Radio and mm astronomy

Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

16.10 Introduction & Overview	*(HL & HB)*
23.10 Emission mechanisms, physics of radiation	*(HB)*
30.10 Telescopes – single-dishs	*(HL)*
06.11 Telescopes – interferometers	**(HB)**
13.11 Instruments – continuum radiation	(HL)
20.11 Instruments – line radiation	(HB)
27.11 Continuous radiation (free-free, synchrotron, dust, CMB)	(HL)
04.12 Line radiation	(HB)
11.12 Radiation transfer	(HL)
18.12 Effelsberg Excursion	
Christmas break	
08.01 Molecules and chemistry	(HL)
15.01 Physics and kinematics	(HB)
22.01 Applications	(HL)
29.01 Applications	(HB)
05.02 last week, no lecture	

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1213.html

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Topics today

- The quest for high spatial resolution

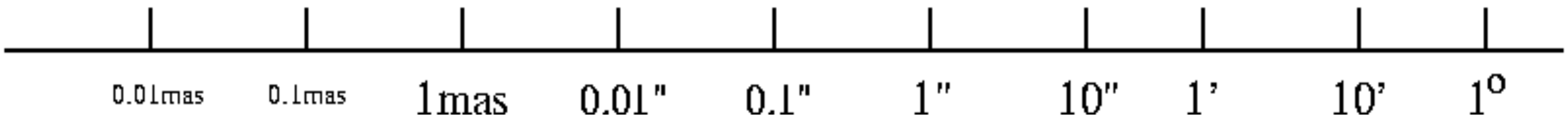
- Basic double slit experiment

- Application to real interferometers

Why Interferometer?

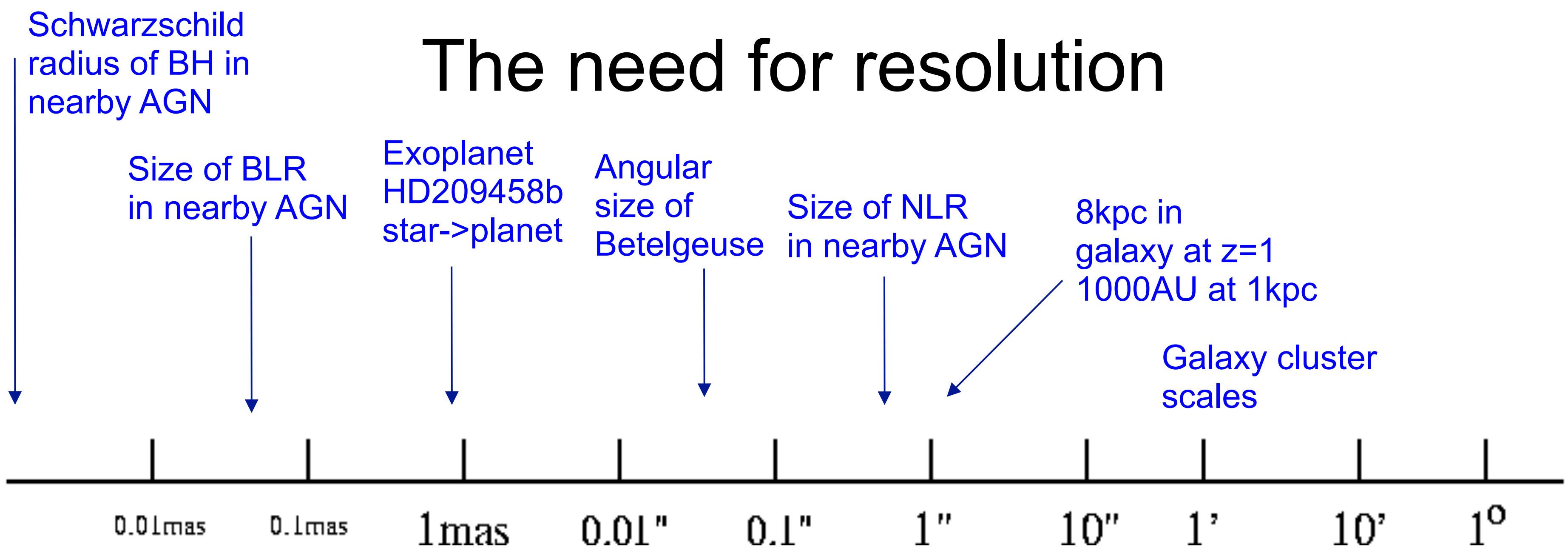
$$\Theta = \lambda/d$$

The need for resolution

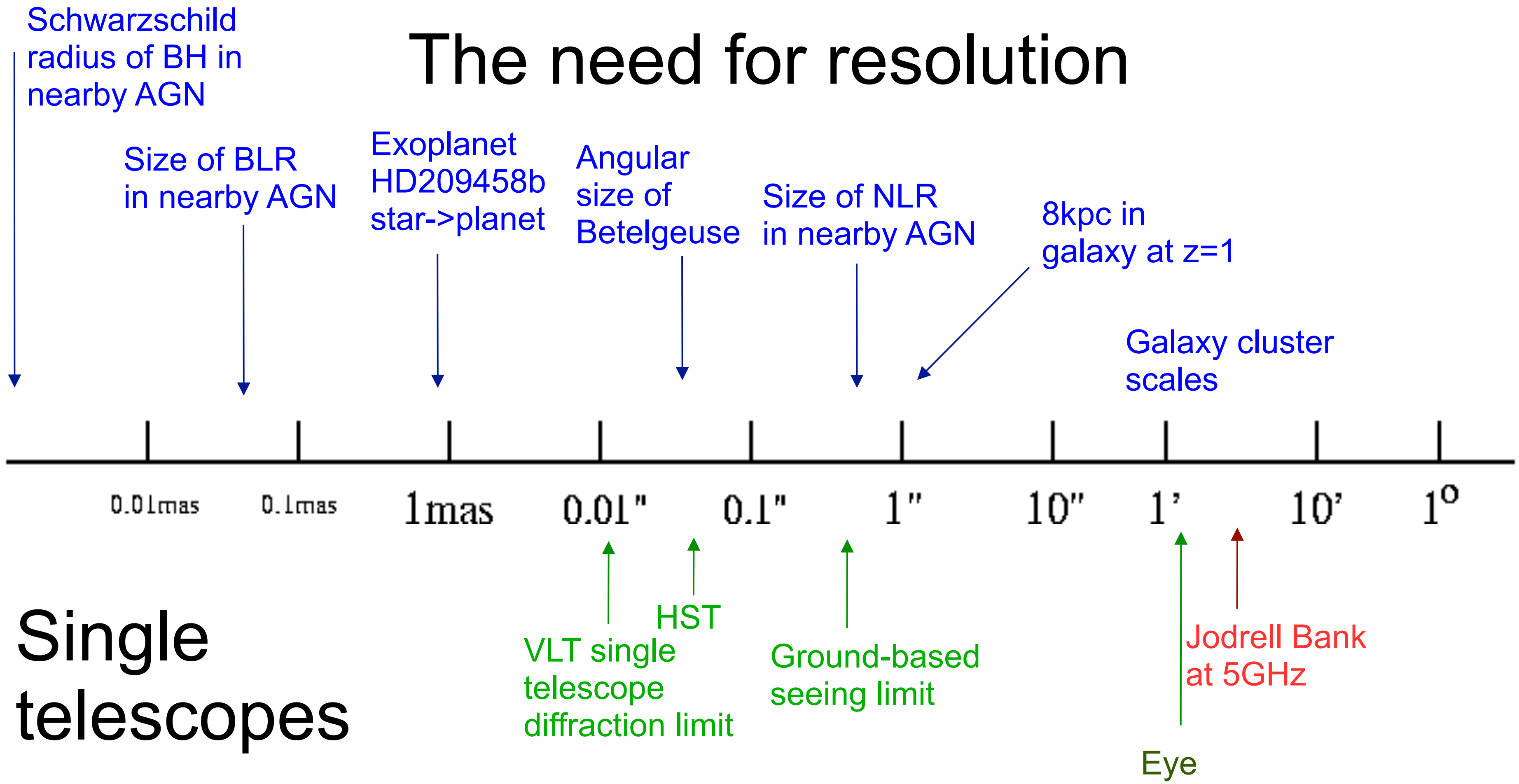


(Following the lecture by Jackson 2008.)

The need for resolution

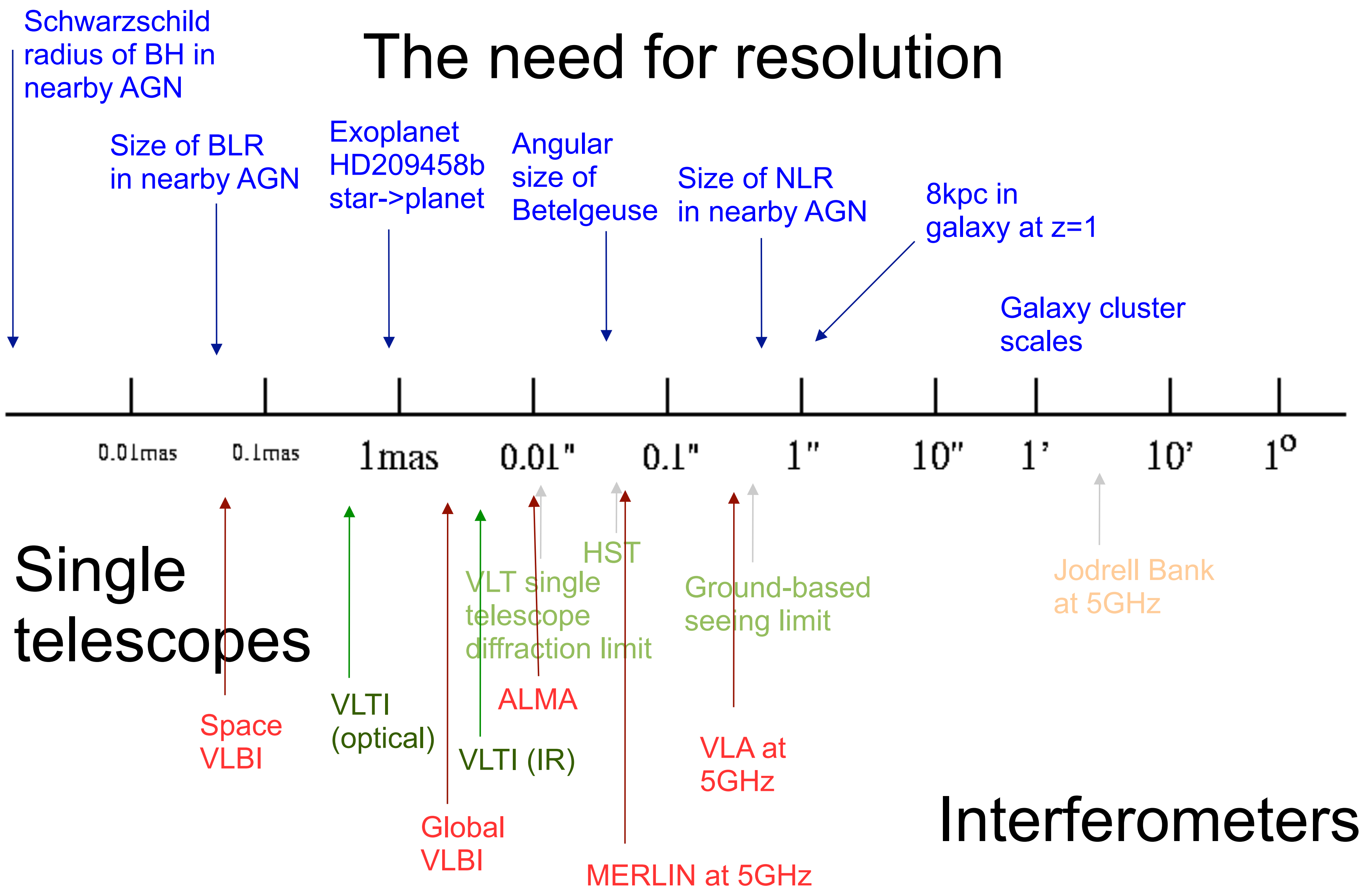


The need for resolution

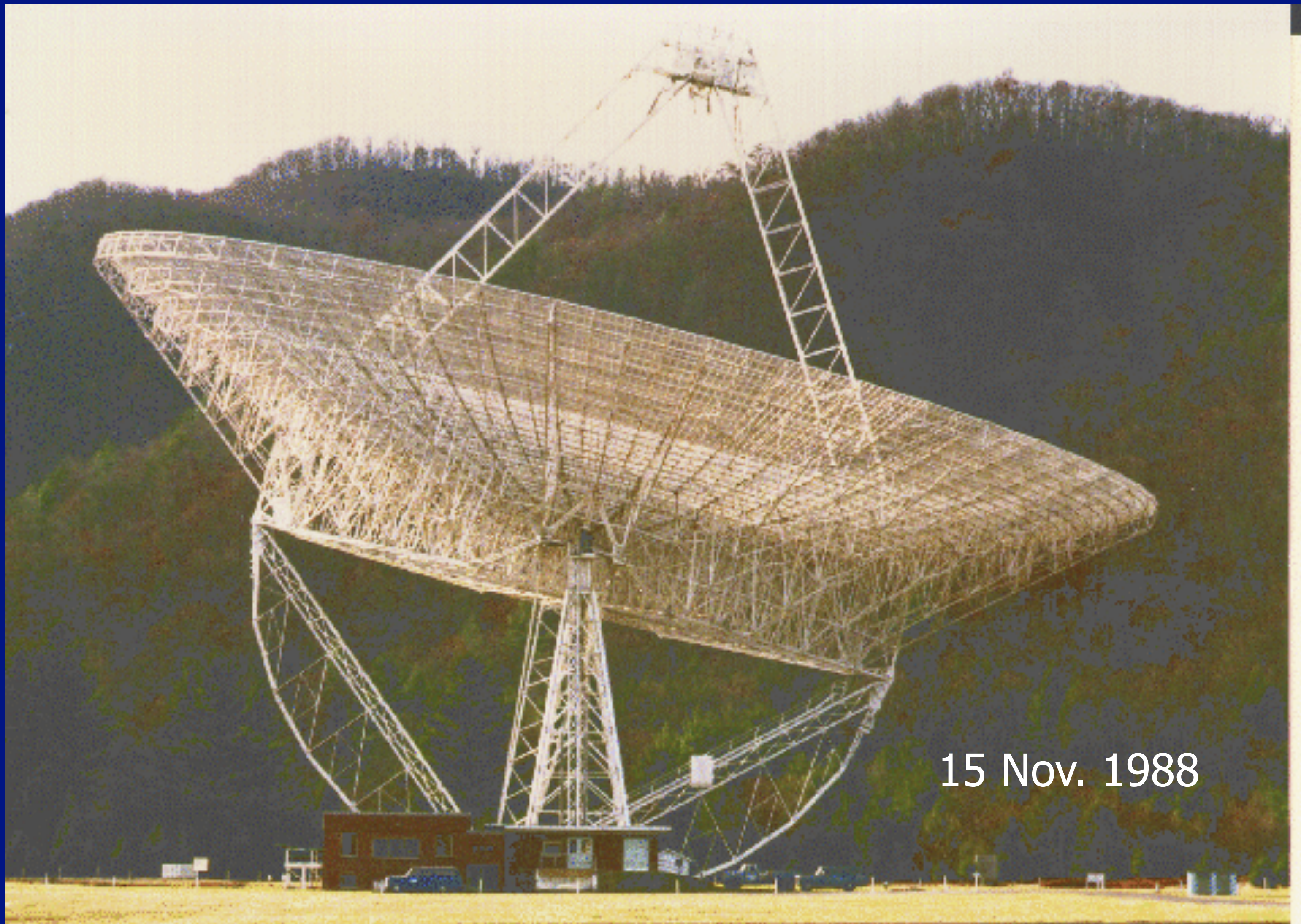


Single telescopes

The need for resolution

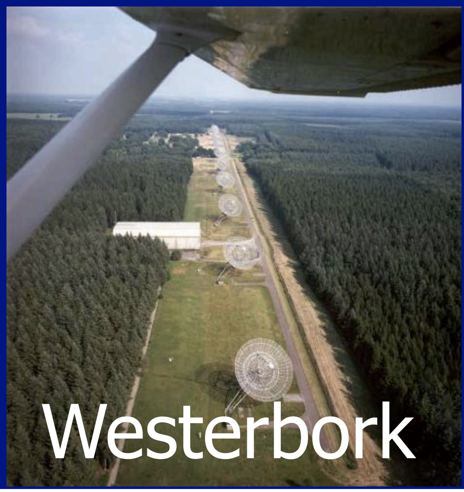


300 Foot Telescope



300 Foot Telescope

Some interferometers

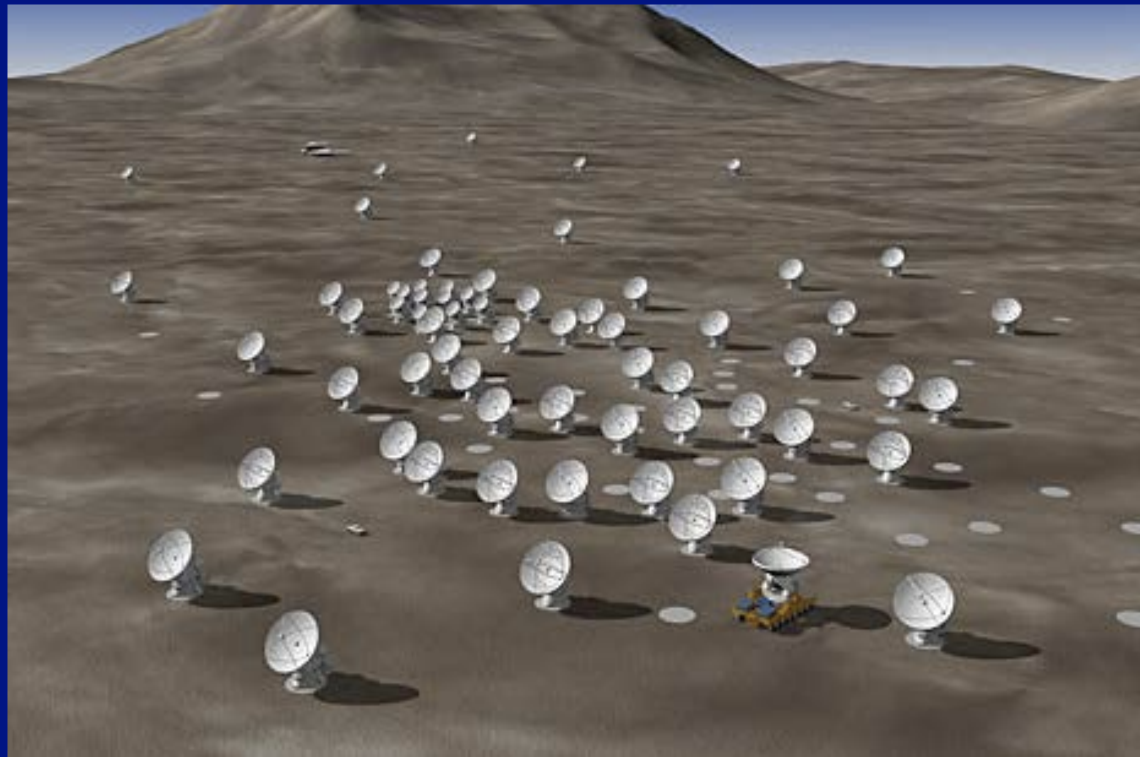


LOFAR

Future project: Square Kilometer Array (SKA) → after 2020

Atacama Large Millimeter Array (ALMA)

~60 dishes in the Atacama desert at 5000m altitude



Topics today

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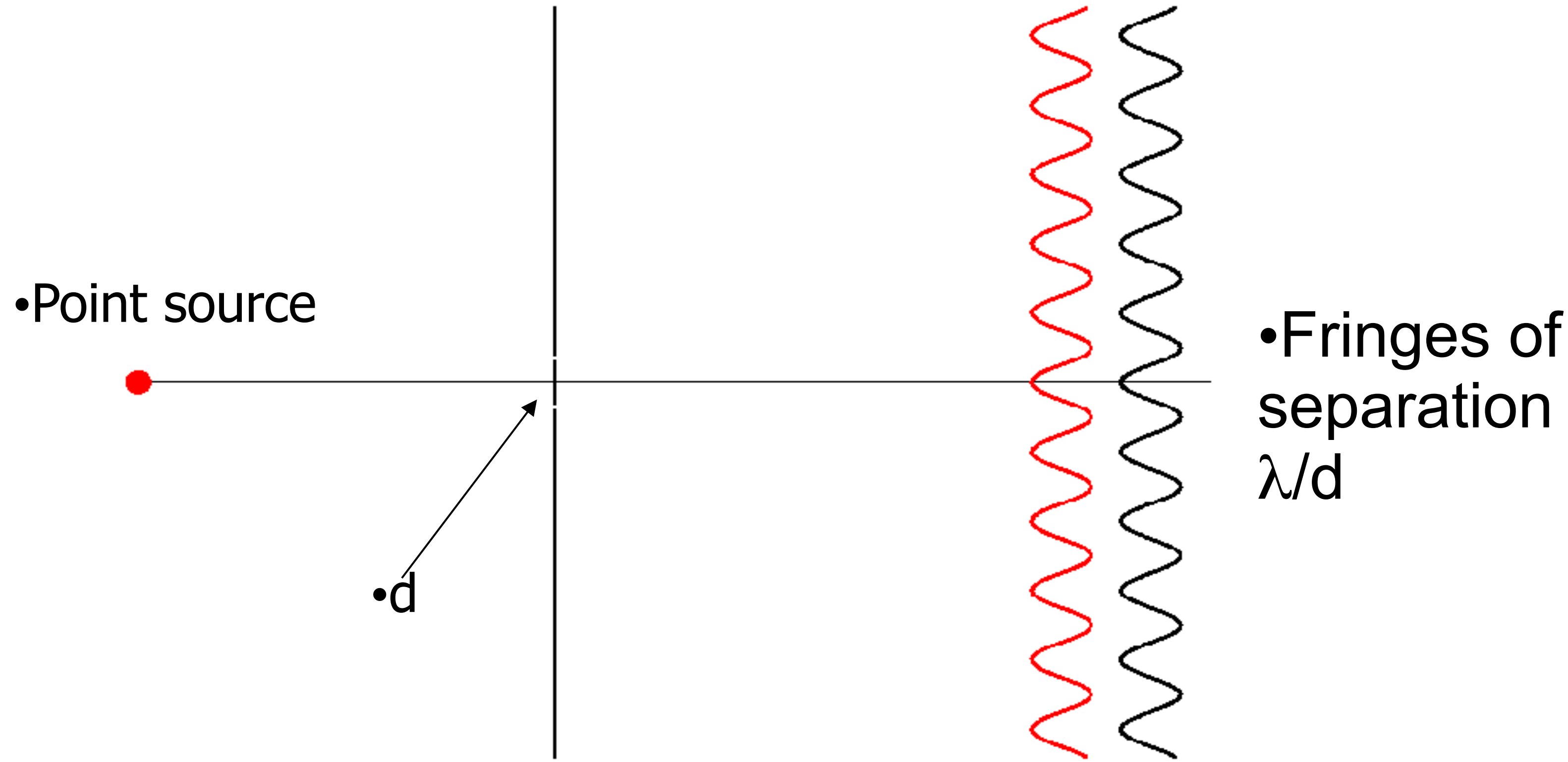
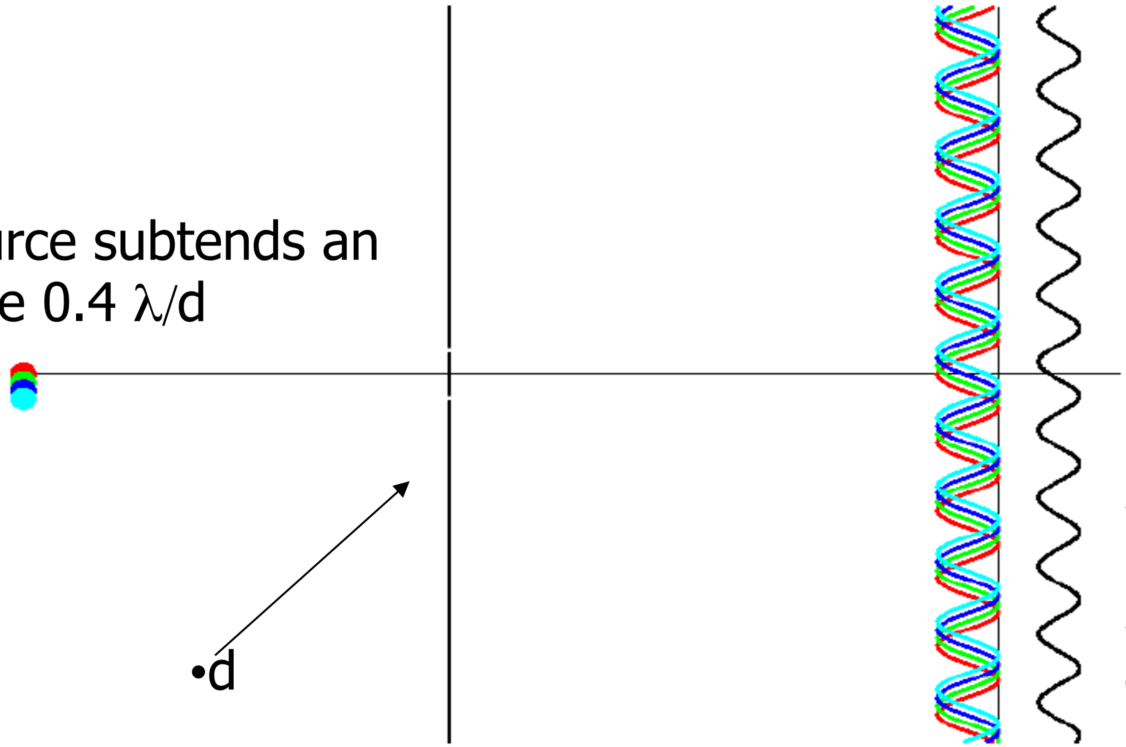
- Basic double slit experiment
- Application to real interferometers

Young's slits revisited



Larger source

- Source subtends an angle 0.4 λ/d

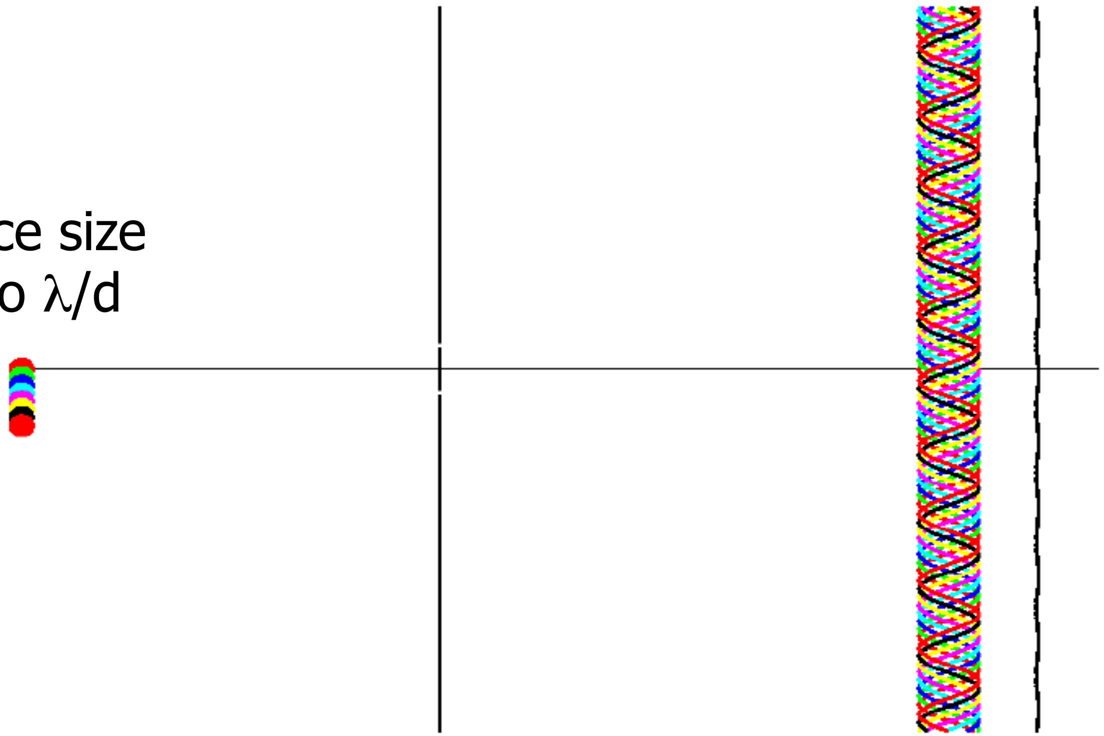


- Fringes move by 0.4 λ/d. Incoherent sources -> add intensities, fringes start to add out destructively

Define |fringe visibility| as (Imax-Imin)/(Imax+Imin)

Still larger source

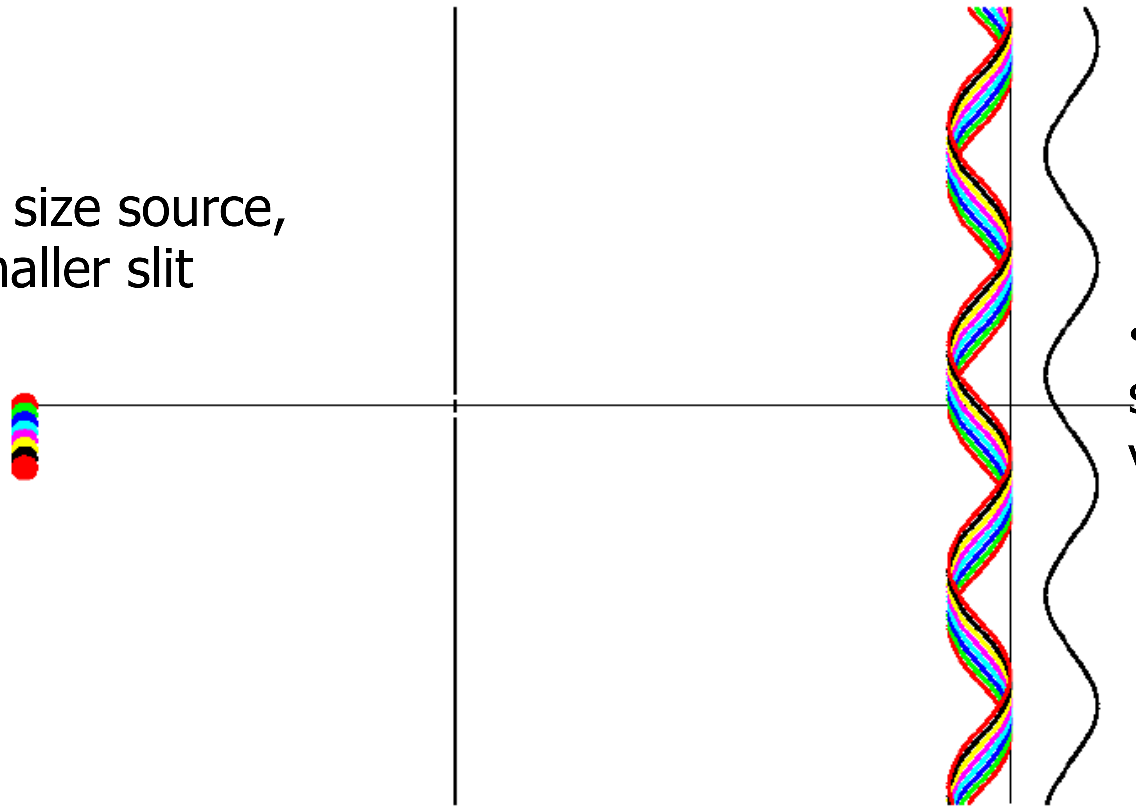
•Source size gets to λ/d



•No fringes remain (cancellation). Little fringing seen for larger sources than λ/d either.

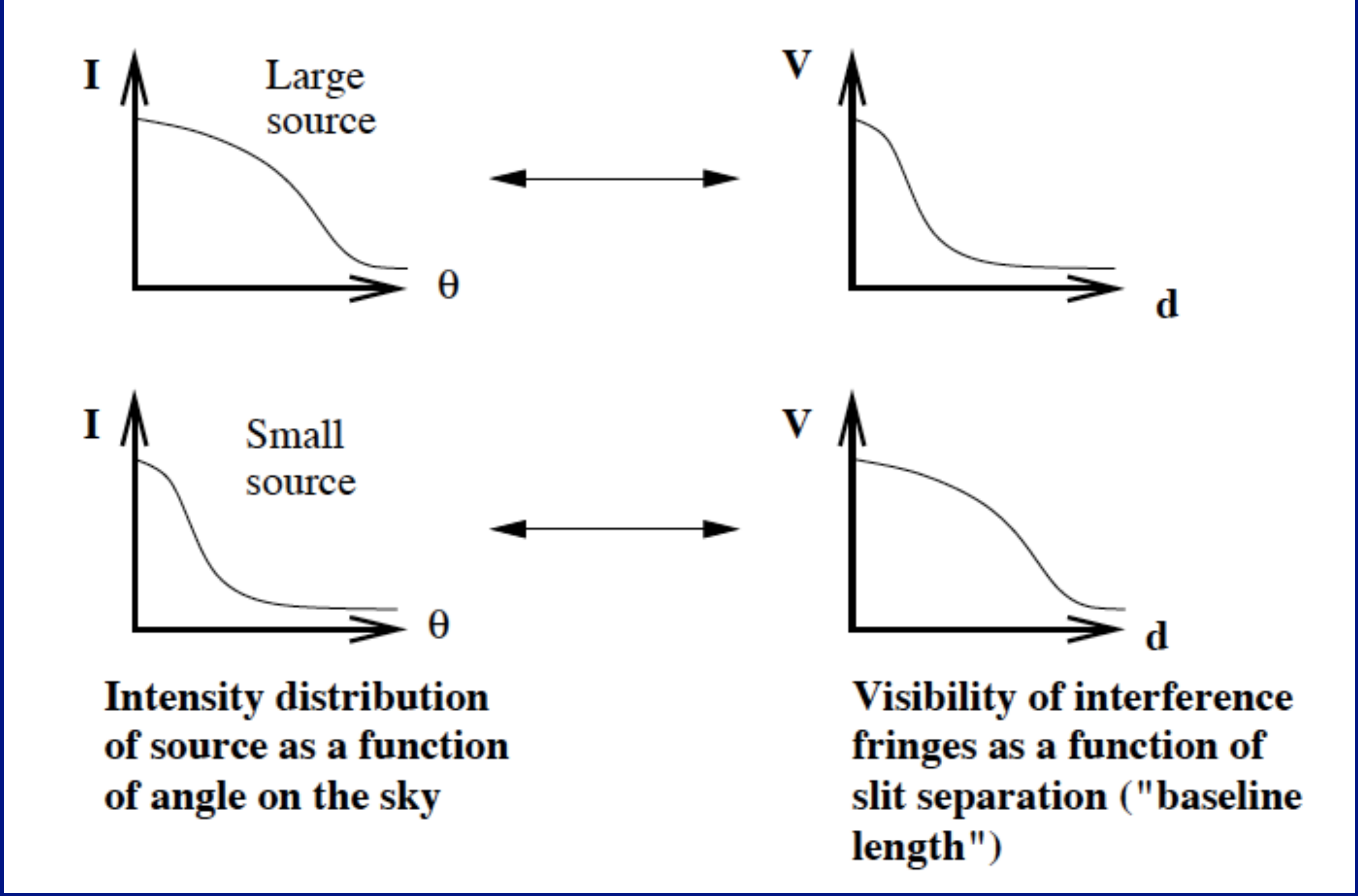
Effect of slit size

- Same size source, but smaller slit



- Increased fringe spacing, so fringes visible again

Visibility: $V = (I_{max}-I_{min})/(I_{max}+I_{min})$



- V decreases with increasing source size. Goes to 0 for source larger λ/d
- For fixed source size, V increase with decreasing d
- For fixed source size and d, V increases with increasing λ

Topics today

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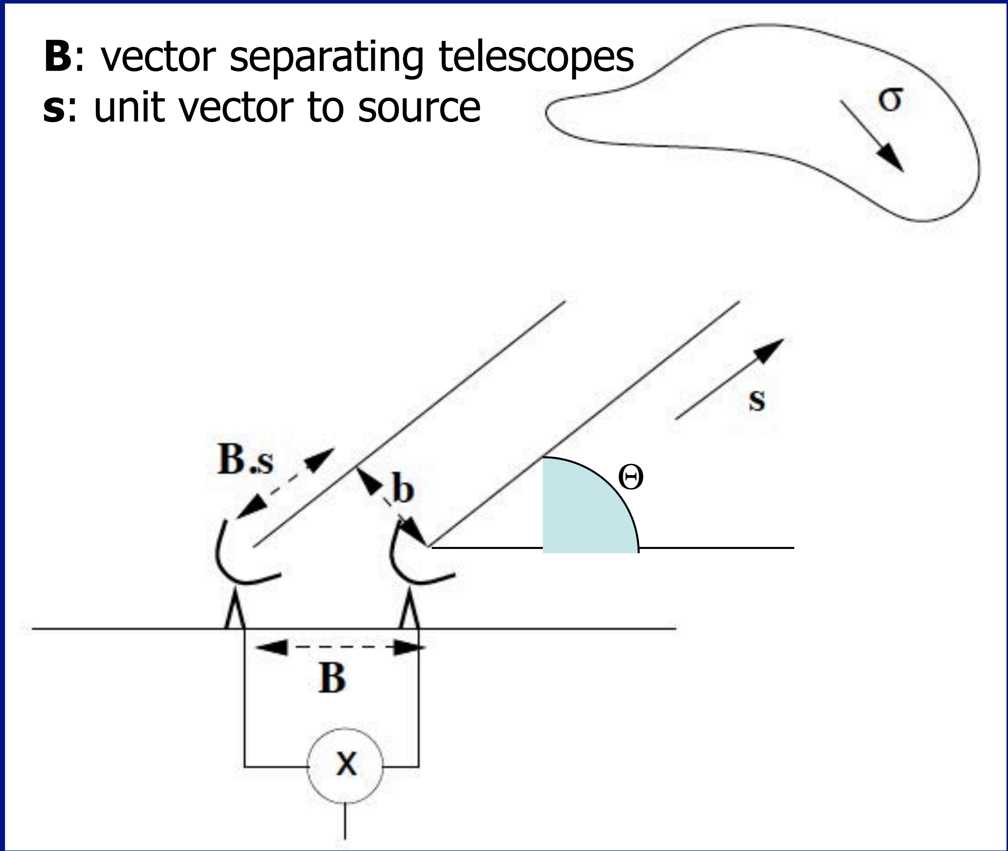
- Basic double slit experiment

- Application to real interferometers

Application to real interferometers I



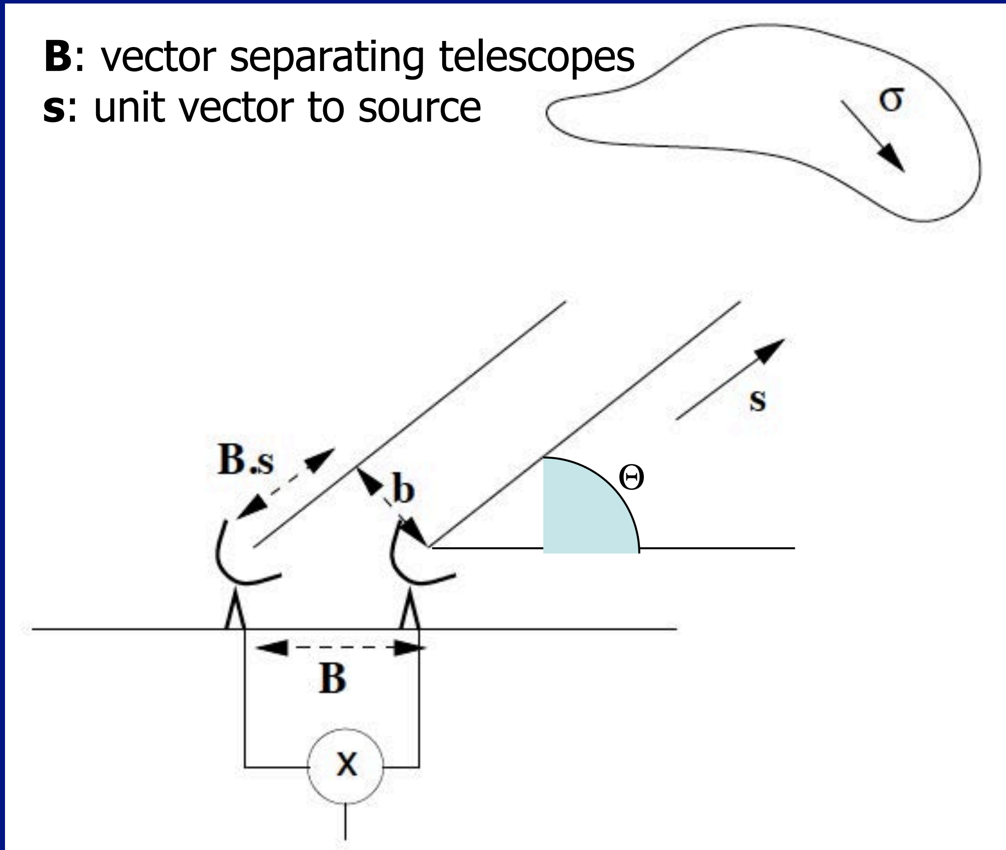
- Path delay is **B.s** = B cos(Θ) → phase delay k**B.s**, where k = 2π/λ

- Response of interferometer:

$$R = \int I(\sigma) e^{ik\mathbf{B}.(\mathbf{s}+\sigma)} d\sigma$$

with s+σ vector to part of source
Since σ||**b** → **B.**σ = **b.**σ

Application to real interferometers II



→ $R = e^{ik\mathbf{B}.\mathbf{s}} \int I(\sigma) e^{ik\mathbf{b}.\sigma} d\sigma$, where $e^{ik\mathbf{B}.\mathbf{s}}$ solely dependent on array geom., thus before int.

→ Response of interferometer is fourier transformation of intensity distribution!

Phase has structure information, amplitude intensity information.

uv plane I

Decompose σ and **b** in Cartesian coordinates:

$\sigma = x\mathbf{i} + y\mathbf{j}$, where **i** and **j** are unit vectors on sky

$\mathbf{b} = u\mathbf{i} + v\mathbf{j}$, where u and v are projections of baseline positions on the sky

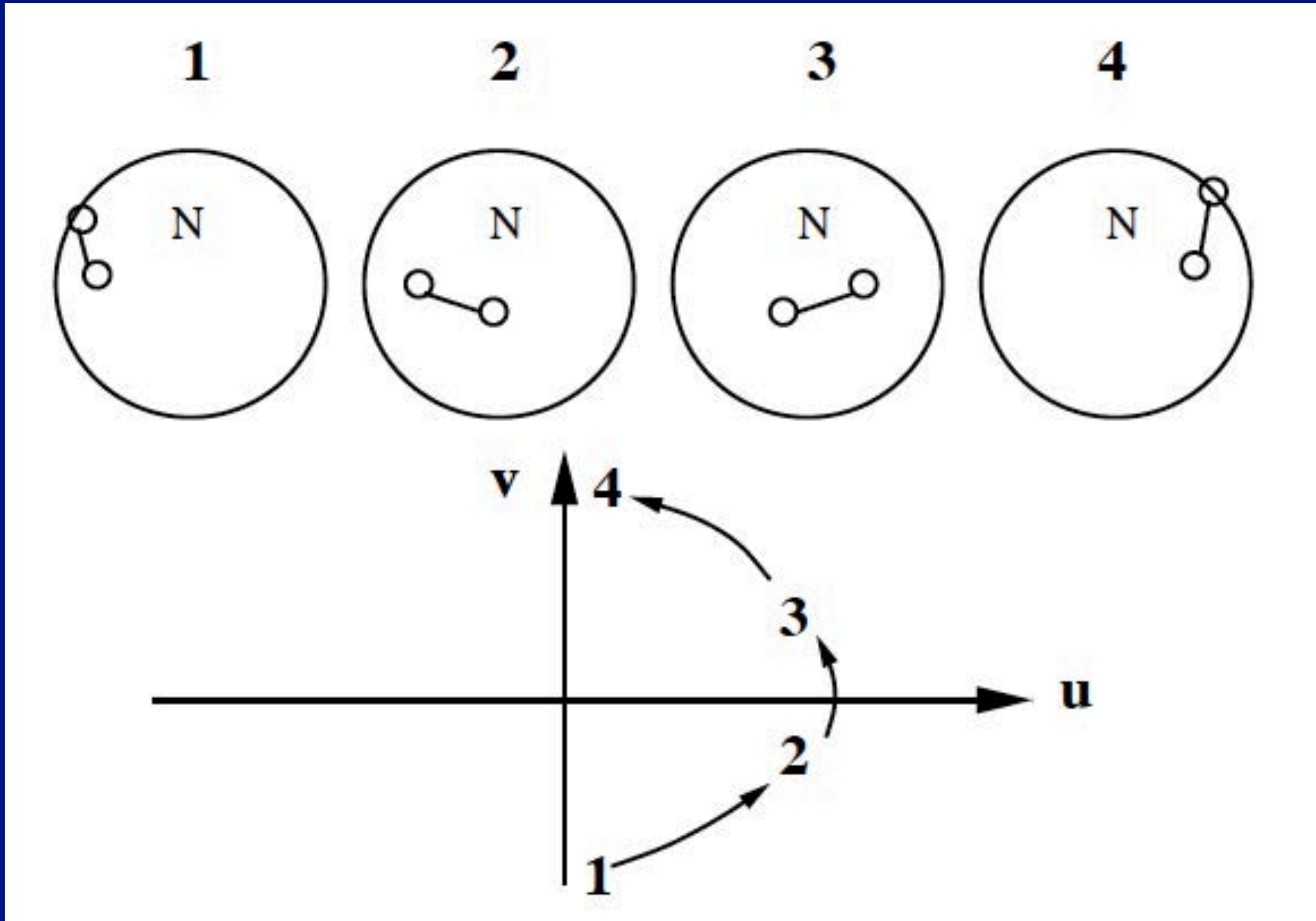
→ $\mathbf{b}.\sigma = ux + vy$

The response after "fringe stopping" then becomes:

$$R(u,v) = \iint I(x,y)e^{2\pi i(ux+vy)}dxdy$$

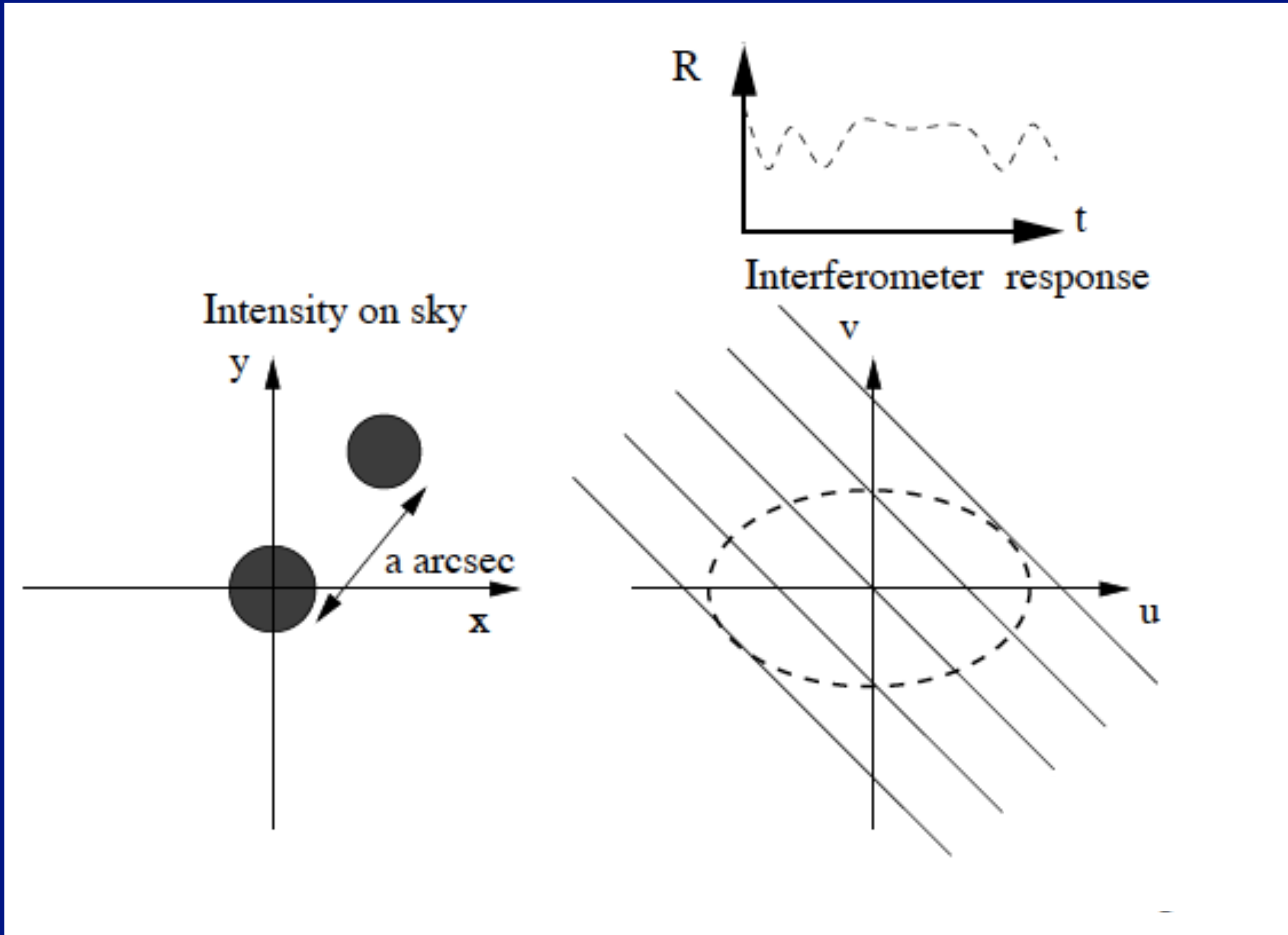
which is an explicit 2D Fourier transformation. u and v are defined in wavelengths, hence k became 2π.

uv plane II



Schematic of uv change with projected baseline on the sky.

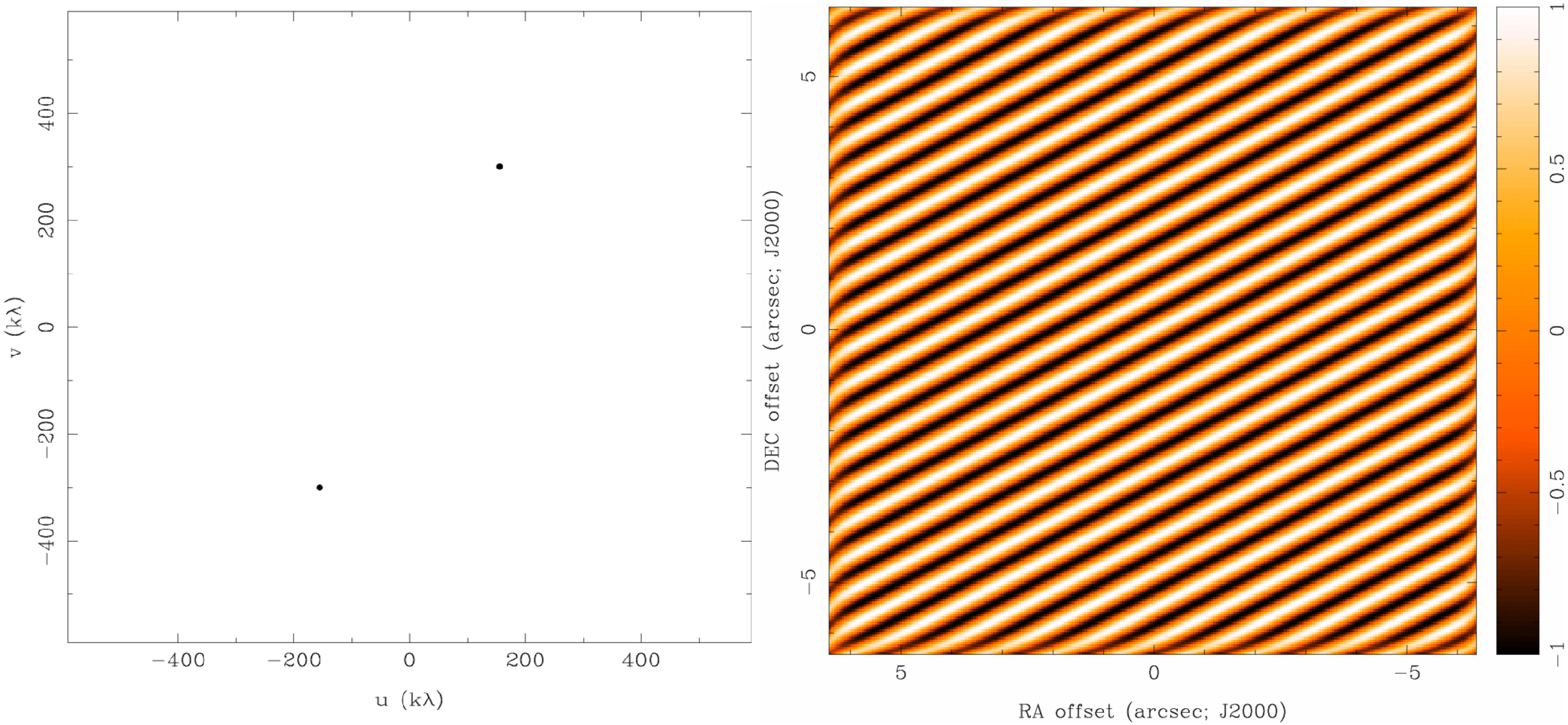
uv plane III



Fourier transform of double source results in stripes in uv-plane.
→ uv ellipse of 1 antenna pair crosses these stripes several times per 24h.

Dirty Beam Shape and N Antennas

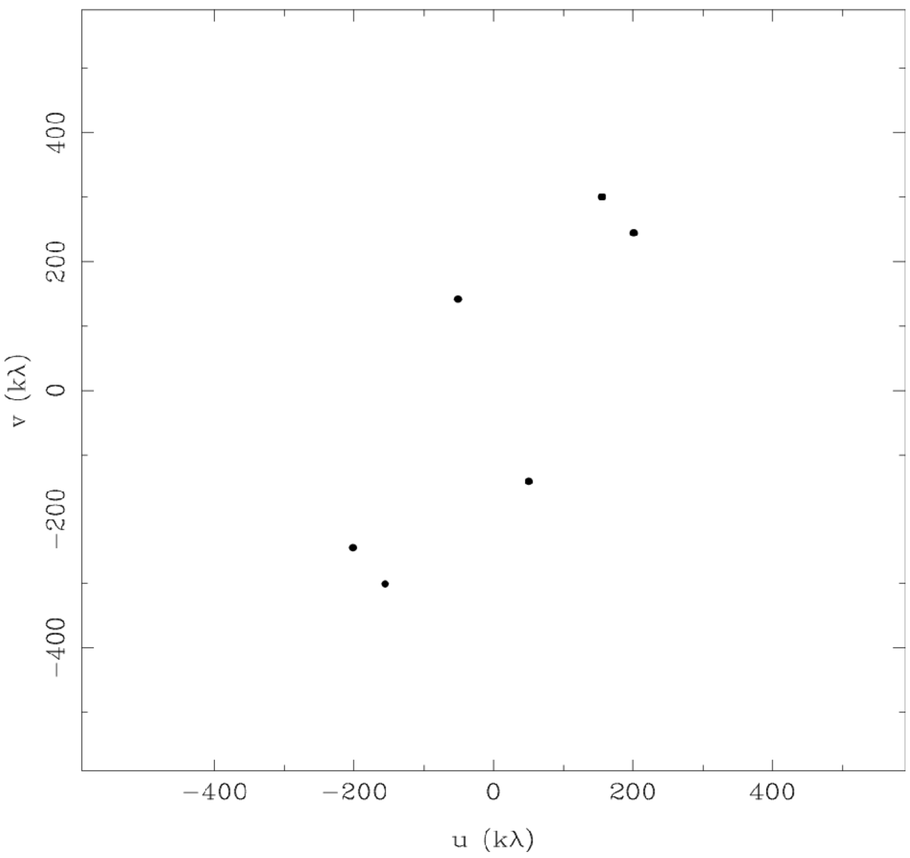
2 Antennas

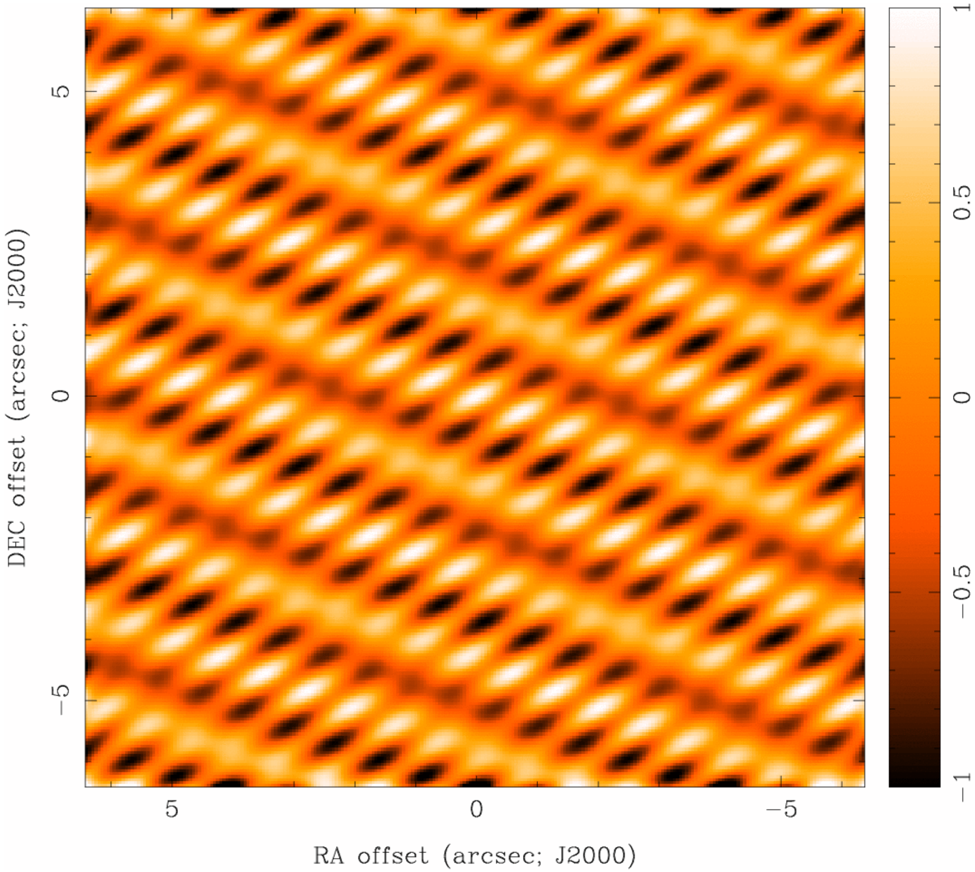


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

3 Antennas

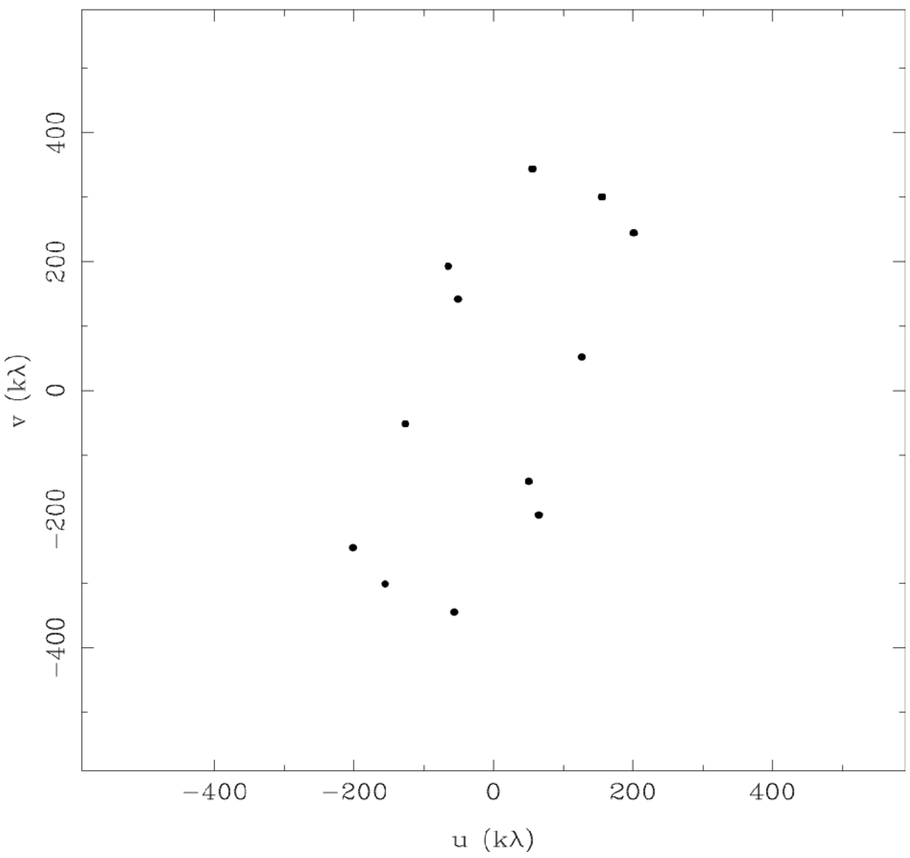


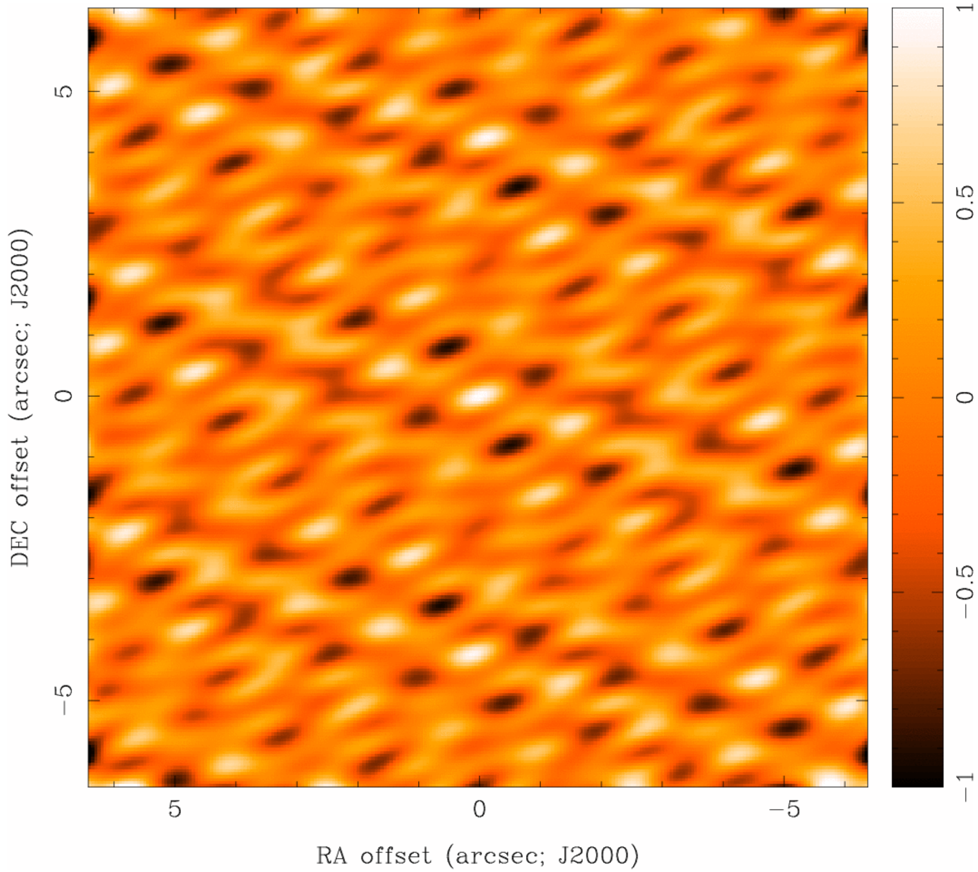


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

4 Antennas

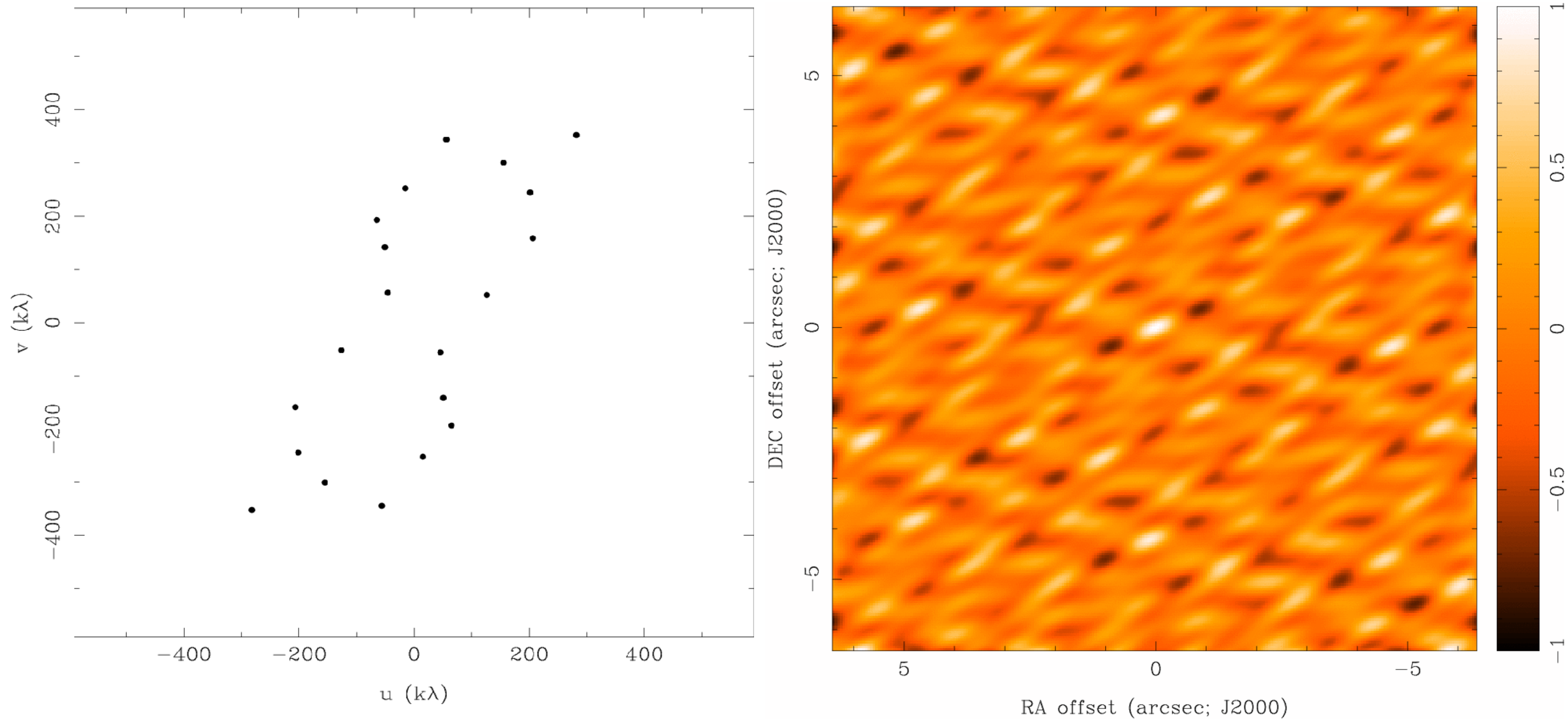




(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

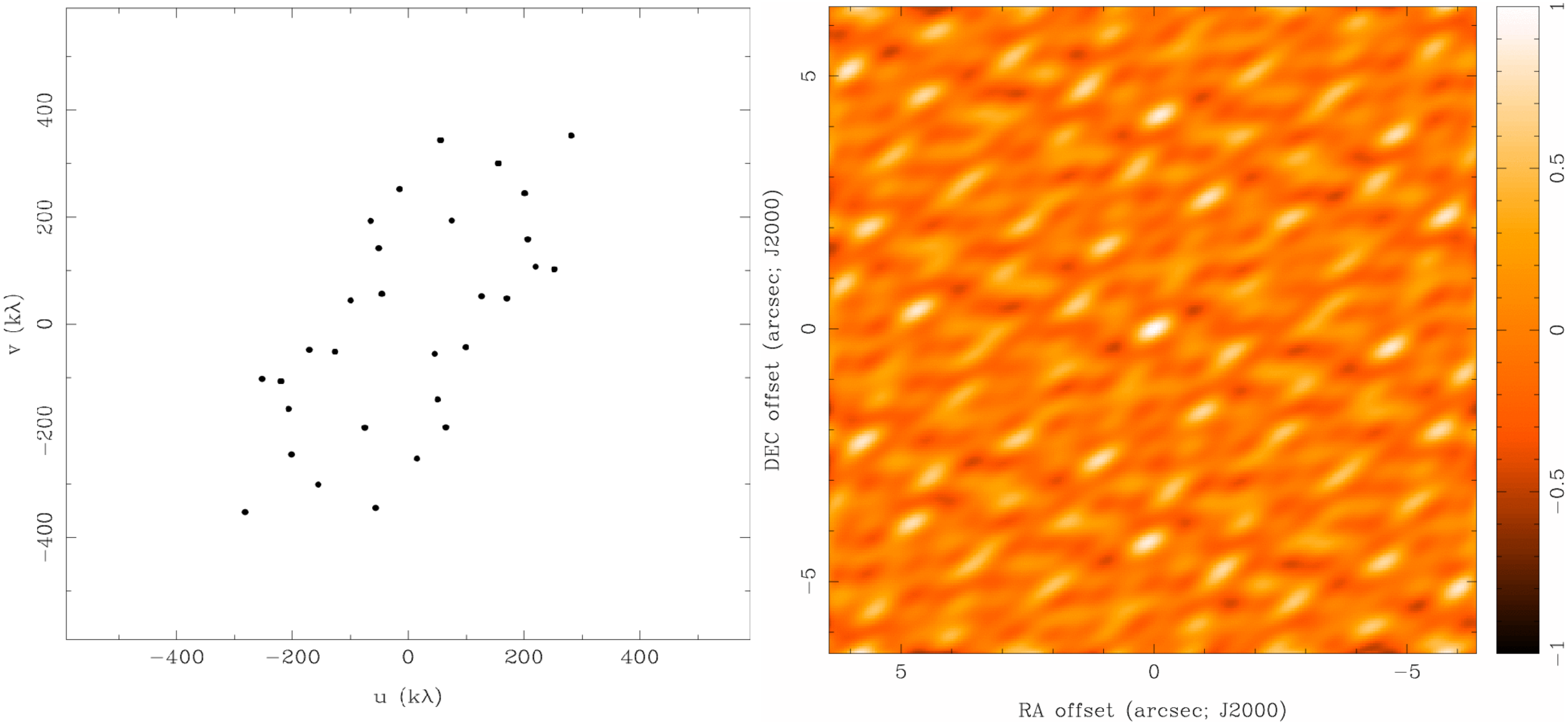
5 Antennas



(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

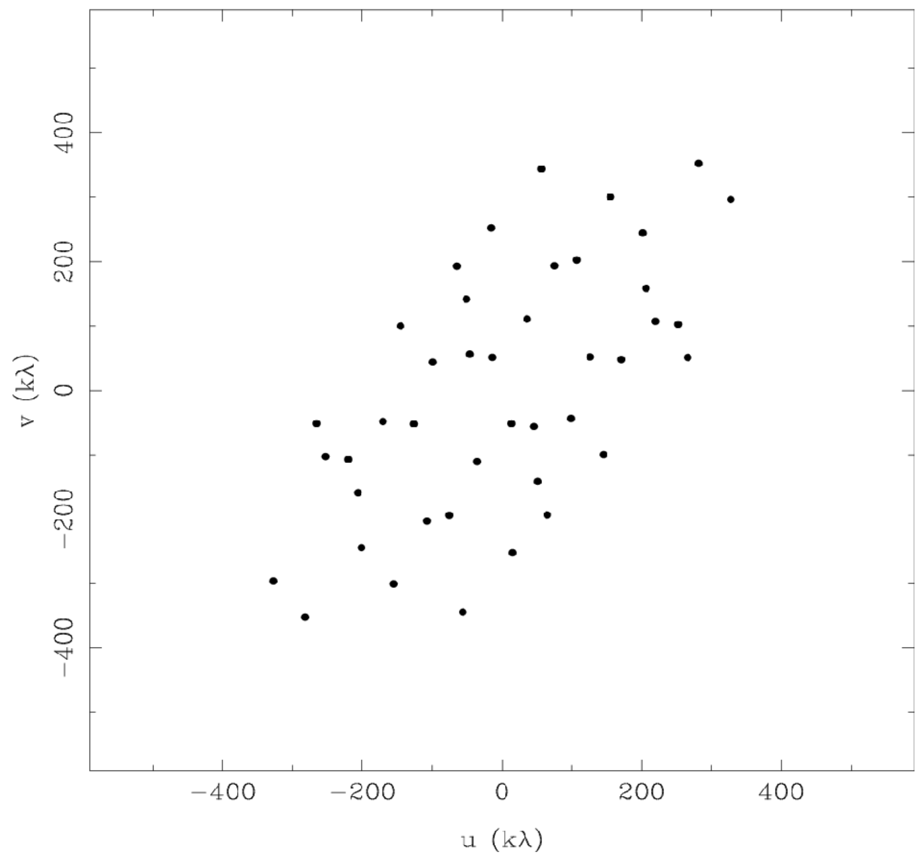
6 Antennas

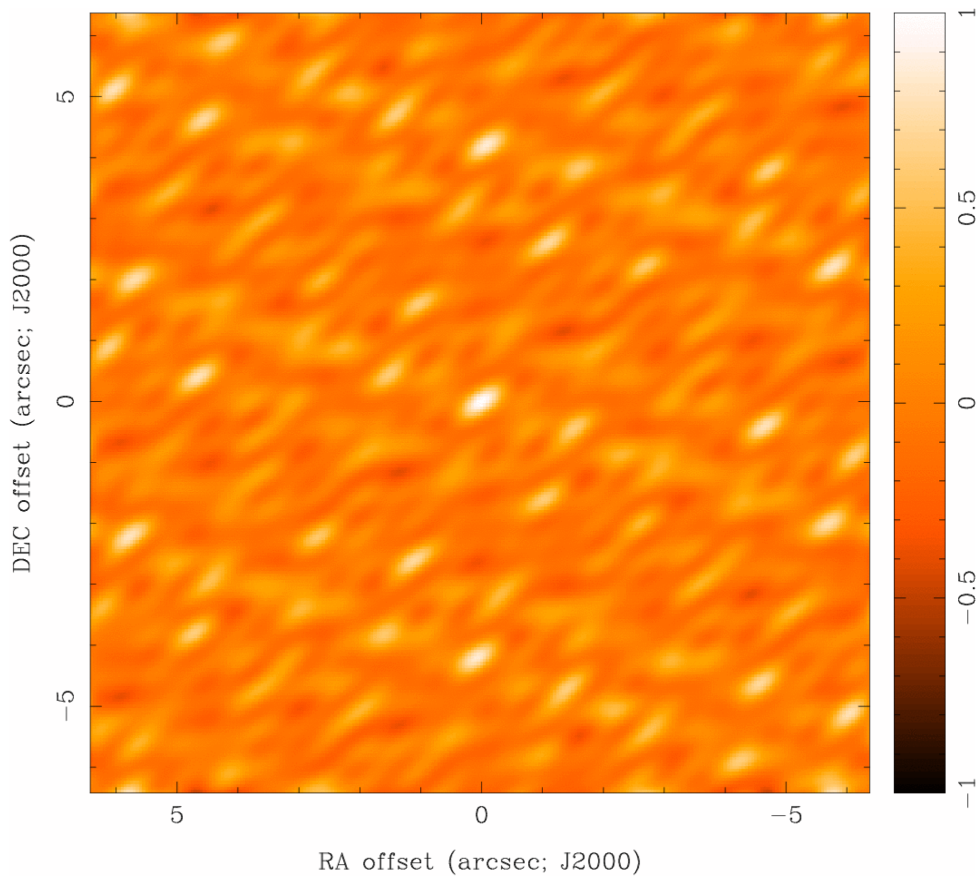


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

7 Antennas

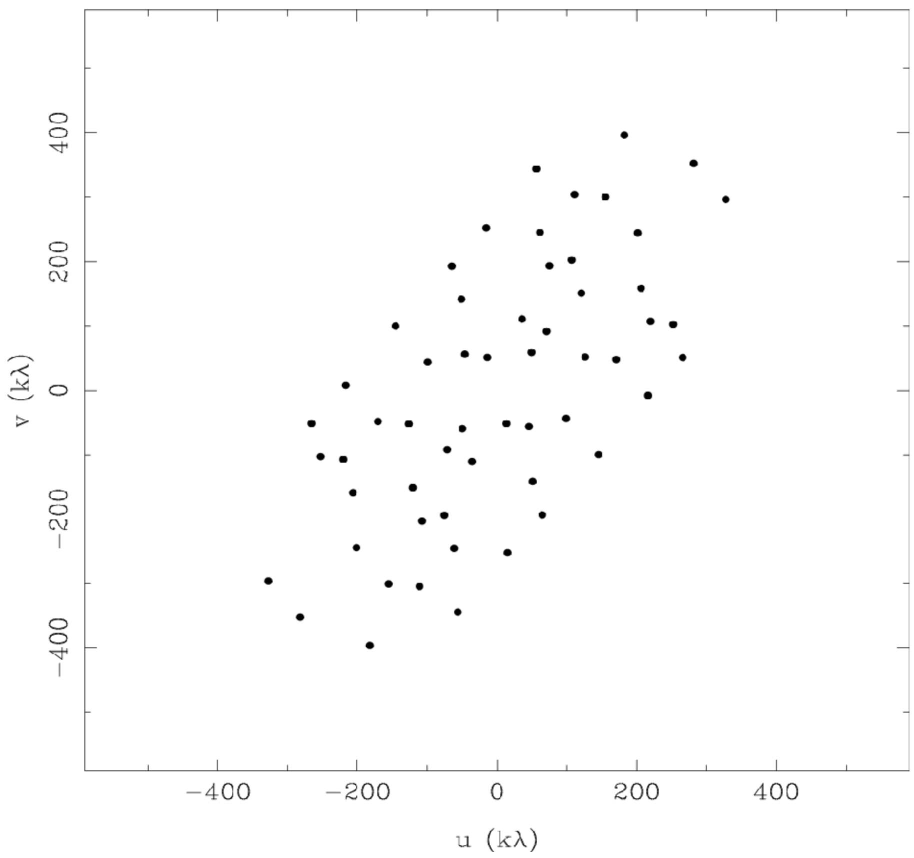


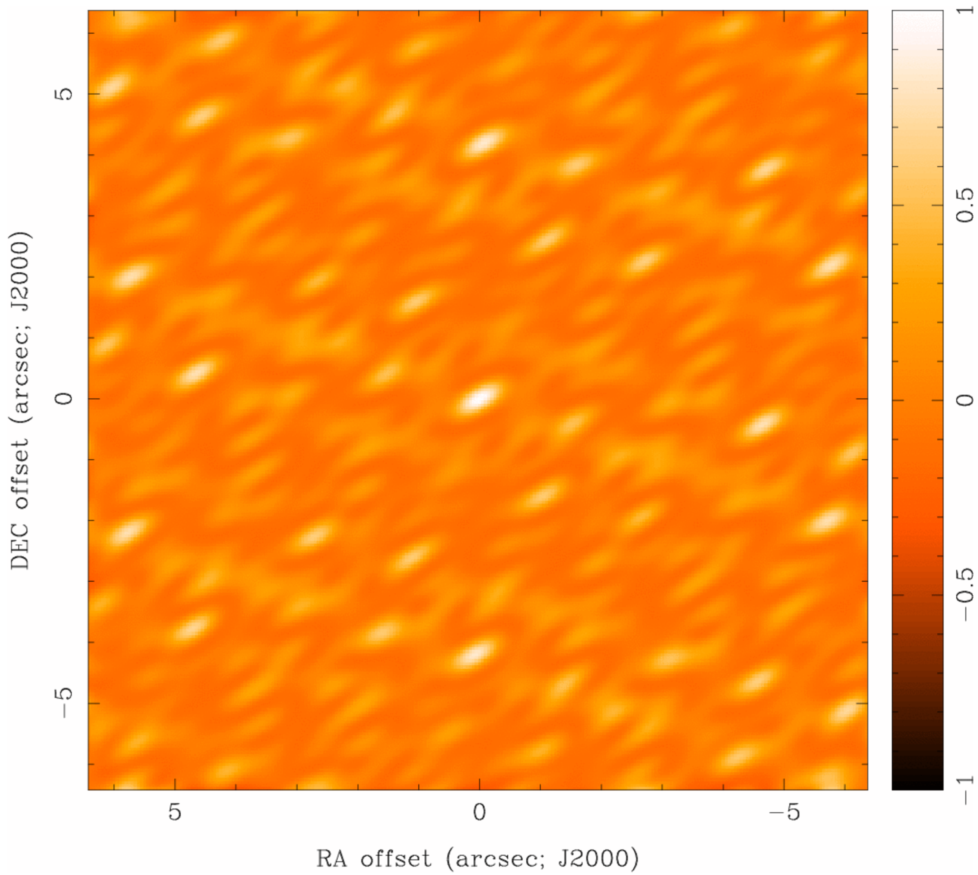


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas

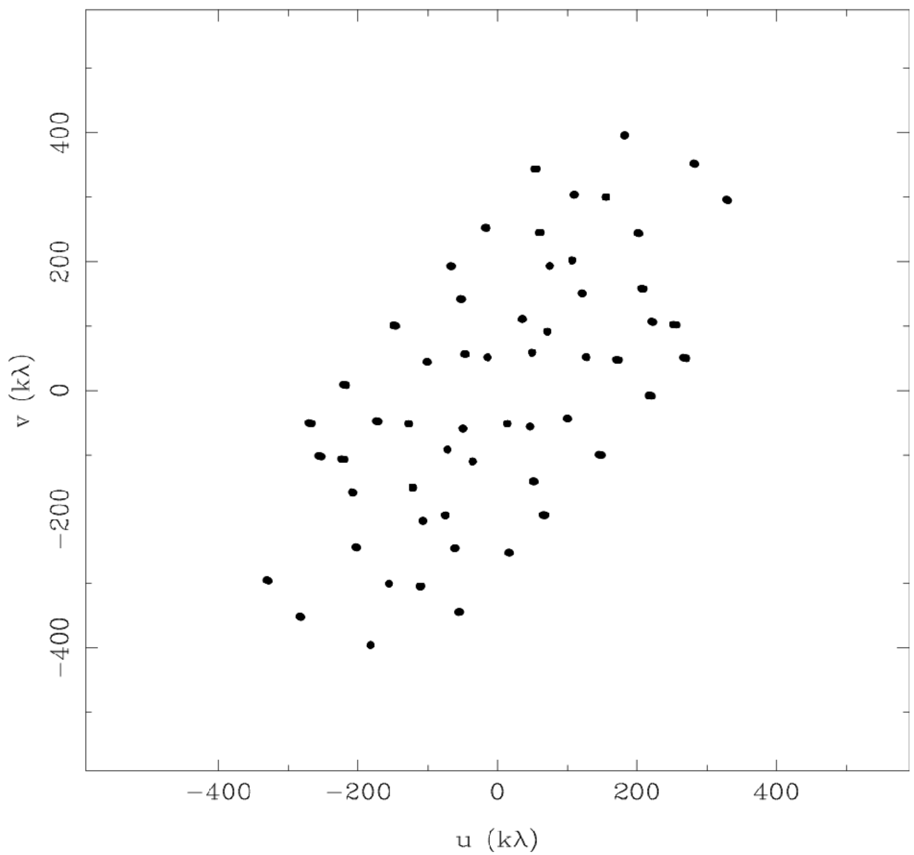


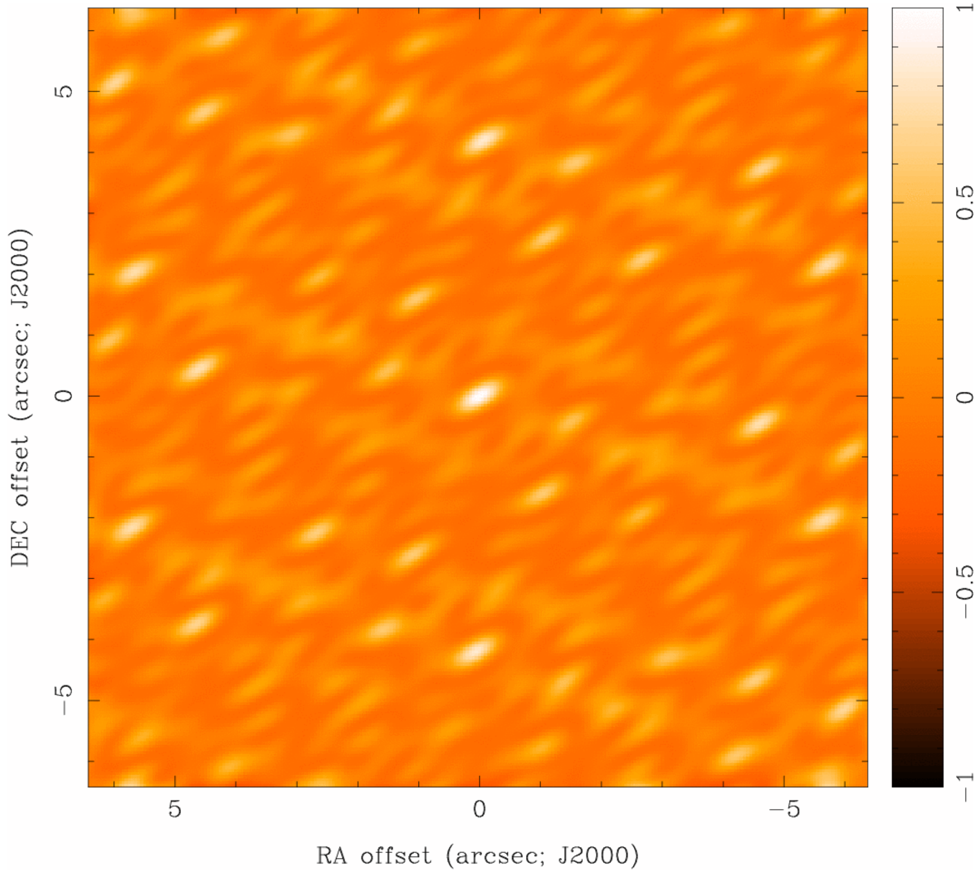


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 6 samples

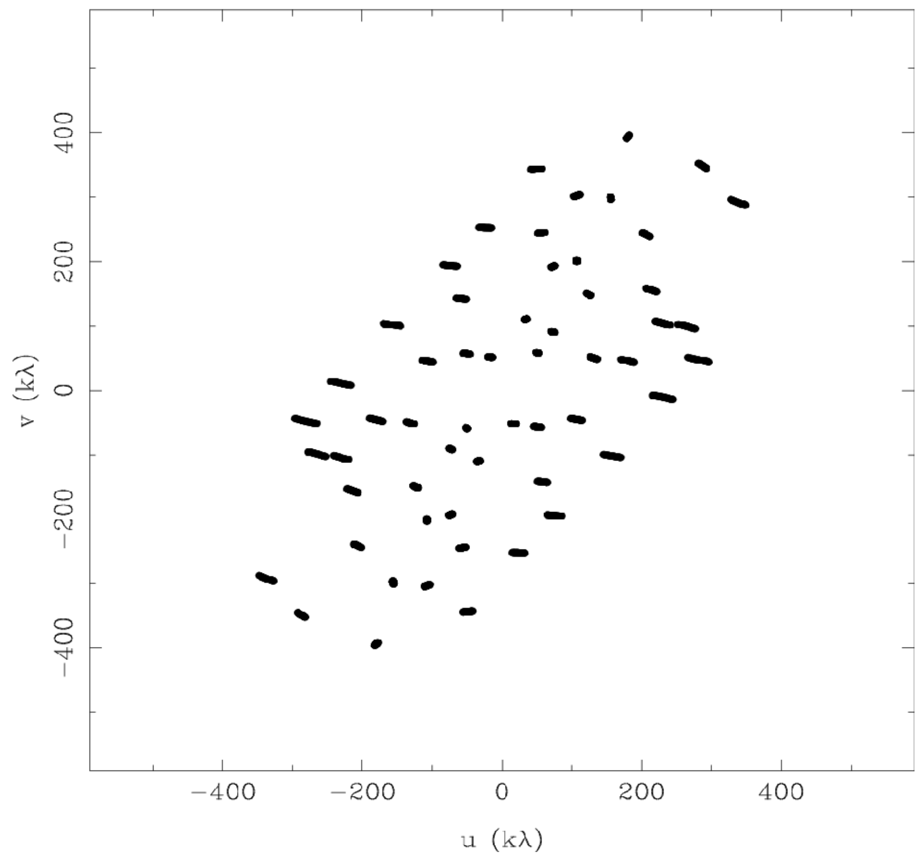


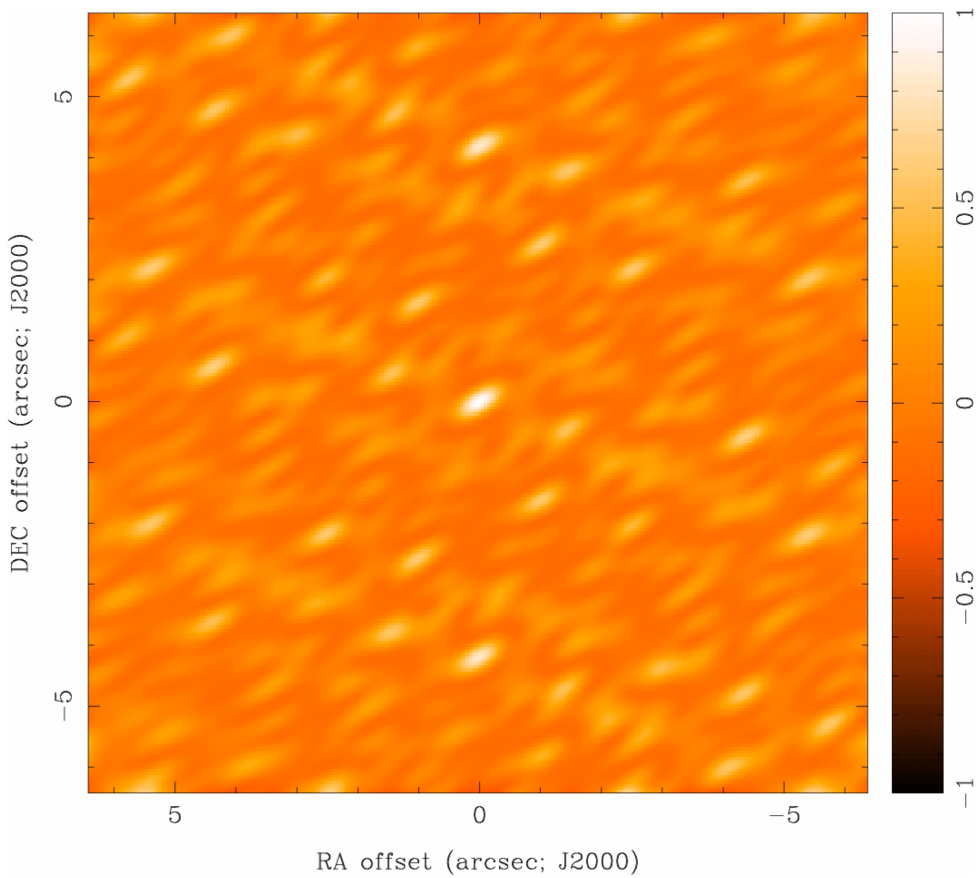


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 30 samples

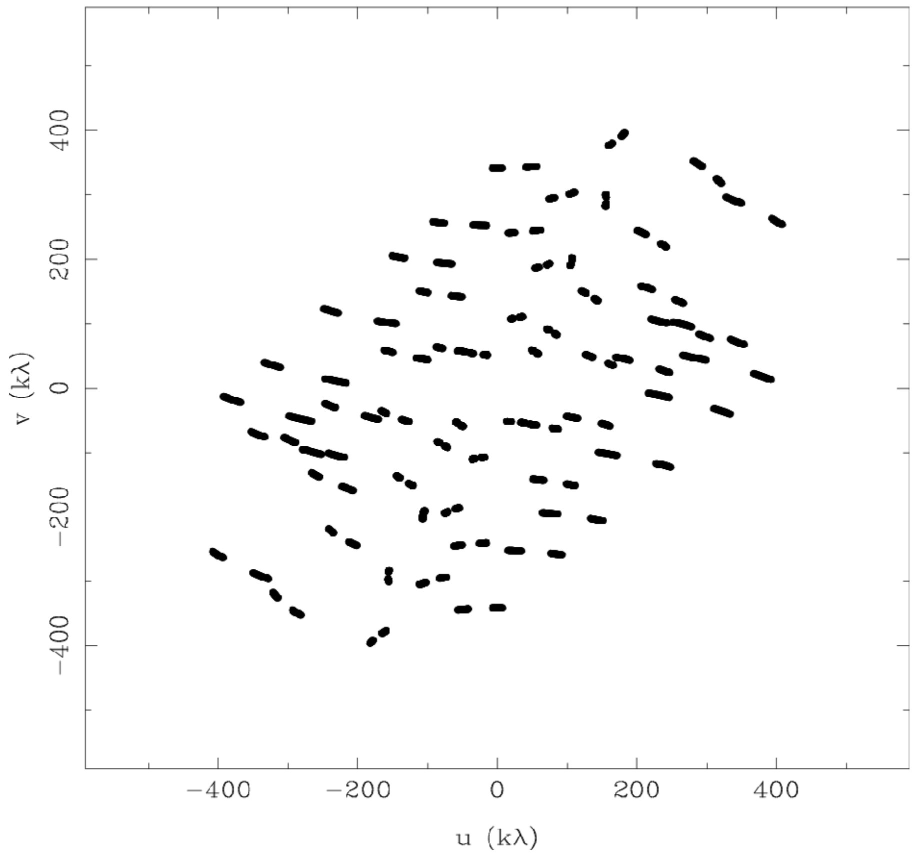


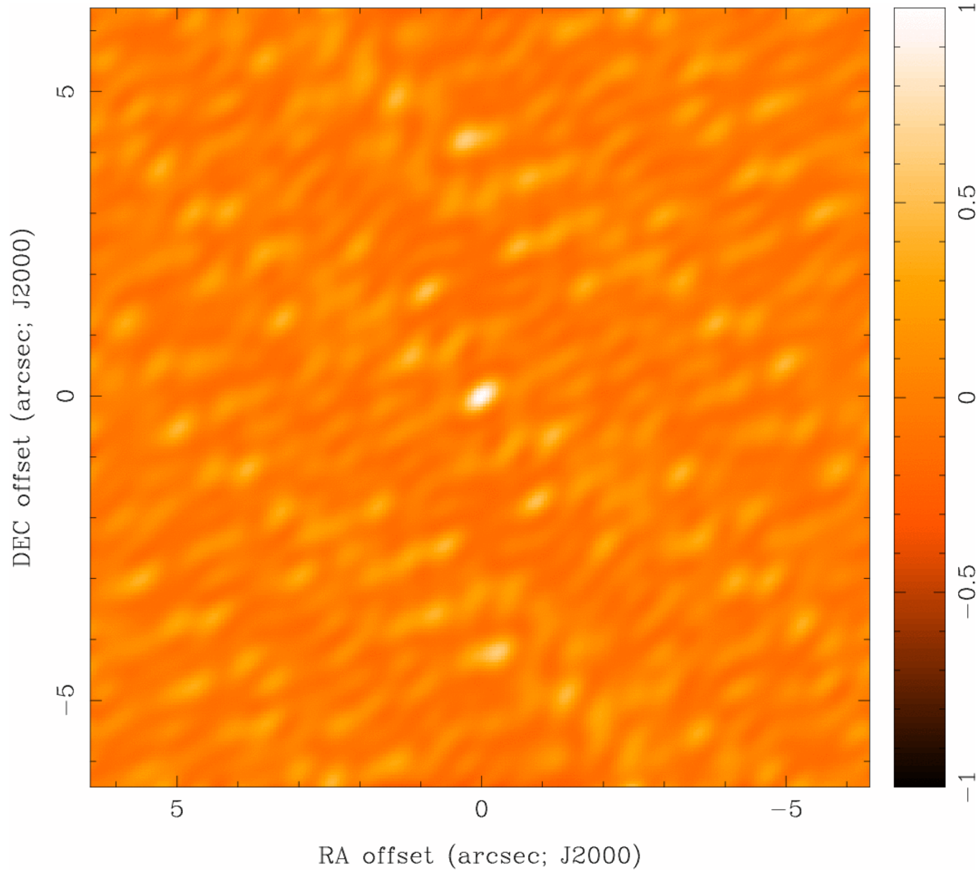


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 60 samples

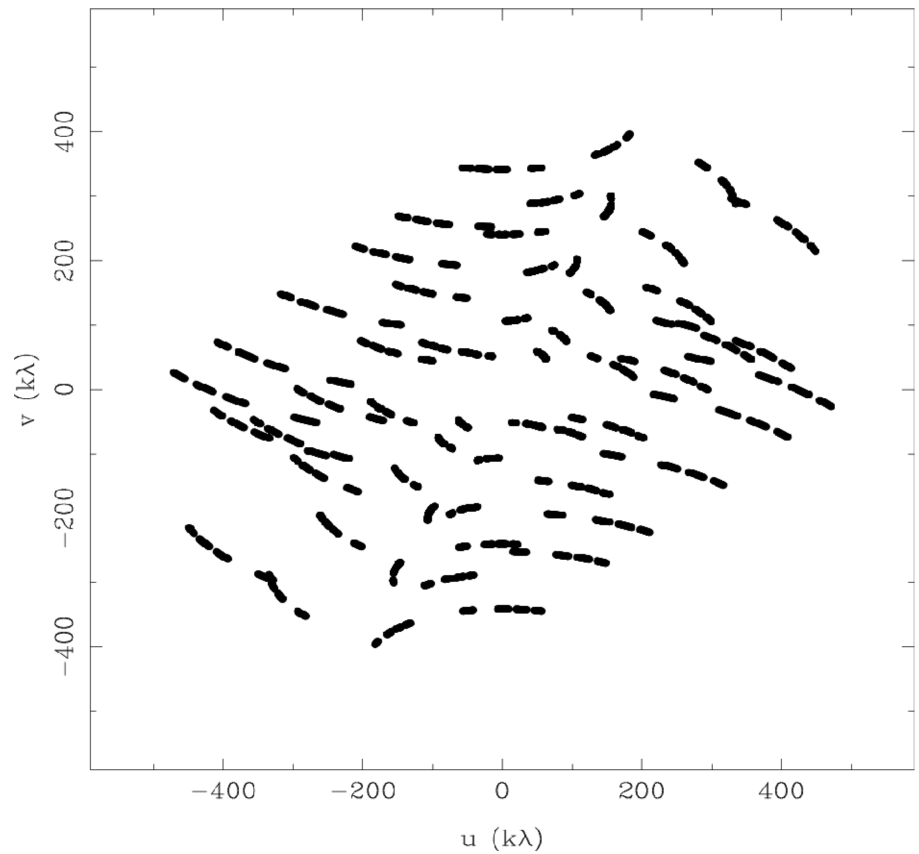


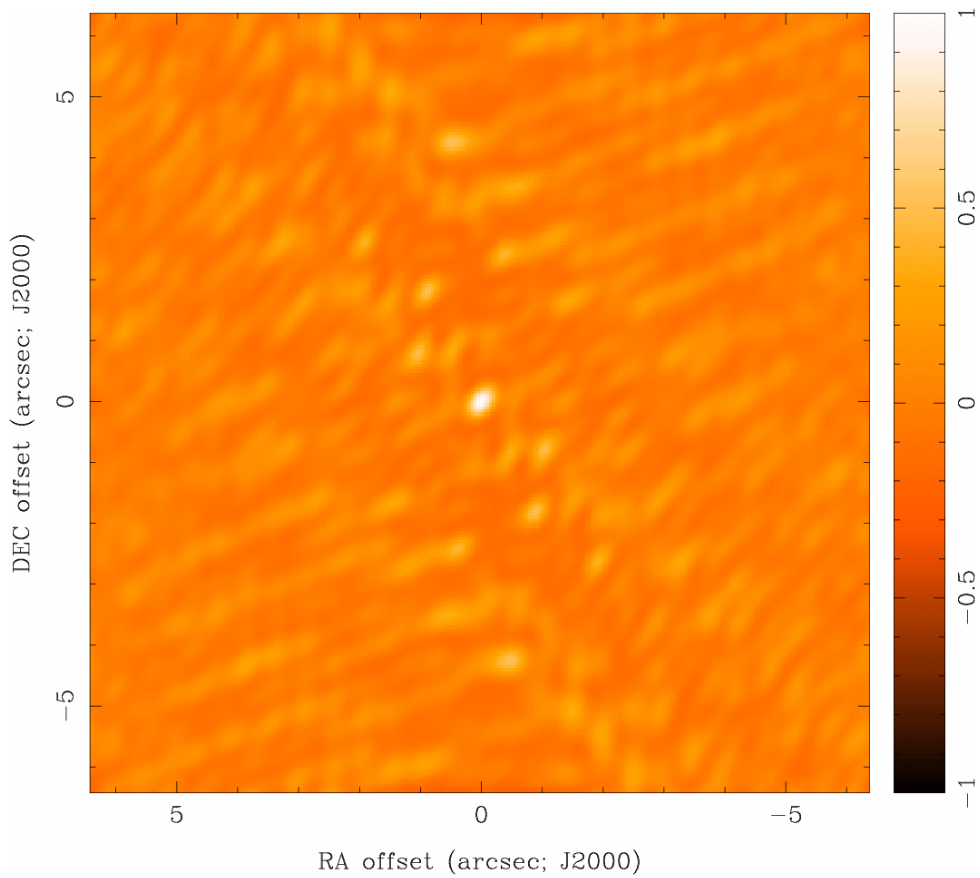


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 120 samples

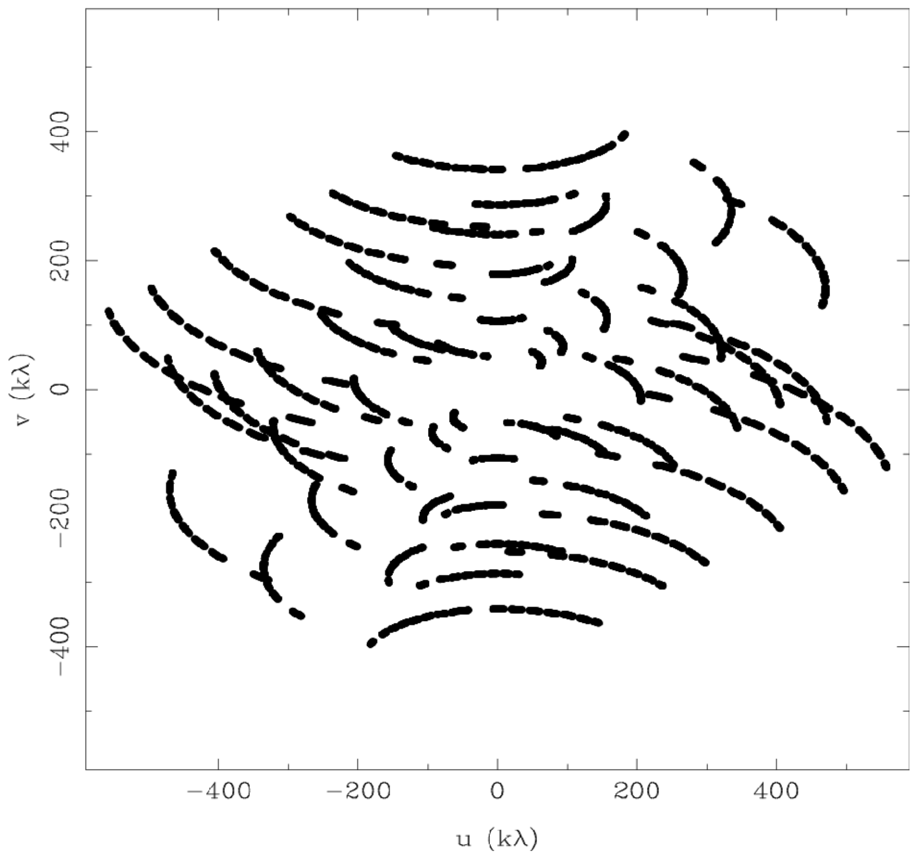


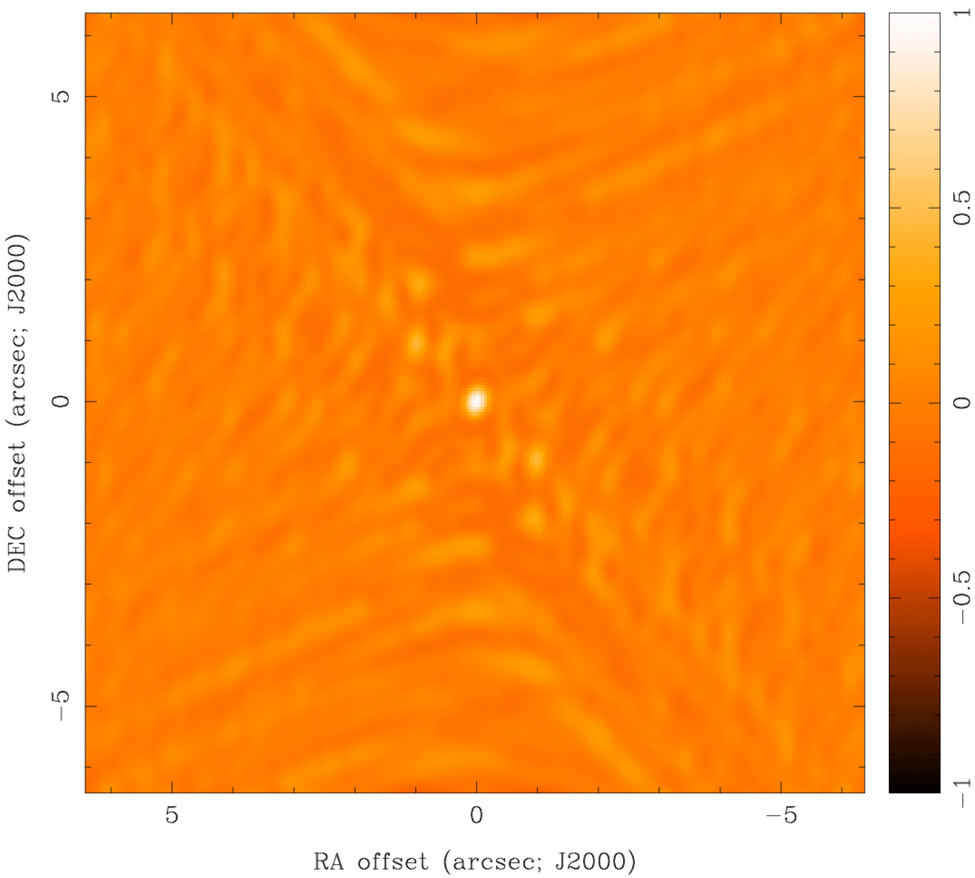


(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 240 samples

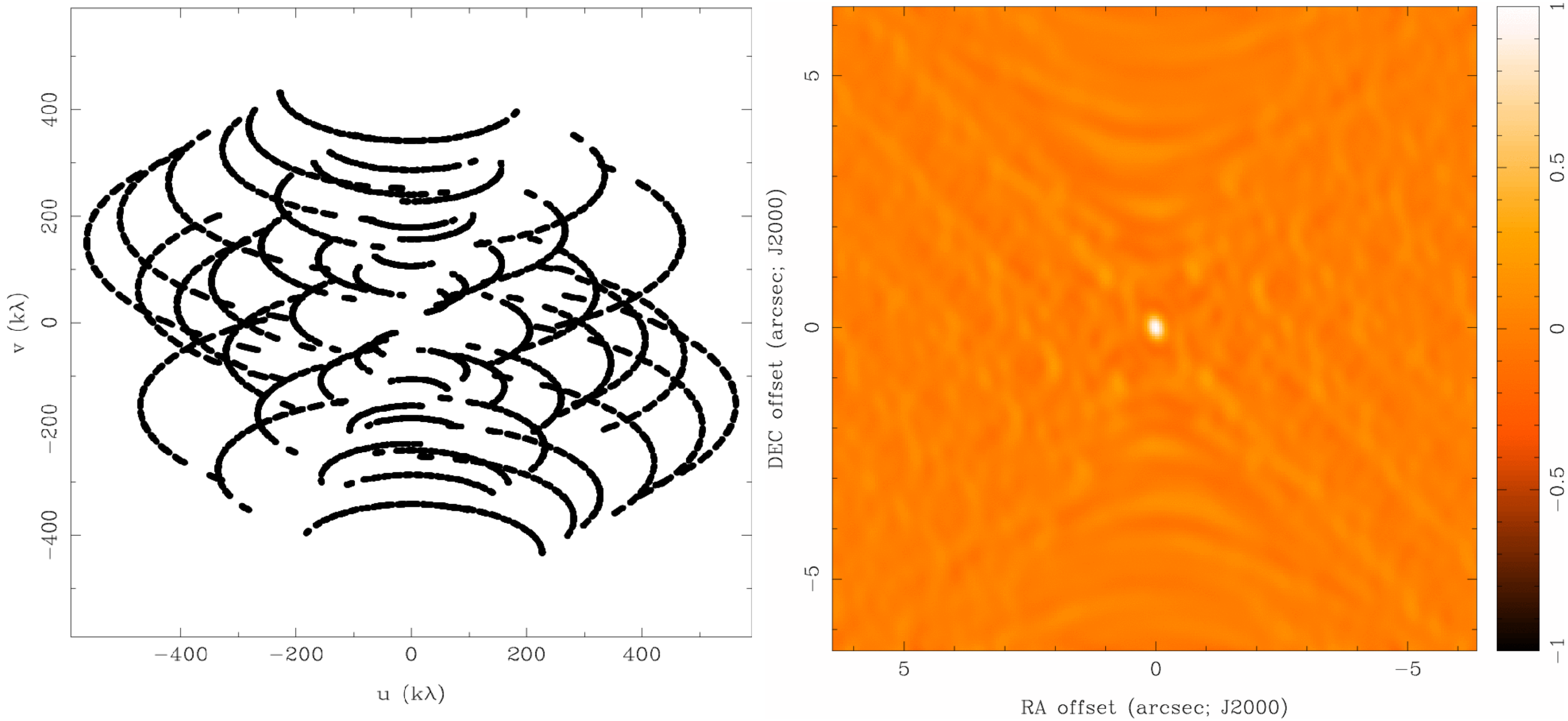




(Courtesy Dave Wilner)

Dirty Beam Shape and N Antennas

8 Antennas x 480 samples



(Courtesy Dave Wilner)

Deconvolution

We want to get: $$I(x,y) = \iint I(u,v) e^{2\pi i(ux+vy)} du dv$$

But we get only the so-called dirty image $$I_D(x,y) = \iint I(u,v) S(u,v) e^{2\pi i(ux+vy)} du dv$$

where $S(u,v)$ is the discrete sampling function in the uv-plane.

Using the convolution theorem, we can write:

$$I_D(x,y) = I(x,y) * B(x,y)$$

where B is: $$B(x,y) = \iint S(u,v) e^{2\pi i(ux+vy)} du dv$$

the co-called dirty beam → fourier transform of sampling function

→ This can be considered as a proxy of the spation resolution.

→ Recovering I(x,y) is deconvolution problem where additional info has to be supplied.

Deconvolution - Cleaning

- First algorithm bei Hogbom 1974, based on the assumption that the image is a superposition of many point sources.

- Identify strongest point in map and subtract the dirty beam at that position, usually 5-10% of intensity to increase stability

- Subtracted component is called clean component.

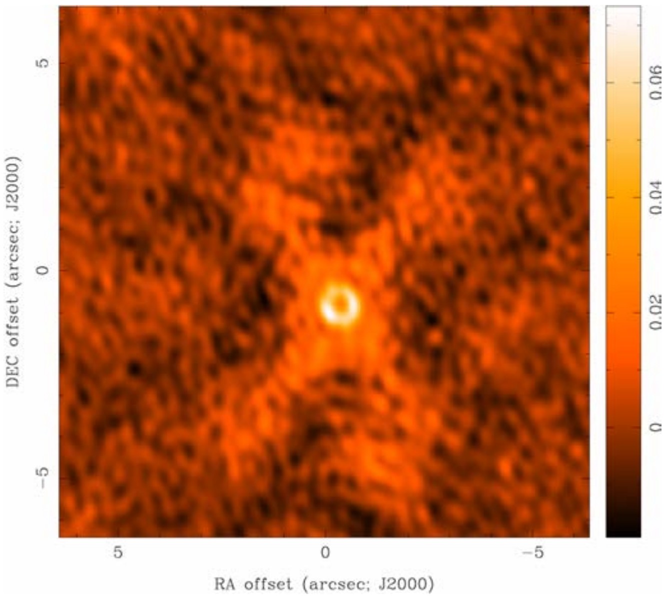
- This is done iteratively until the residual map only contains noise. Usually several 100 iterations.

- The clean component map is then again convolved with the so-called "clean beam". To derive the final map the residuals are added.

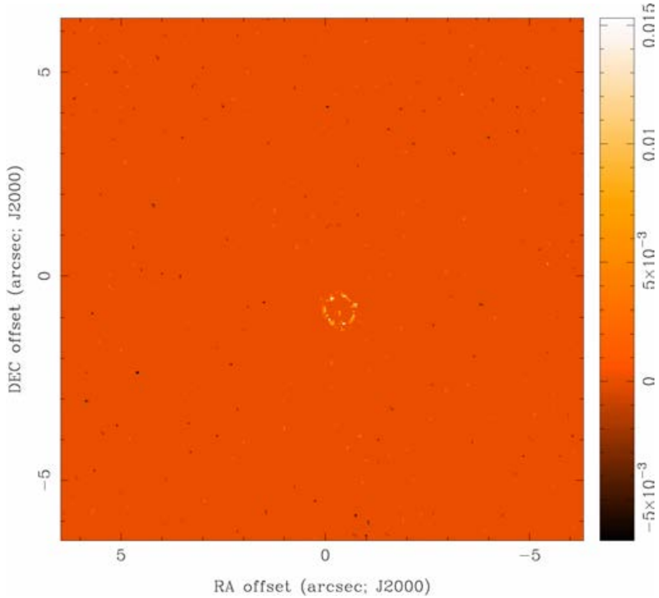
- The clean beam is usually a 2-D Gaussian fit to the central peak of the dirty beam.

Clean Example

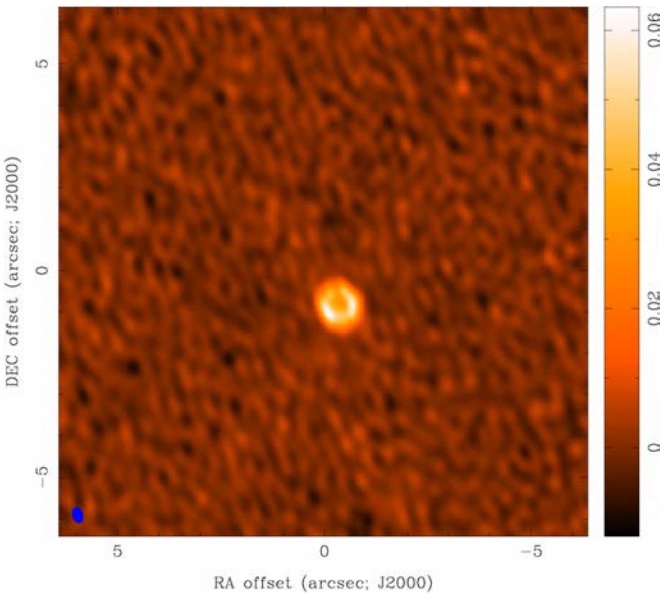
dirty image



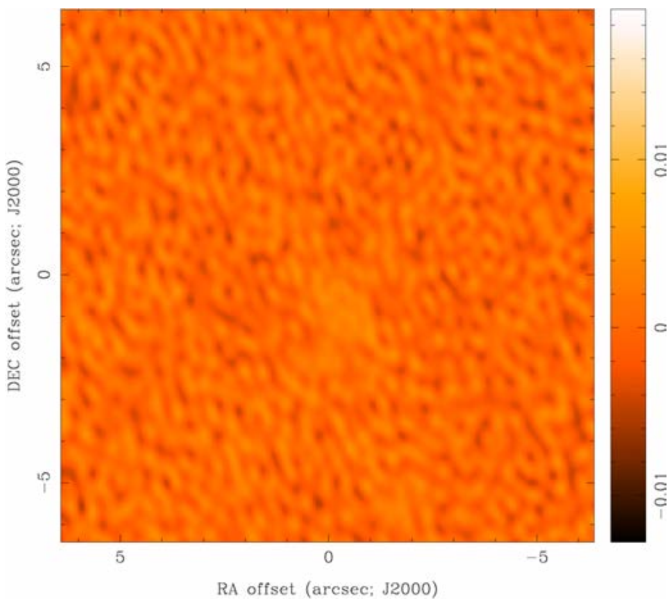
clean component model



restored image

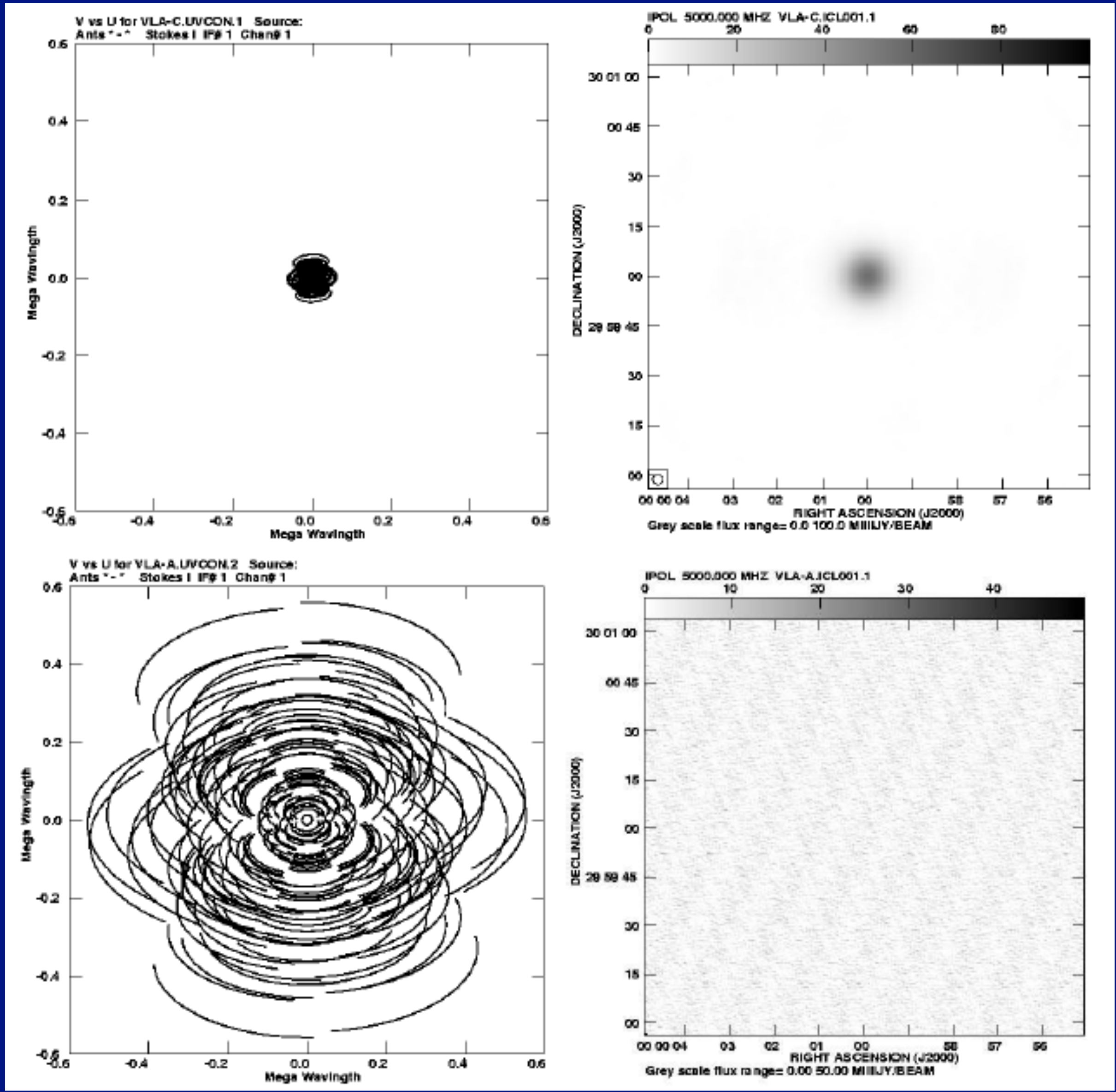


residual map



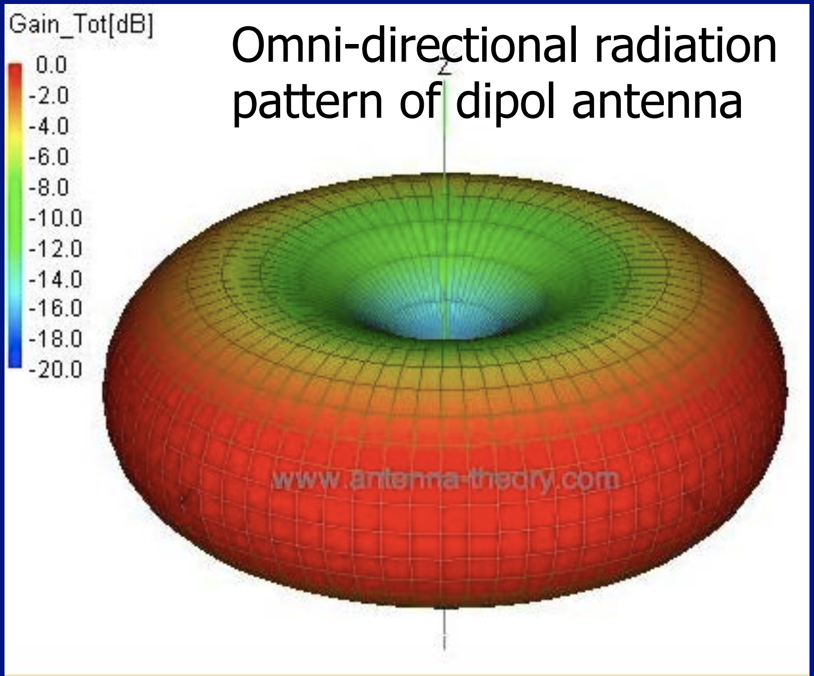
40

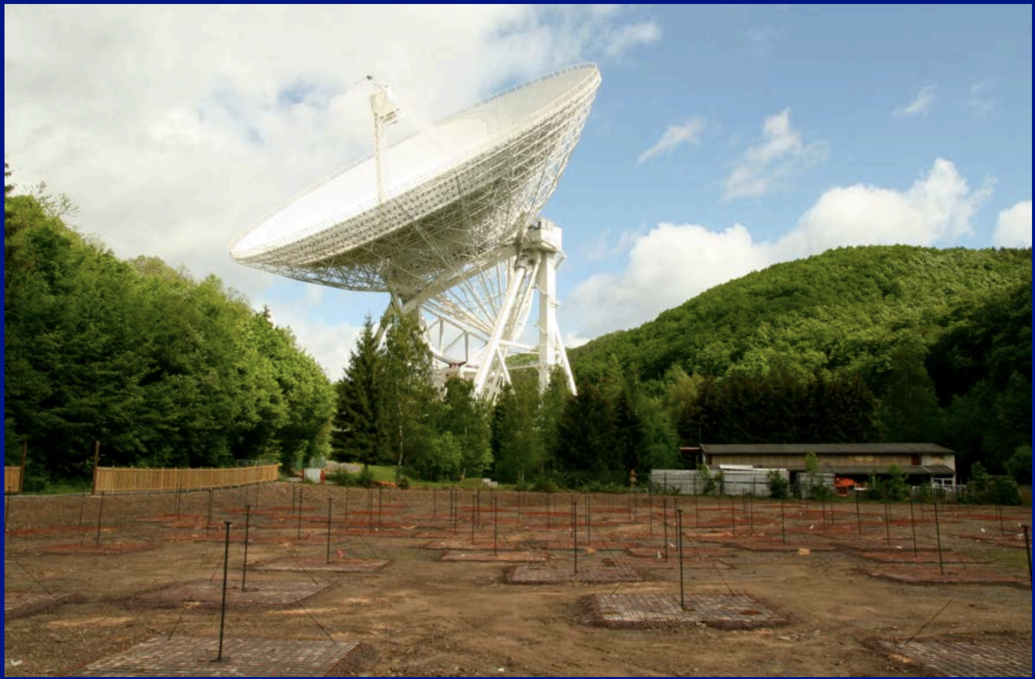
uv plane V



Simulations of obs. of a large Gaussian source with short and long baselines.

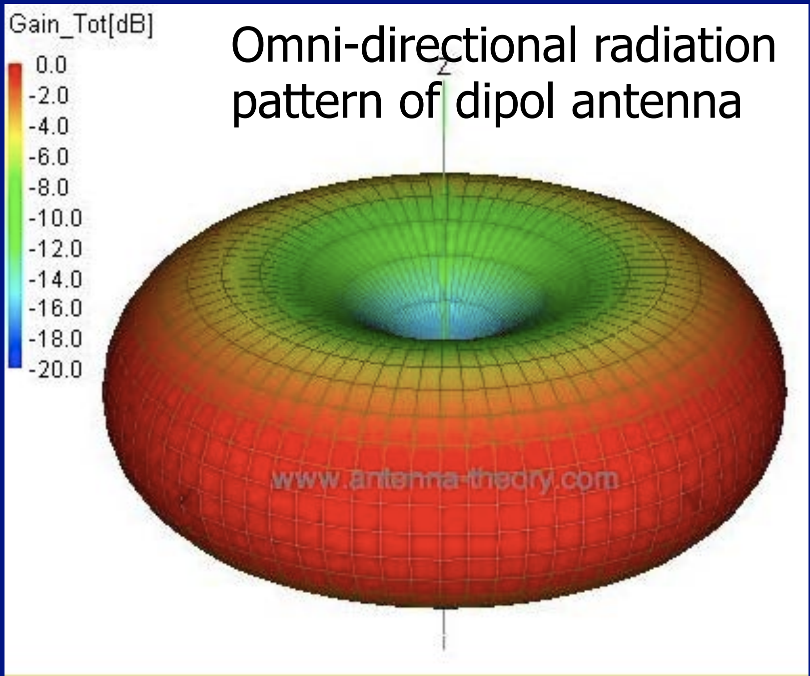
Phased array interferometry I





- LOFAR – low-frequency array
- 10 to 250 MHz, corresponds to 30m to 1.2m wavelengths.
- Resolution: 1292 km, i.e., 0.65" at 60 MHz, 0.2" at 240 MHz
- The direction (beam) is chosen electronically by introducing phase delays between antennas (see next slide).
- Can observe several directions simultaneously.
- 40 stations in Netherland, a few more in Germany, UK, France, Sweden.
- Hardware comparably cheap, software requirements enourmous!

Phased array interferometry I



Omni-directional radiation pattern of dipol antenna

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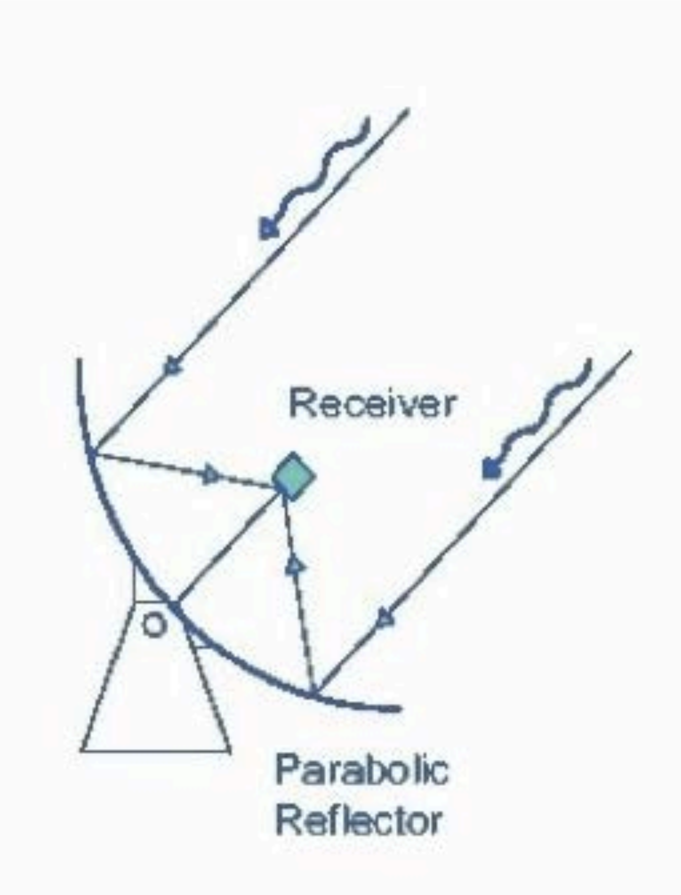
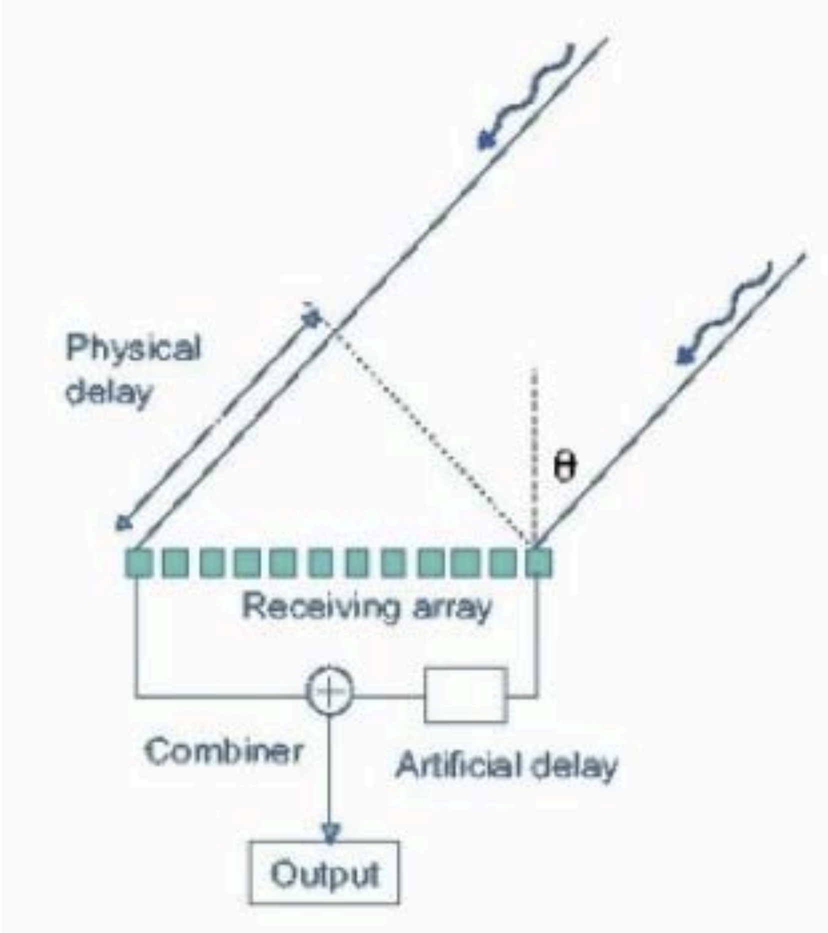
Phased array interferometry II

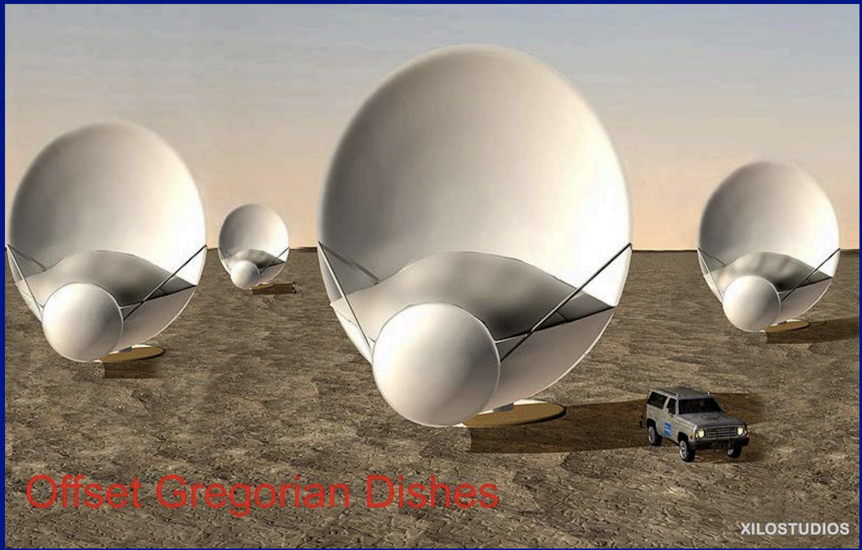


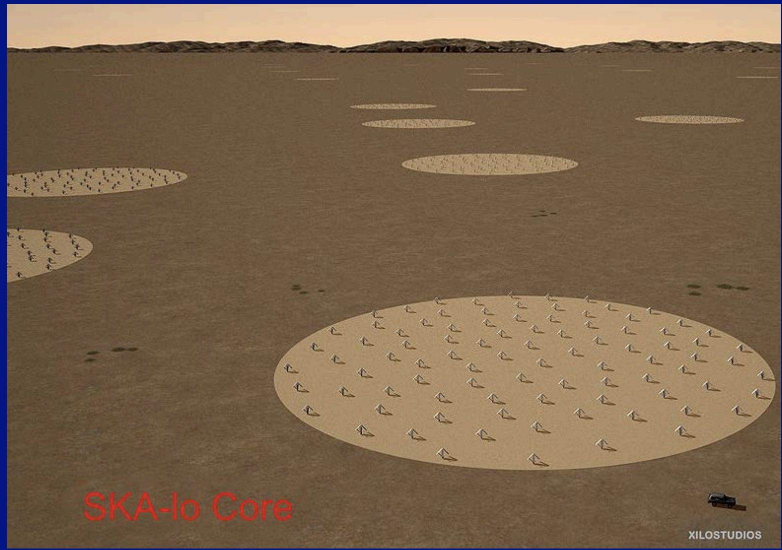


- Dish size corresponds to largest distance between dipoles
- Baseline corresponds to distance between stations.

- Future of phased arrays → Square kilometer array (SKA)

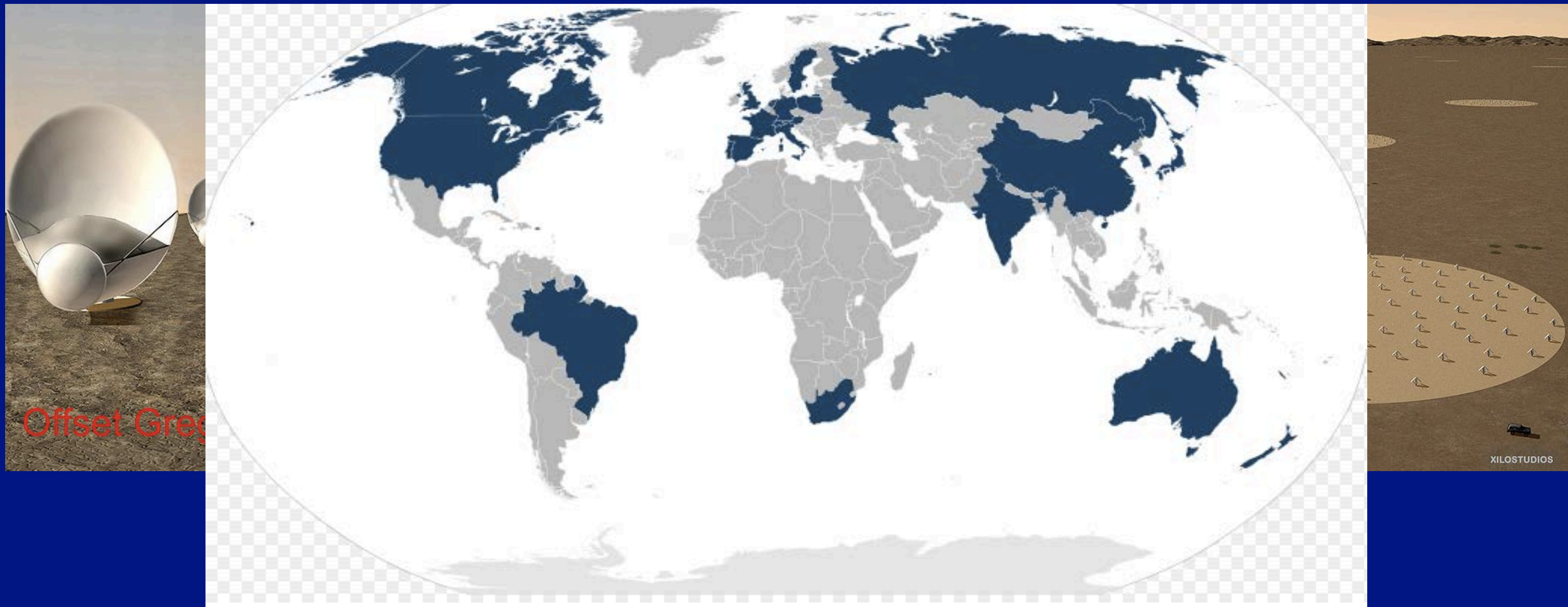
Square kilometer array (SKA)





- Total collecting area of approximately 1 square kilometer
- Combination of phased array and parabola dishes
- World-wide consortium, location in South Africa and Australia
- Frequencies between 70MHz and 10GHz (or even higher)
- Start planned for 2019, finished maybe by 2023 …

Square kilometer array (SKA)



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Radio and mm astronomy

Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

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More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1213.html

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