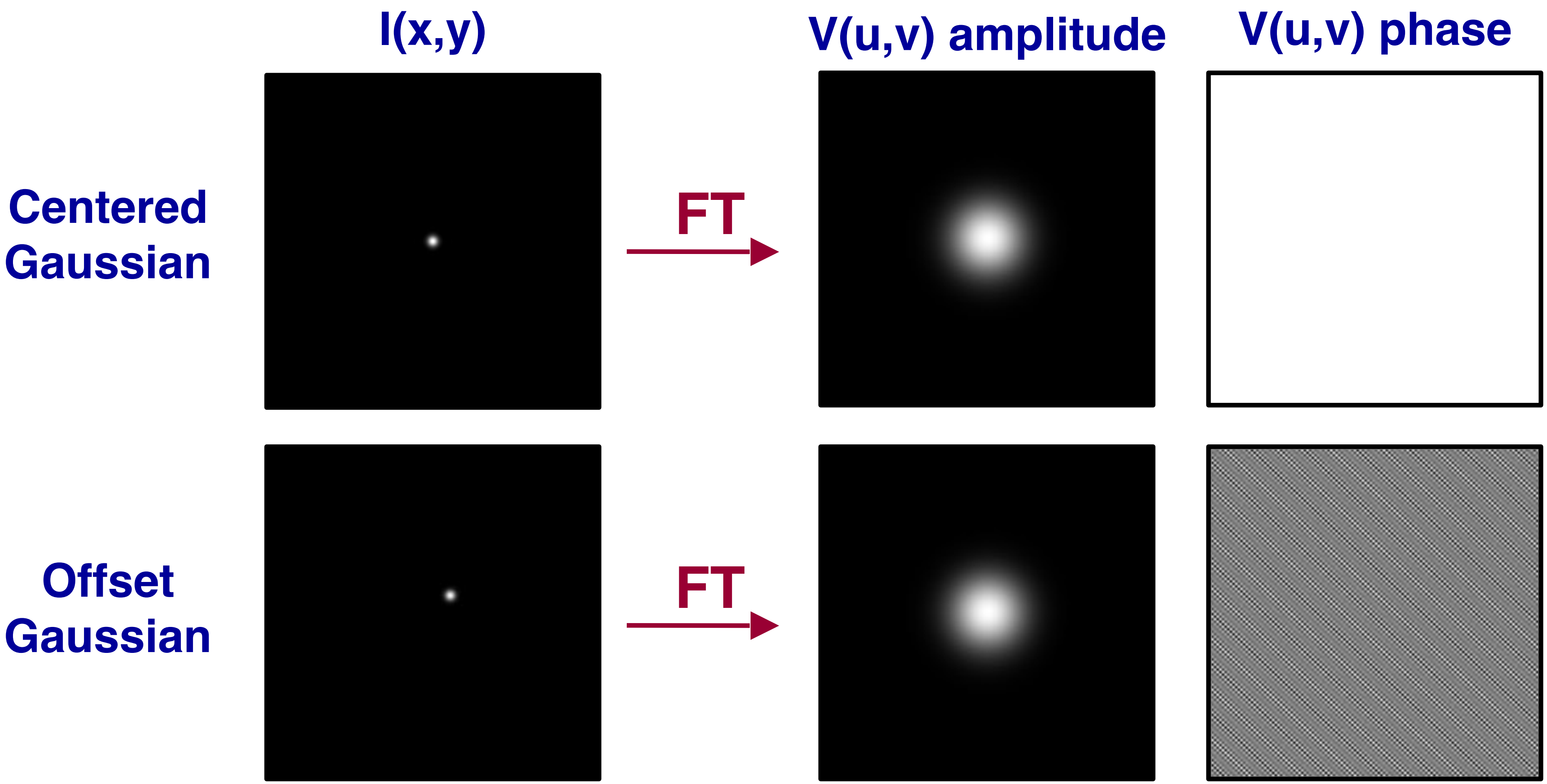
FT →

Bessel Function!

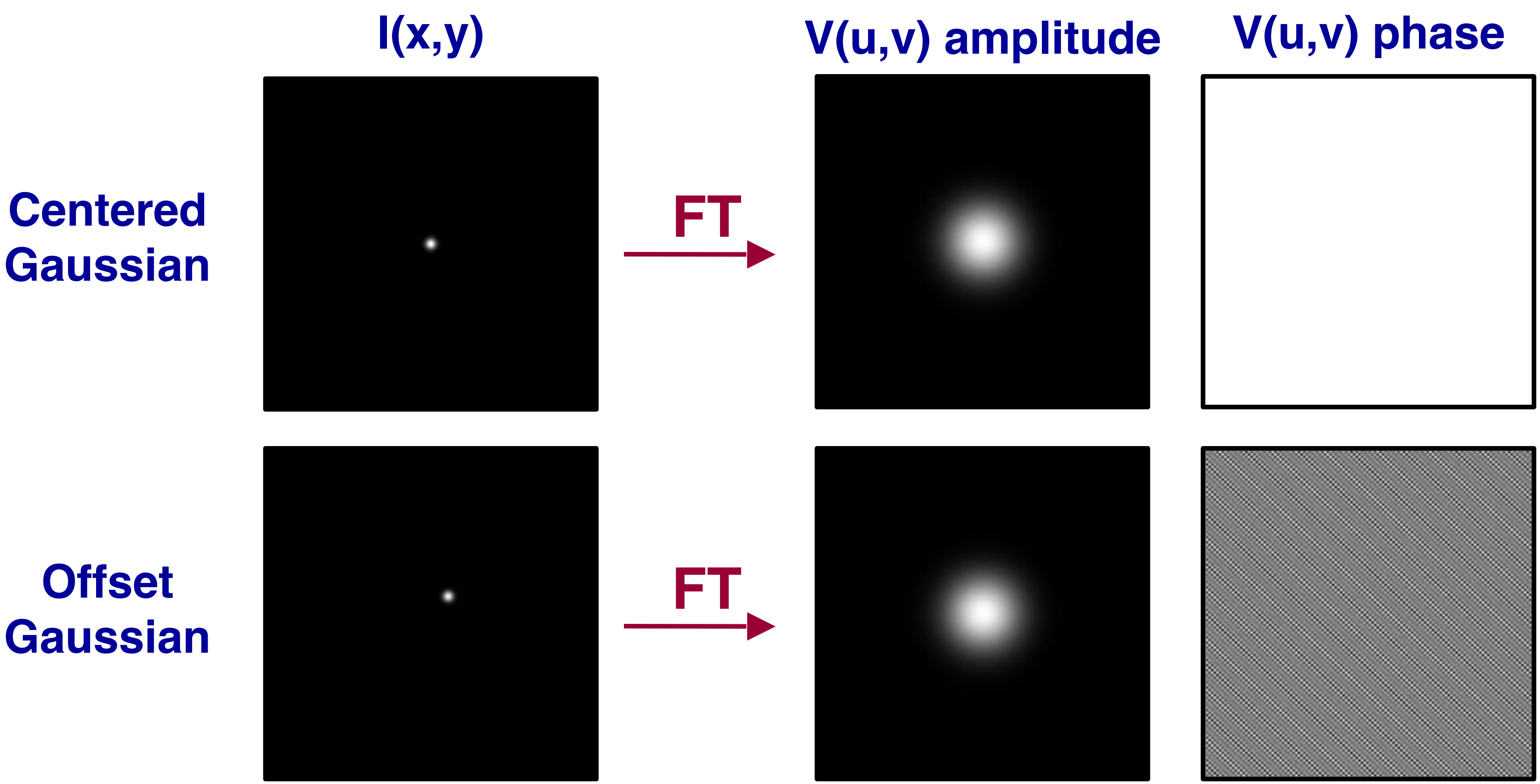
Rules of the Fourier Transform:

Sharp features (edges) result in many high spatial features

Examples of 2D Fourier Transforms



Examples of 2D Fourier Transforms



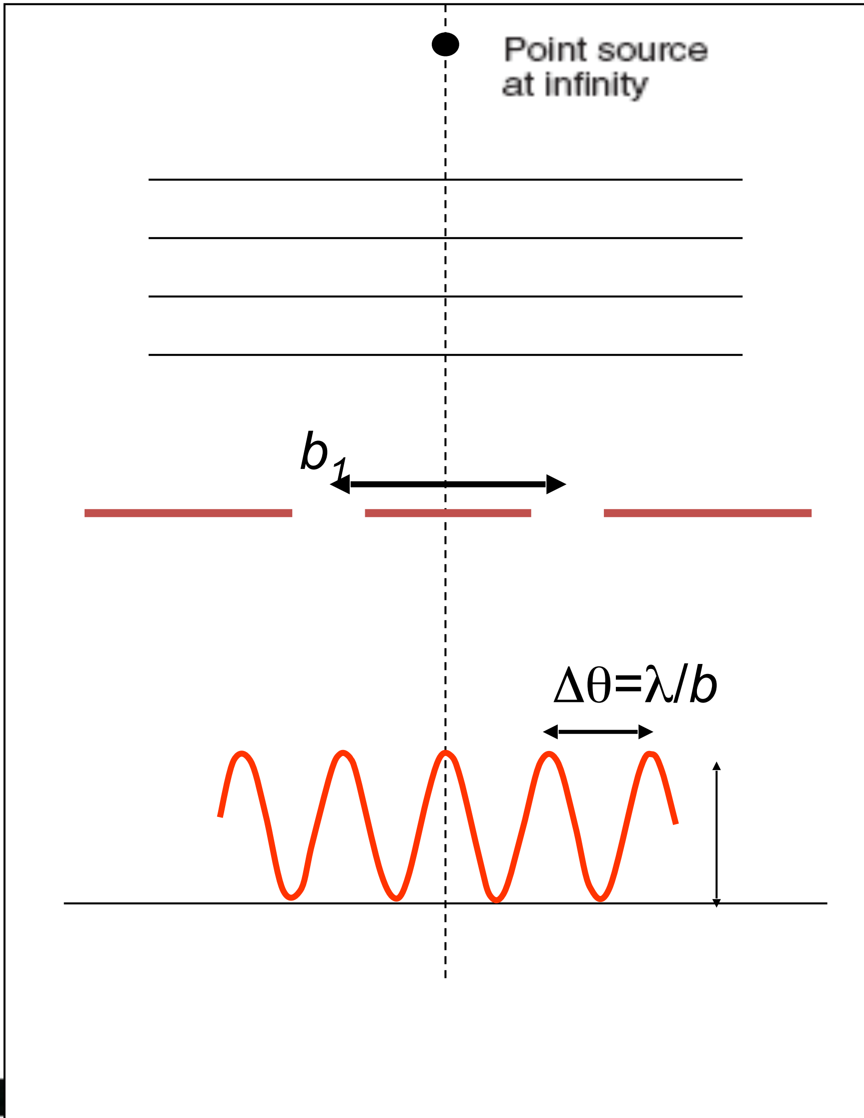
Rules of the Fourier Transform:

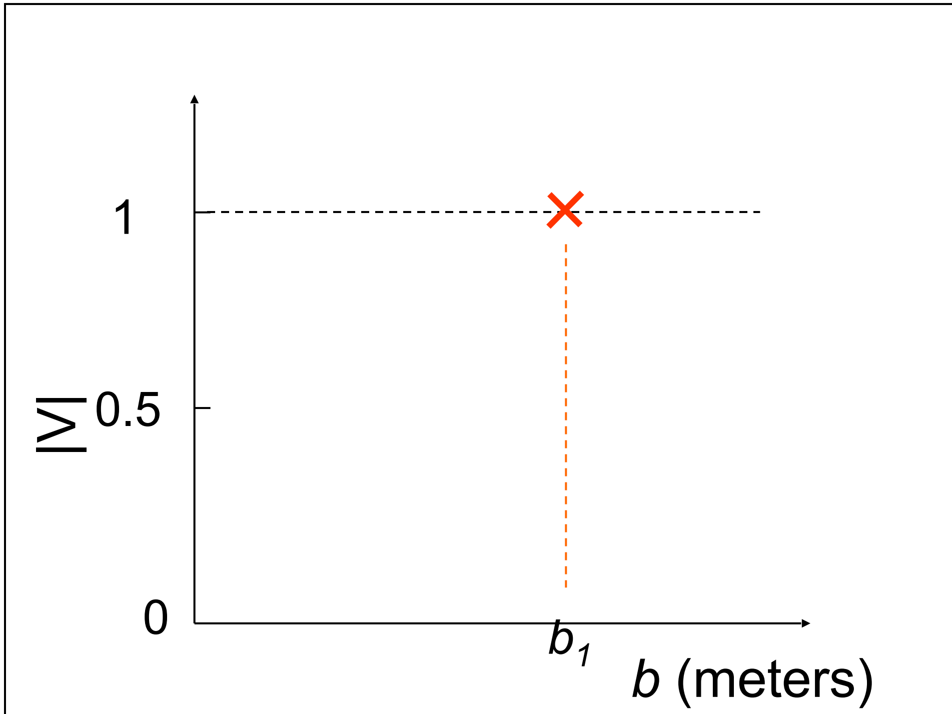
Amplitude tells you ‘how much’ of a spatial frequency

Phase tells you ‘where’ the spatial frequency is

Visibility and Sky Brightness

Graphic courtesy Andrea Isella

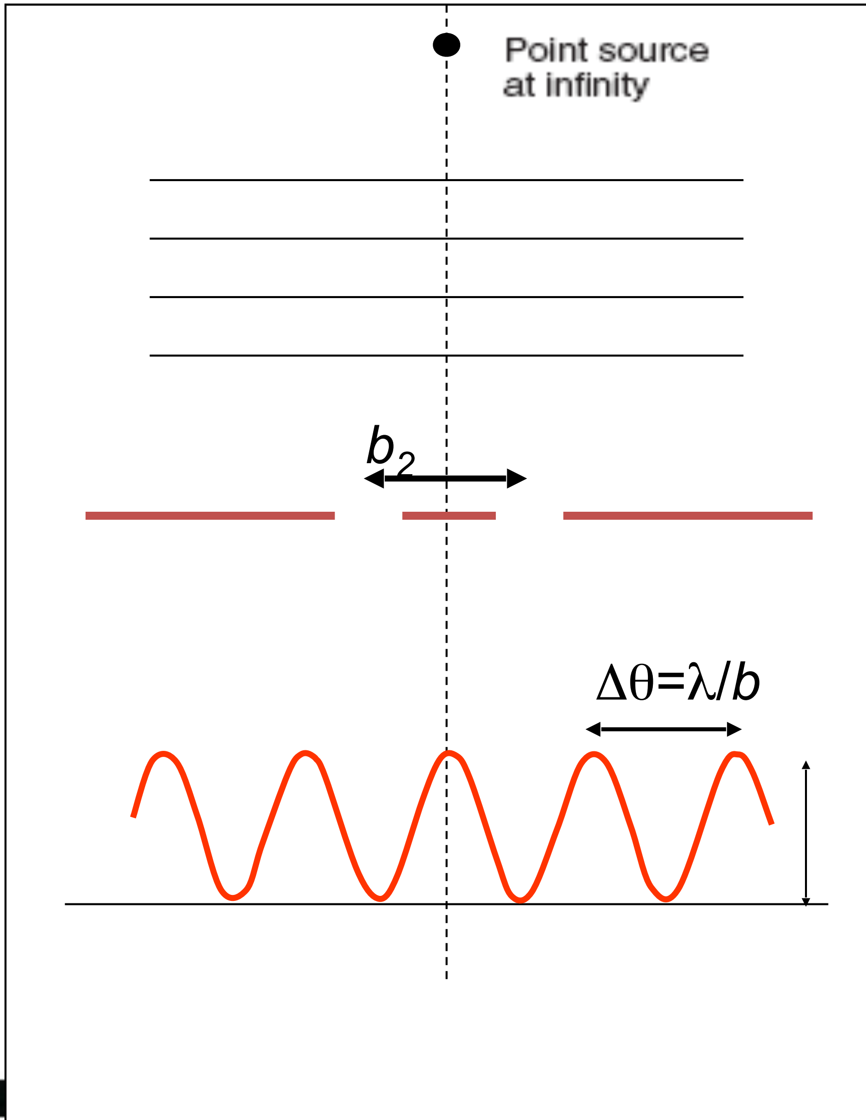


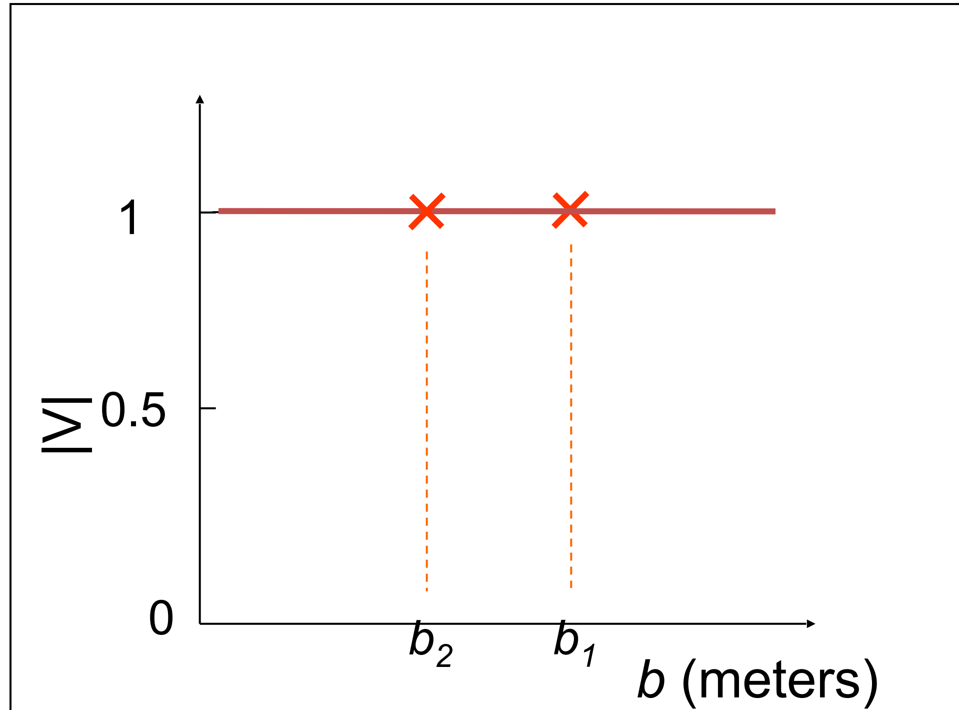


$$|V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{\textit{Fringe Amplitude}}{\textit{Average Intensity}}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella

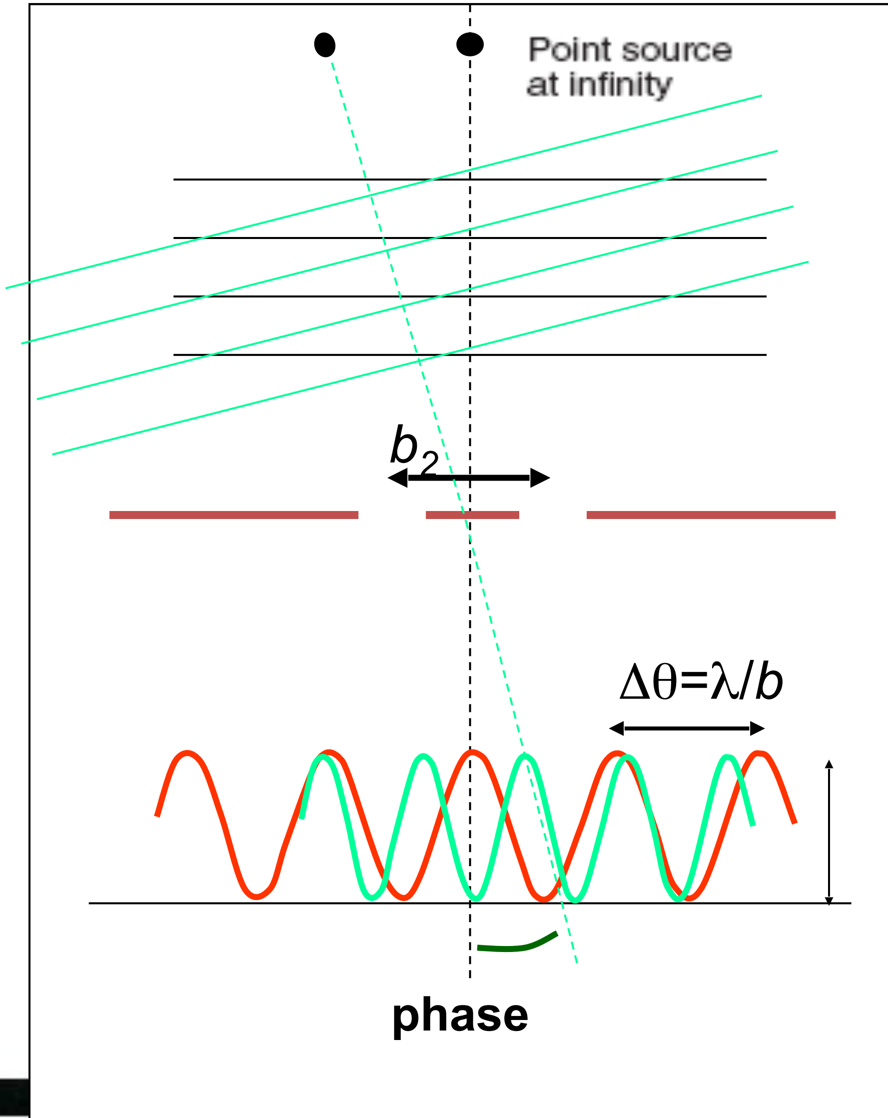


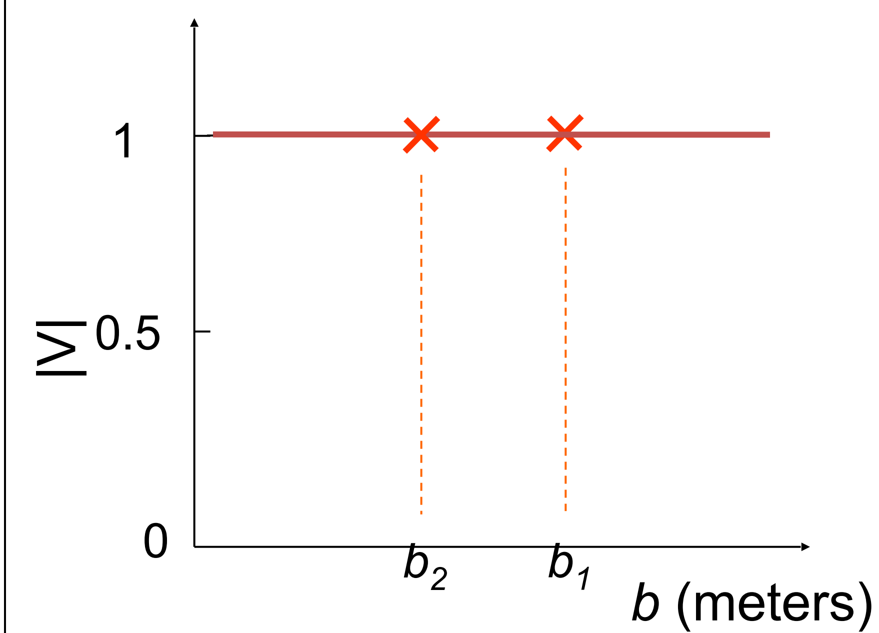


$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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

Visibility and Sky Brightness

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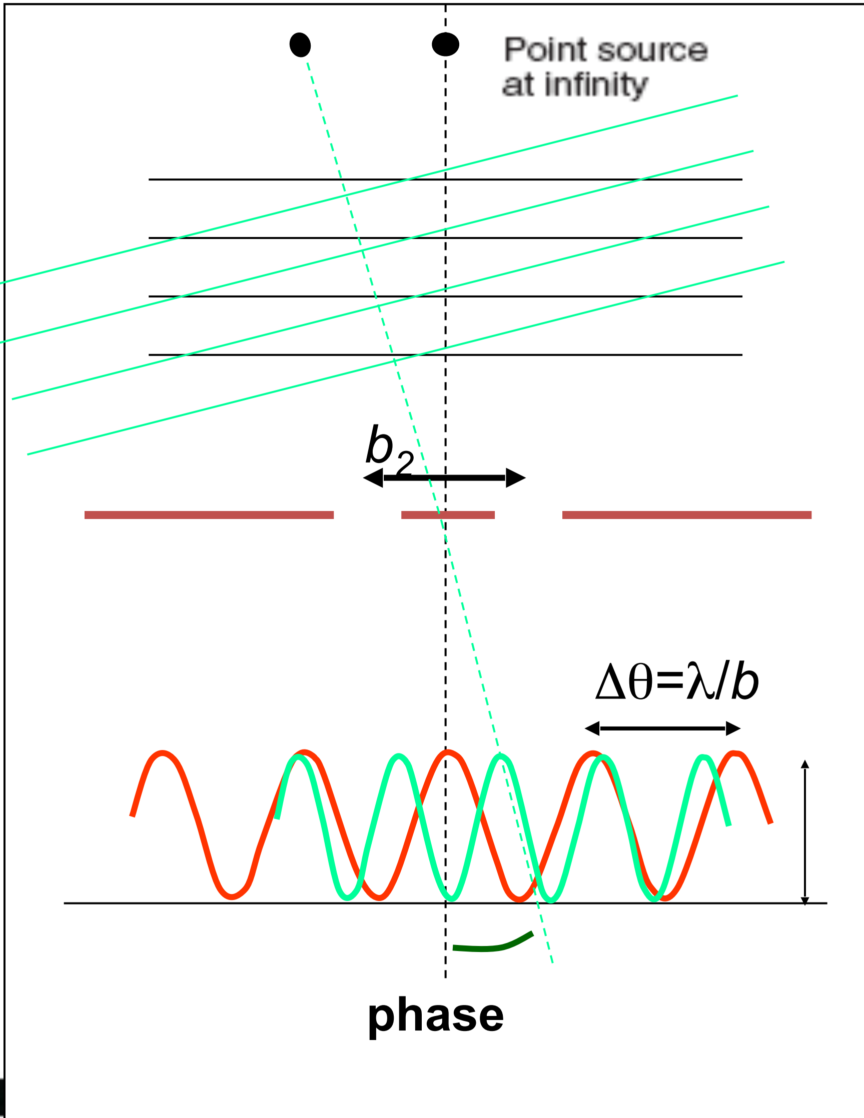
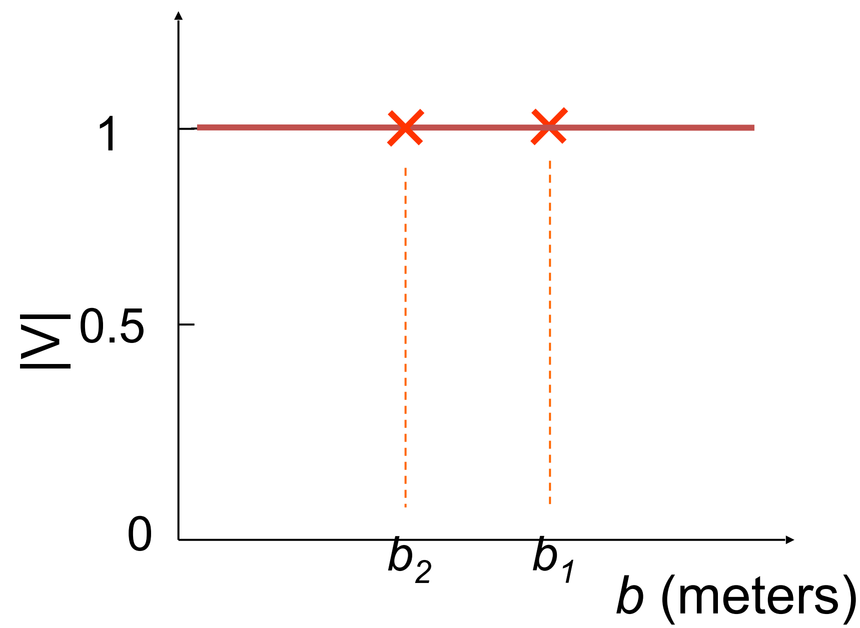




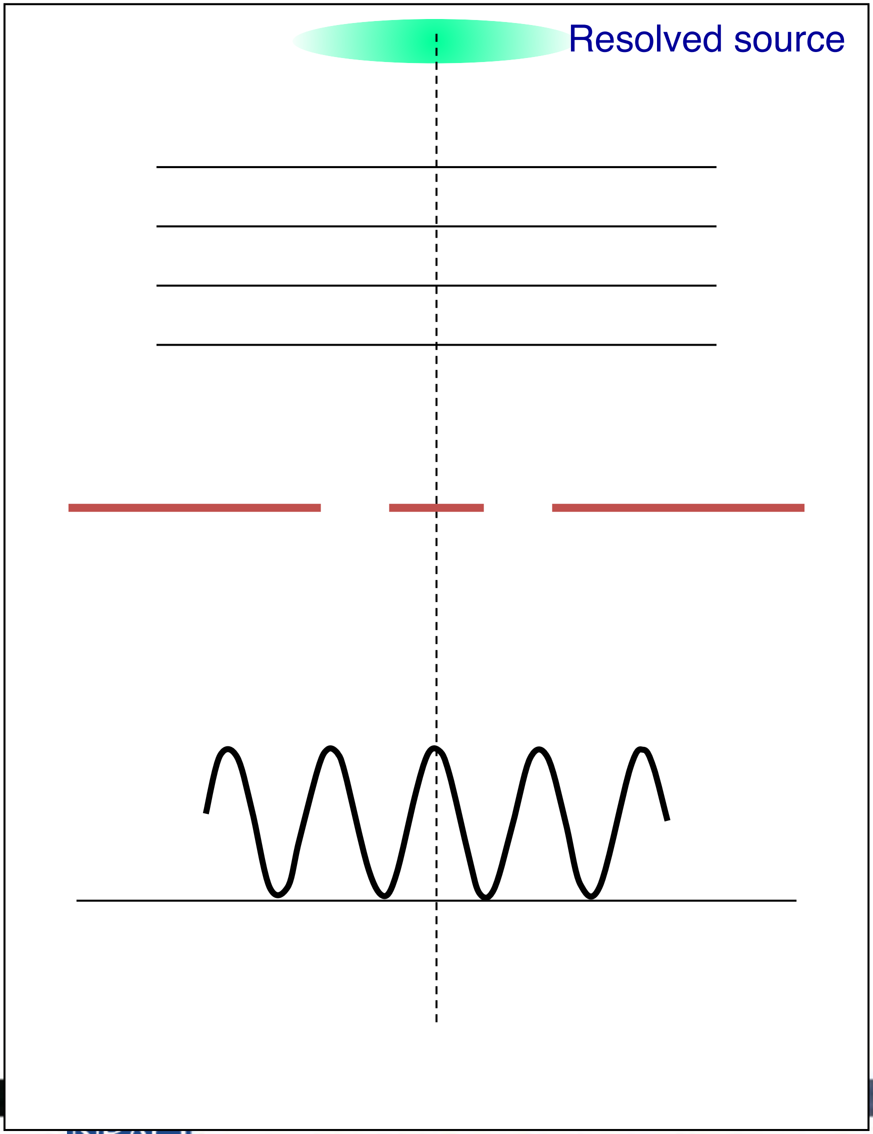
$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{Fringe\ Amplitude}{Average\ Intensity}$$

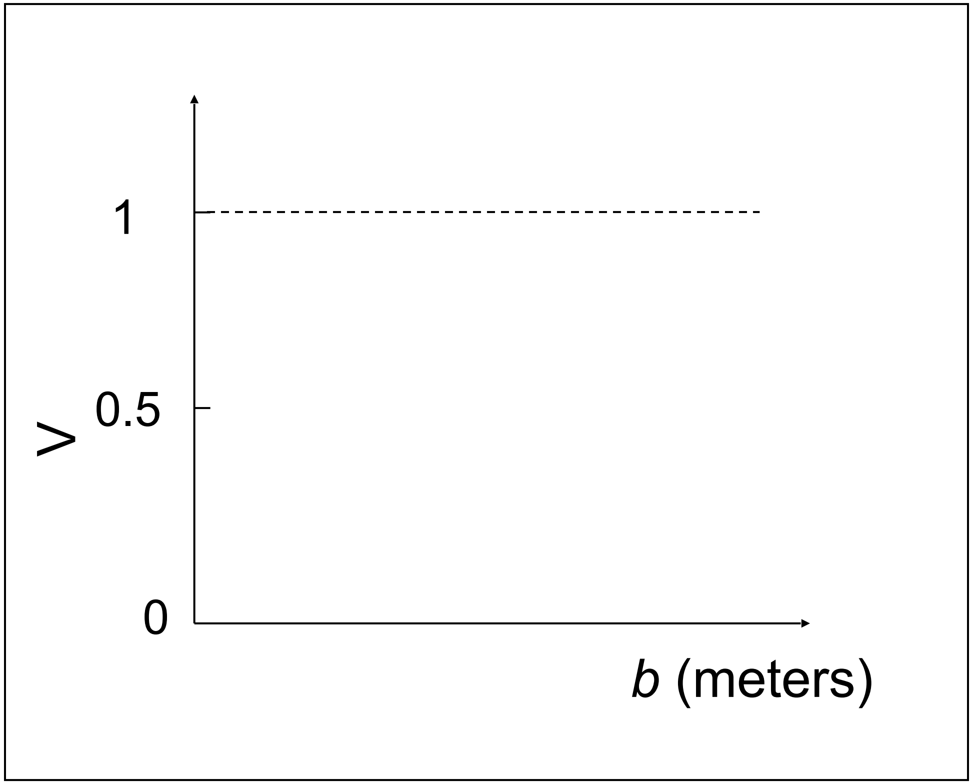
The visibility is a **complex** quantity:

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

Visibility and Sky Brightness

Graphic courtesy Andrea Isella

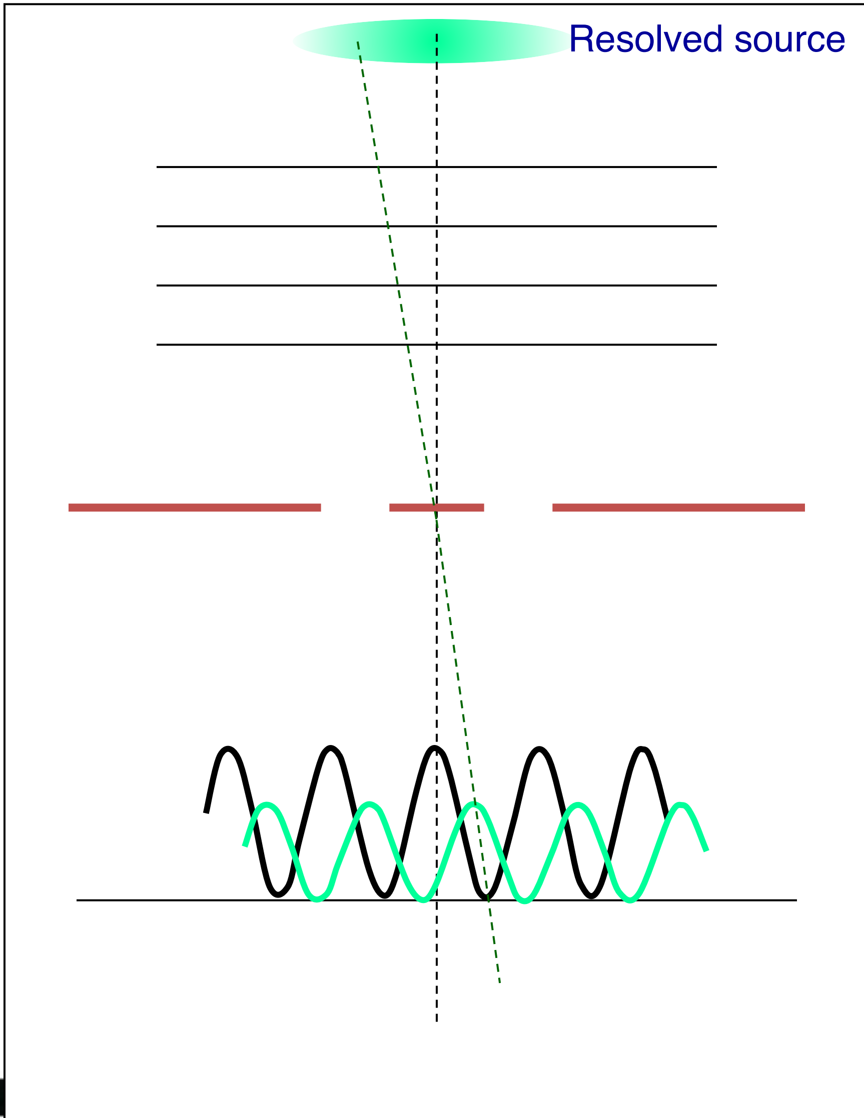


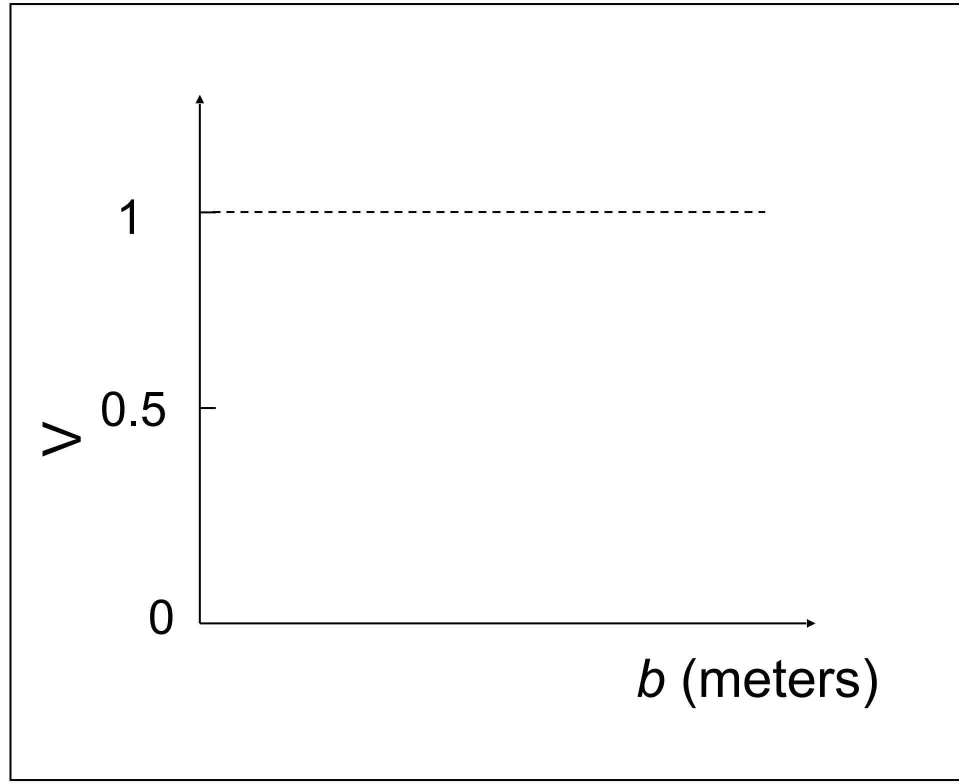


$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\textit{Fringe Amplitude}}{\textit{Average Intensity}}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella

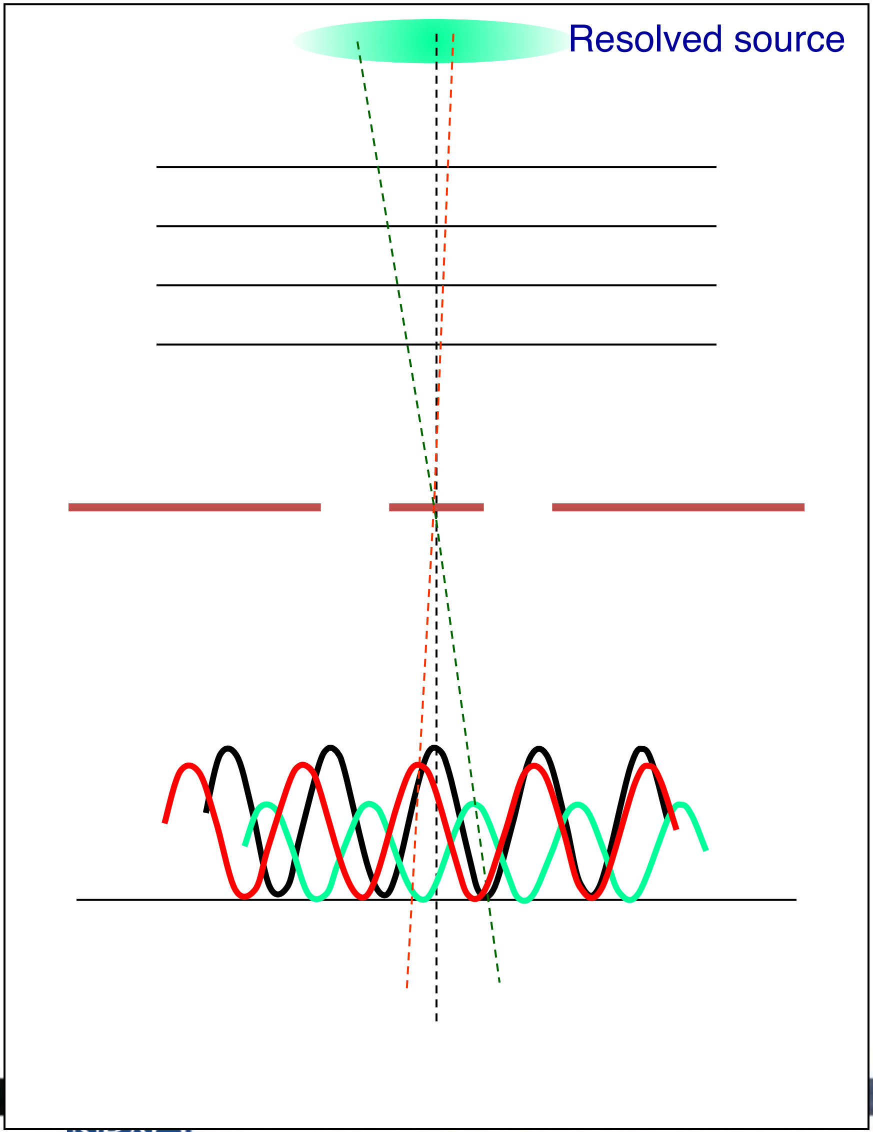


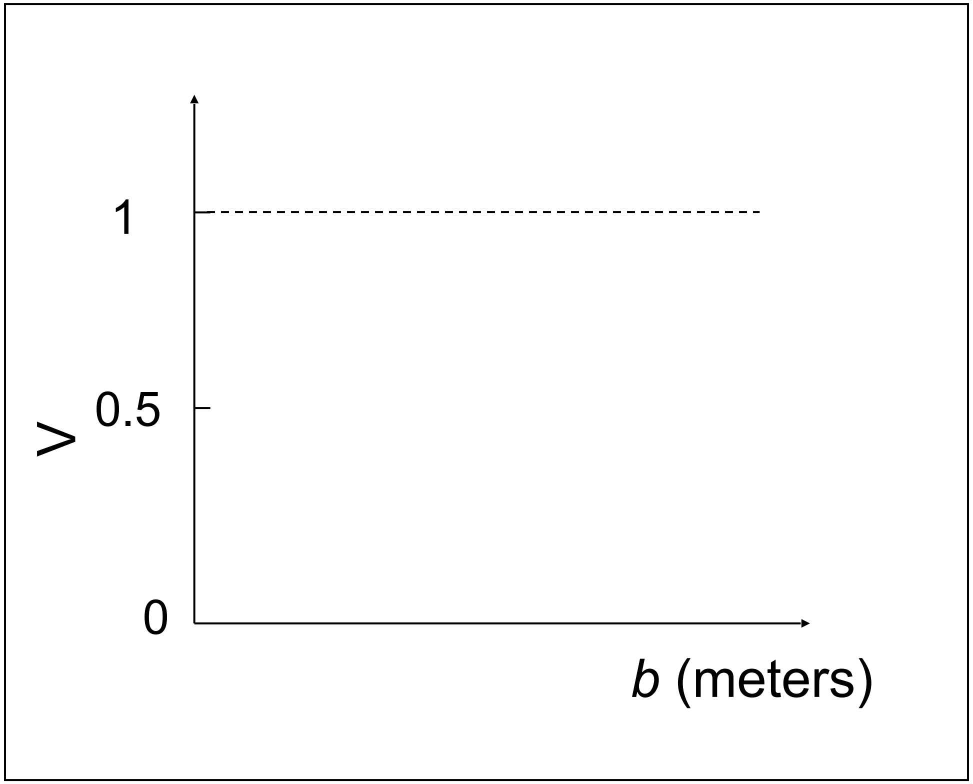


$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\textit{Fringe Amplitude}}{\textit{Average Intensity}}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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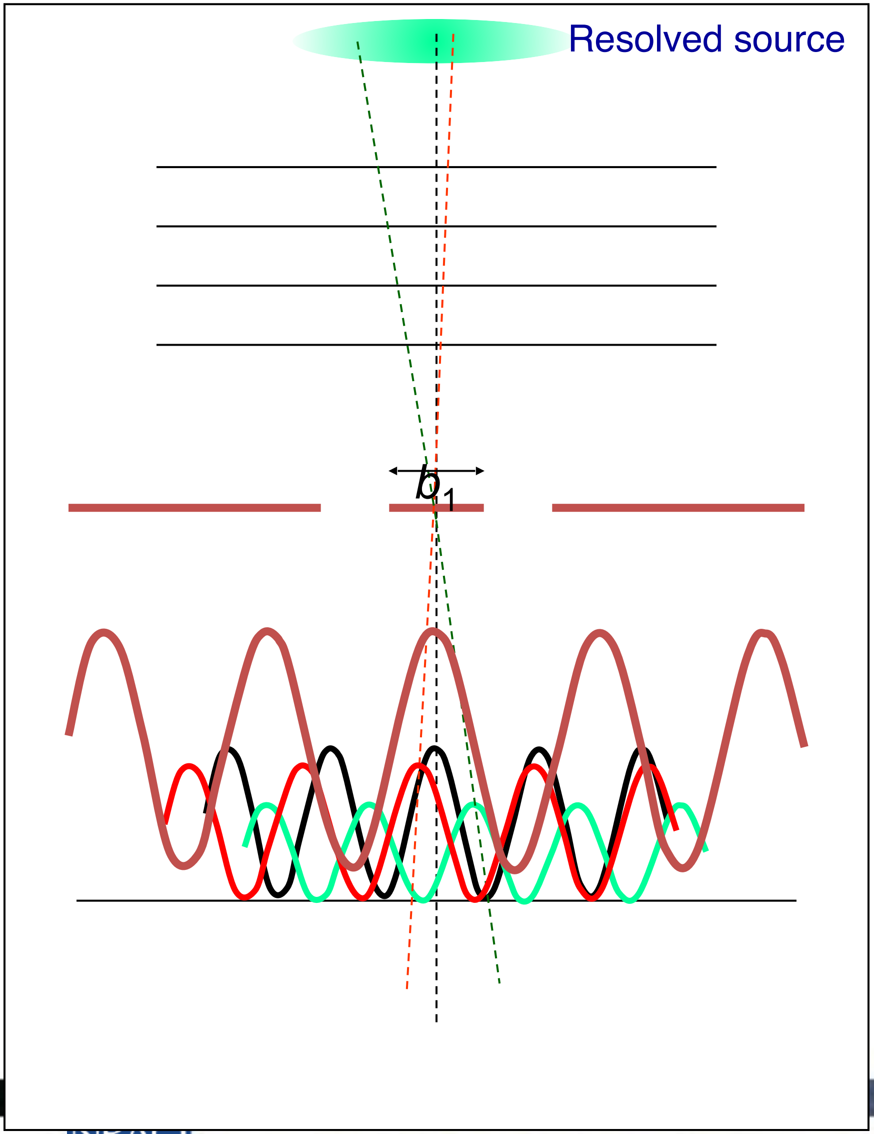
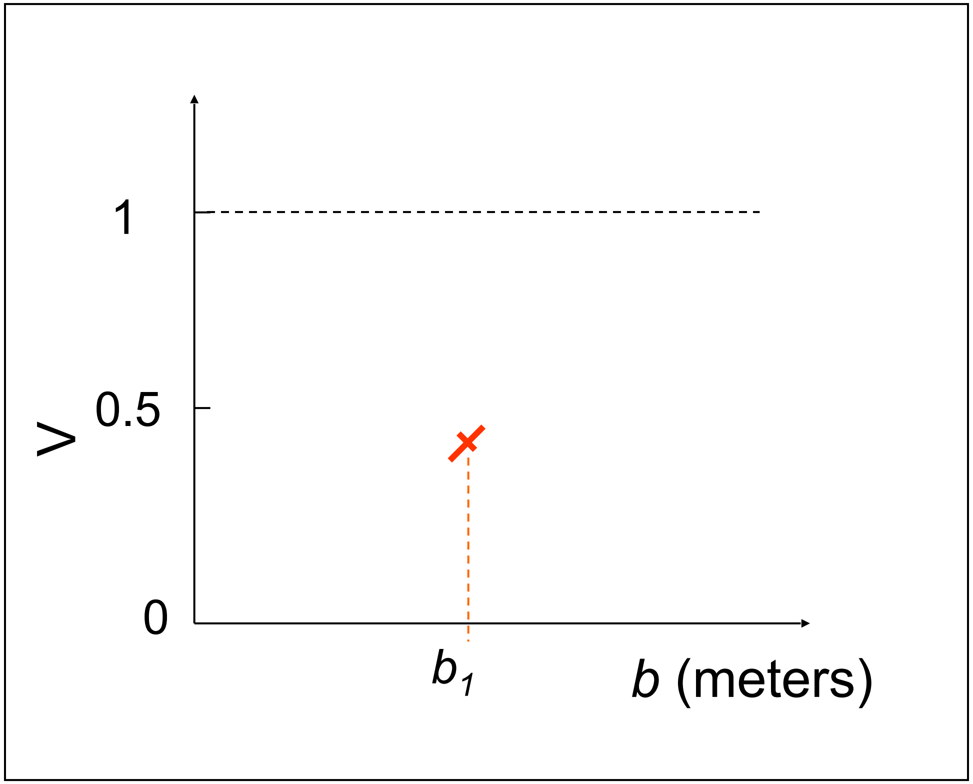
Visibility and Sky Brightness

Graphic courtesy Andrea Isella

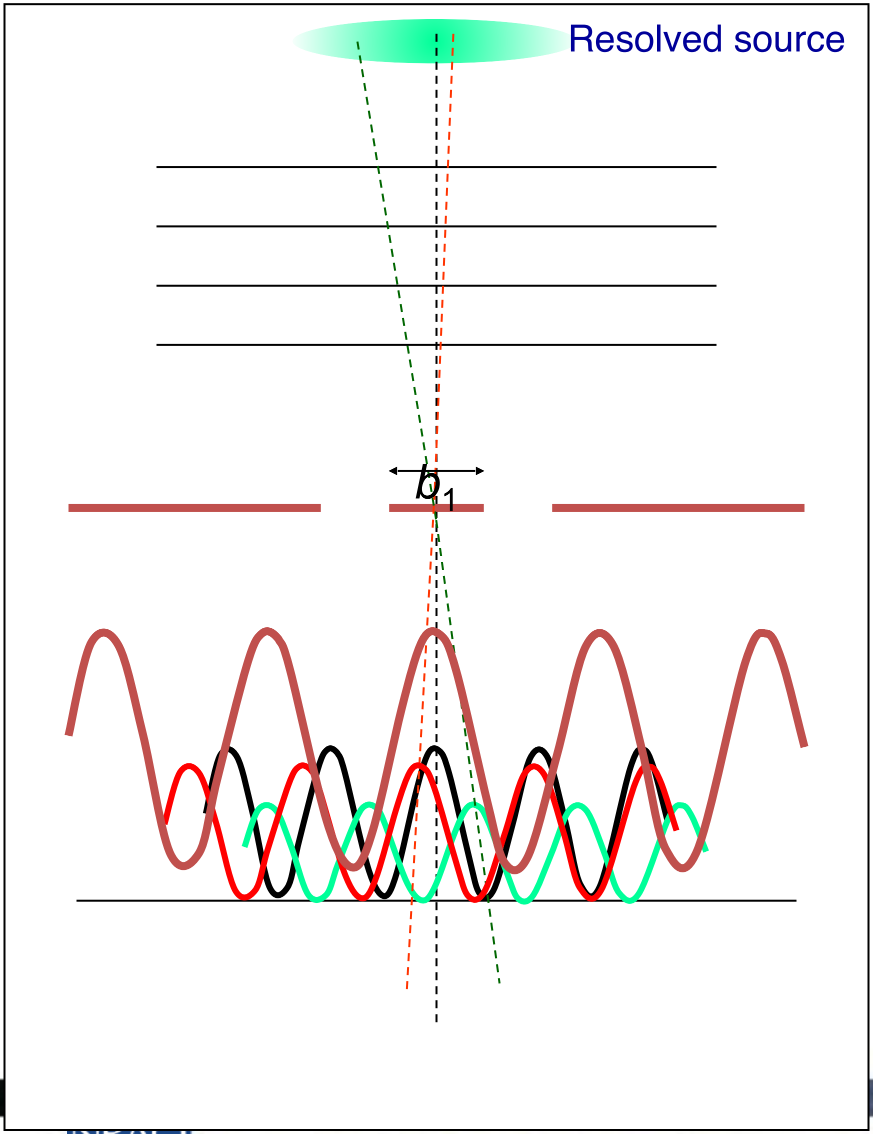


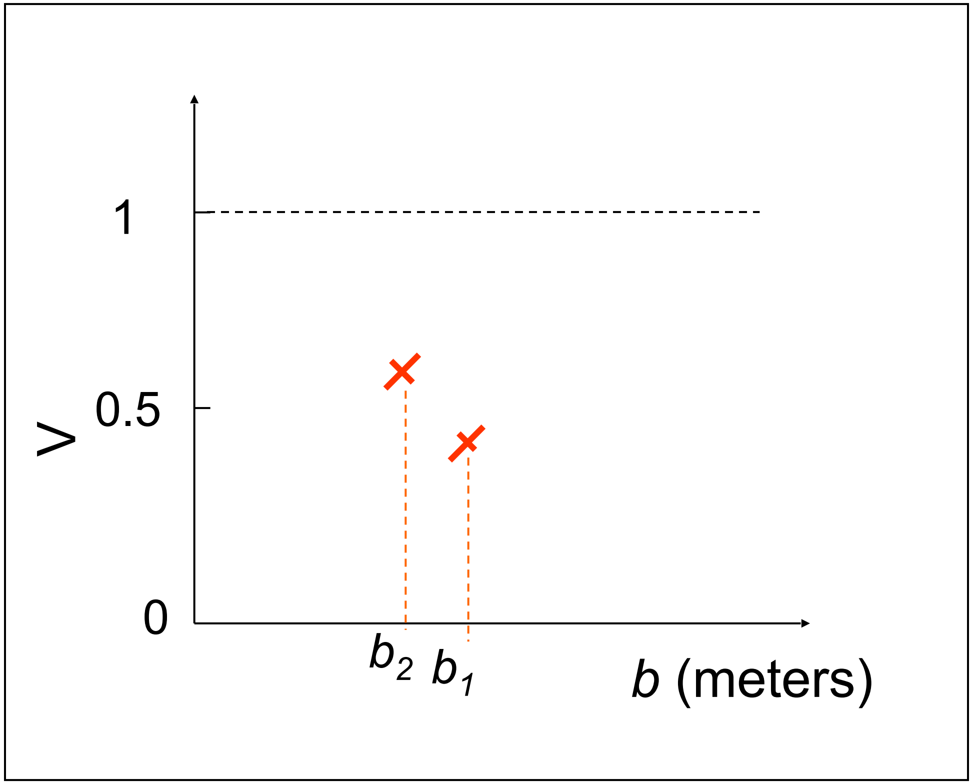


$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\textit{Fringe Amplitude}}{\textit{Average Intensity}}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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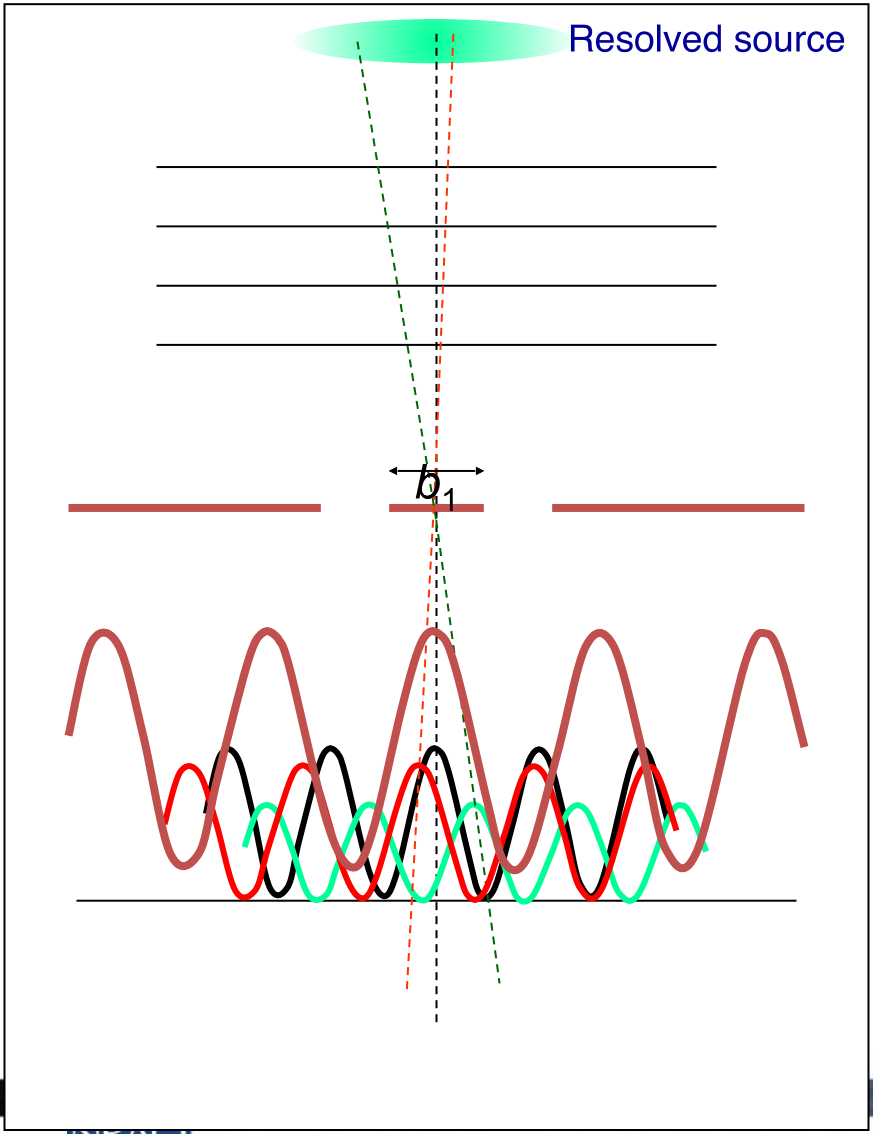
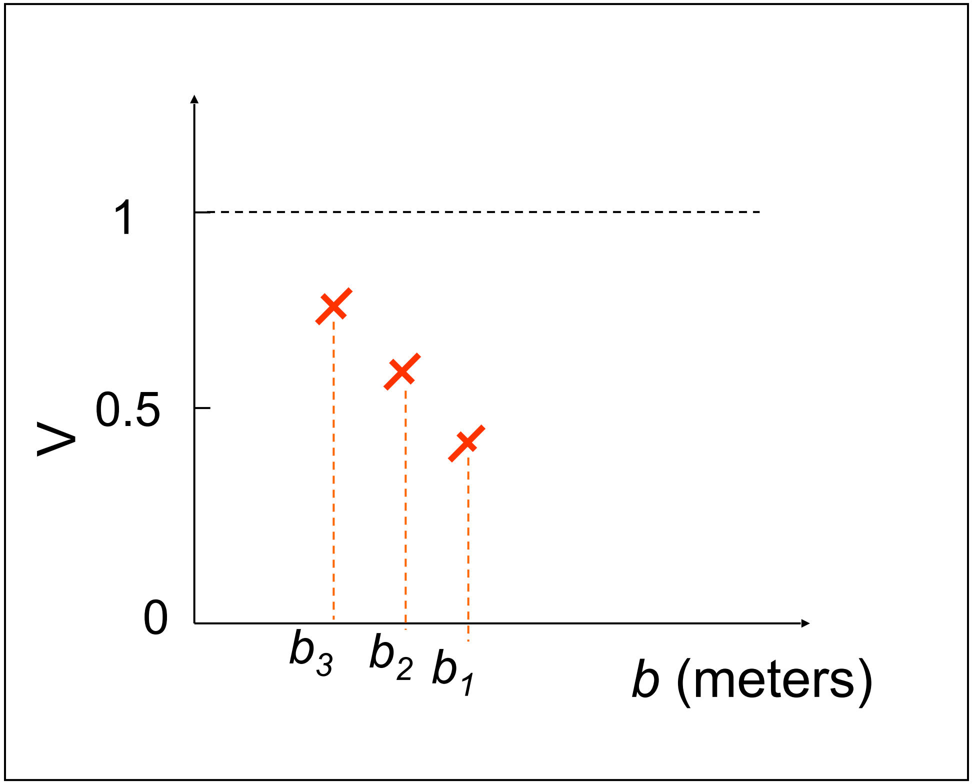
Visibility and Sky Brightness

Graphic courtesy Andrea Isella

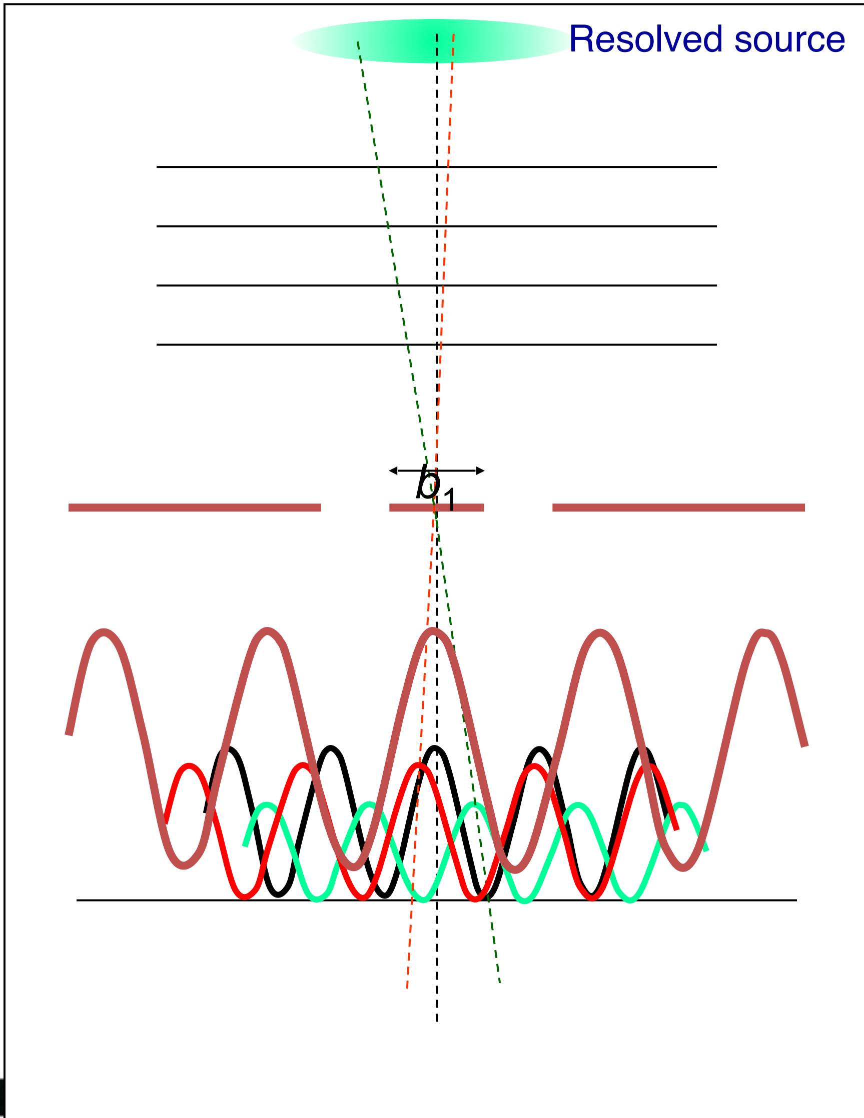


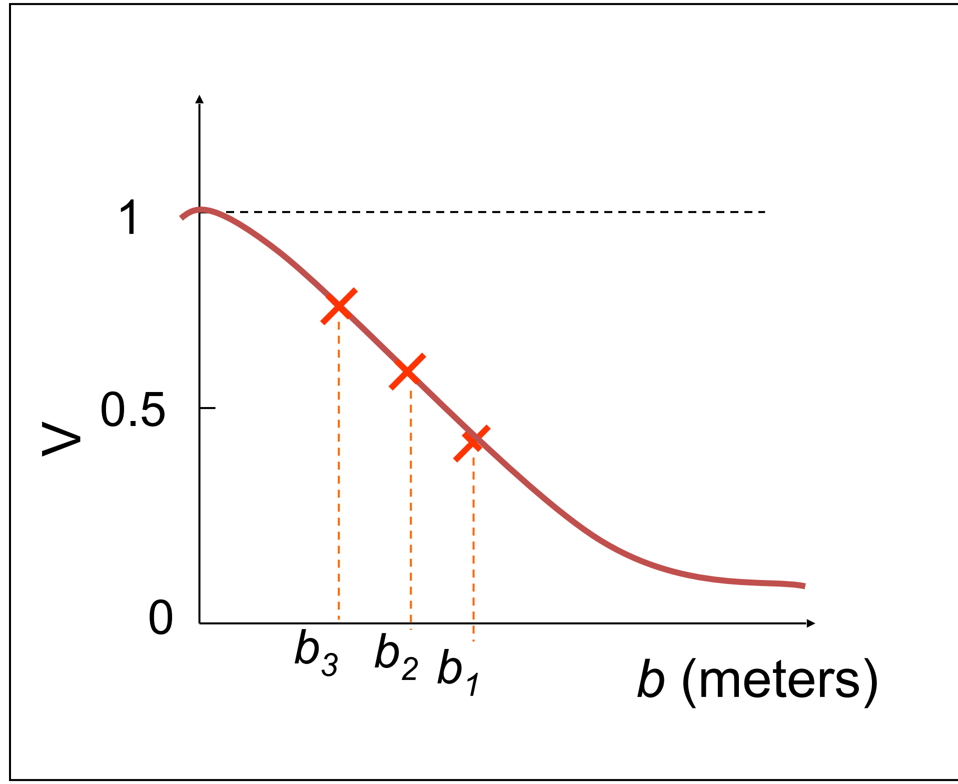


$$|V| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\textit{Fringe Amplitude}}{\textit{Average Intensity}}$$

Visibility and Sky Brightness

Graphic courtesy Andrea Isella





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

Basics of Aperture Synthesis

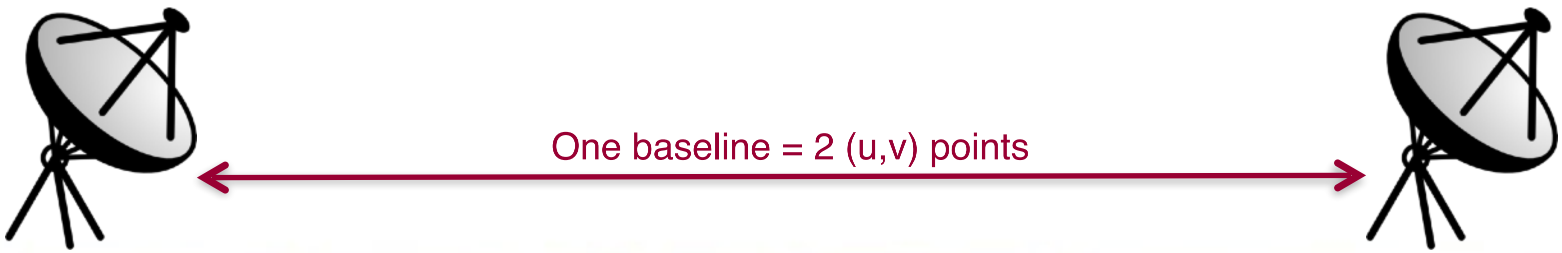
Idea: Sample V(u,v) at a enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{max}, v_{max})

One pair of antennas = one baseline

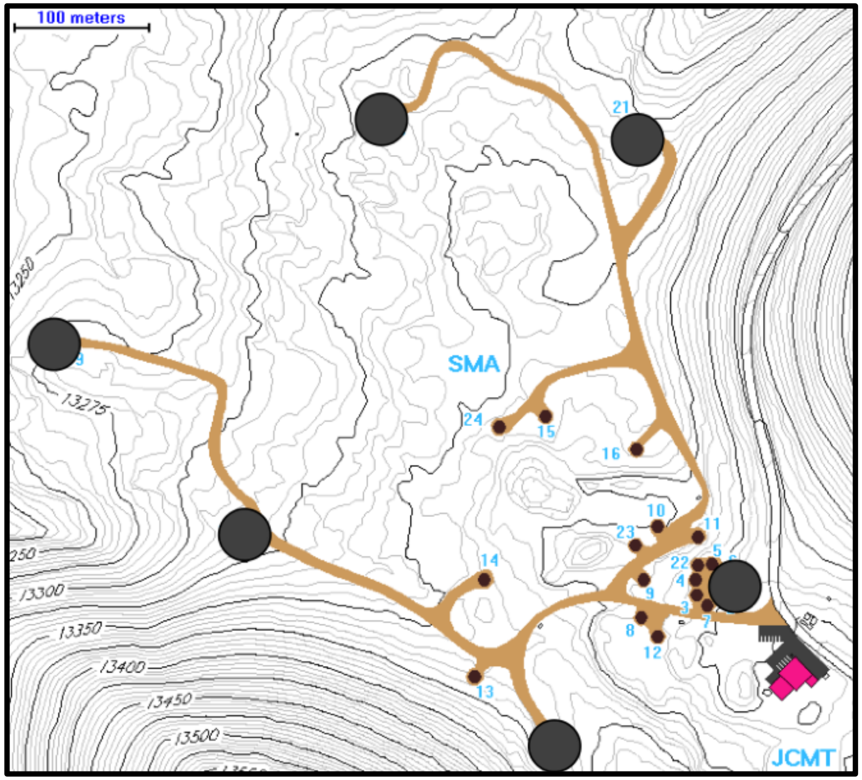
For **N antennas**, we get **N(N-1) samples** at a time

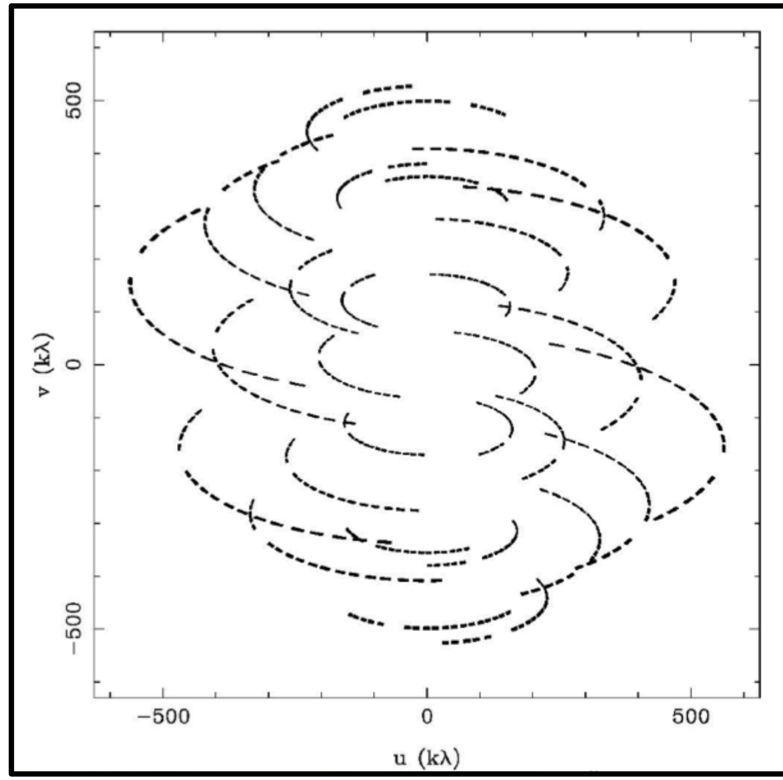
How do we fill in the rest of the (u,v) plane?

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



(u,v) Plane Sampling





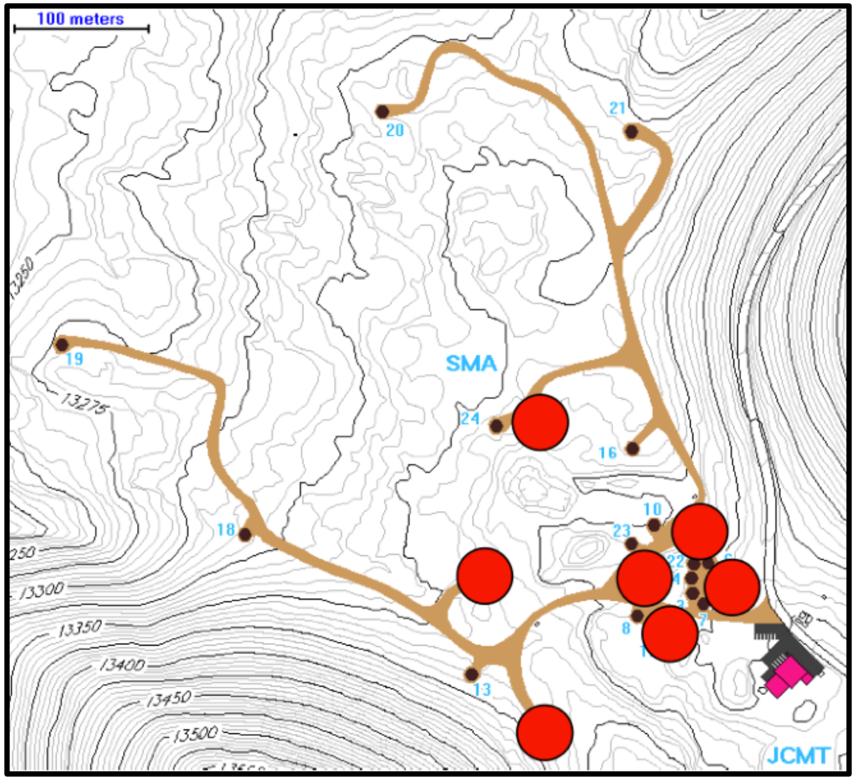
Very Extended SMA configuration

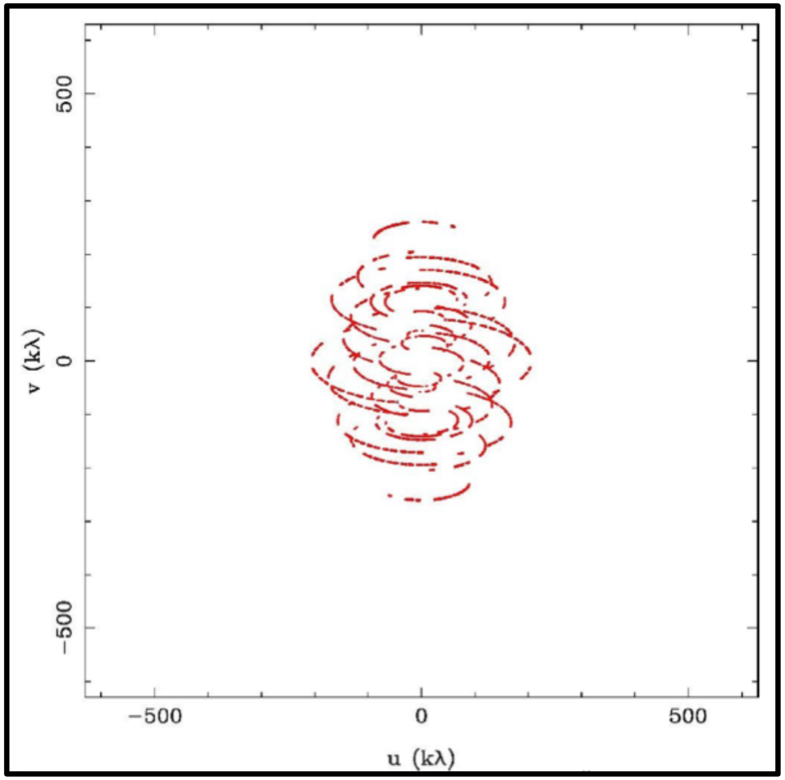
(most extended baselines)

345 GHz, DEC = +22

NRAO

(u,v) Plane Sampling



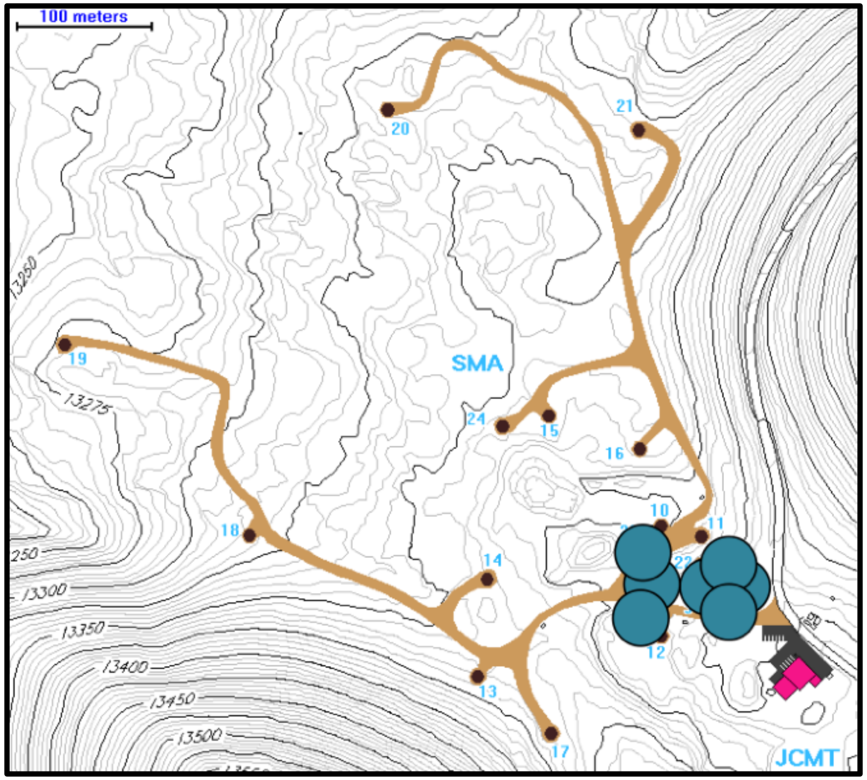


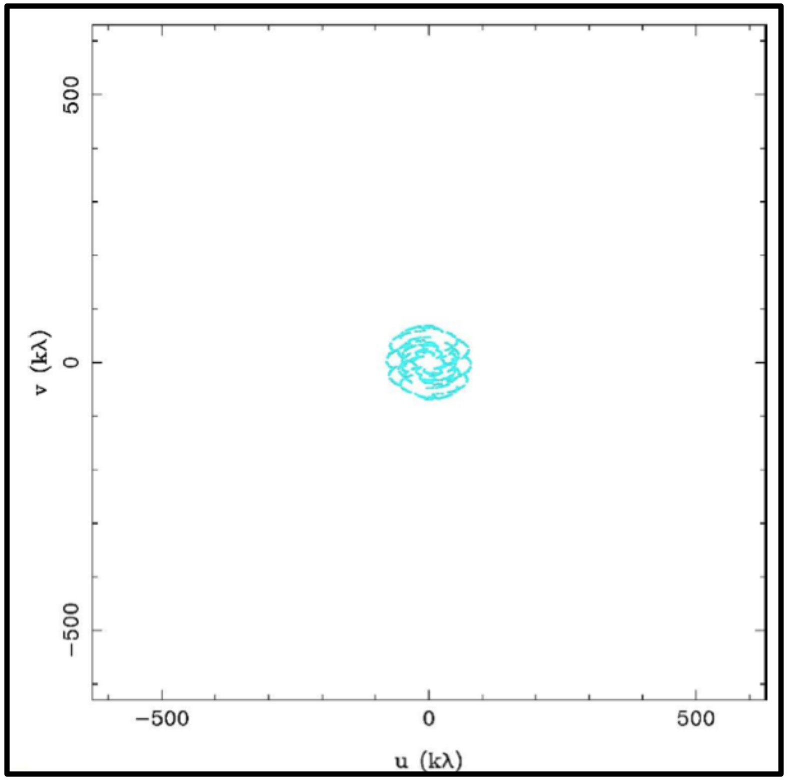
Extended SMA configuration

(extended baselines)

345 GHz, DEC = +22

(u,v) Plane Sampling



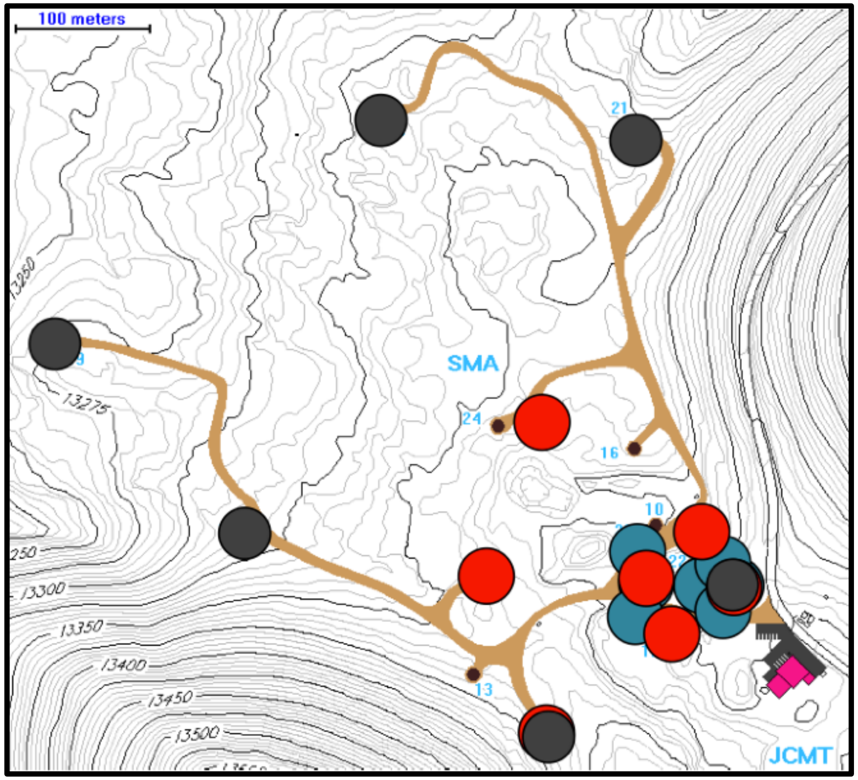


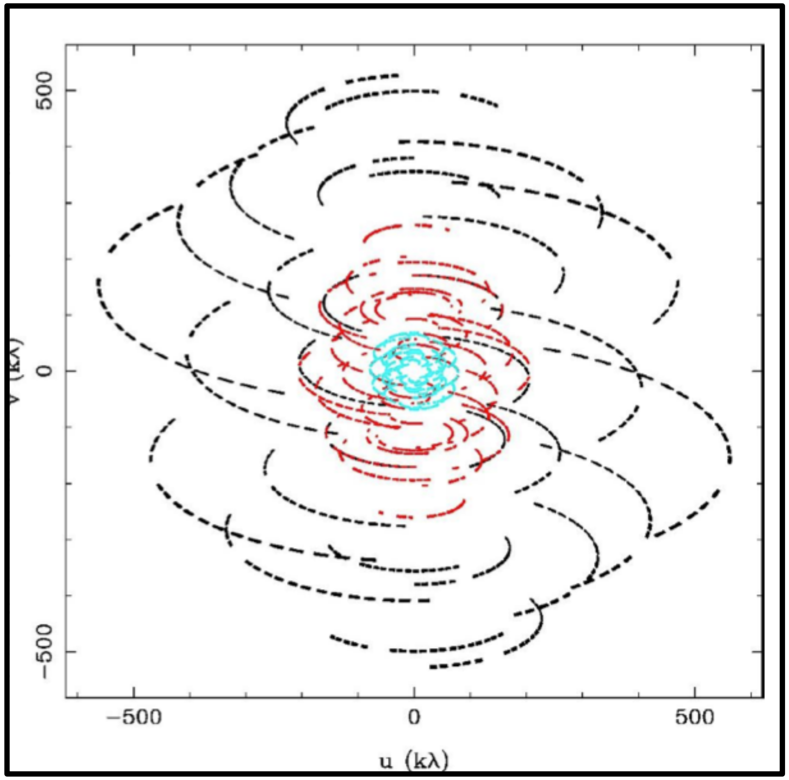
Compact SMA configuration

(compact baselines)

345 GHz, DEC = +22

(u,v) Plane Sampling

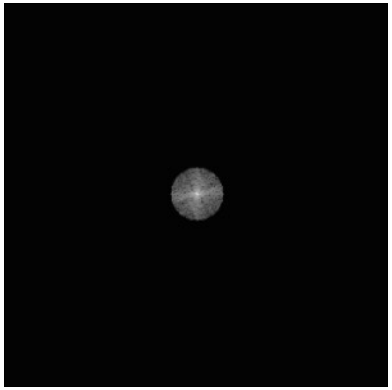
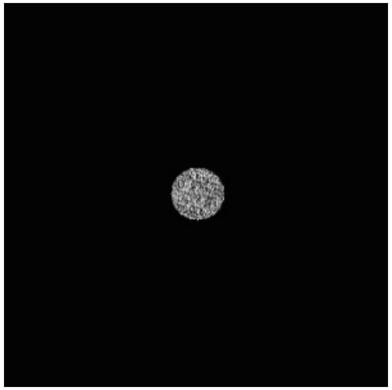
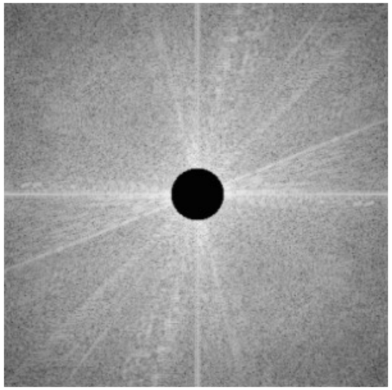
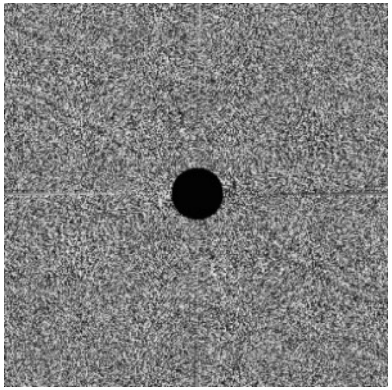




Combine multiple configurations to get the most complete coverage of the (u,v) plane

Implications of (u,v) Coverage

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

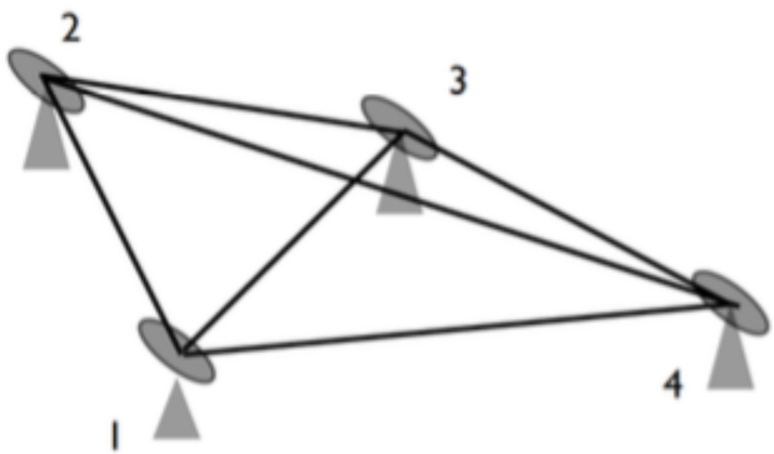
	V(u,v) amplitude	V(u,v) phase		I(x,y)
Missing High Spatial Frequencies			FT →	
Missing Low Spatial Frequencies			FT →	

NRAO

Multi-element interferometer

A 2-element interferometer produces a single response: r_{12}

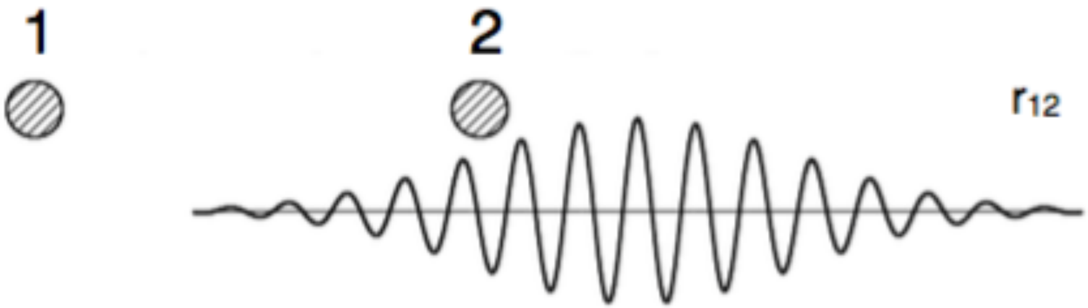
A N-element interferometer produces N(N-1)/2 responses



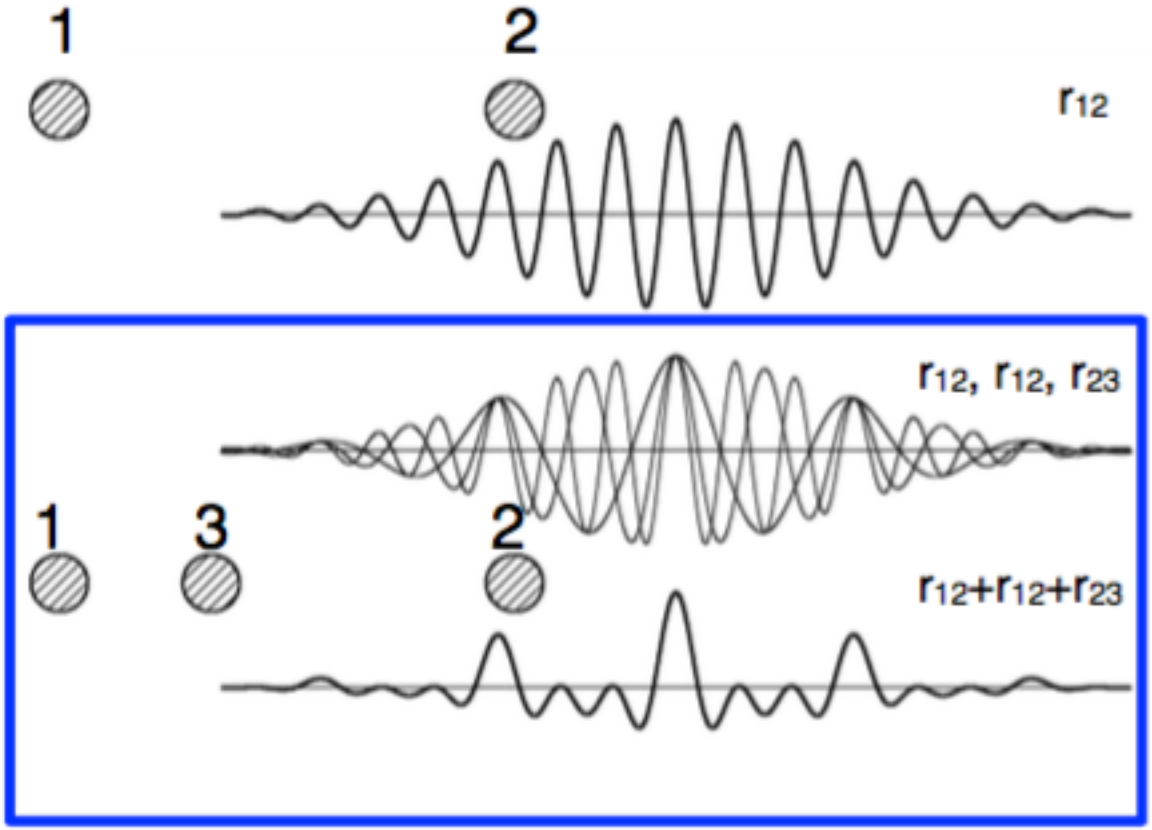
For N=4, 6 baselines responses are measured: r_{12}, r_{13}, r_{14}, r_{23}, r_{24}, r_{34}.

Each interferometer pair presents its own sinusoid at a frequency proportional to the fringe angular spacing

More fringes, the lower the sidelobes in the synthesized beam



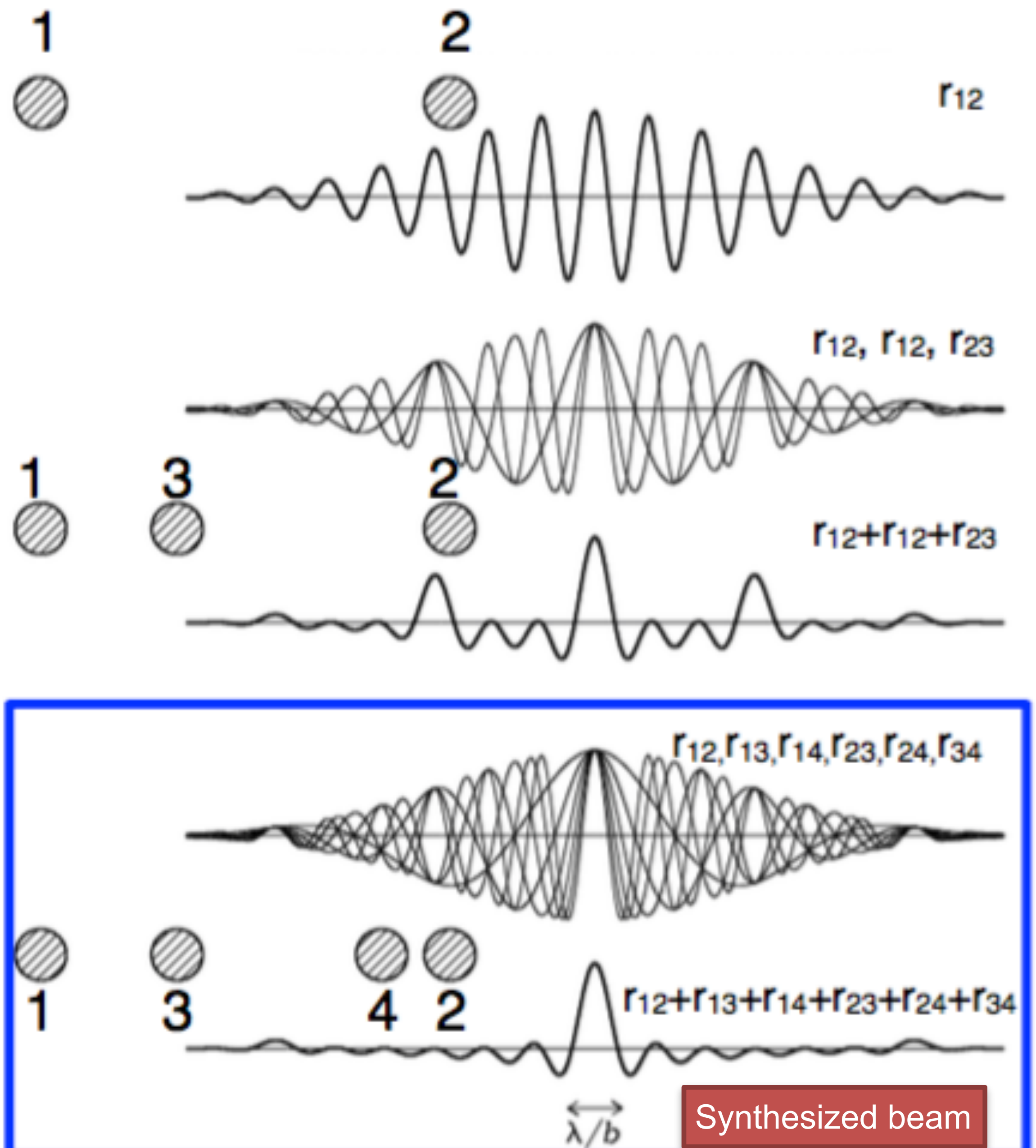
Instantaneous synthesized beam is obtained by averaging the fringe patten of all pairs of baselines



Instantaneous synthesized beam is obtained by averaging the fringe patten of all pairs of baselines

Long baselines have narrow angular fringe and are sensitive to compact structures

Short baselines have large angular fringe and are sensitive to extended structures



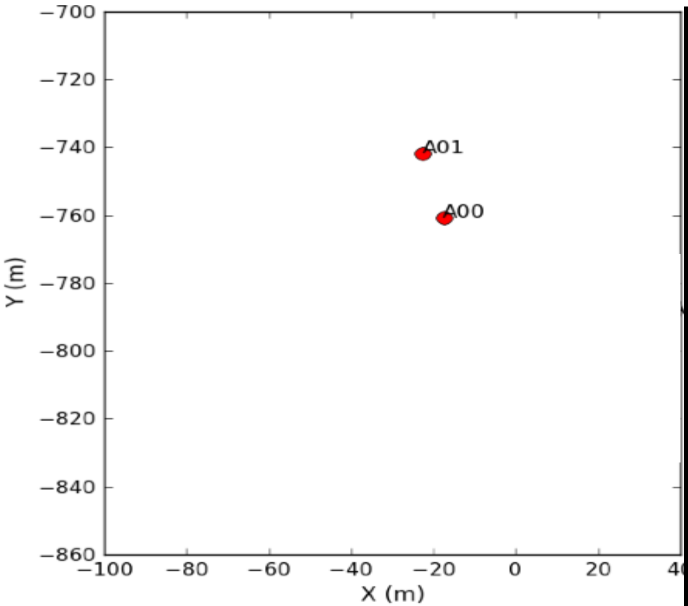
Instantaneous synthesized beam is obtained by averaging the fringe patten of all pairs of baselines

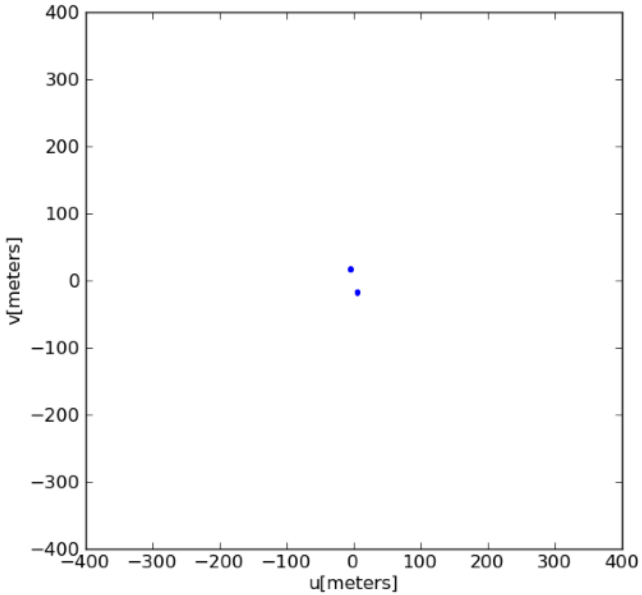
Long baselines have narrow angular fringe and are sensitive to compact structures

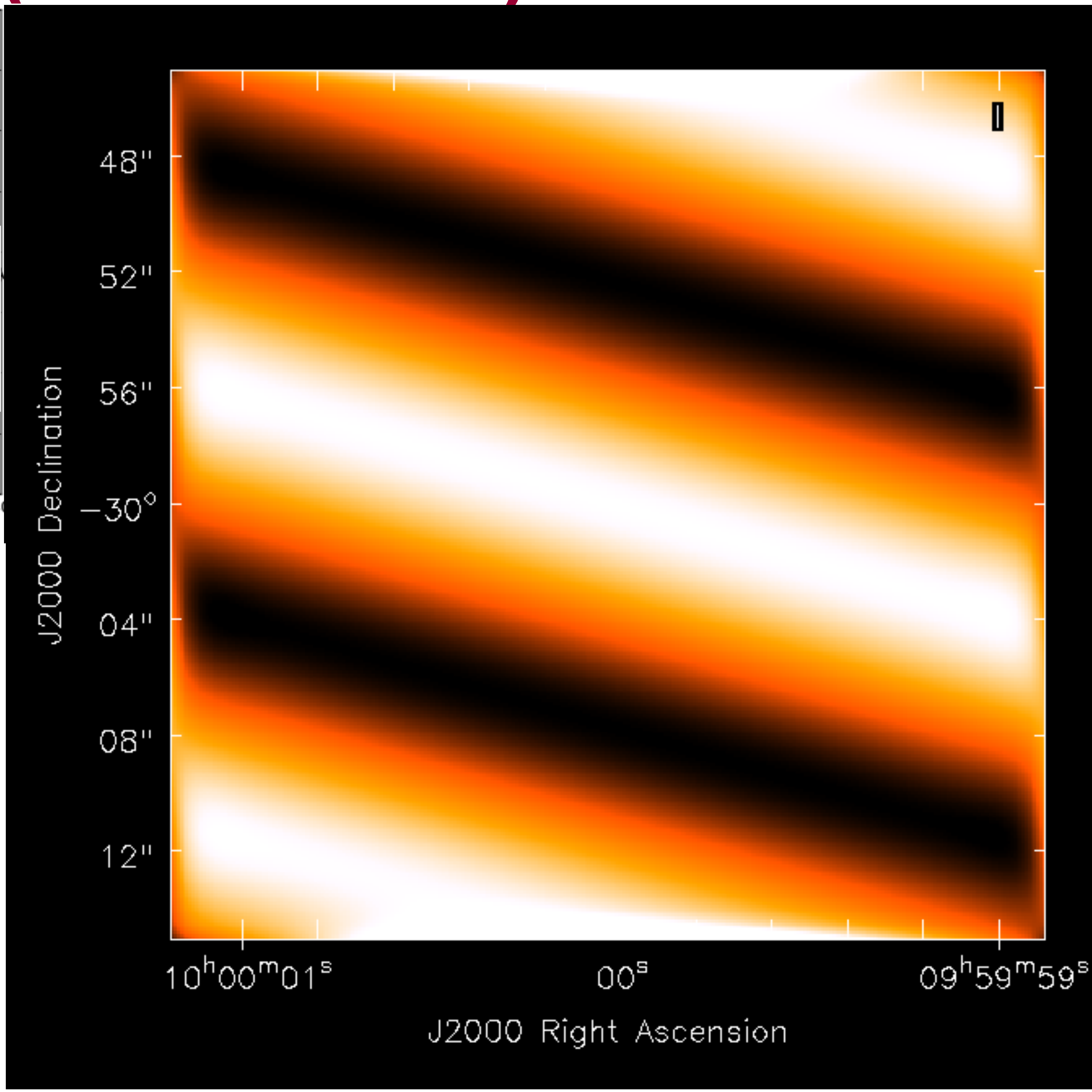
Short baselines have large angular fringe and are sensitive to extended structures

NRAO

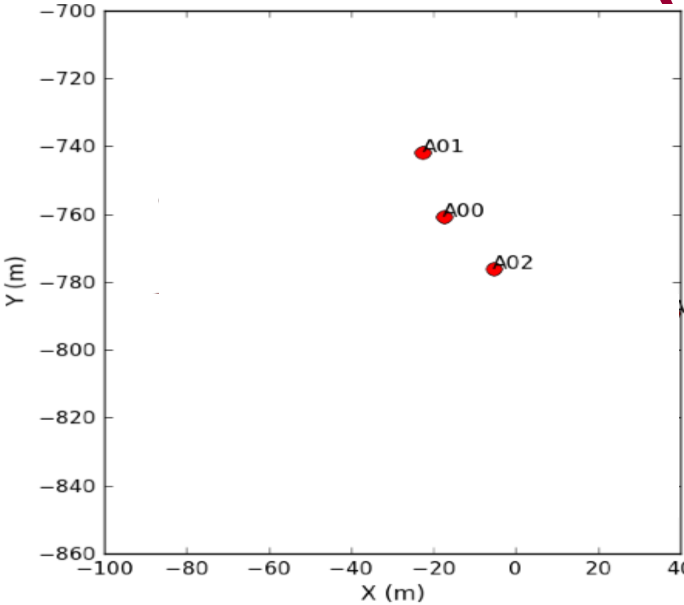
Example: Fringe pattern with 2 Antennas (one baseline)

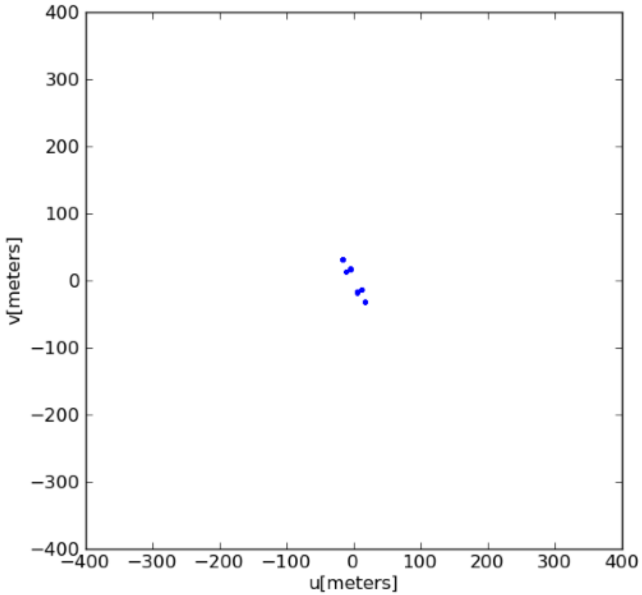


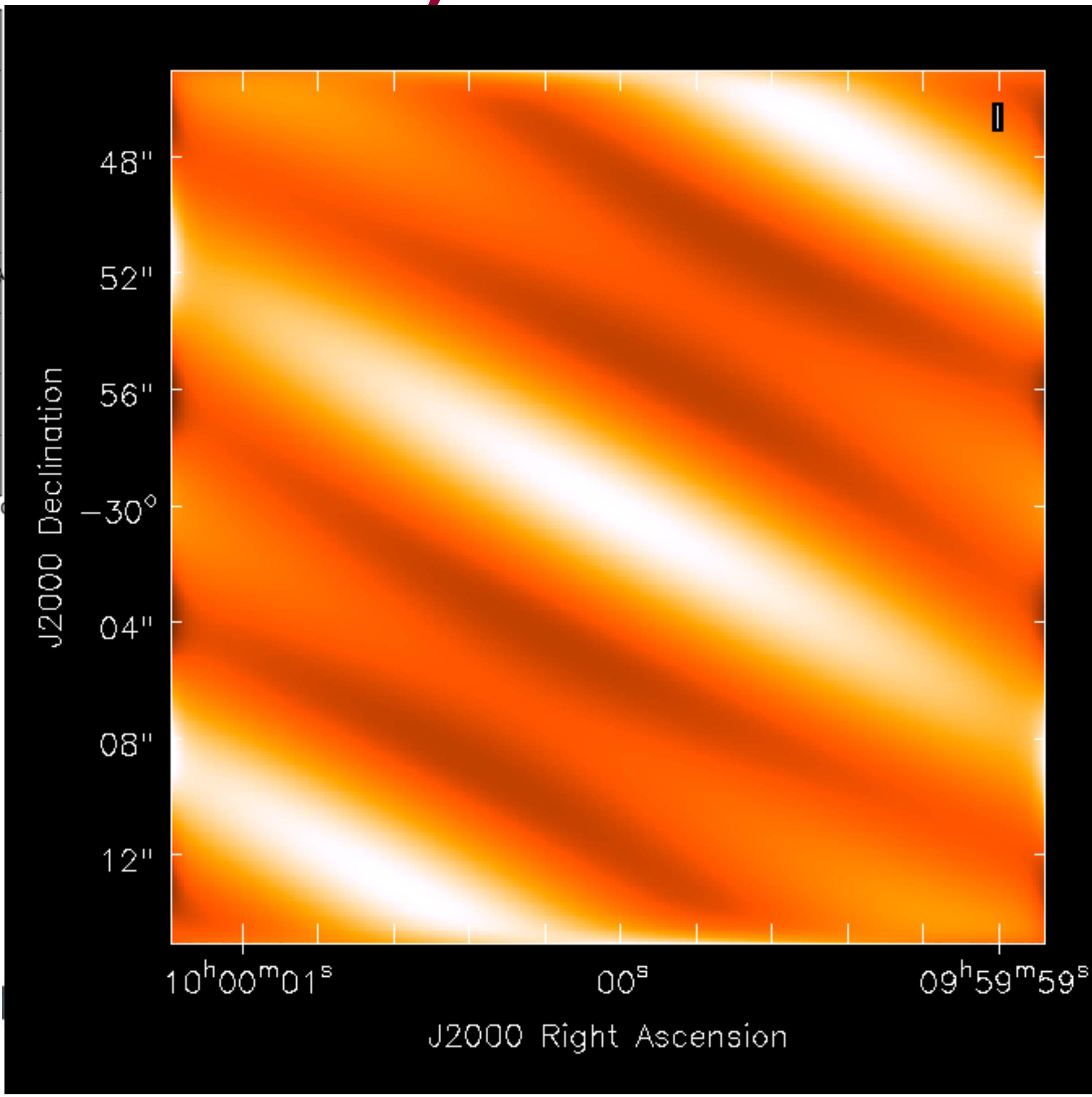




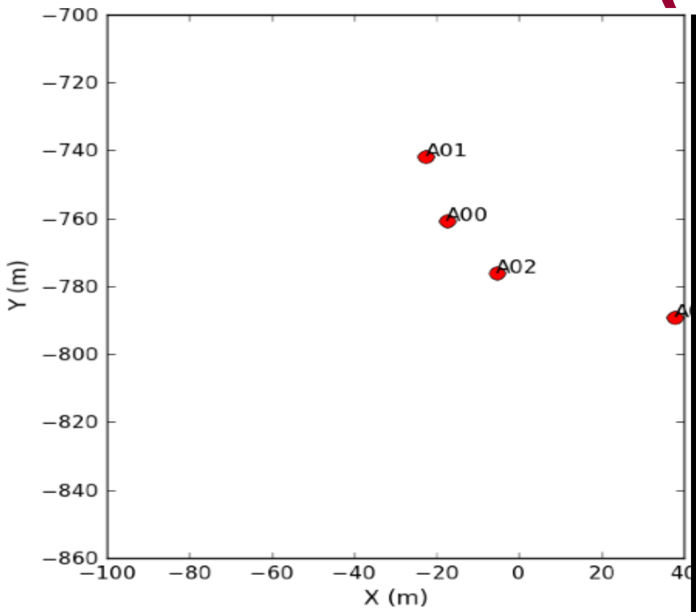
Example: Fringe pattern with 3 Antennas (3 baselines)

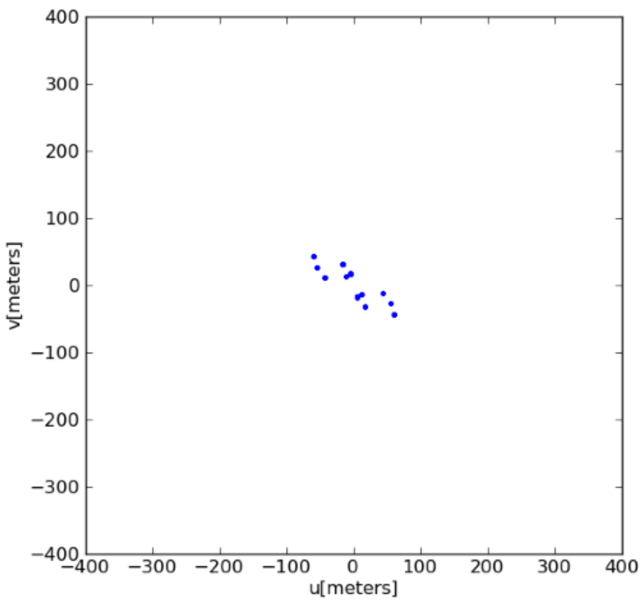


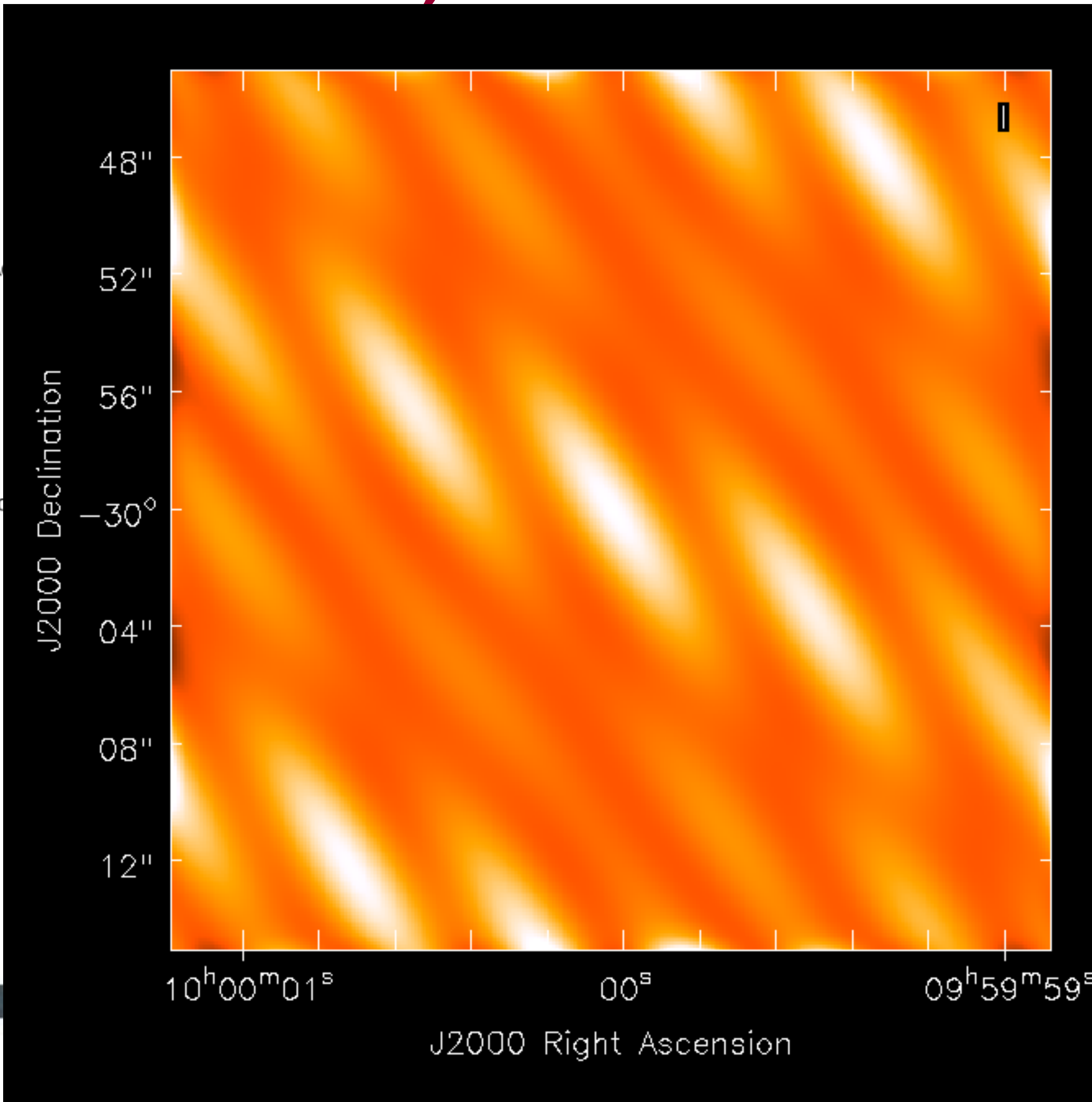




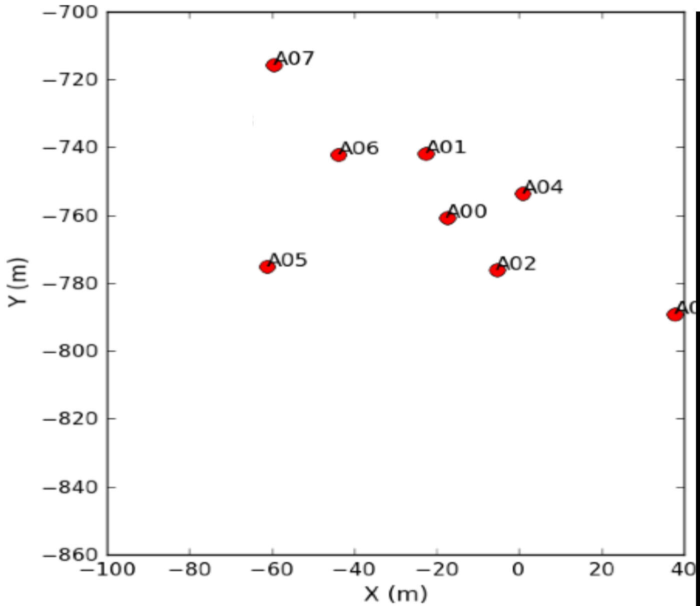
Example: Fringe pattern with 4 Antennas (6 baselines)

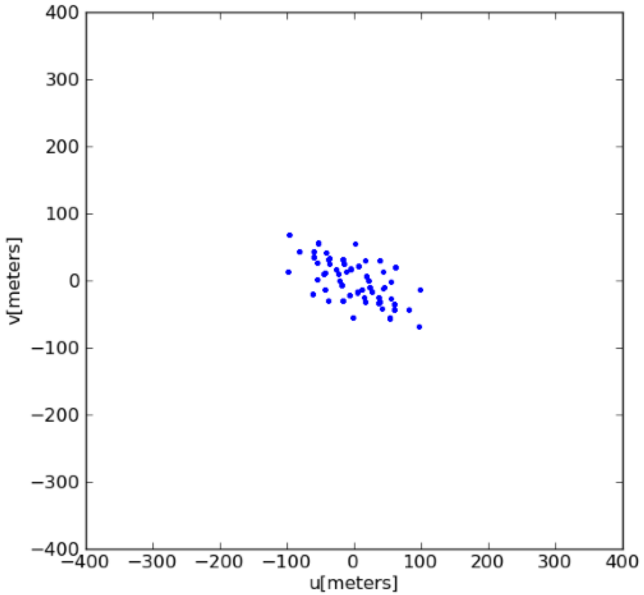


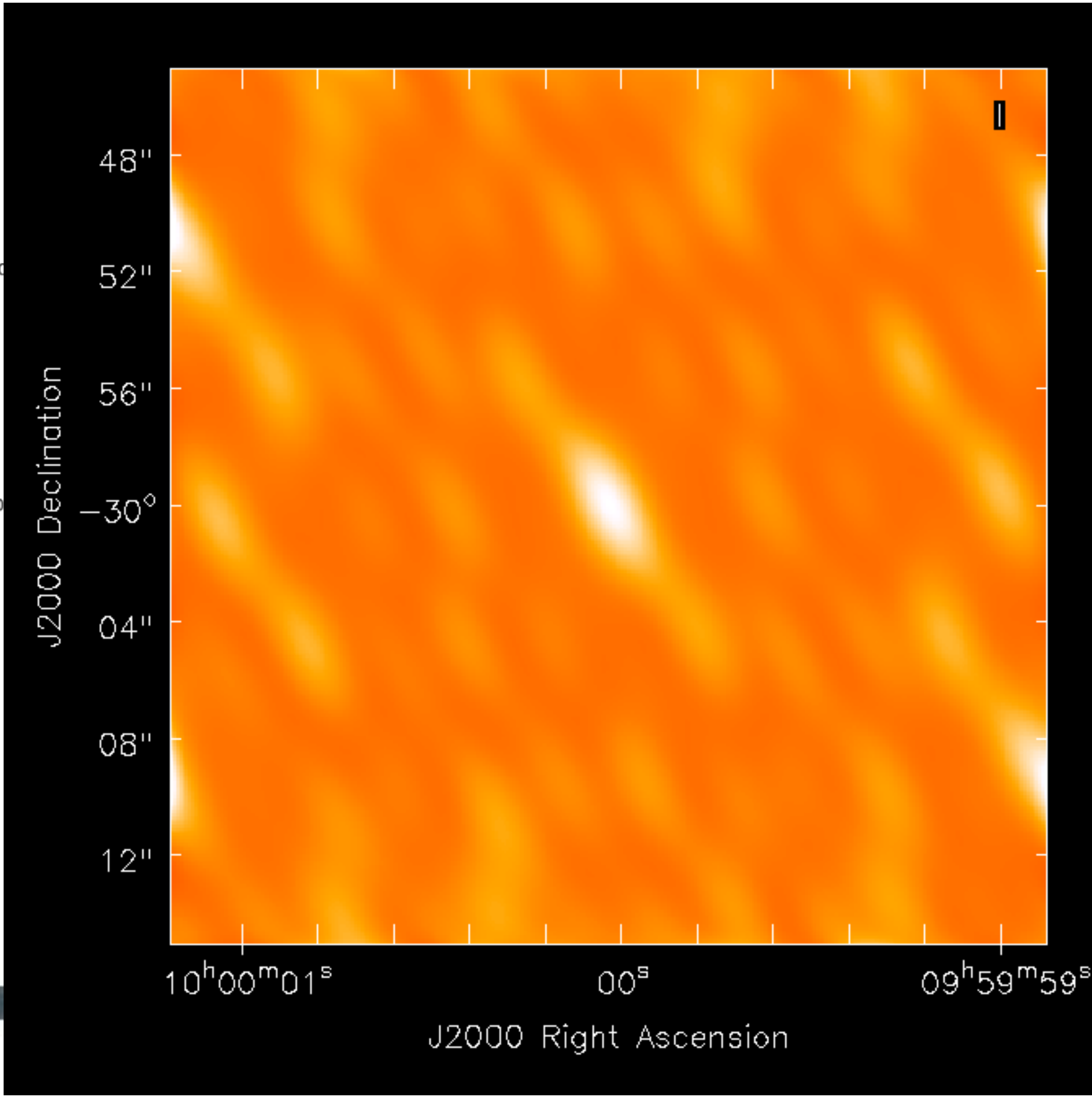




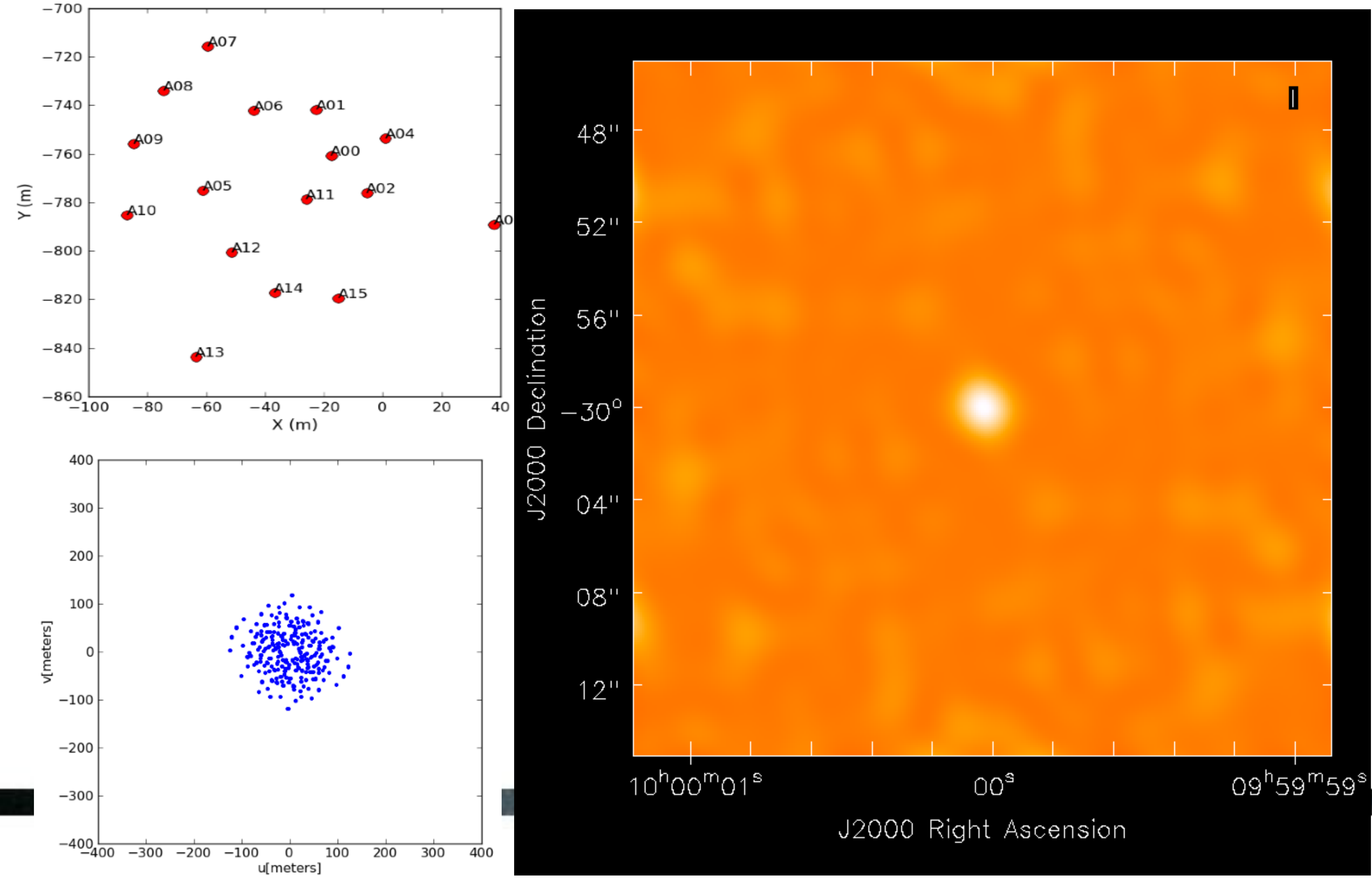
Example: Fringe pattern with 8 Antennas (28 baselines)



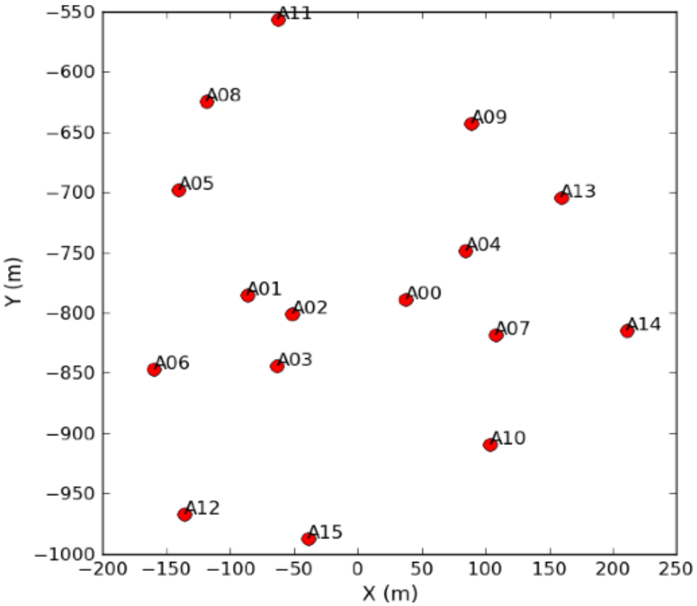


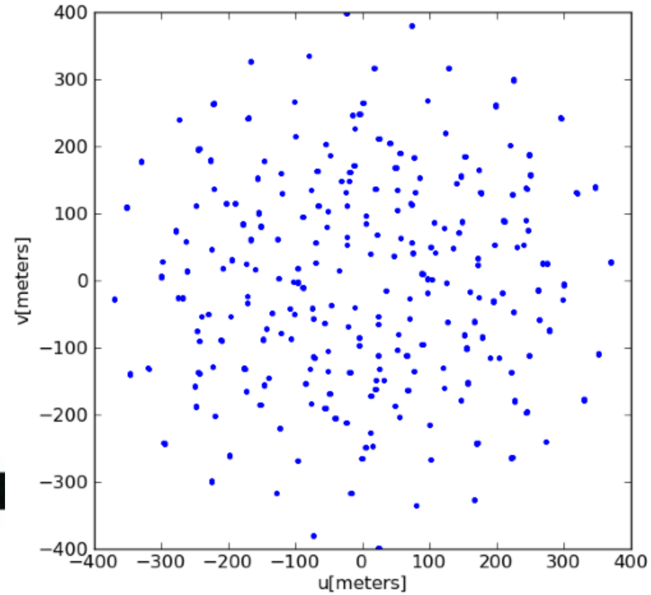


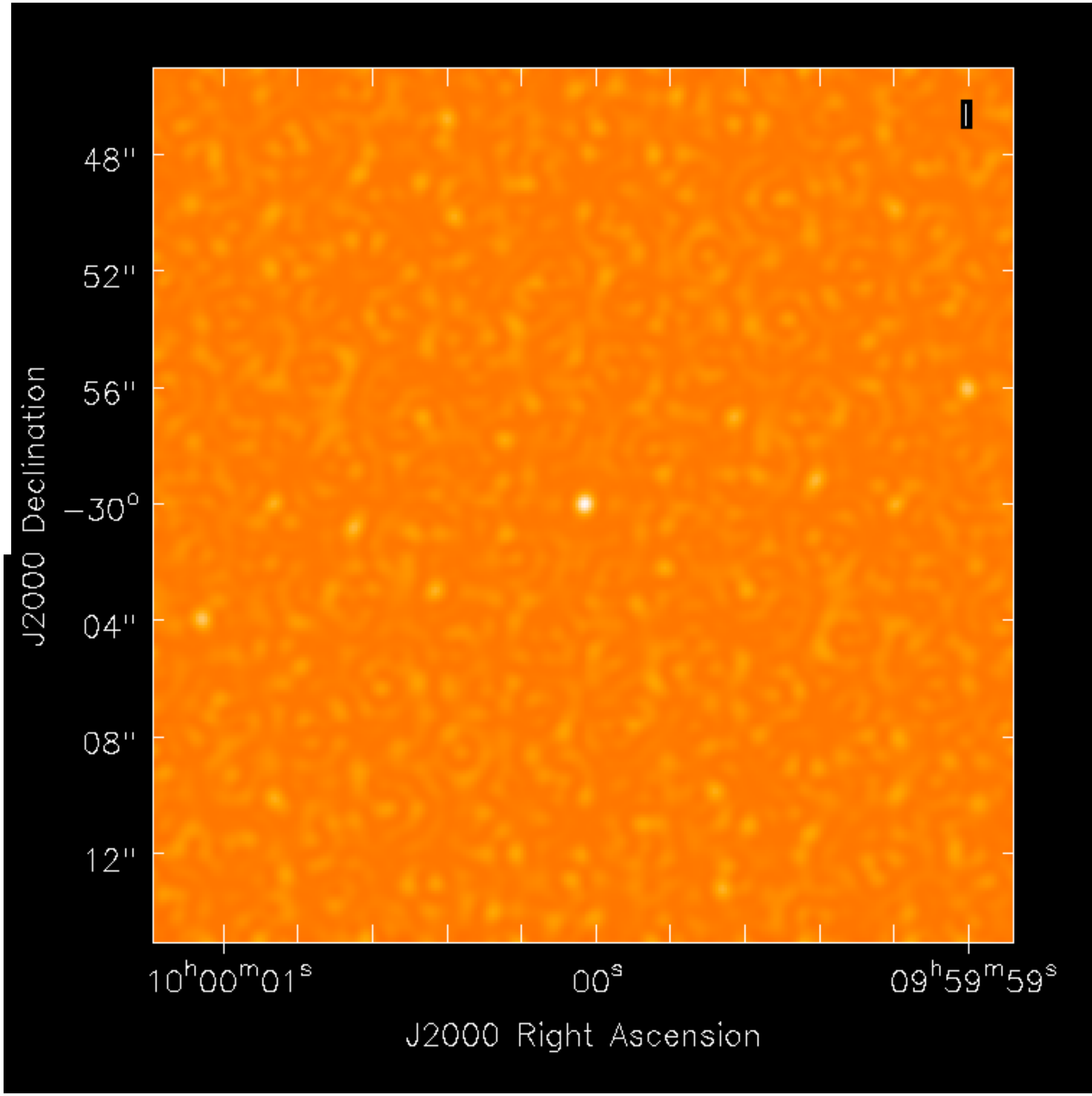
16 Antennas – Compact Configuration



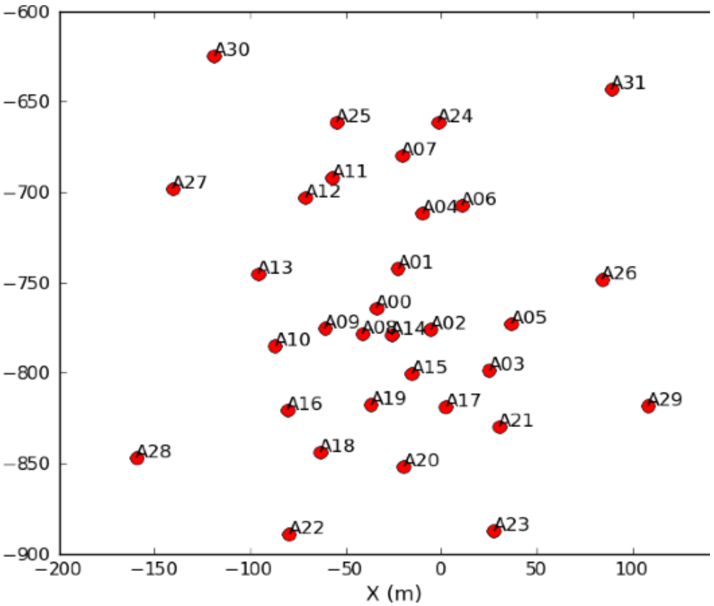
16 Antennas – Extended Configuration

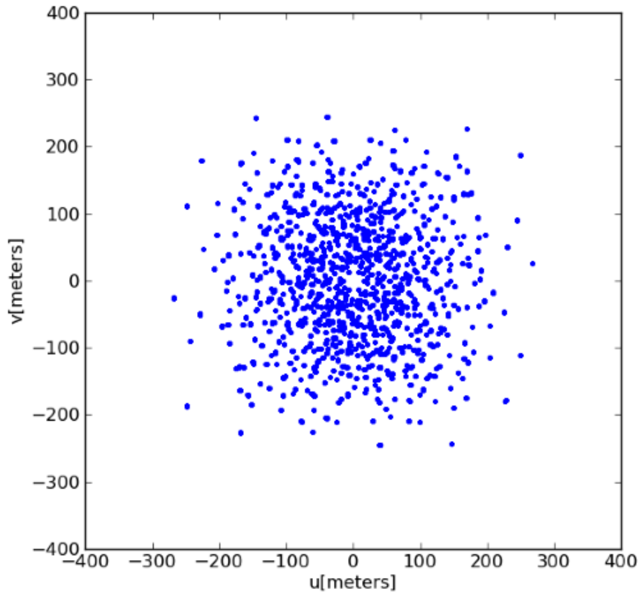


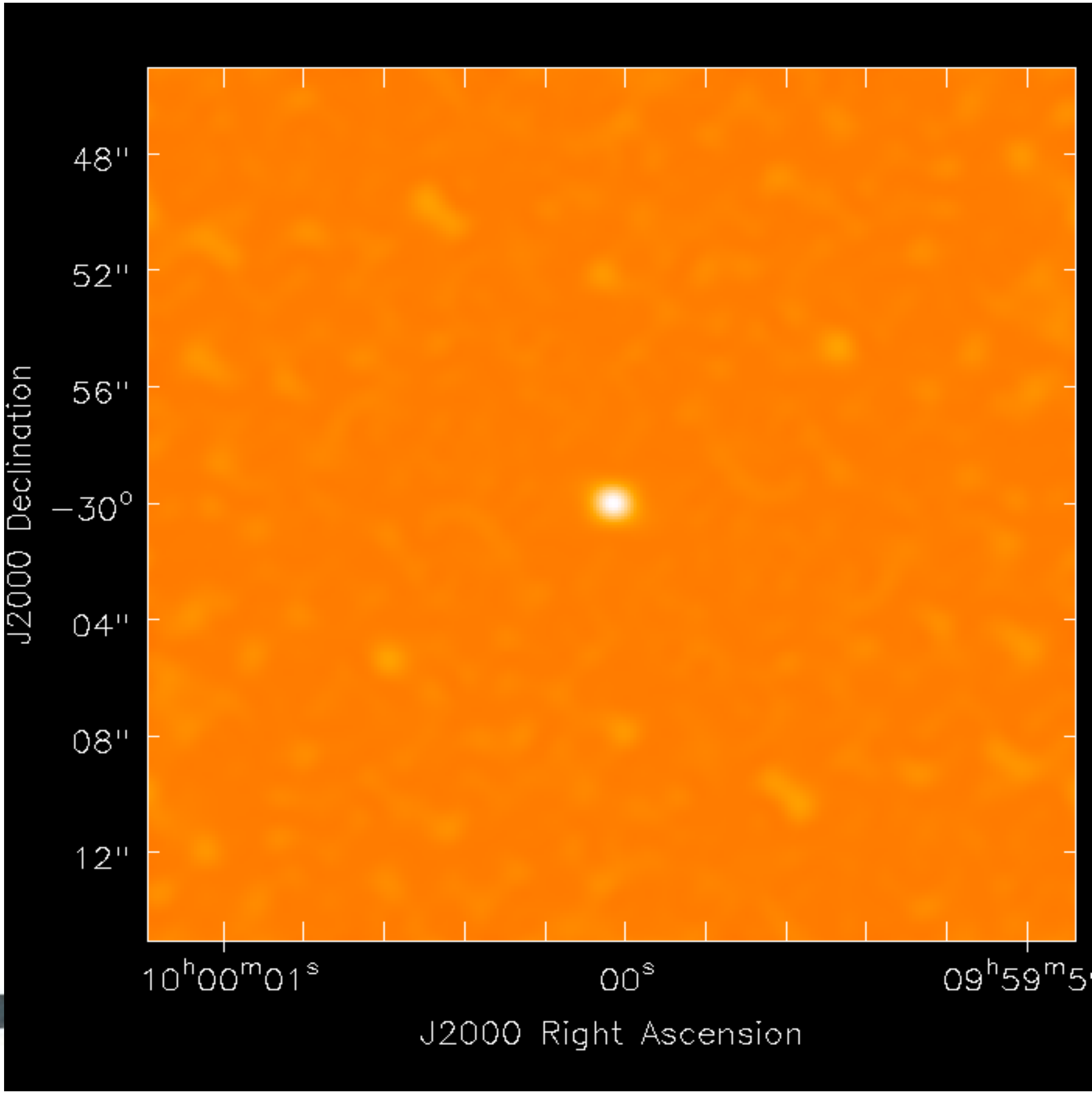




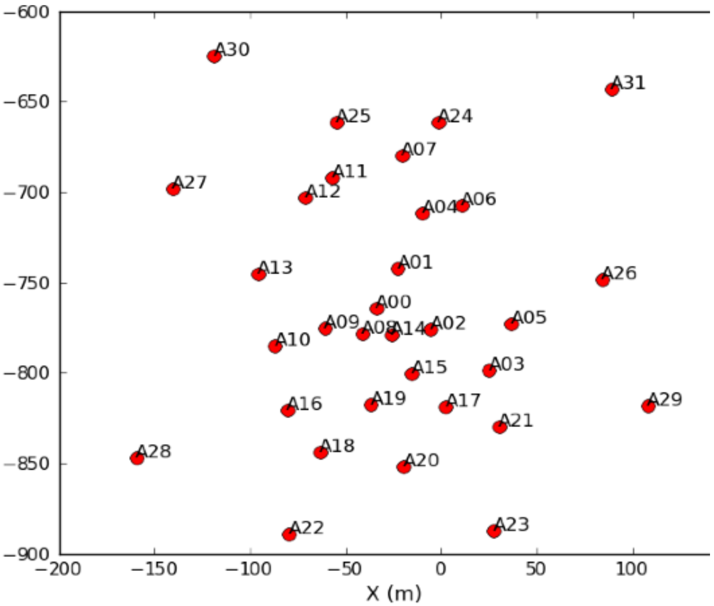
32 Antennas – Instantaneous

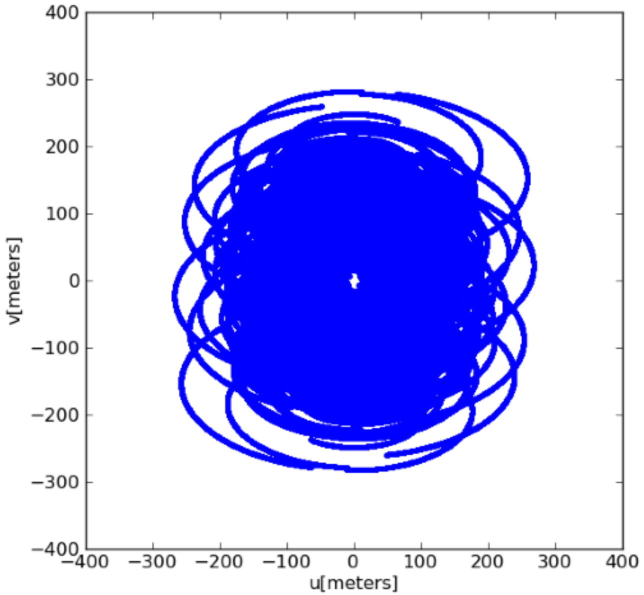


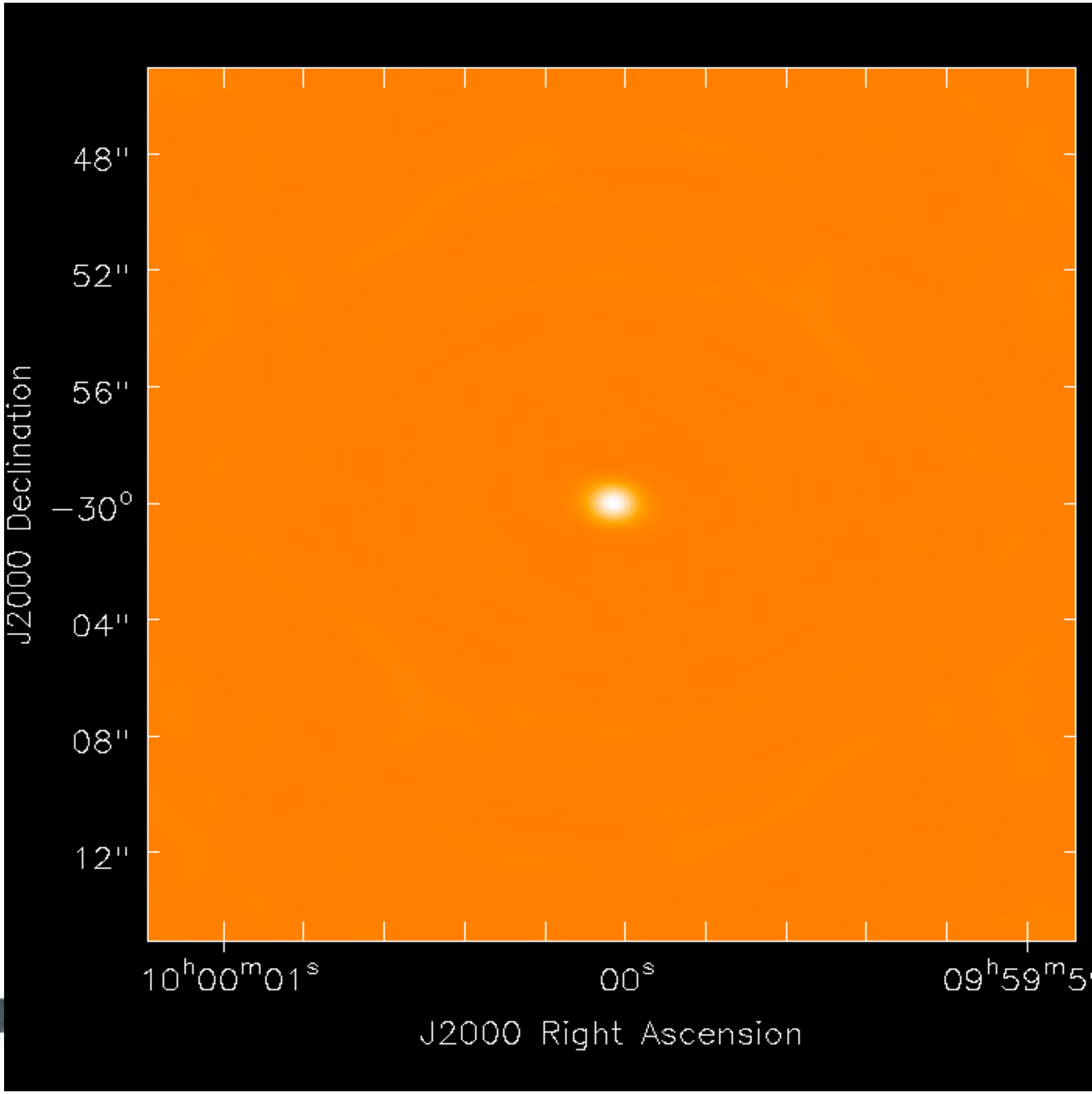




32 Antennas – 8 hours

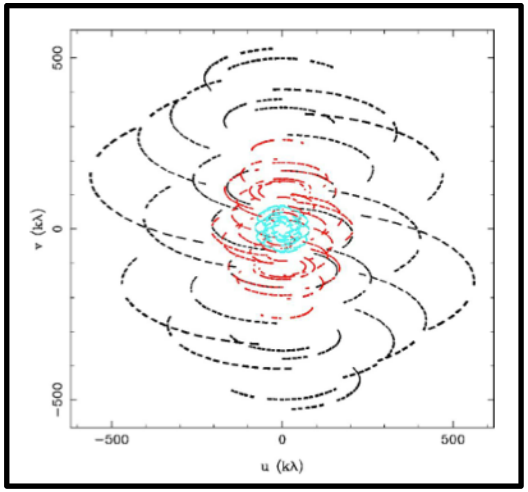






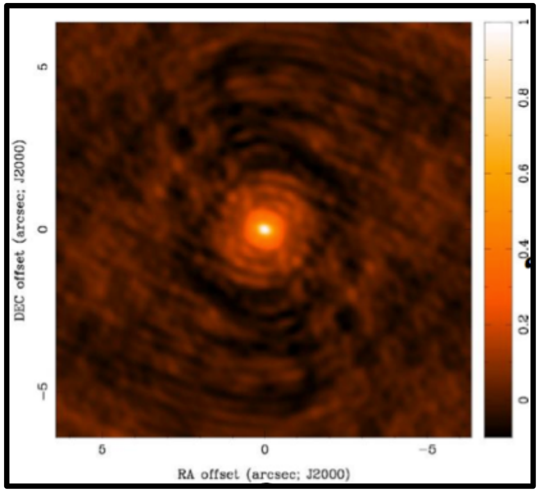
The Dirty Beam

S(u,v)

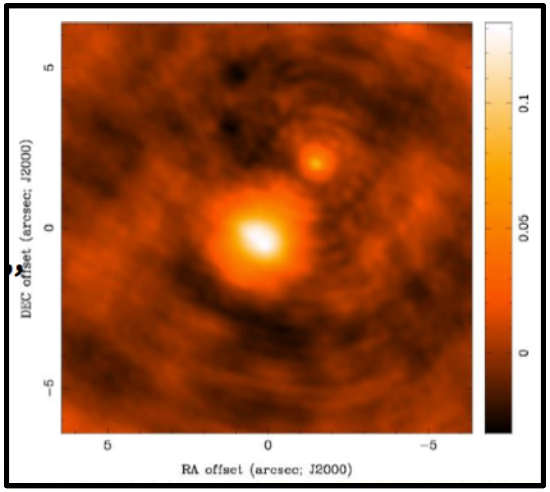


FT

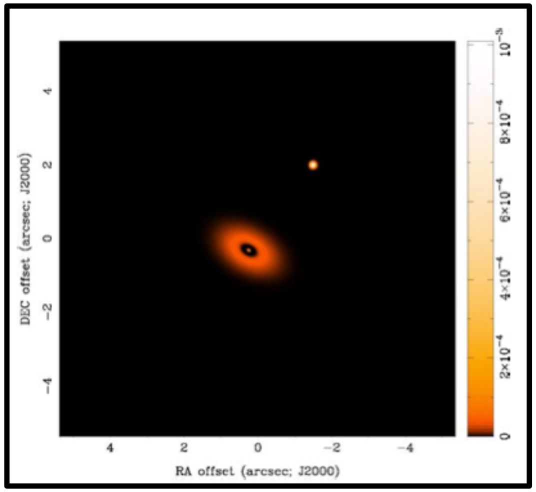
s(x,y)
"Dirty Beam"



*(Convolution)



$T_D(x,y)$
"Dirty Image"



T(x,y)

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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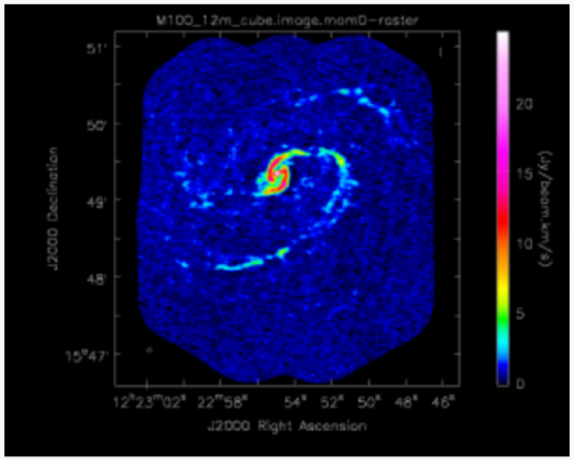
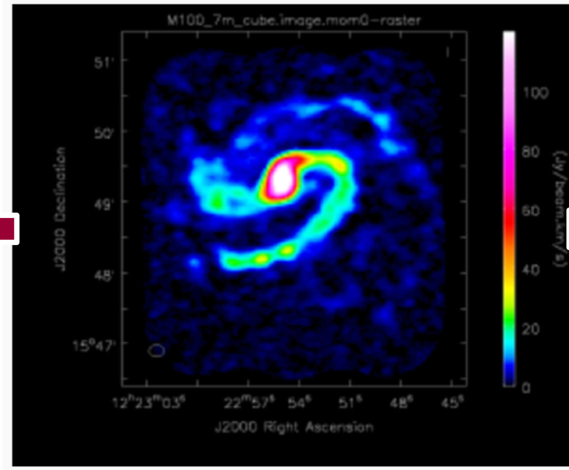
Characteristic Angular Scales: M100

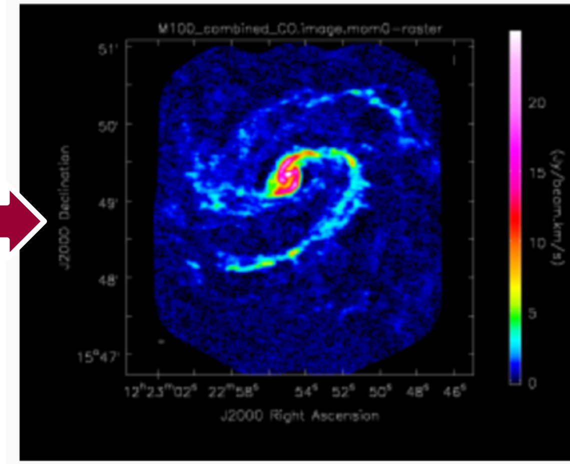
ALMA 12m



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!

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Interferometry: Spatial Scales

- 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

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

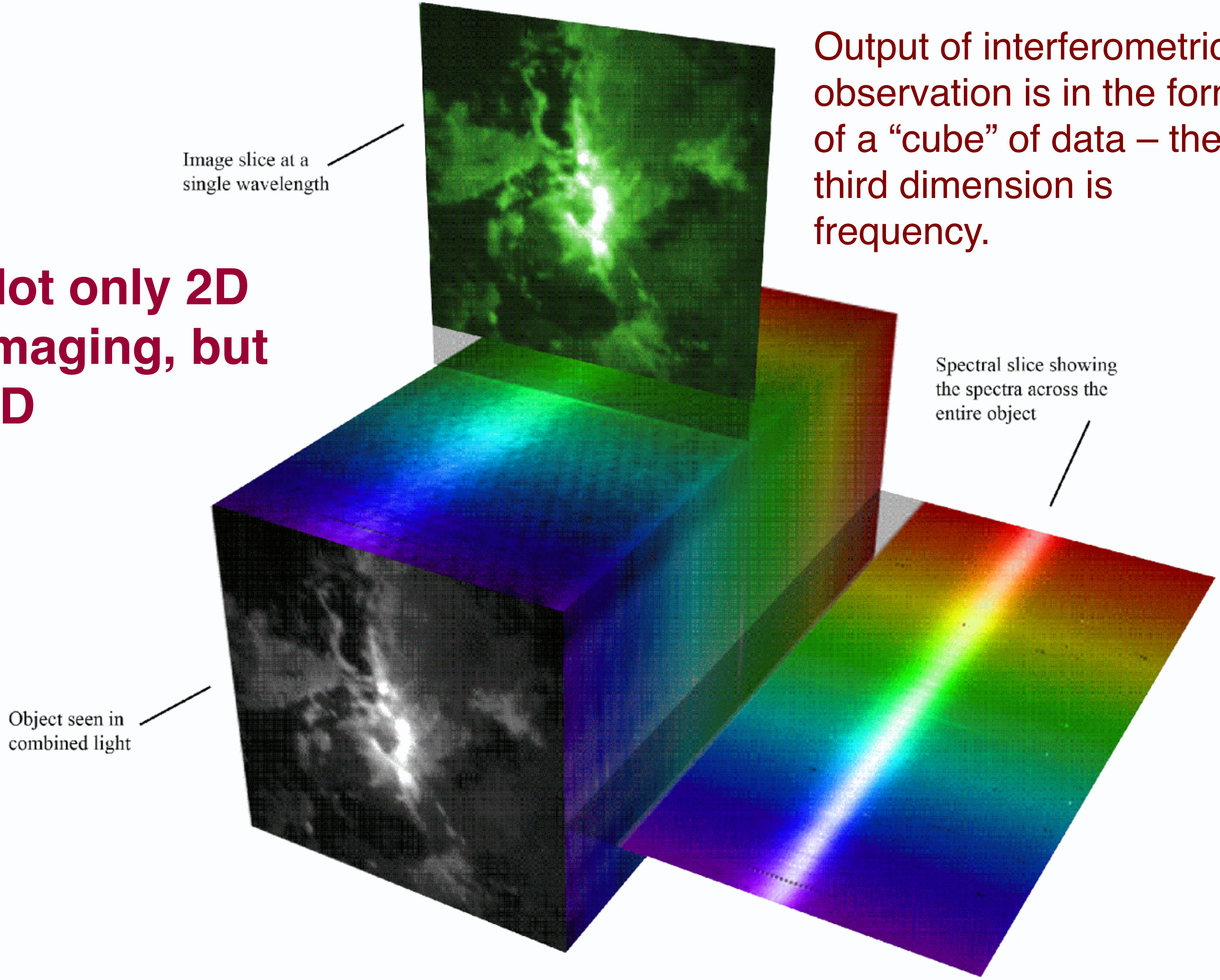
Table A-1: Angular Resolutions (AR) and Maximum Recoverable Scales (MRS) for the Cycle 8 configurations

Config	Lmax		Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin		100 GHz	150 GHz	185 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m	45 m	AR	12.5”	8.4”	6.8”	5.5”	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”
C-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”
C-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”
C-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”
C-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”
C-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”
C-6	2.5 km	AR	0.31”	0.20”	0.17”	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”
C-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”
C-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”			

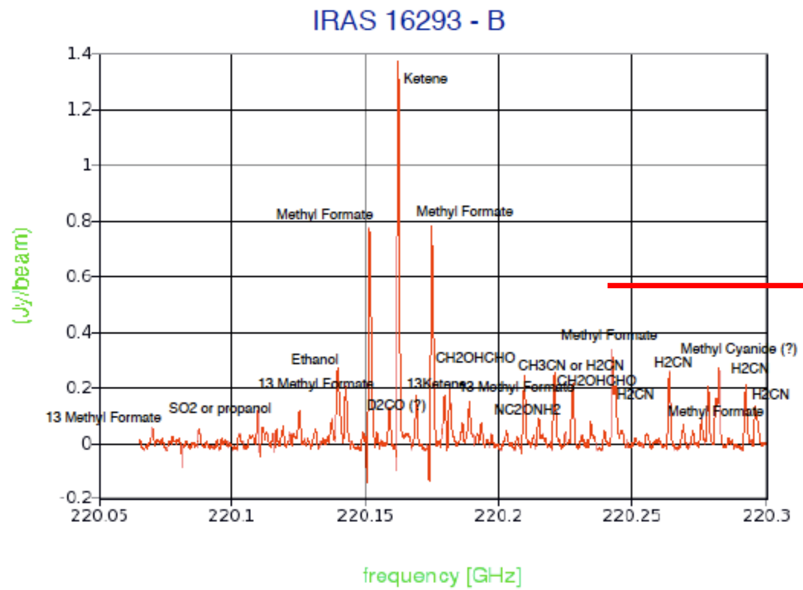
From the ALMA Cycle 8 Proposal Guide

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

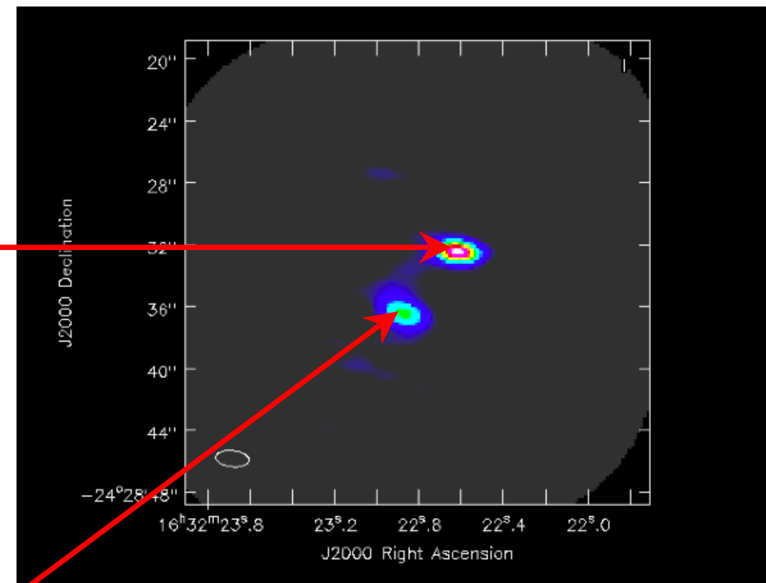
Not only 2D imaging, but 3D



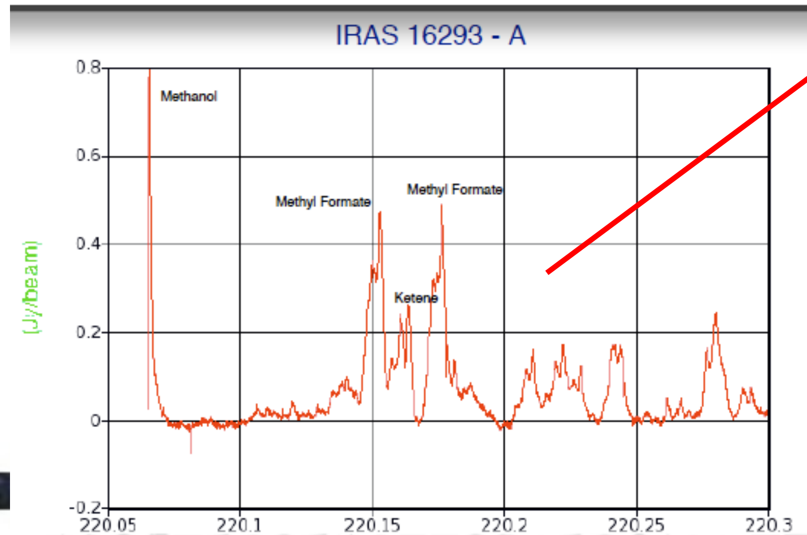
Sometimes the most interesting science lies in the third dimension



Band 6



J. Turner & ALMA CSV team

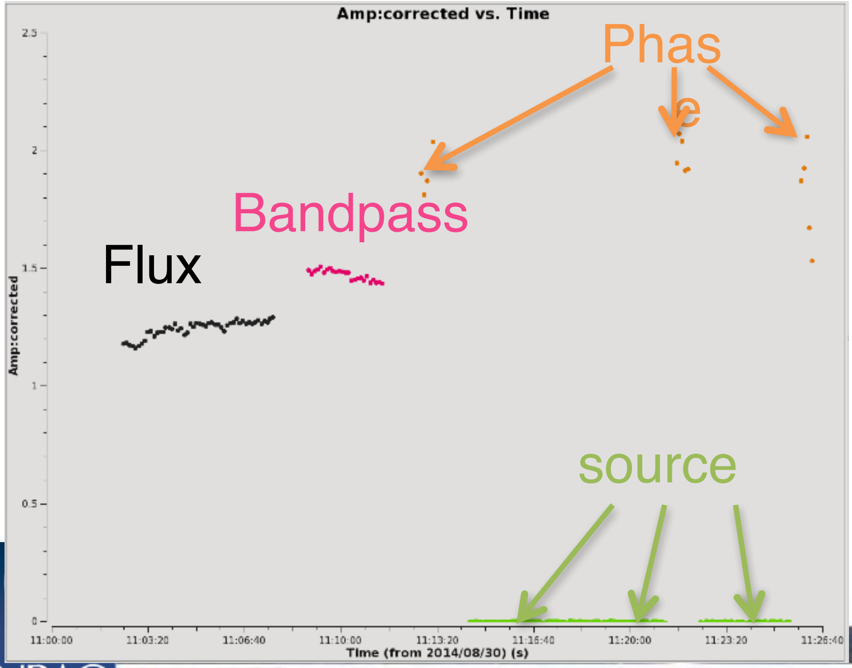


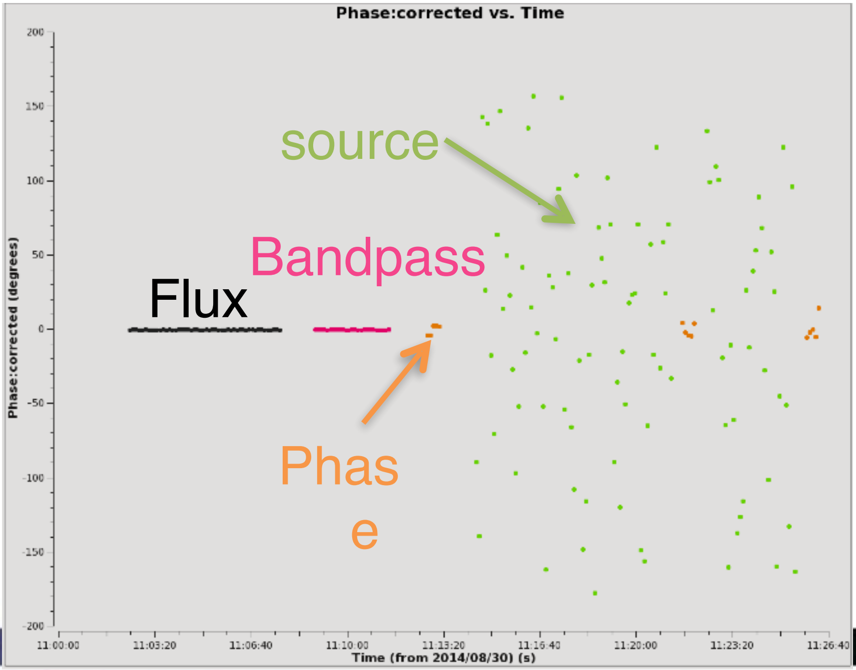
Young Low Mass Stars: IRAS16293

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

A Brief Word on Calibration

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





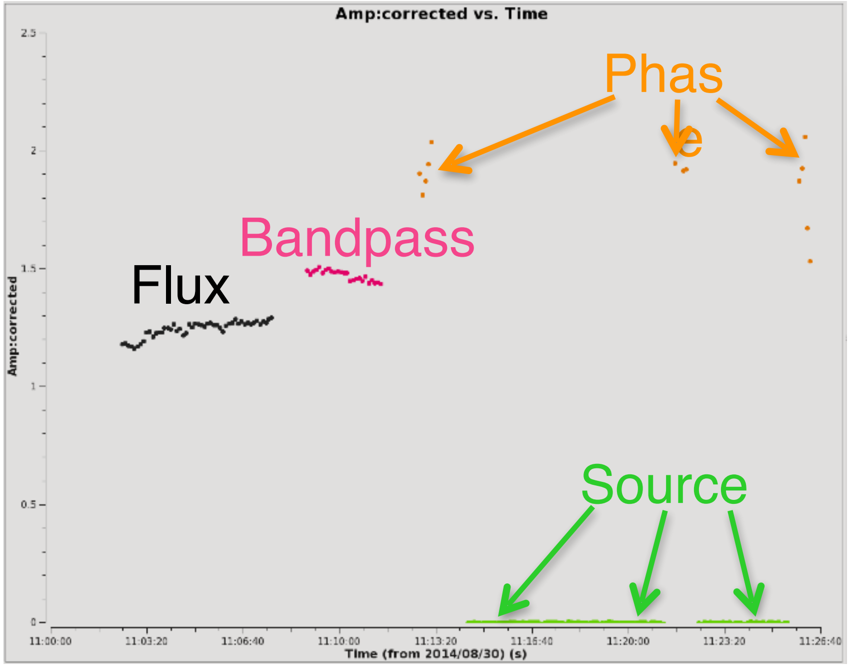
A Brief Word on Calibration

Calibration requirements (Handled by ALMA):

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



Calibration Process

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

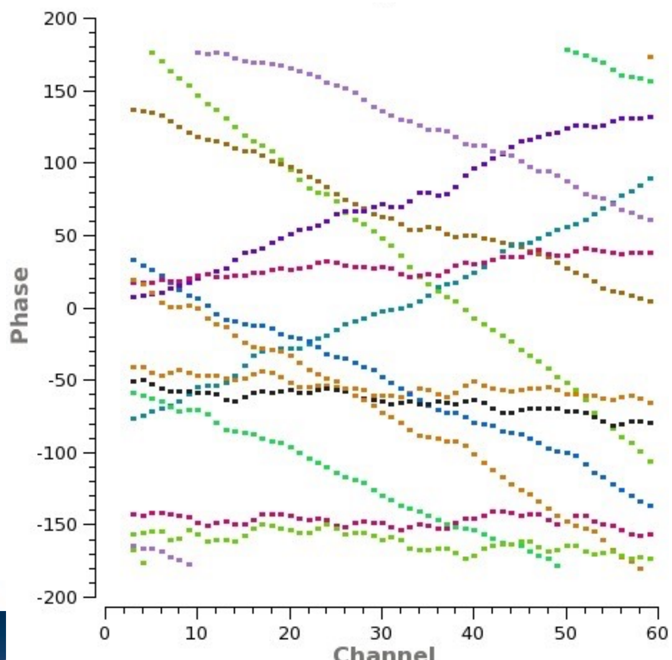
Steps in calibrating interferometric data:
(Note: You don't have to worry about these in your observational set up!)

- 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

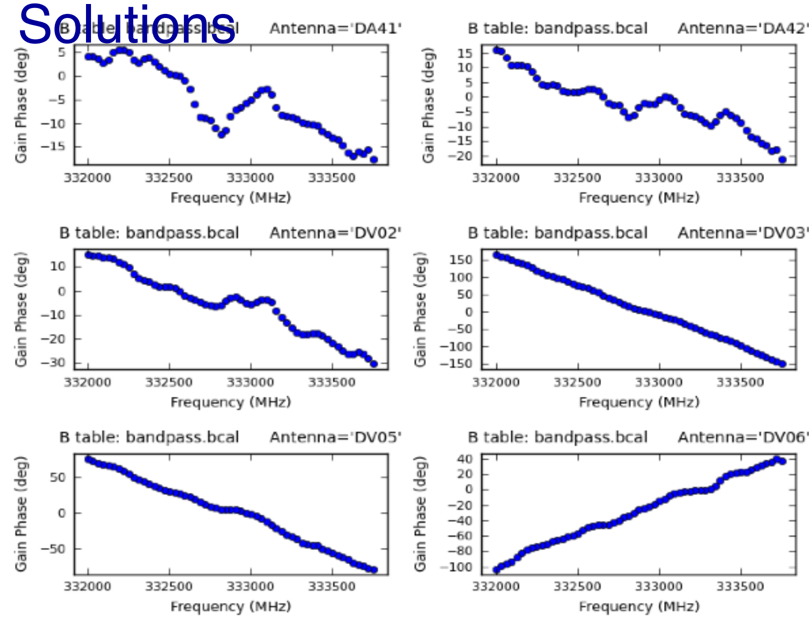
Bandpass Calibration: Phase

* Analogous to optical "flat fielding" + bias subtraction for each antenna.
* Primarily correcting for frequency dependent telescope response (i.e. in the correlator/spectral windows)
* Done once in an SB, uses bright point sources like quasars
* Typically, baseline responses are inverted to antenna-based correction

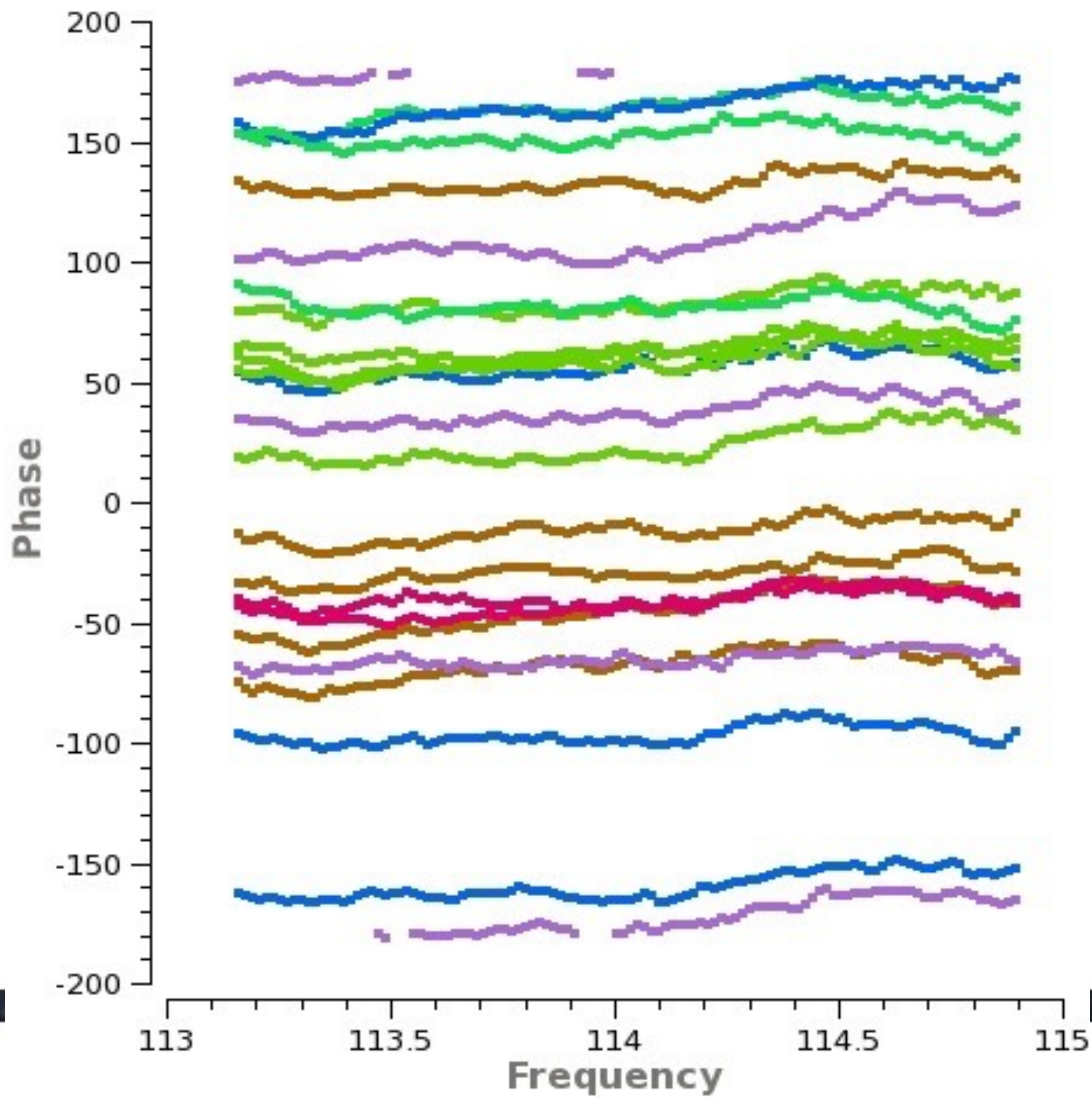
Baselines to one antenna



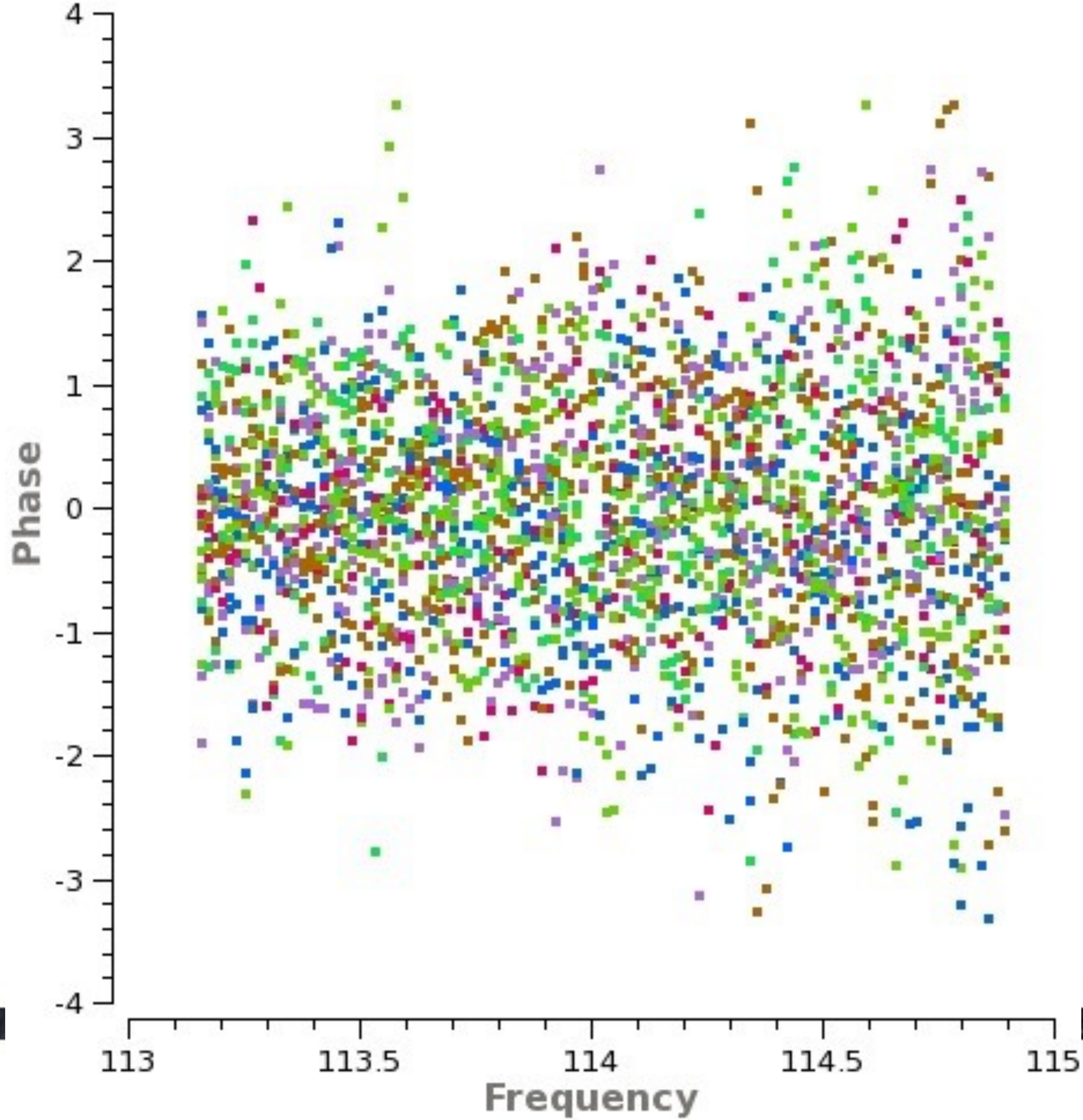
Antenna-based Bandpass Solutions



Bandpass Phase vs. Frequency (Before)

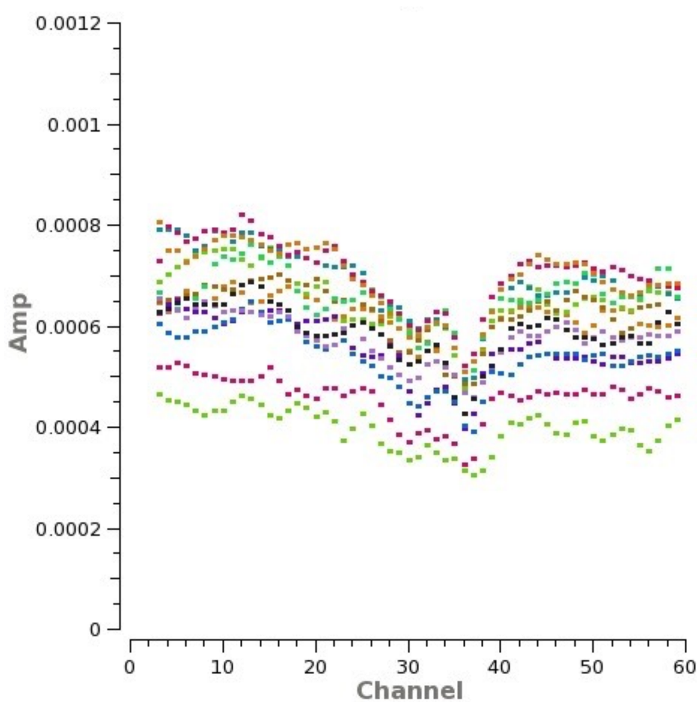


Bandpass Phase vs. Frequency (After)

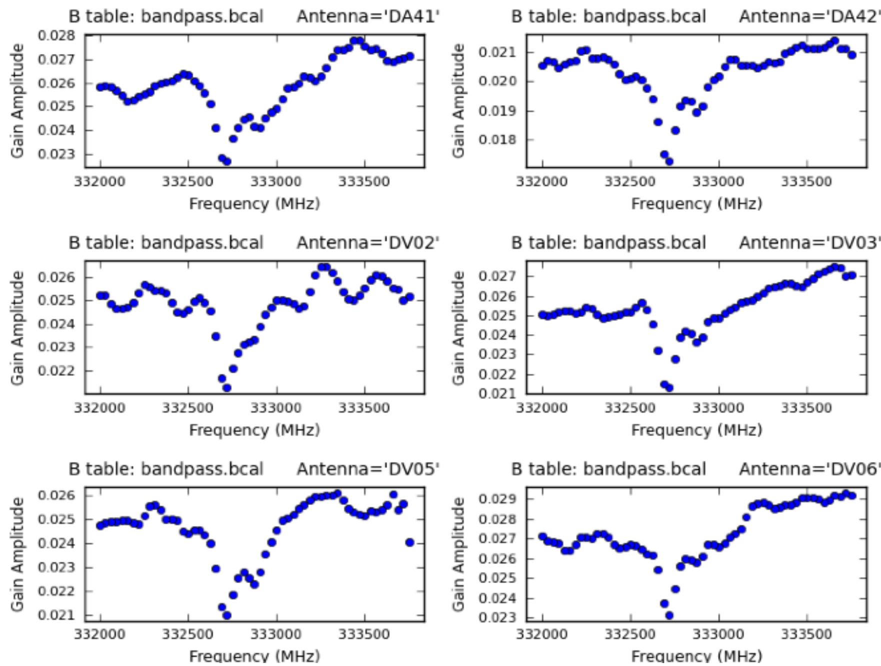


Bandpass Calibration: Amplitude

Baselines to one antenna



Amplitude Before Bandpass Calibration

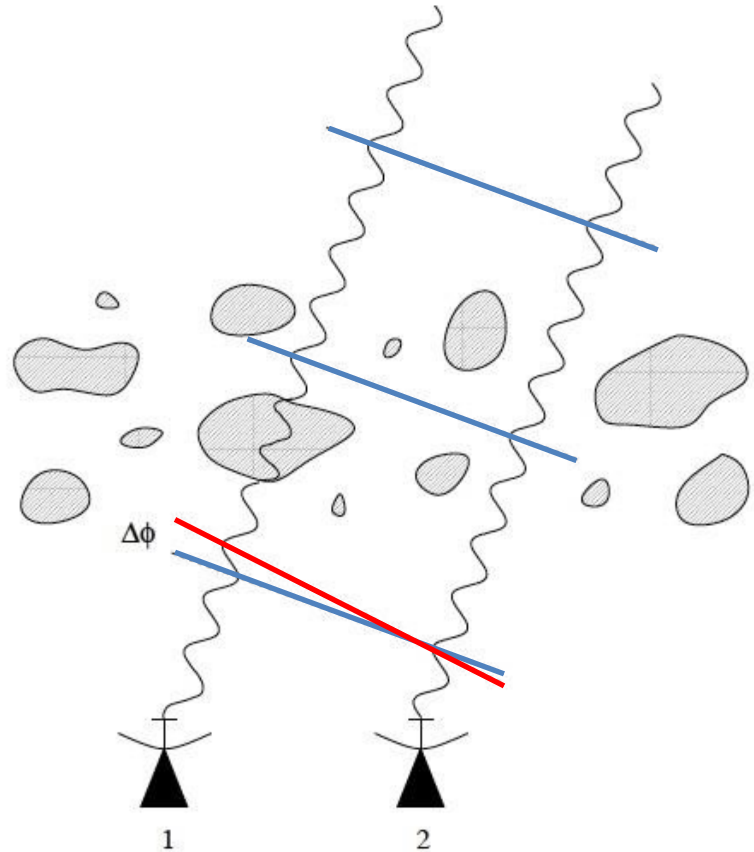


Bandpass solutions for individual antennas

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)

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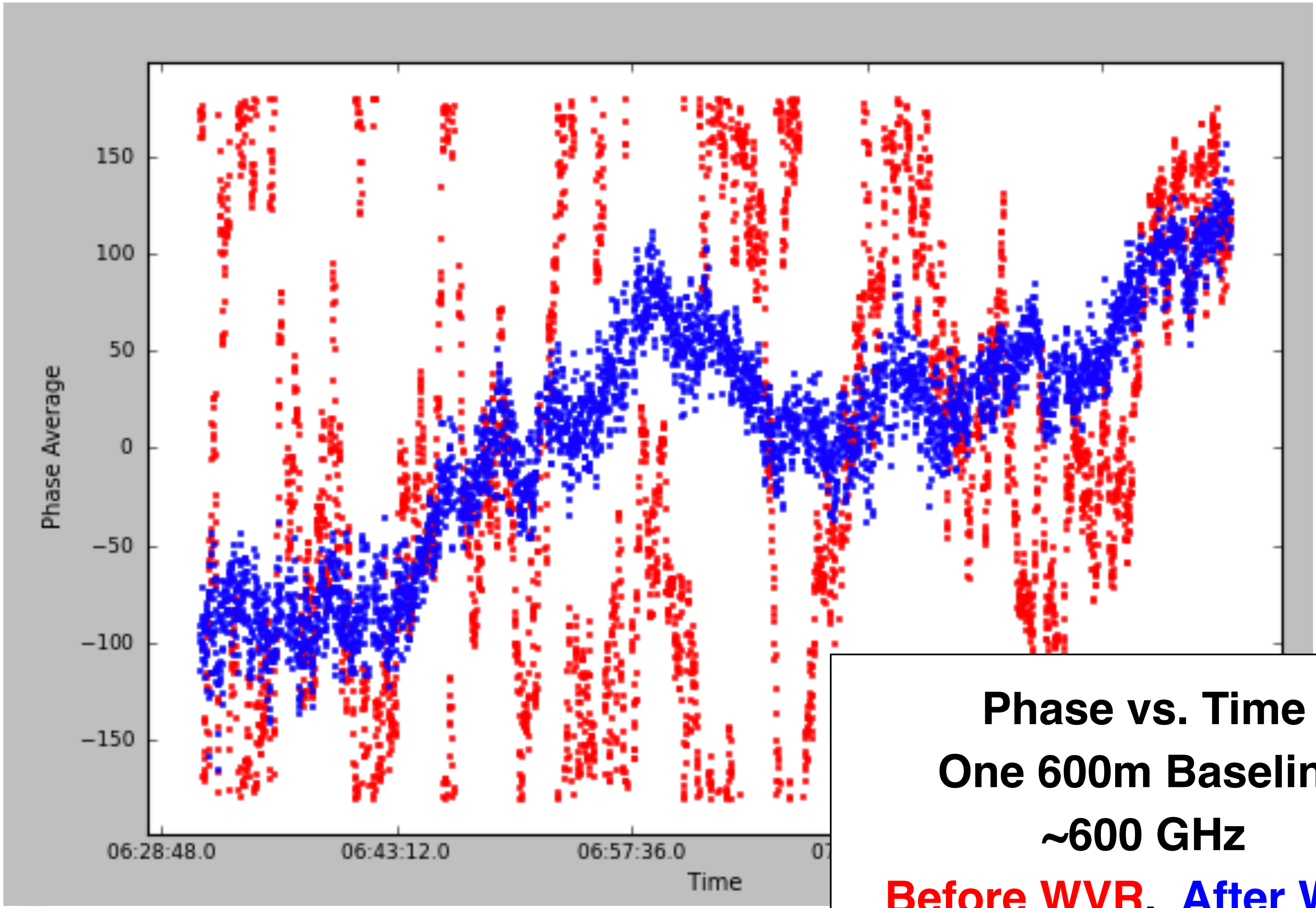
Water Vapor Correction on ALMA



Phase vs. Time

One 600m Baseline

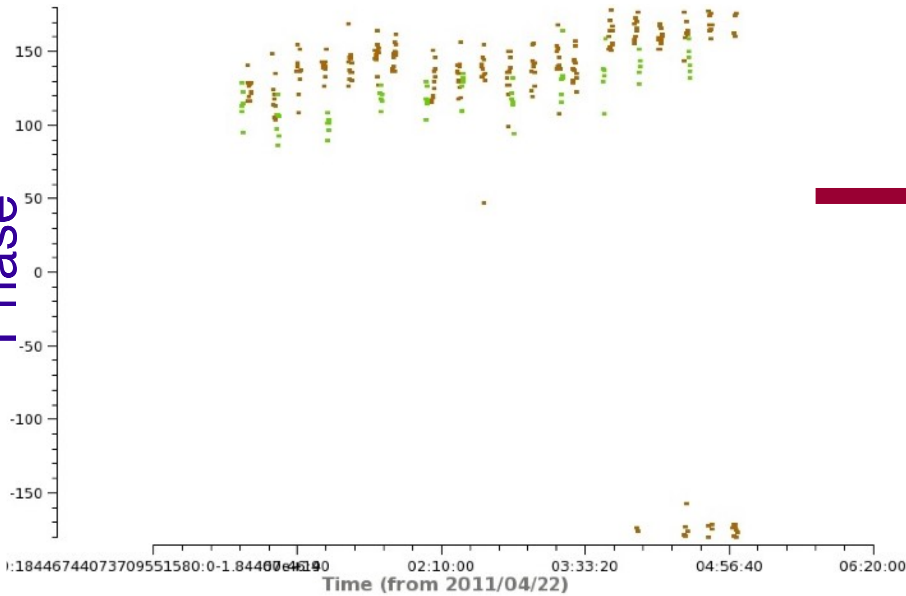
~600 GHz

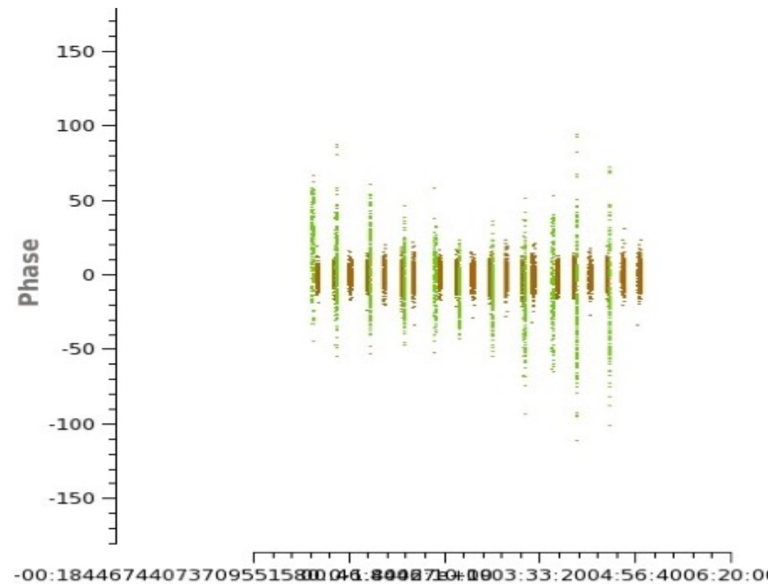
Before WVR, After WVR

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.

Phase





Time

Corrected using point source mode

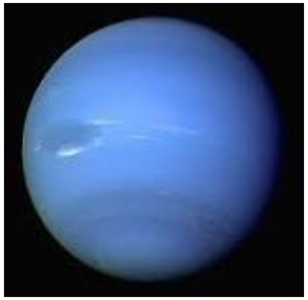
Flux (or Amplitude) Calibration

Two Steps:

1. Use calibration devices with known temperatures (hotload and ambient load) to measure System Temperature frequently.

2. 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 modeled very well.

The derived amplitude vs. time corrections for the flux calibrator are then applied to the science target.



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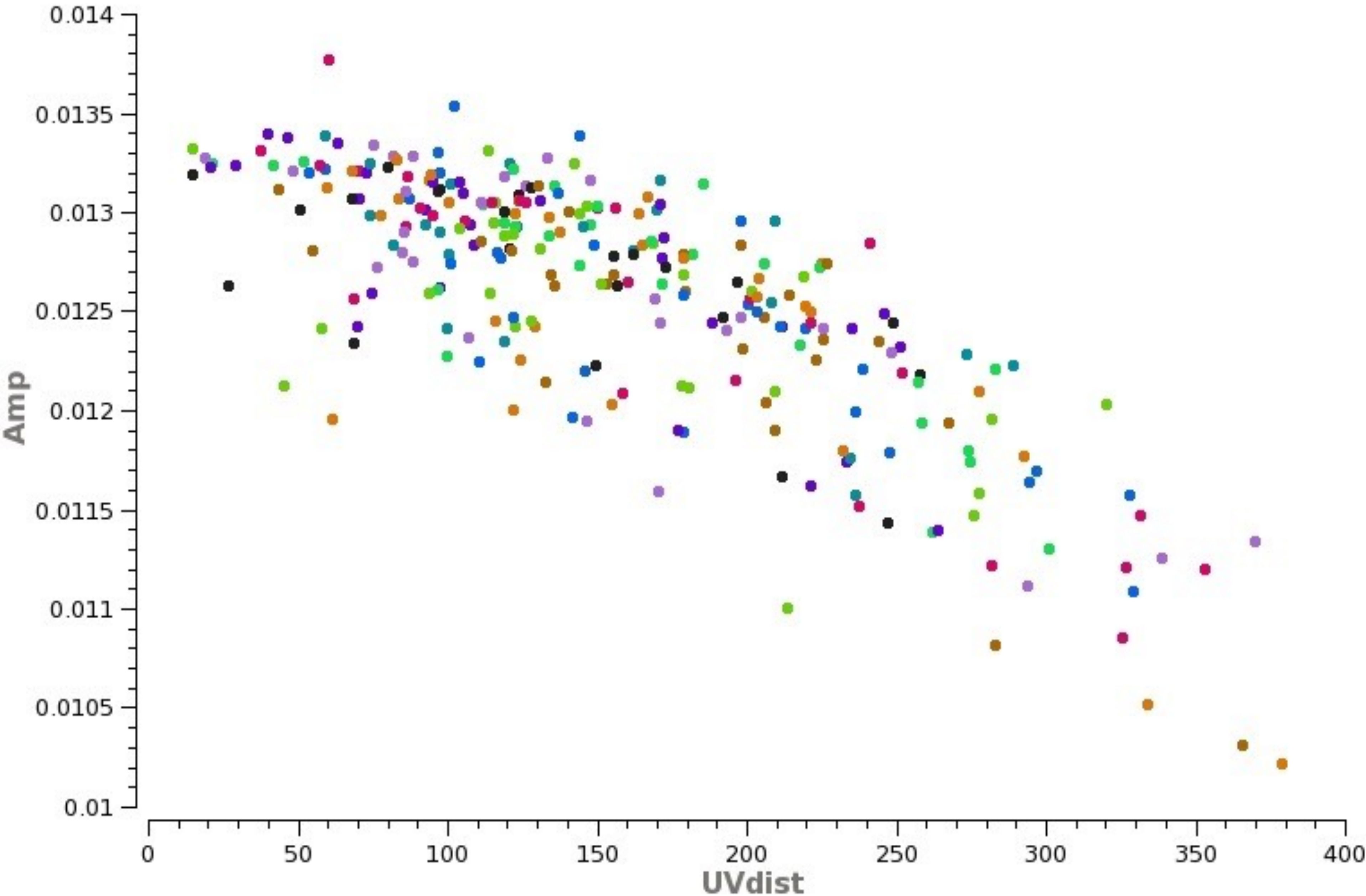
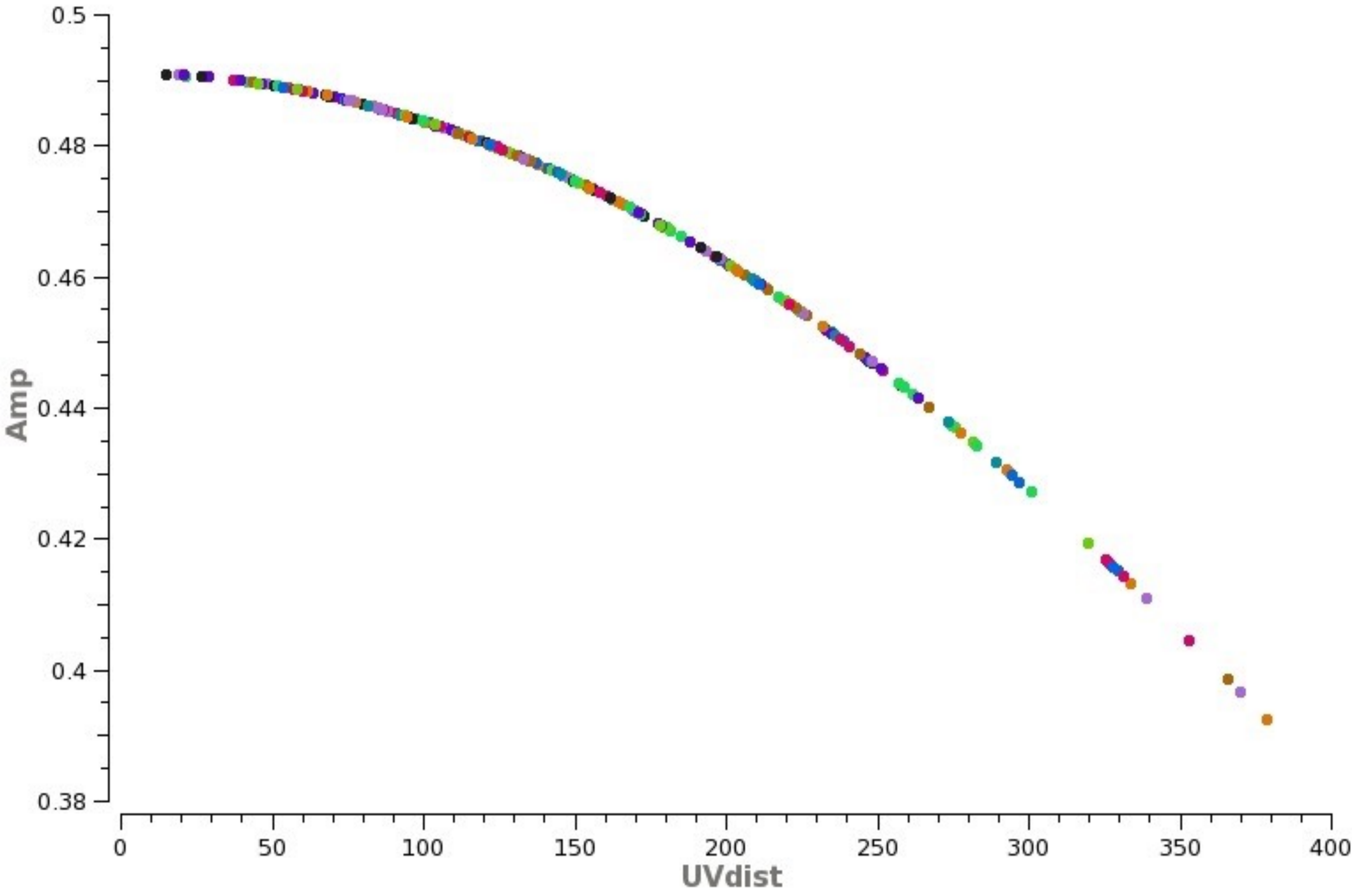
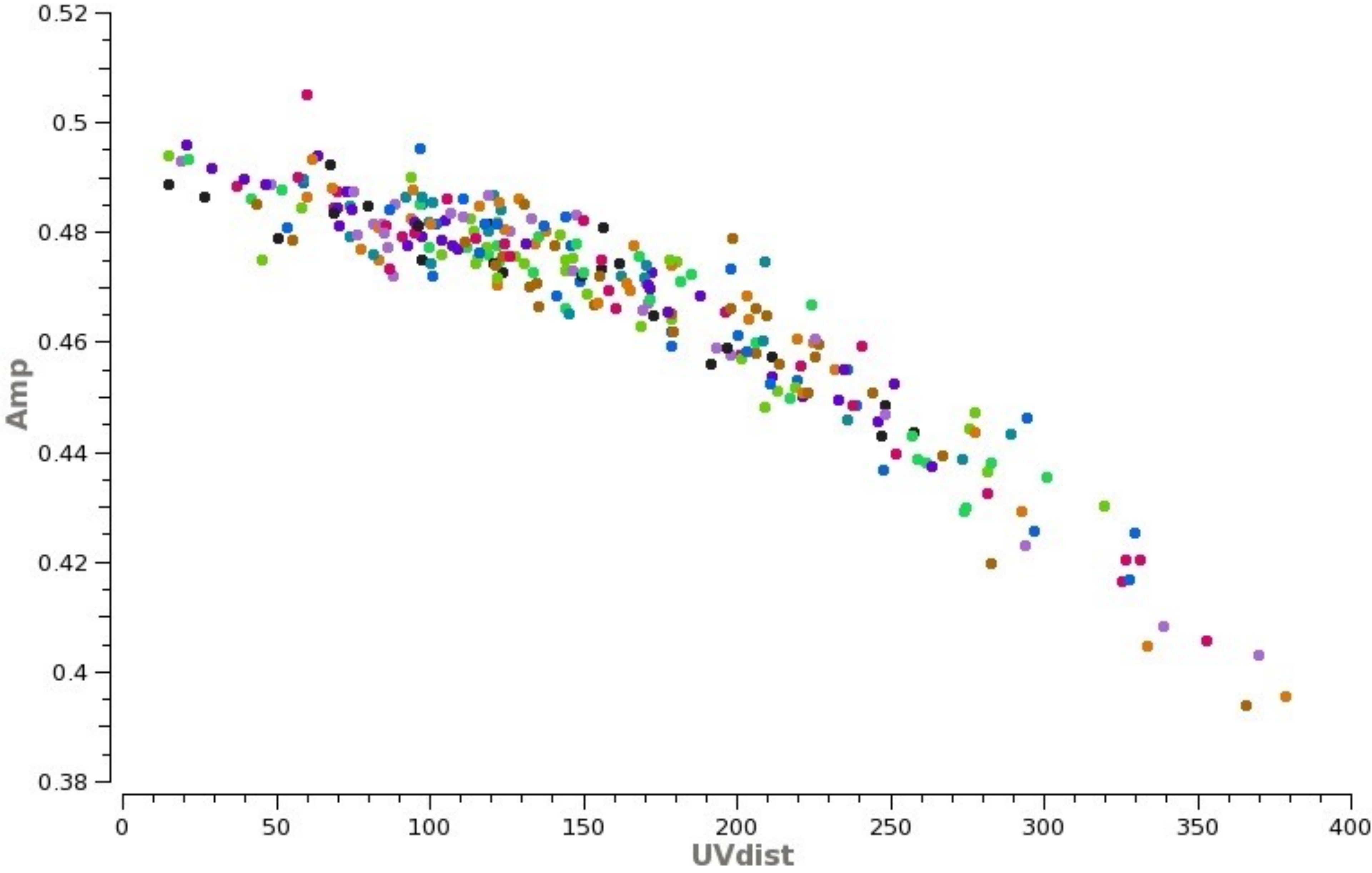
Amp-Calibrators Amp vs. uv-distance (Before)



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



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



Good Future References

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