RADIO INTERFEROMETRY

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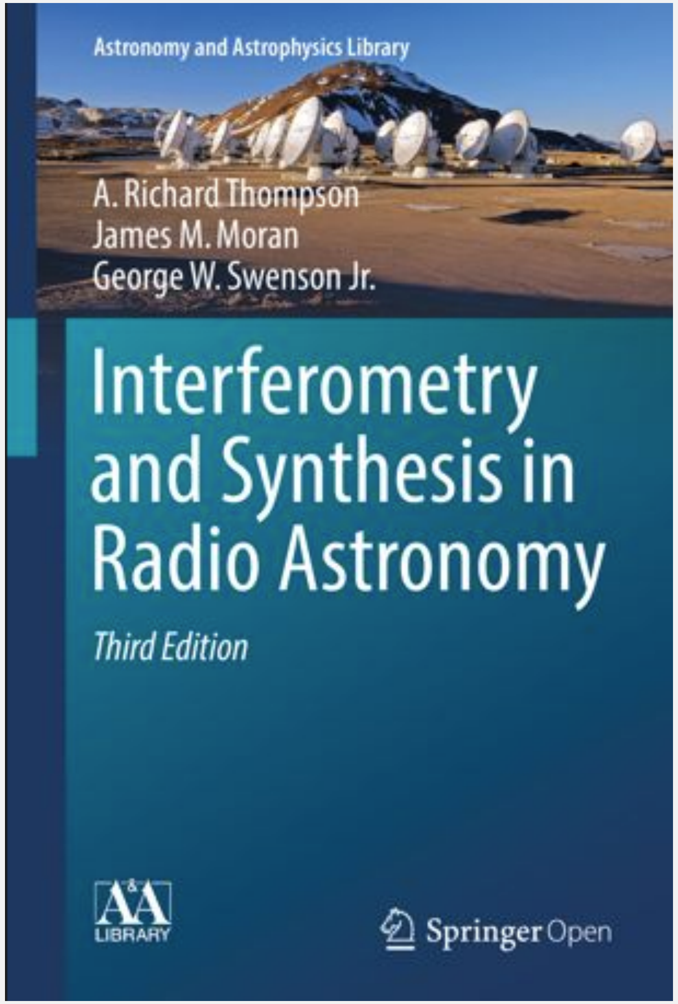
Holy Books of the World

Buddhism: Tipitaka
Christianity: Bible
Hinduism: Bhagavad Gita
Islam: Kuran
Judaism: Tanakh
Radio Interferometry: Thompson, Moran & Swenson



Third Edition available for FREE!

https://www.springer.com/gp/book/978331944291 In General

https://link.springer.com/book/10.1007%2F978-3-319-44431-4 In Mexico

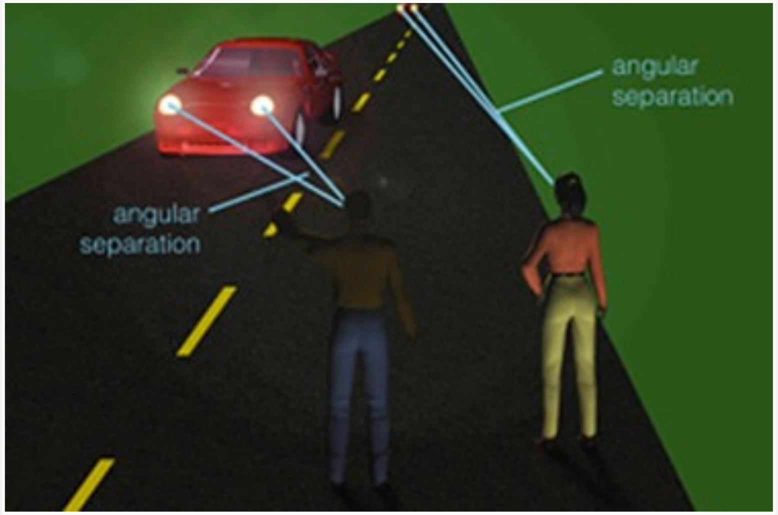
At least three different ways to view/analyze interferometers…

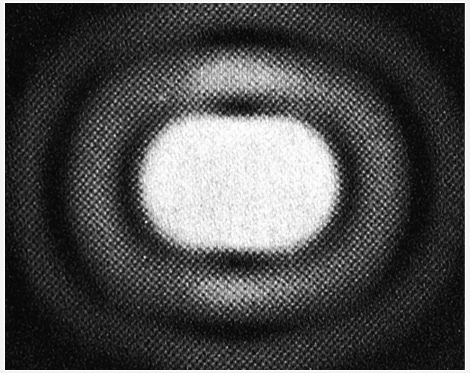
1. An antenna with non-contiguous parts
   or a single huge antenna, with much of the surface missing.
   Analysis in terms of `fringes'; appropriate for adding interferometers

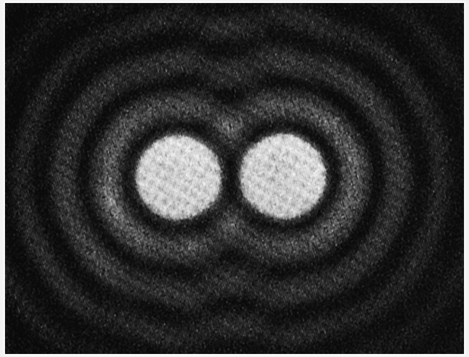
2. Electric field of the astronomical source can be measured in a plane on
   the sky, by locating two antennas in a parallel plane on the Earth.
   The antennas measure the correlation function of the field, which is
   the Fourier Transform of the source brightness distribution.

3. Two antennas receiving a signal from a point source from direction ψ, with
   an excess travel distance B cos ψ to the further antenna. This produces an
   interference pattern with a `fringe phase' which can be `stopped' by inserting
   a delay into the signal path.

Why use interferometers at all?







Optical Telescopes

$$\frac{500\ nm}{8\ m} = 0.00000006$$

Earth-based limit about one arcsec
(seeing limited, not diffraction limited)

Radio Telescopes

$$\frac{1\ cm}{30\ m} = 0.0003$$

About one arcmin

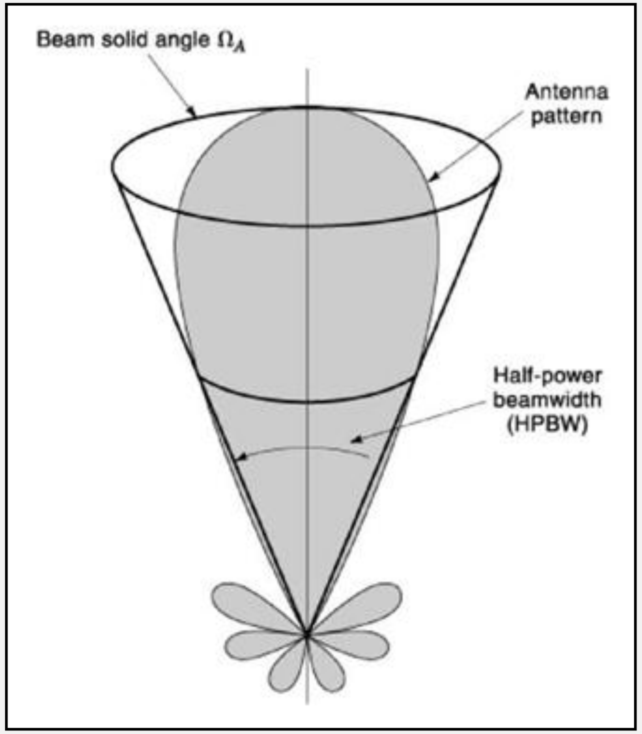
About 70,000 AU at 1 kpc
or about 1000X the Solar System

The Problem of Angular Resolution

$$\Theta \sim \lambda / D$$

Angle ~ wavelength / telescope diameter

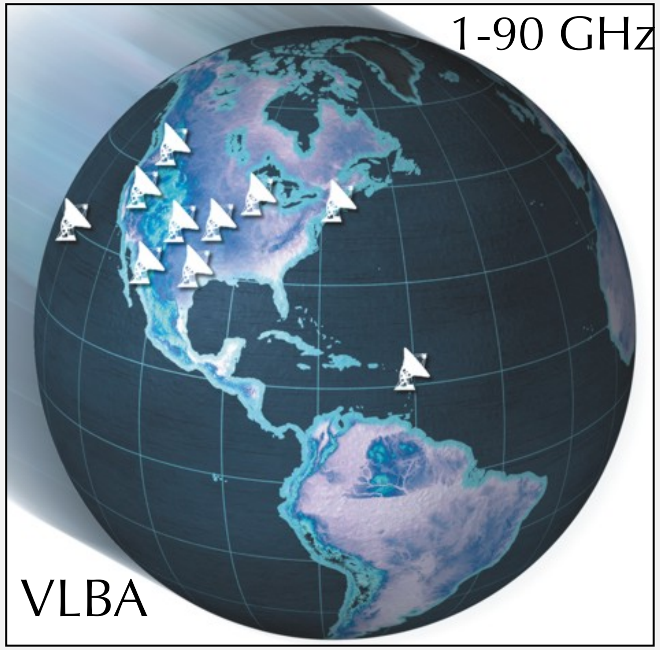
For single-dish telescopes, this is both the Field-of-View and the Angular Resolution



$$\Theta \sim \lambda/B$$

B is the *baseline*, or the *separation between* antennas

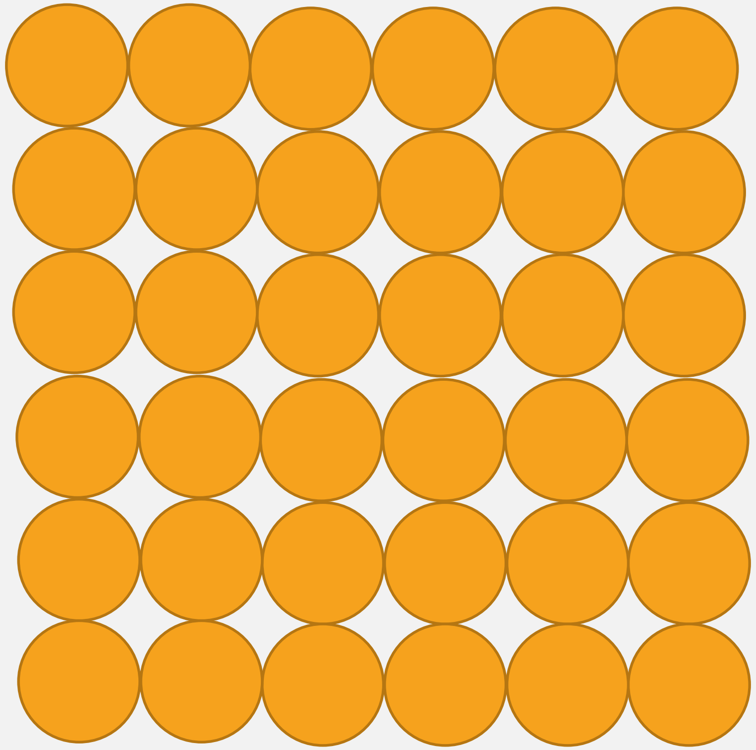
Micro-arcsec resolution is possible

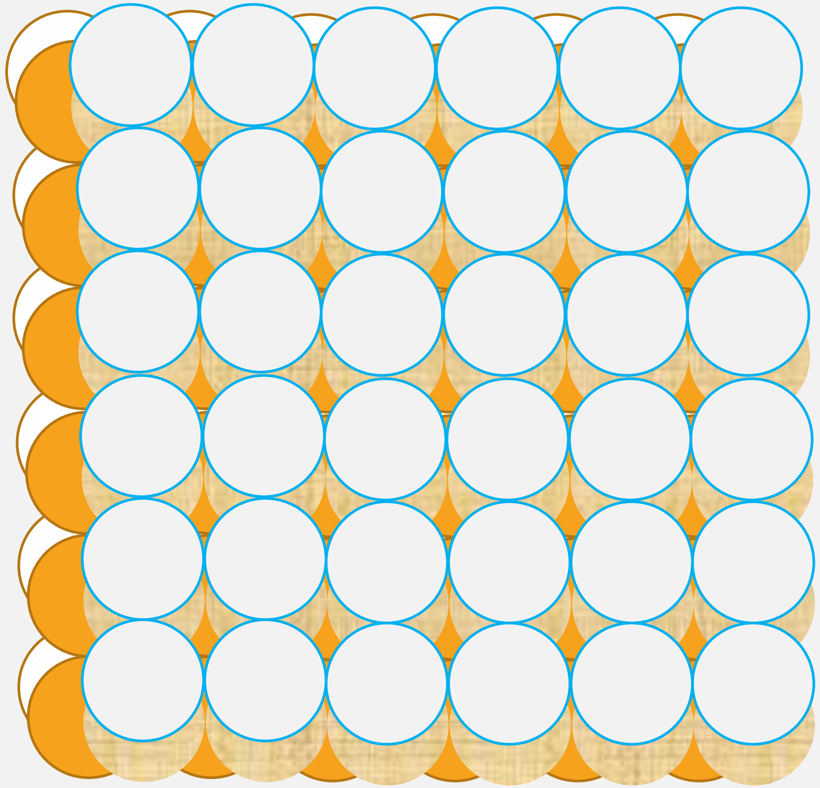


Two beam sizes now important:

1) Primary beam (field of view) from diameter D
2) Synthesized beam (resolution) from spacing B

Making Images with Single-Dish Telescopes



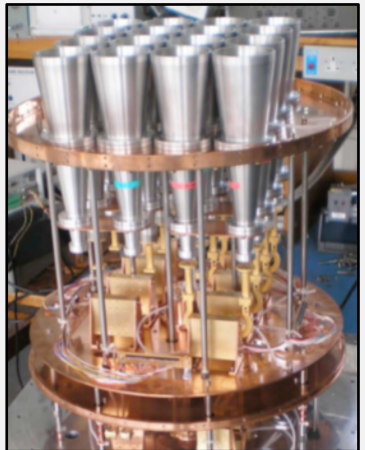


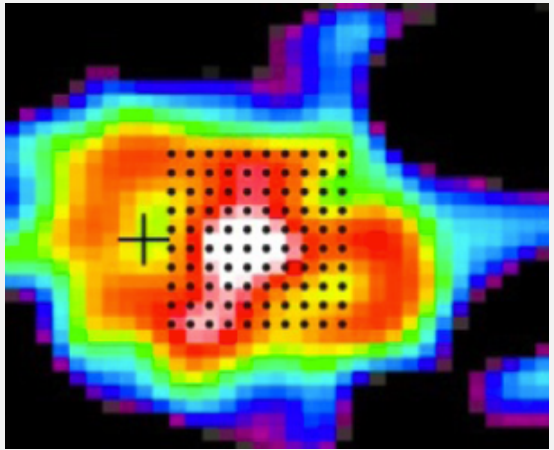
Even worse!
4 x 36 = 144 pointings
for 'half-beam' sampling
that satisfies the
Nyquist Criterion

OTF: On The Fly mapping
via raster scanning is
another option

6 x 6 pixels from 36 pointings
vs 2048 x 2048 in optical CCDs!

FPA: Focal Plane Arrays (multi-pixel feeds)
Speed both multiple pointings and OTF mapping

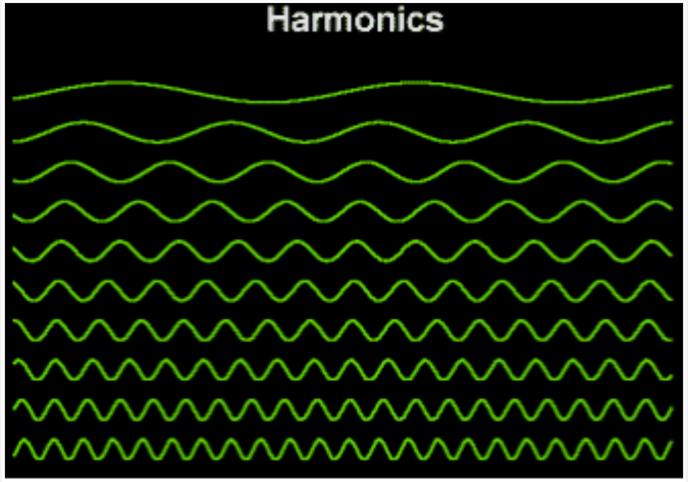


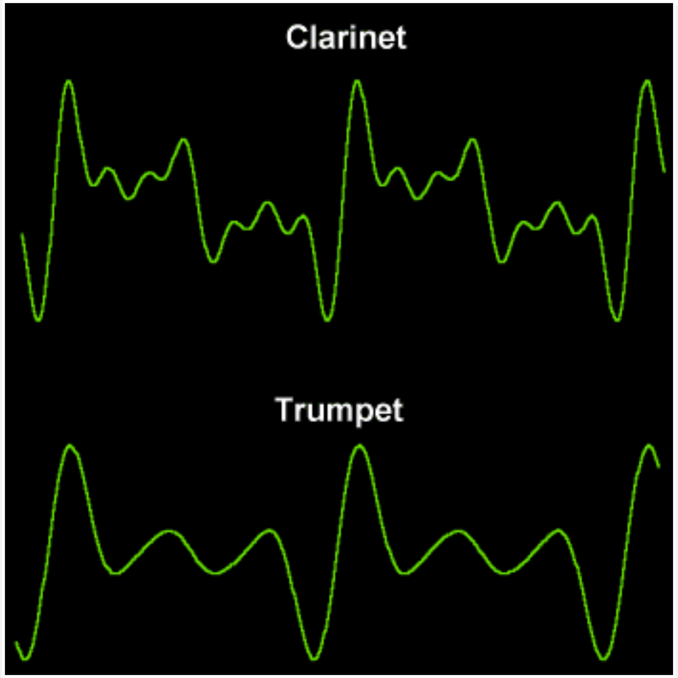


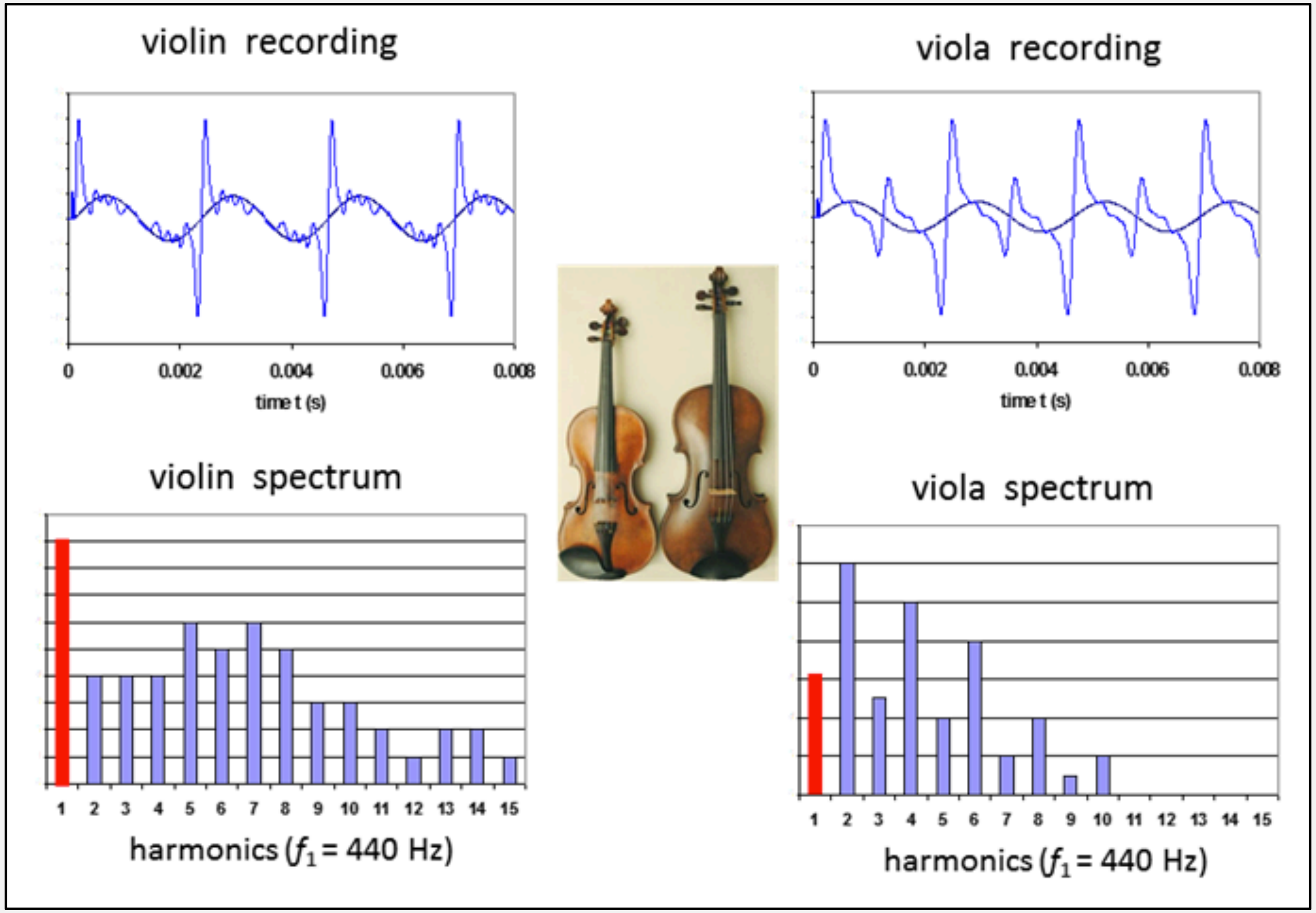
But how do we
make images with
an interferometer?

Problem: How to form something (anything!) from sines and cosines?

Solution is well-known from music: Fourier Synthesis

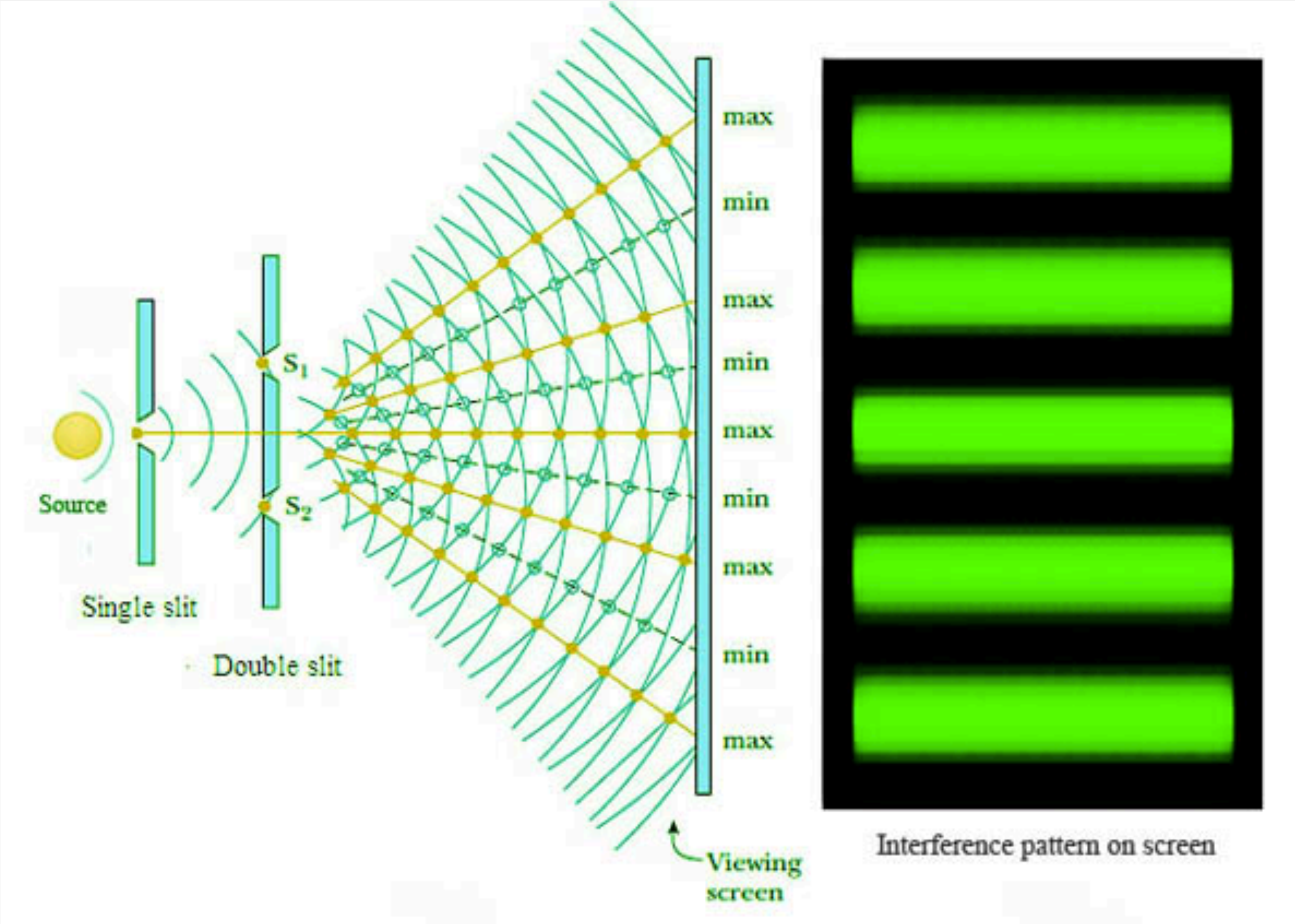






For images we'll use *spatial*, rather than *temporal* frequencies

Antenna pairs act so as to form a two-slit interference pattern



Maxima occur when

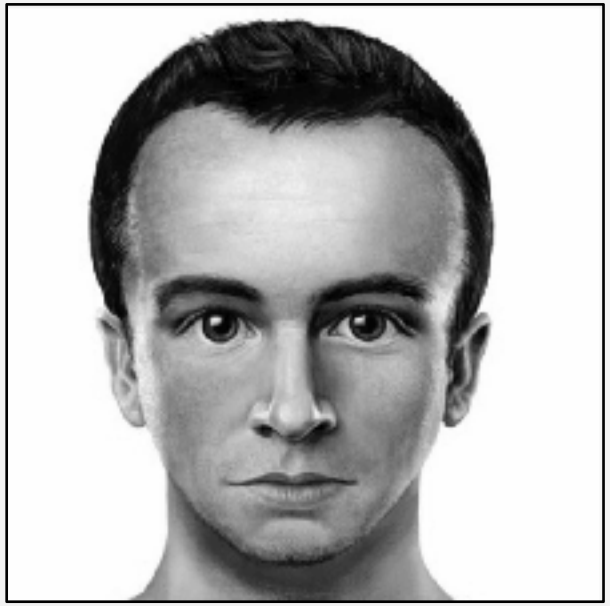
$$d \sin\theta = n\lambda$$

Spacing of maxima is: $y = n\frac{\lambda D}{d}$

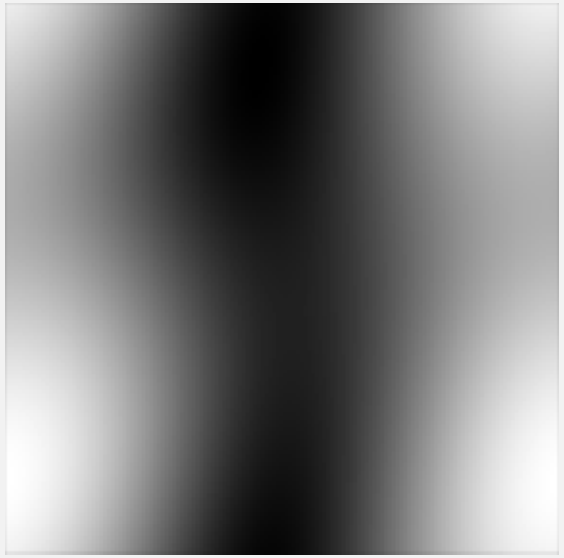
Small slit spacing gives a large pattern spacing

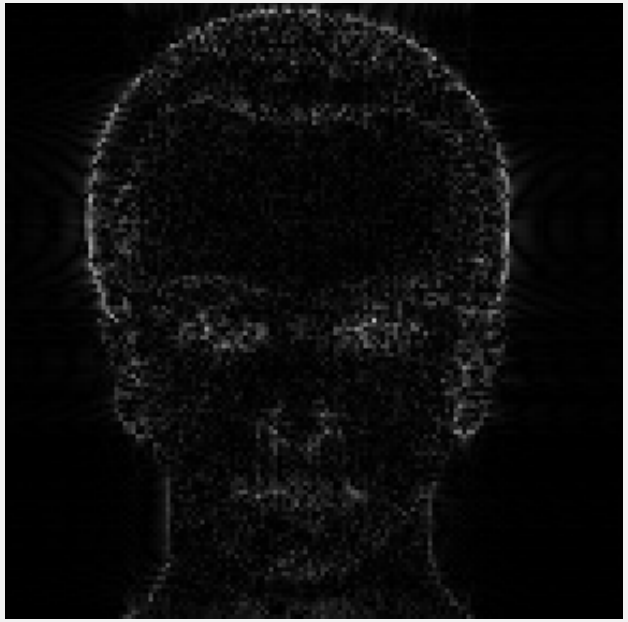
Large slit spacing gives a small pattern spacing

Closely spaced antennas sample low spatial frequencies: they see big things
Widely spaced antennas sample high spatial frequencies: they see small things



Low Spatial Frequencies Show Larger Shapes





High Spatial Frequencies
Show Fine Details but lose
The Bigger Shapes

Getting the Fourier Components

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

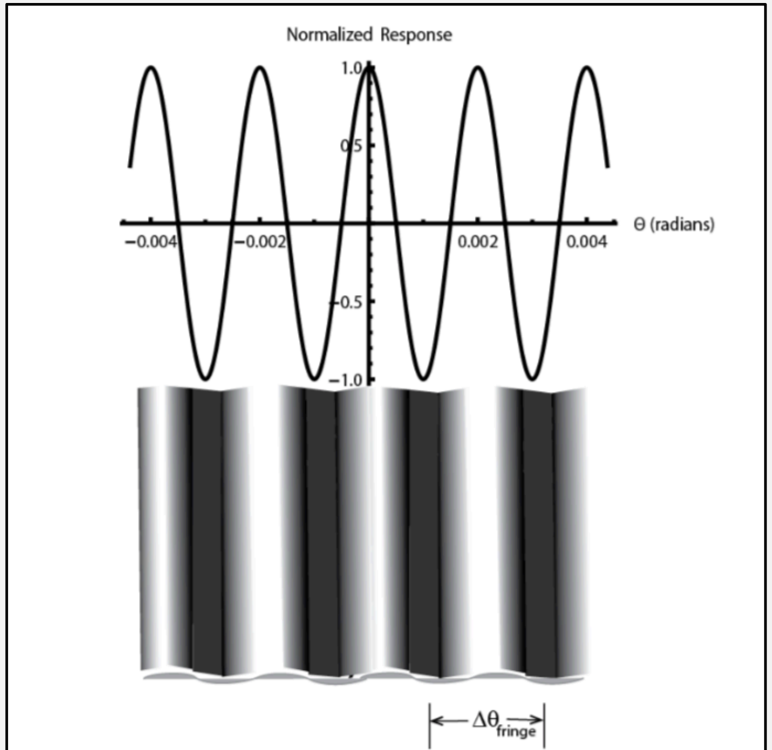
Sky brightness = Fourier Transform of the Visibilities in *uv* space

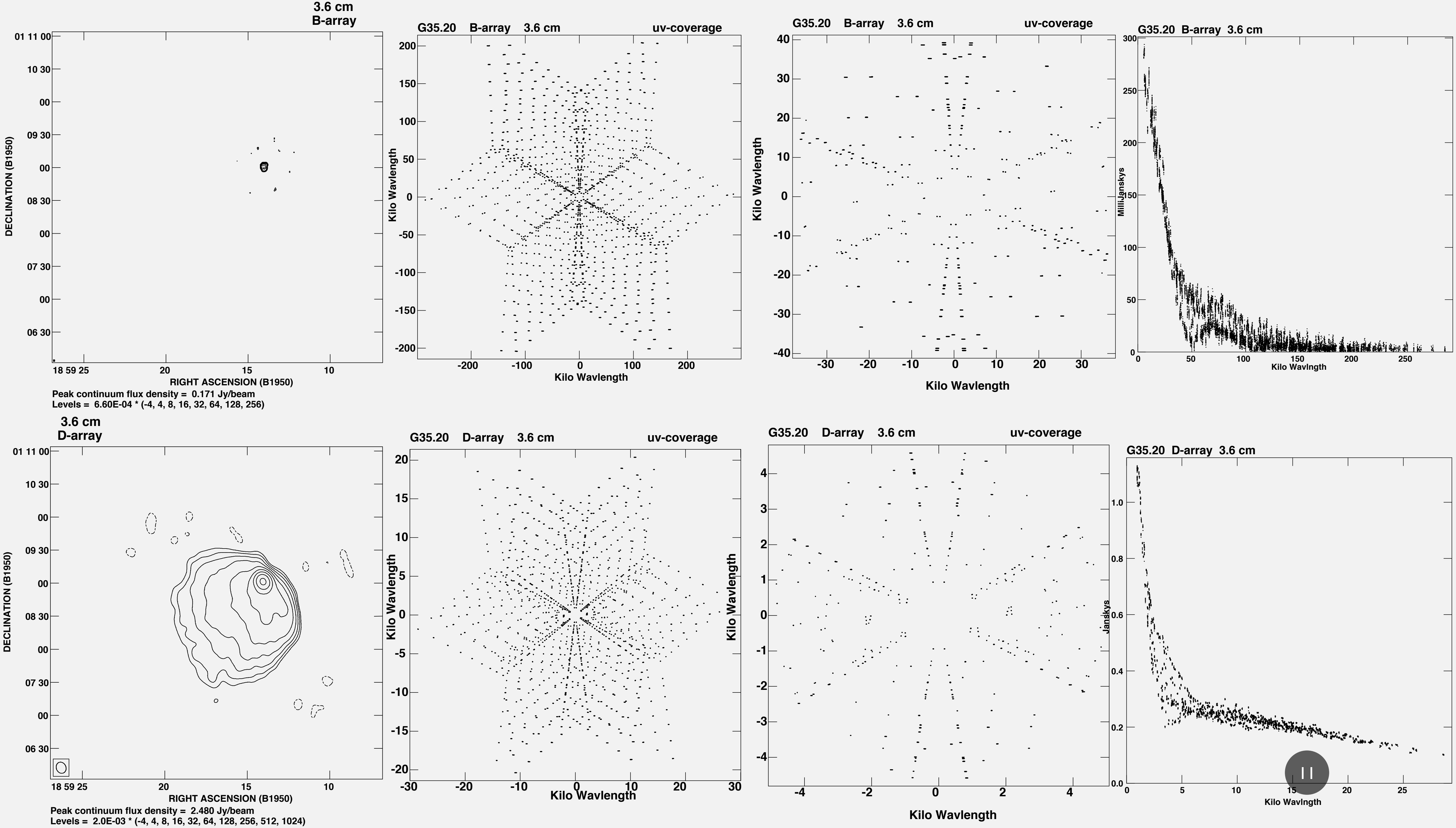
(x, y) in radians $\quad u = \frac{b_x}{\lambda} \quad v = \frac{b_y}{\lambda} \quad (u, v)$ in kilo or mega wavelengths

Visibilities are the cross-correlation of the antenna signals, corrected for the fringe function

$$\langle E_1 \cdot E_2 \rangle = \frac{E_0^2}{2} \, cos\left(2\pi \frac{b}{\lambda} sin\omega_E t\right)$$

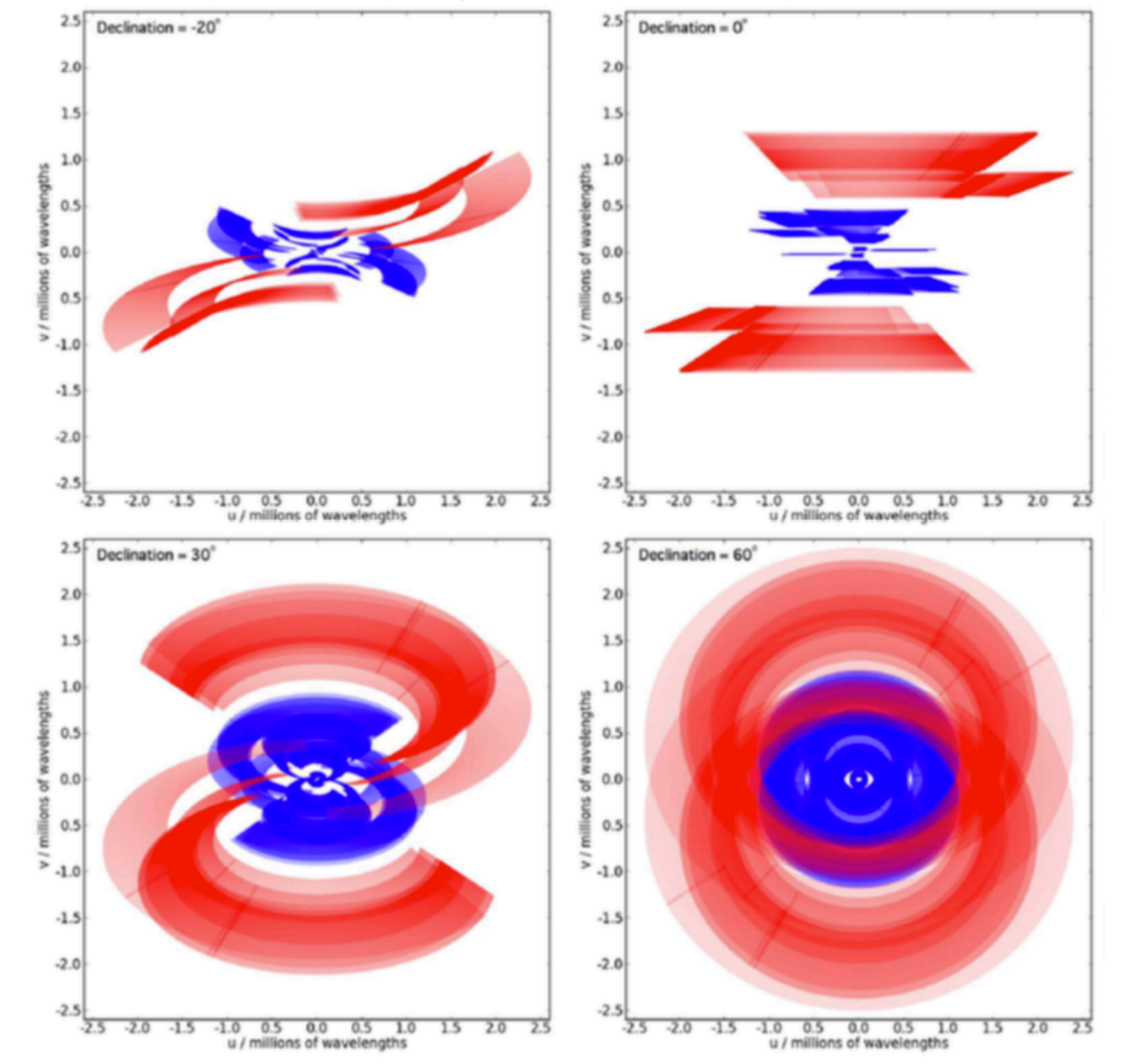
The fringe function, due to Earth Rotation





3.6 cm
B-array
DECLINATION (B1950)
RIGHT ASCENSION (B1950)
Peak continuum flux density = 0.171 Jy/beam
Levels = 6.60E-04 * (-4, 4, 8, 16, 32, 64, 128, 256)
G35.20 B-array 3.6 cm uv-coverage
Kilo Wavlength
G35.20 B-array 3.6 cm uv-coverage
Kilo Wavlength
G35.20 B-array 3.6 cm
Milli Janskys
Kilo Wavlngth
3.6 cm
D-array
DECLINATION (B1950)
RIGHT ASCENSION (B1950)
Peak continuum flux density = 2.480 Jy/beam
Levels = 2.0E-03 * (-4, 4, 8, 16, 32, 64, 128, 256, 512, 1024)
G35.20 D-array 3.6 cm uv-coverage
Kilo Wavlength
G35.20 D-array 3.6 cm uv-coverage
Kilo Wavlength
G35.20 D-array 3.6 cm
Janskys
Kilo Wavlngth

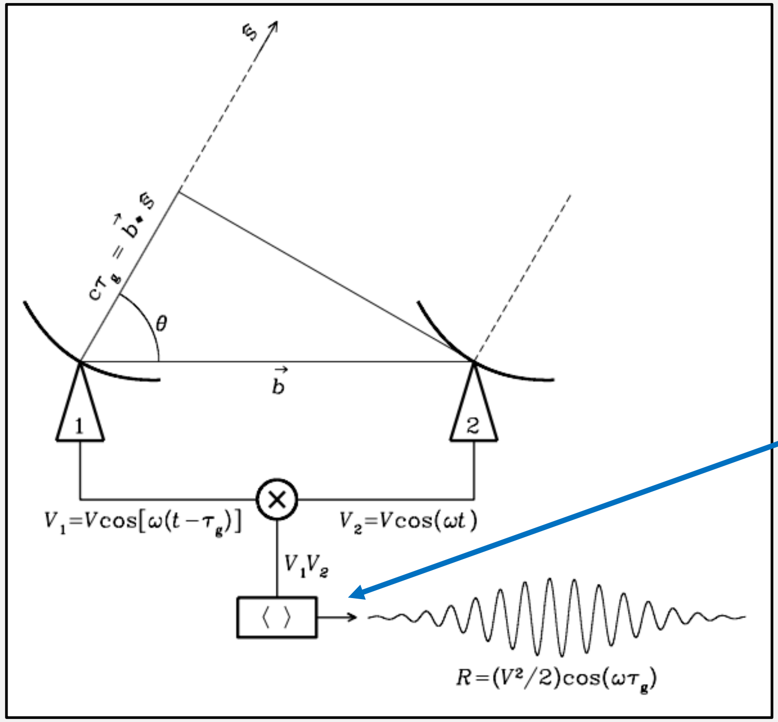
The effects on uv coverage by adding the Goonhilly antenna to e-MERLIN



Heywood et al. 2011

Better coverage of the *uv* plane gives better images!

If we have *Radio Interferometry*, Why do we need VLBI? and What's so special about it?



Connected-element interferometers have a *real-time* connection between the antennas

The correlation of the antenna signals occurs in real-time

But what if we need baselines so long that
real-time connections don't work?
Suppose we need 1 milli-arcsec resolution at 30 GHz

Solution is to *record the data* at each antenna, for later correlation

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

1 mas is 4.85 x 10^{-9} radians
30 GHz is 1 cm wavelength

$$4.85 \times 10^{-9} = \frac{1\ cm}{2000\ km}$$

VLBI vs Connected-Element Interferometry: What's so different?

A) Each antenna needs an atomic clock

B) High brightness temperature sources are needed

C) Only a small field of view can be imaged (BW smearing is extreme)

A) Greater Hardware Requirements

The correlation process requires very precise time-stamping of the data, hence the need for atomic clocks at each station

Lots of disk storage capacity is needed

Year	Sustainable Rate (Mbps)	Disk purchase (TB)	Disk cost ($/GB)	Other costs ($/GB)	~ cost
1	256	825	1	.15	$1.0M
2	512	825	.75	.15	$0.8M
3	1024	1750	.50	.10	$1.0M
Total		3300			$2.8M

Shipping & Correlation Infrastructure is needed

B) What's the deal with brightness temperature?

Resolution depends on antenna *separation*
Sensitivity depends on antenna *area*

VLA in D-array		VLBA
$27 \times 25\ \frac{\pi^2}{4}$ = 1664 m^2	True collecting area	$10 \times 25\ \frac{\pi^2}{4}$ = 620 m^2
$\pi\ (0.5\ km)^2$ = 785,000 m^2	Spanning area	$\pi\ (4000\ km)^2$ = 5 x 10^{13} m^2
10^{-3}	Fractional area	10^{-11}

High source brightness temperature is needed ~ 10^6 K

Not all astronomical sources can be detected!

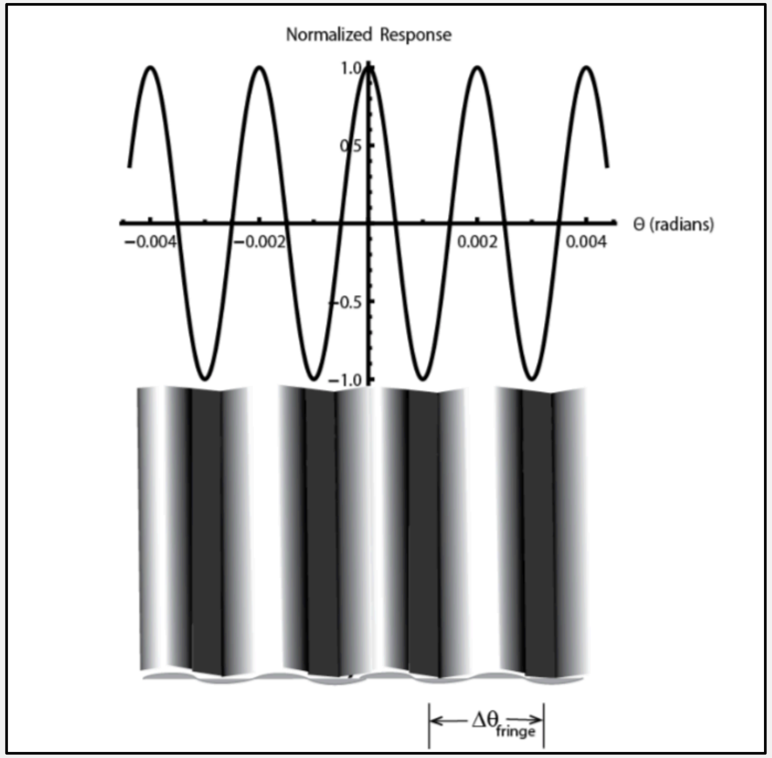
C) Why the small field of view?

Bandwidth and Time Smearing
limit the angular area over which
an image can be made

Typical map dimensions are < 1 arcsec

Multiple positions may be mapped with multiple correlations

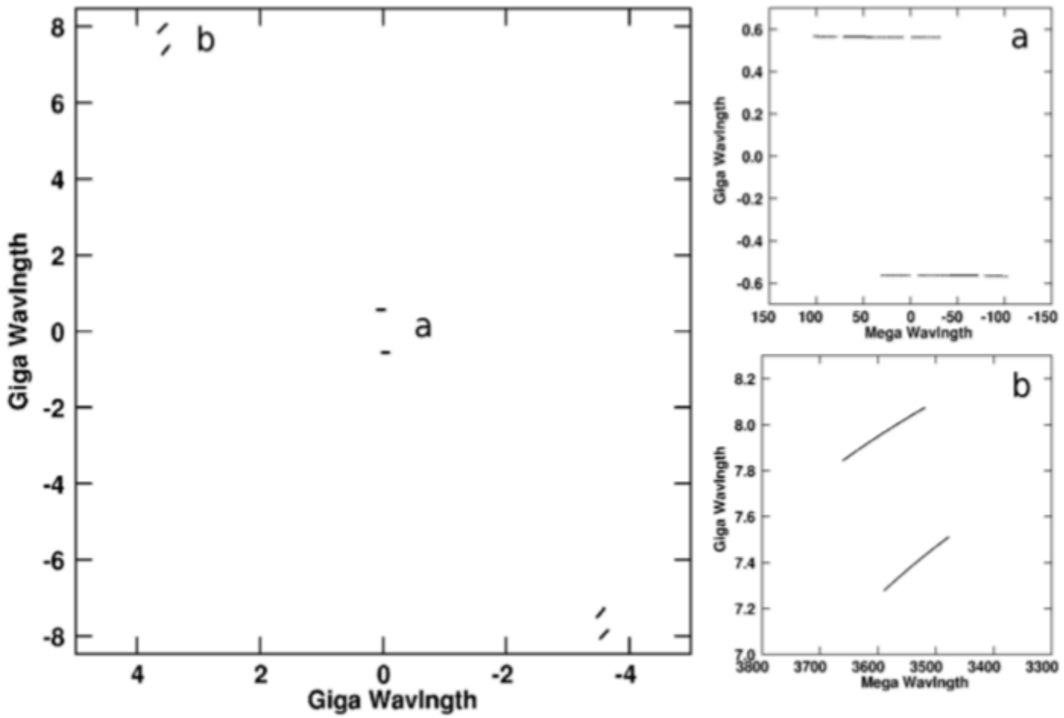
Software correlators allow these positions to be mapped *simultaneously*

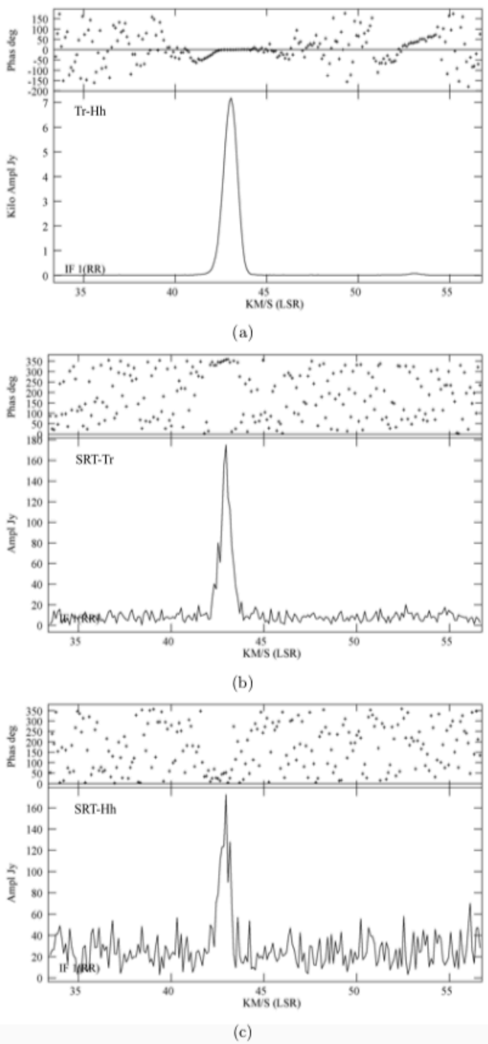


How many antennas do you need to make an image?

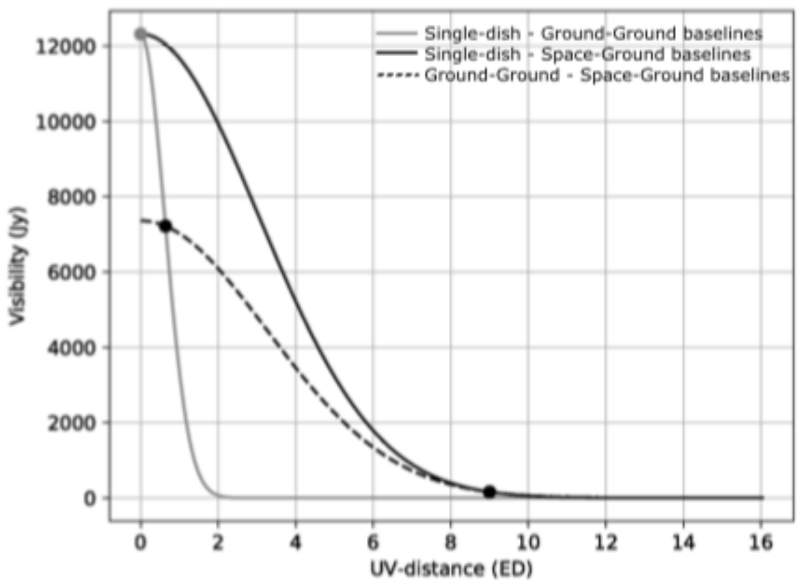
1. Radio Astron (in Space)
2. Torun (in Poland)
3. Hartebeesthoek (in South Africa)

With such poor uv coverage imaging is not really possible; the visibilities must be modeled





Bayandina et al. (2019, accepted)



No hard rule, but ≳ 6 or 8 needed for imaging

3 antennas needed for phase closure
4 antennas needed for amplitude closure