Principles of Interferometry I

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Astronomy is an observational science

- We cannot interact with the object we are studying as the experimental sciences can.
- We have a 2D view of a 3D universe
- Information about the universe comes almost exclusively from electromagnetic radiation.
- This places a high demand on our ability to form images and understand the measurement process

Introduction to Interferometry

Synthesis Imaging in Radio Astronomy

- I (1989) ASP Conf. Series vol. 6
- II (1999) ASP Conf. Series vol. 180

Interferometry and Synthesis in Radio Astronomy

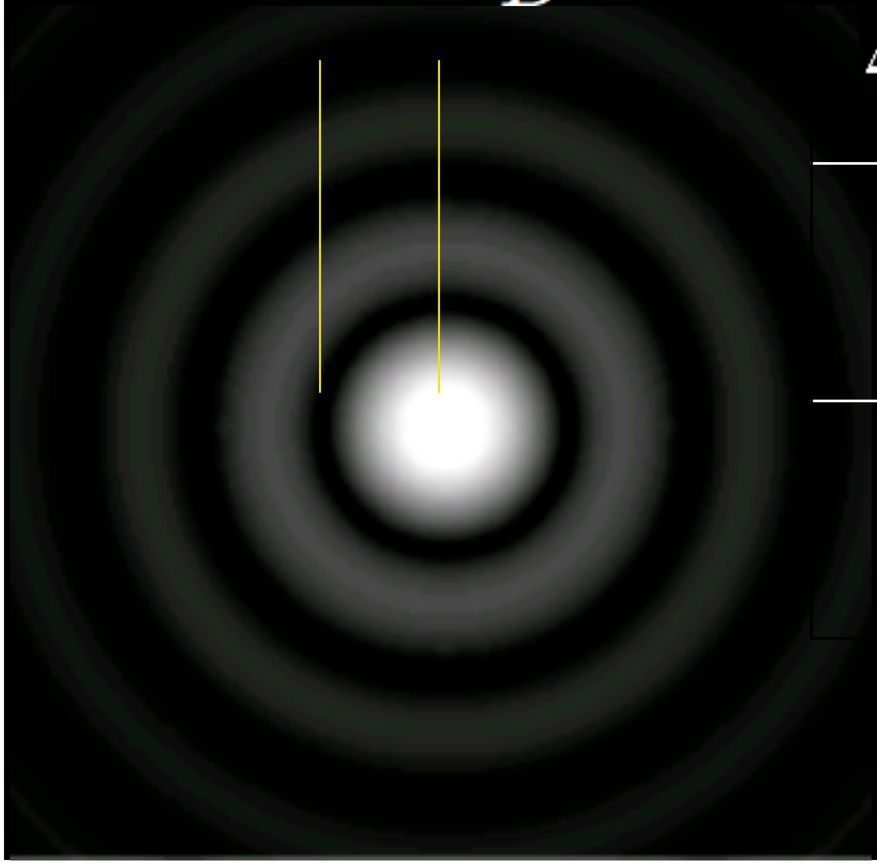
- Thompson, Moran & Swenson (2001)

Astronomical images

Intensity
Frequency Spectrum
Polarization properties

Diffraction limits

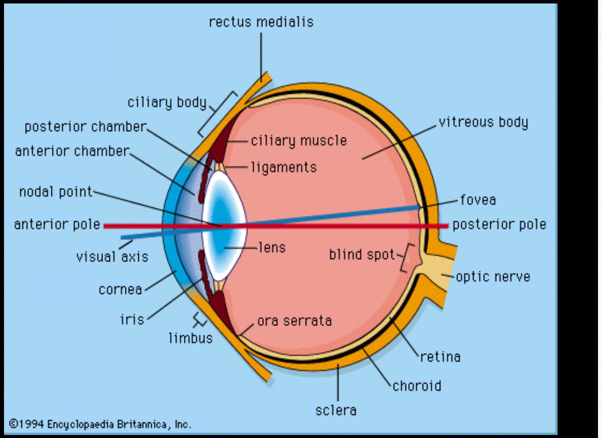
$$\Delta\theta \approx \frac{1.22\lambda}{D}$$



$\Delta\theta = 1''$	λ	D
Optical	500 nm	125 mm
Radio	20 cm	50 km

Direct imaging onto a focal plane

$\Delta\theta$ $1'$ $2''$ $10'$



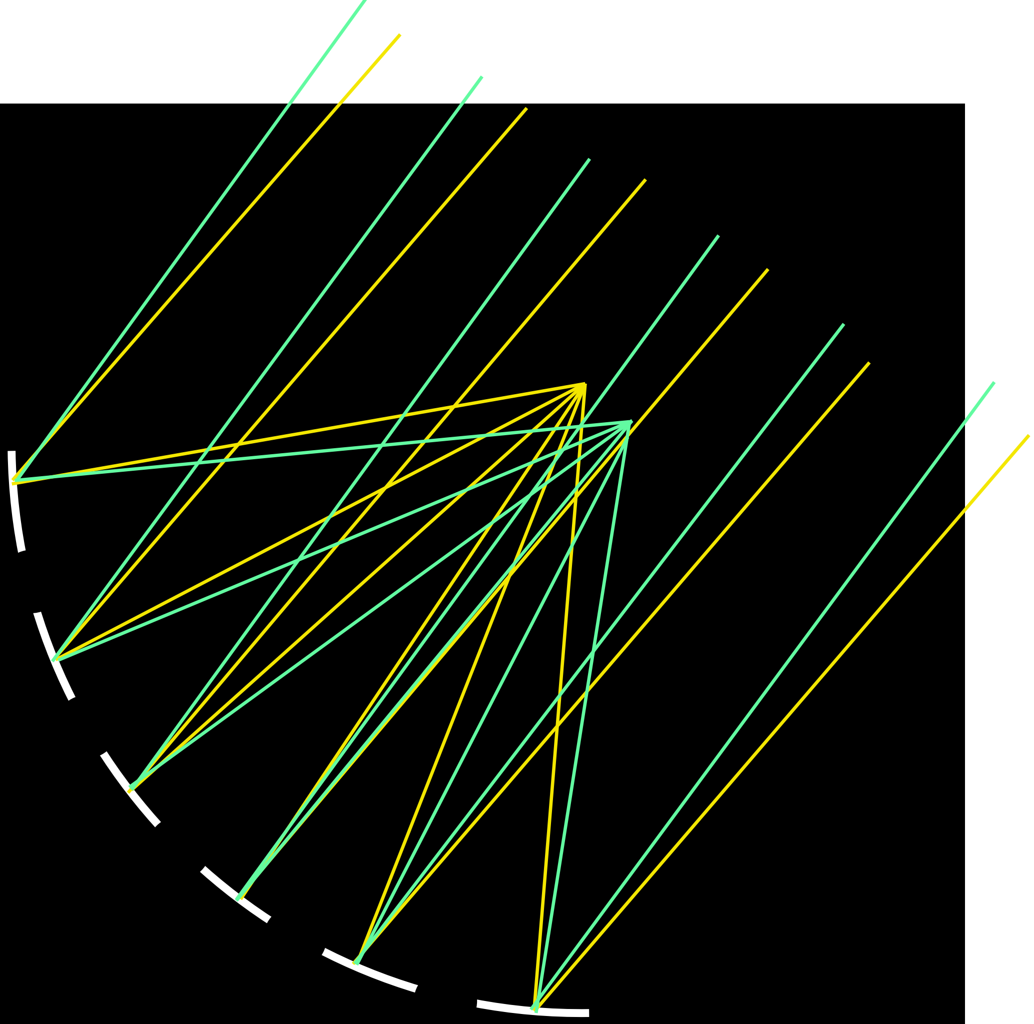
Synthesis telescopes

Indirect imaging

Indirect imaging

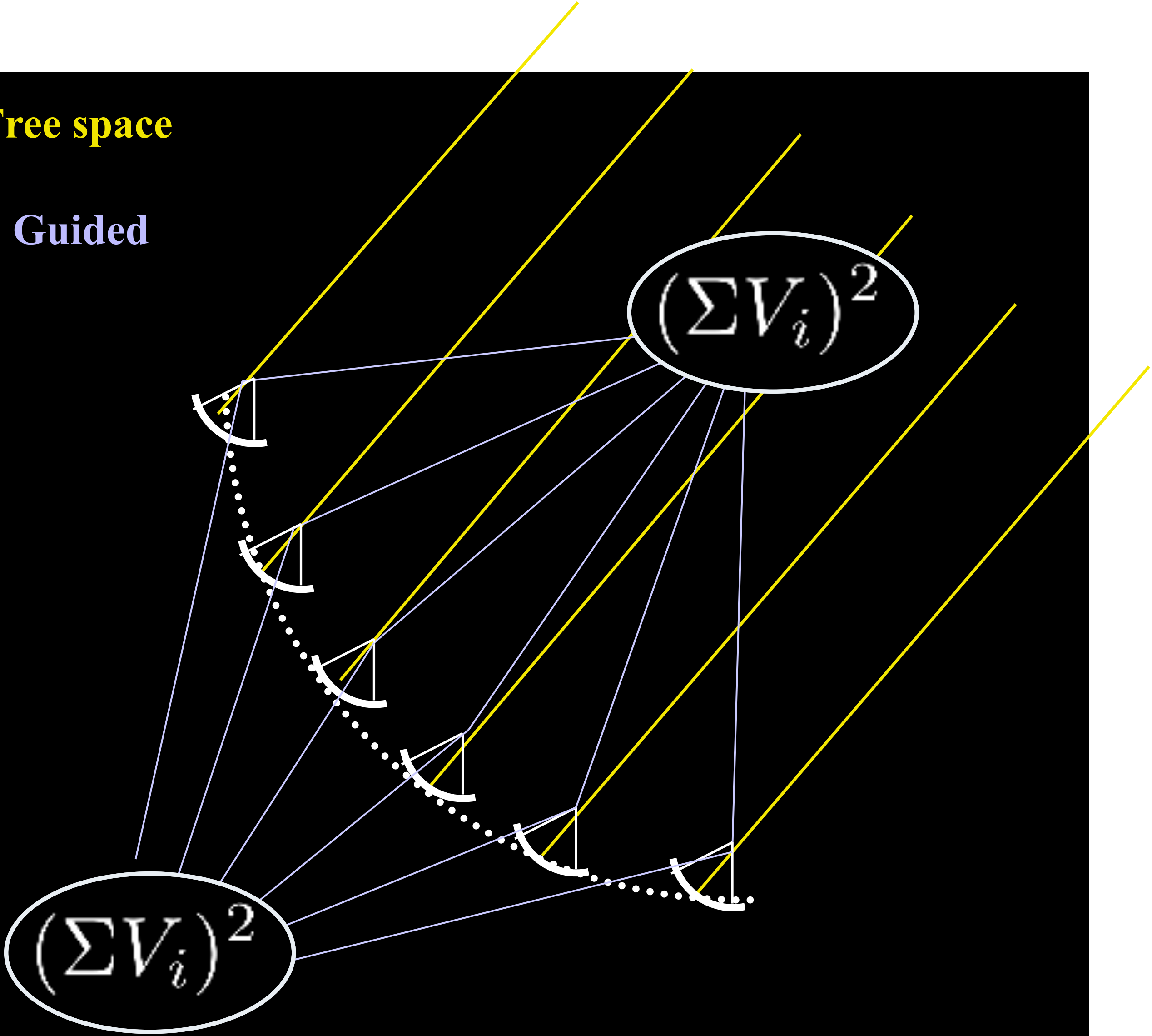
- Used where we cannot form a direct map of the object on the focal plane.
- We infer the properties of the object from certain characteristics of the received electromagnetic field
- It is not intuitive!

Single
dish …

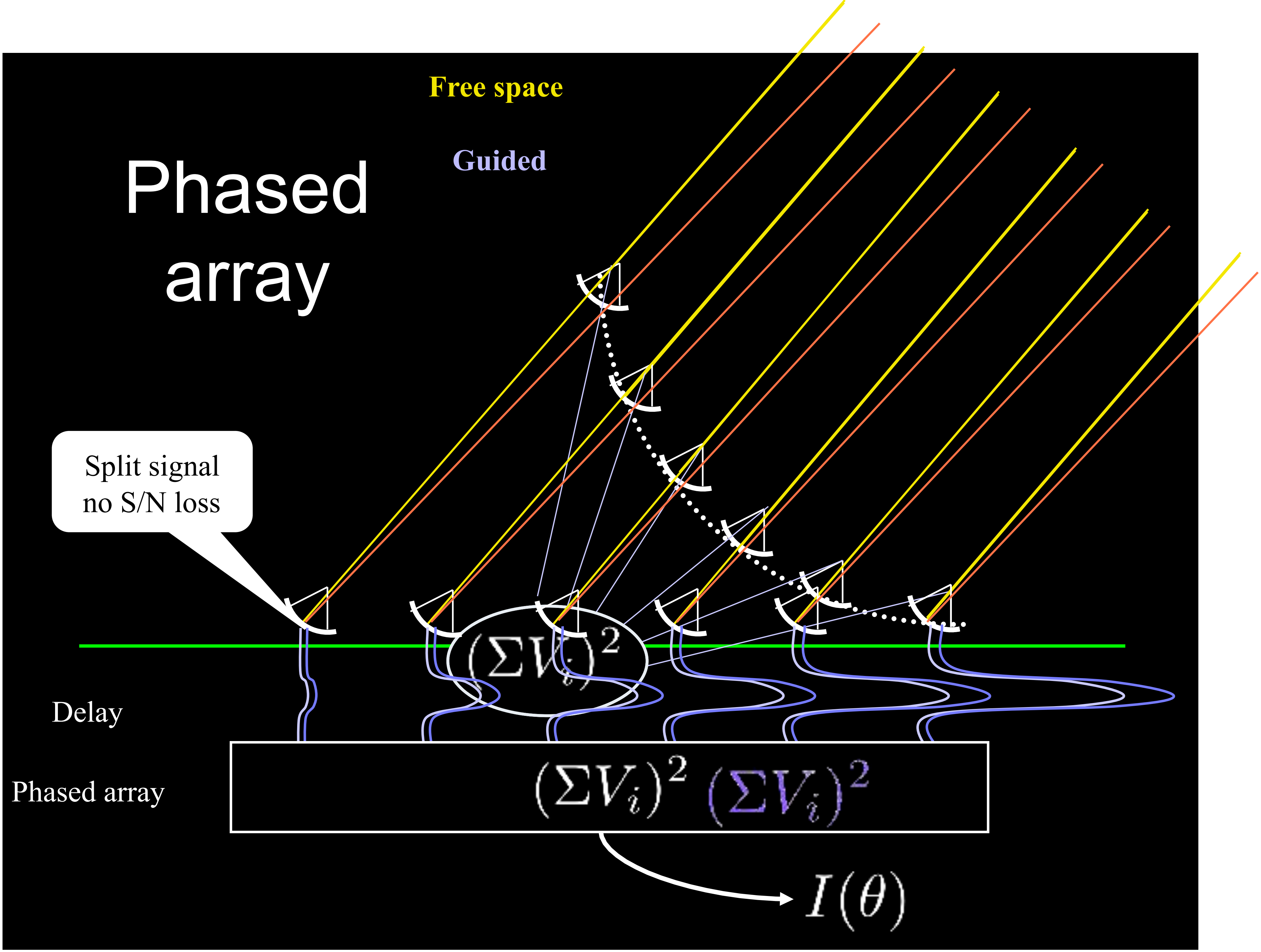


Free space

Guided



Phased array



Free space

Guided

Split signal
no S/N loss

$(\Sigma V_i)^2$

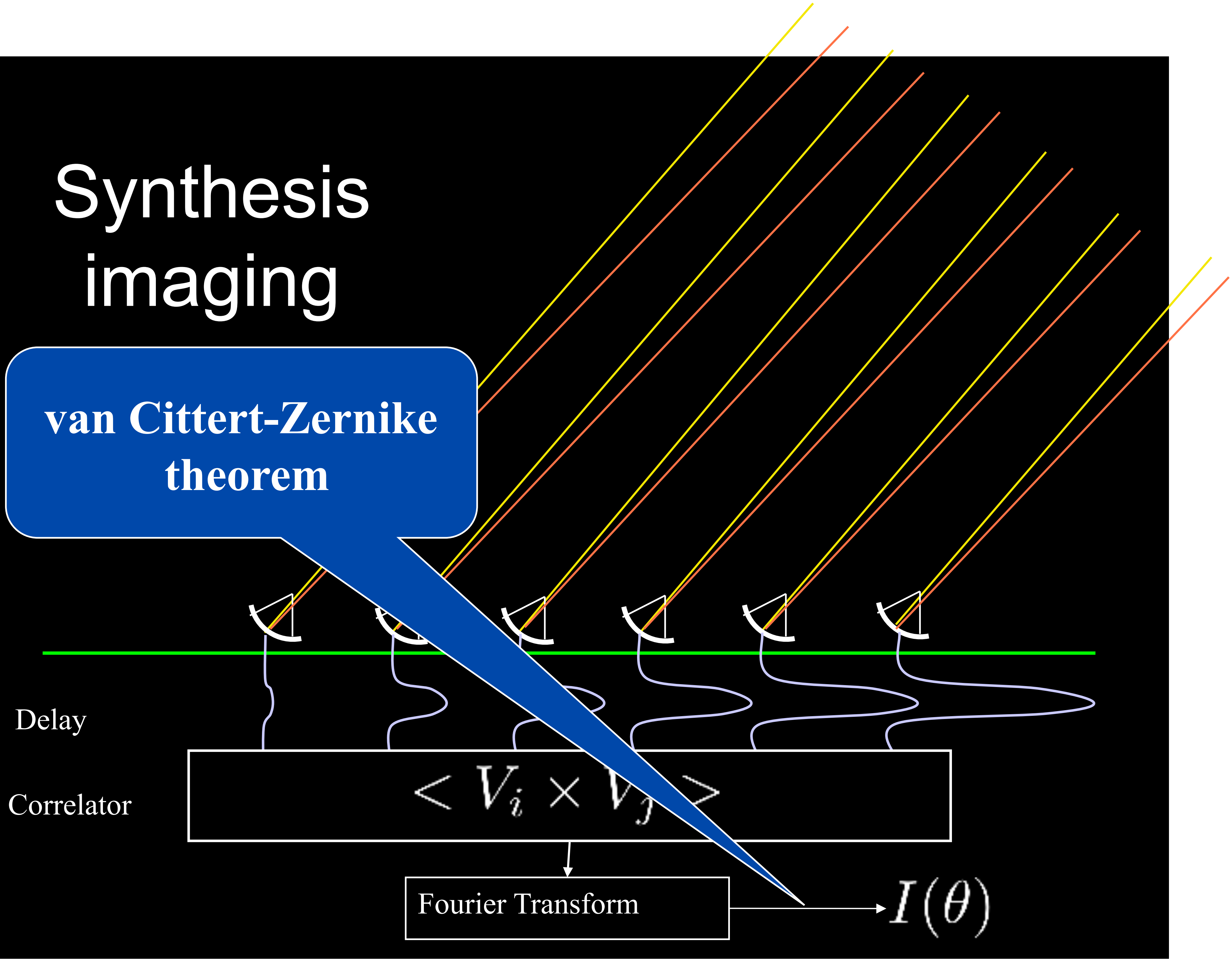
Delay

Phased array

$(\Sigma V_i)^2$ $(\Sigma V_i)^2$

$I(\theta)$

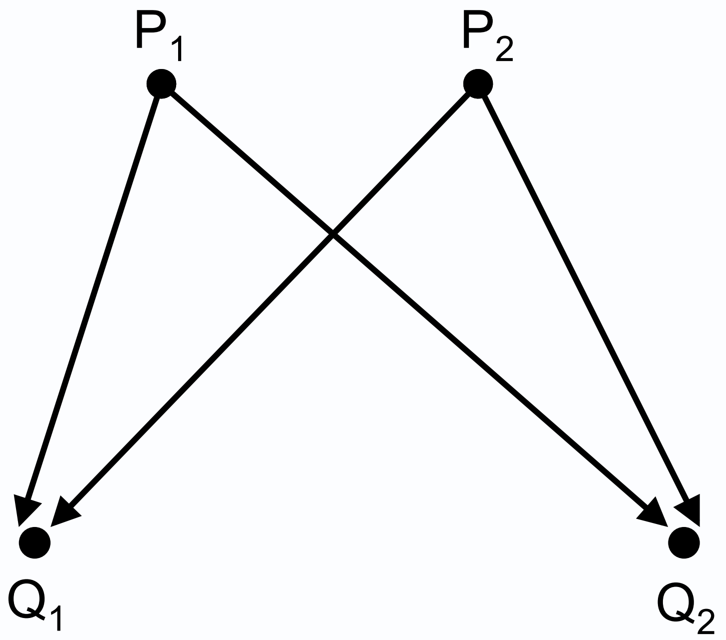
Synthesis imaging



van Cittert-Zernike theorem

Spatial Coherence

P_1 & P_2
spatially incoherent sources



At distant points Q_1 & Q_2
The field is partially
coherent

van Cittert-Zernike theorem

The spatial coherence function is the Fourier Transform of the brightness distribution

Physics: propagation of coherence

Radio source emits independent noise from each element

- Electrons spiraling around magnetic fields
- Thermal emission from dust, *etc.*

As electromagnetic radiation propagates away from source, it remains coherent

By measuring the correlation in the EM radiation, we can work backwards to determine the properties of the source

Physics: propagation of coherence

Van Cittert-Zernicke theorem states that the

Sky brightness and Coherence function are a Fourier pair

Mathematically:

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

where *V* is the visibility (or spatial coherence function, a measure of the correlation), I is the brightness (or specific intensity, in watts per m^2 per hertz per steradian – or Jy/beam), *l* and *m* are the orthogonal direction cosines of the source structure, and *u* and *v* are the orthogonal components of projected baselines (measured in wavelengths).

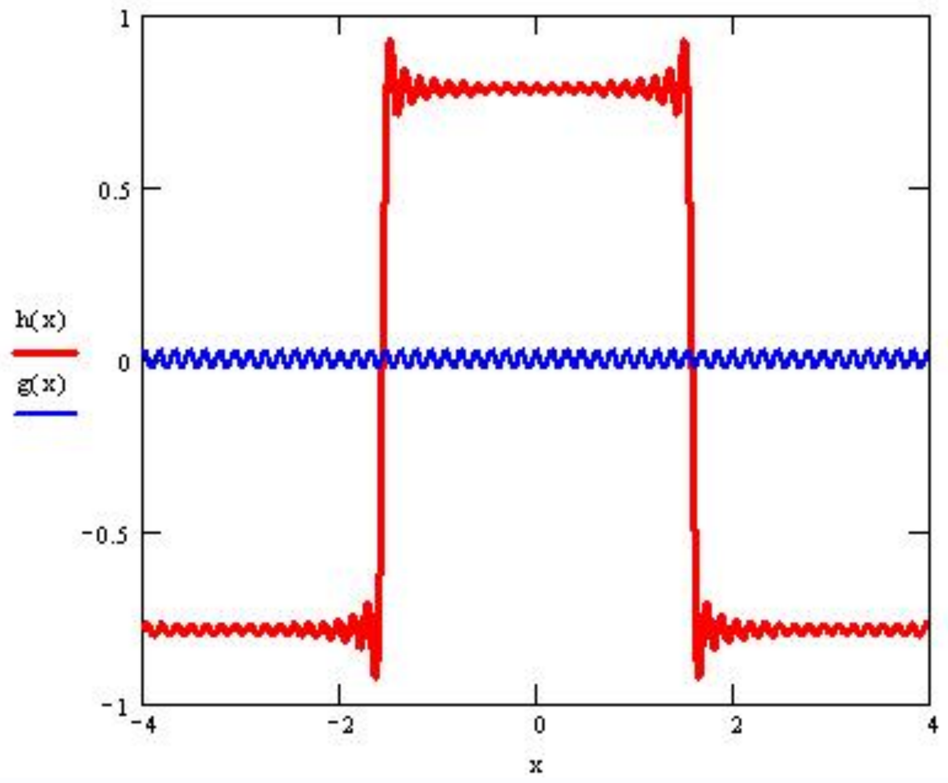
Complex (but not complicated!)

Fourier decomposition

- We can decompose the 2-dimensional intensity distribution into its Fourier components
- An interferometer (pair of antennas) can measure a component
- An array of n antennas has $n(n-1)/2$ baselines
- Each baseline samples a Fourier component of the source structure determined by its projected baseline length and its orientation

Fourier synthesis

In general, **any** function can be composed – or "*synthesised*" – from a number of sines of different <u>periods</u>, <u>amplitudes</u> and <u>phases</u>.

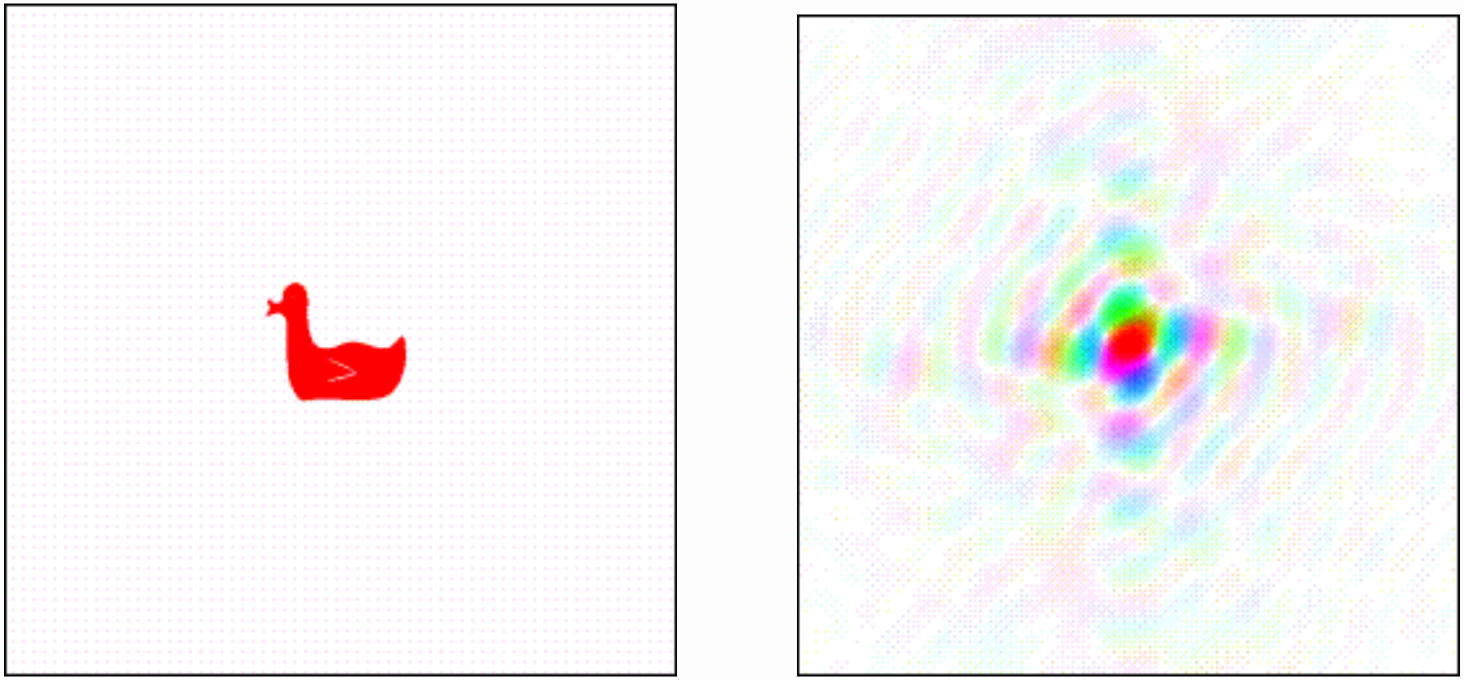


Very briefly…

- Fine detail, or sharp changes, requires high spatial frequencies
- Broad detail, or extended structure, requires low spatial frequencies
- Therefore, when proposing to use the ATCA, you need to consider the structure of your source and the best array configuration(s) for studying it

Fourier Transform examples

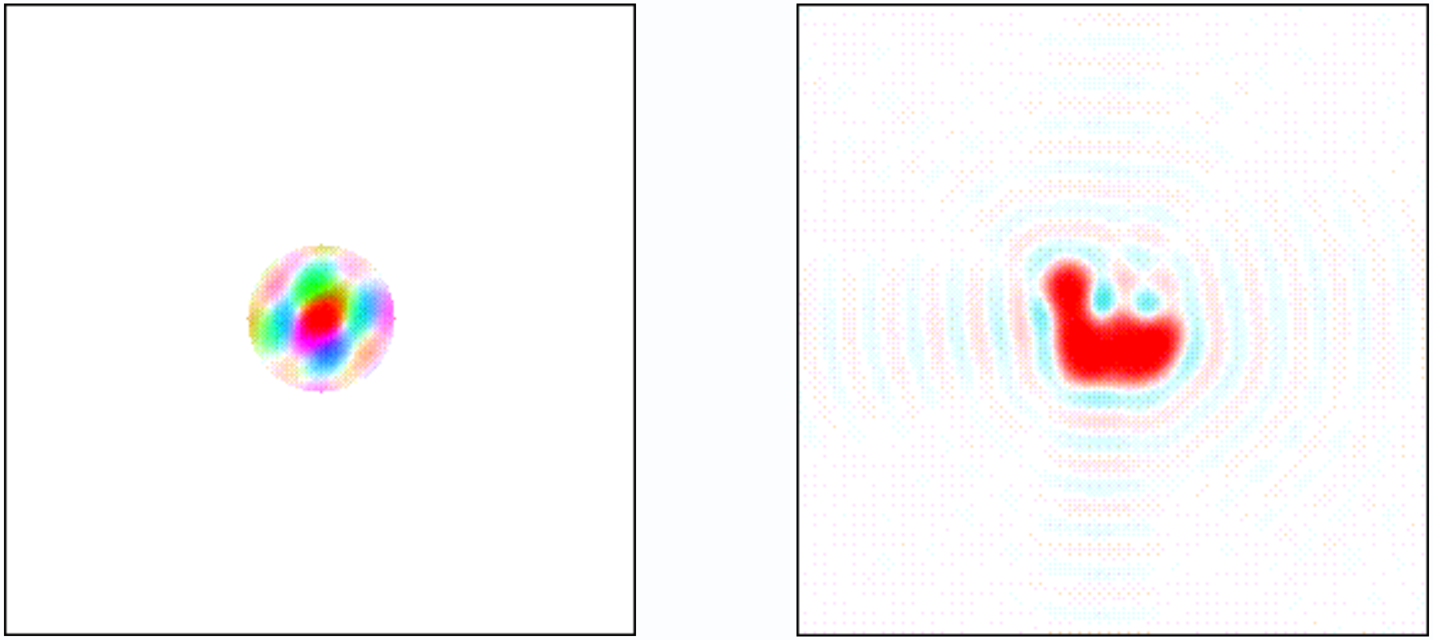
from Kevin Cowtan’s Picture Book of Fourier Transforms



A duck and its Fourier Transform.

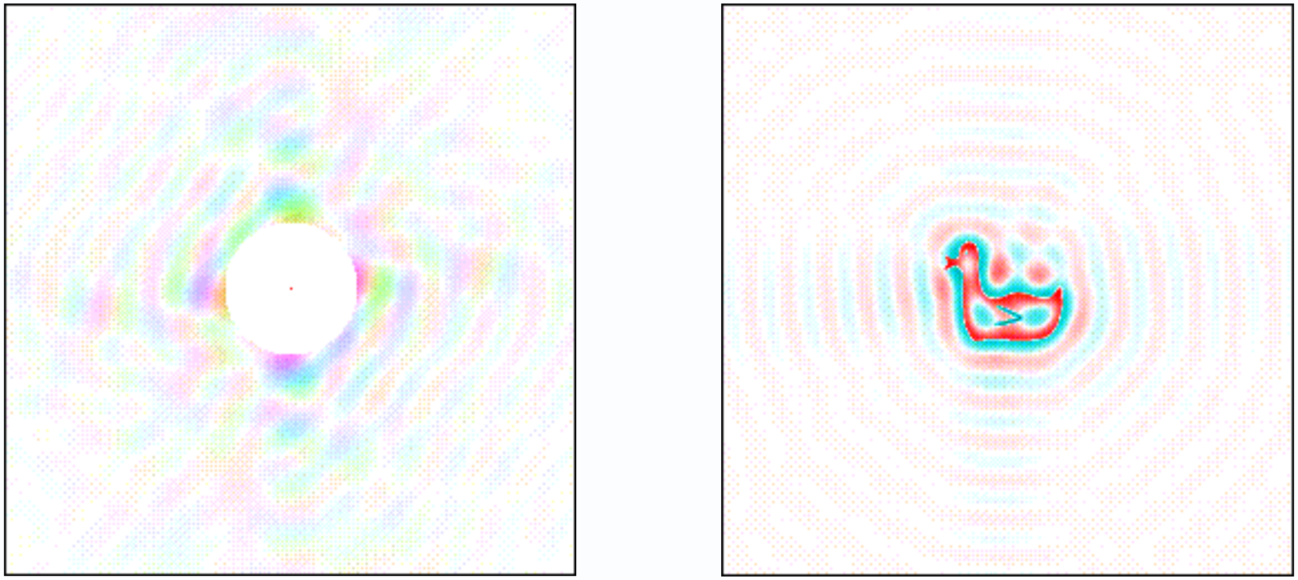
http://www.ysbl.york.ac.uk/~cowtan/fourier/fourier.html

Fourier Transform examples



If we only have the low resolution terms of the diffraction pattern, we only get a low resolution duck. There is considerable loss of detail. Note the ripples around the duck.

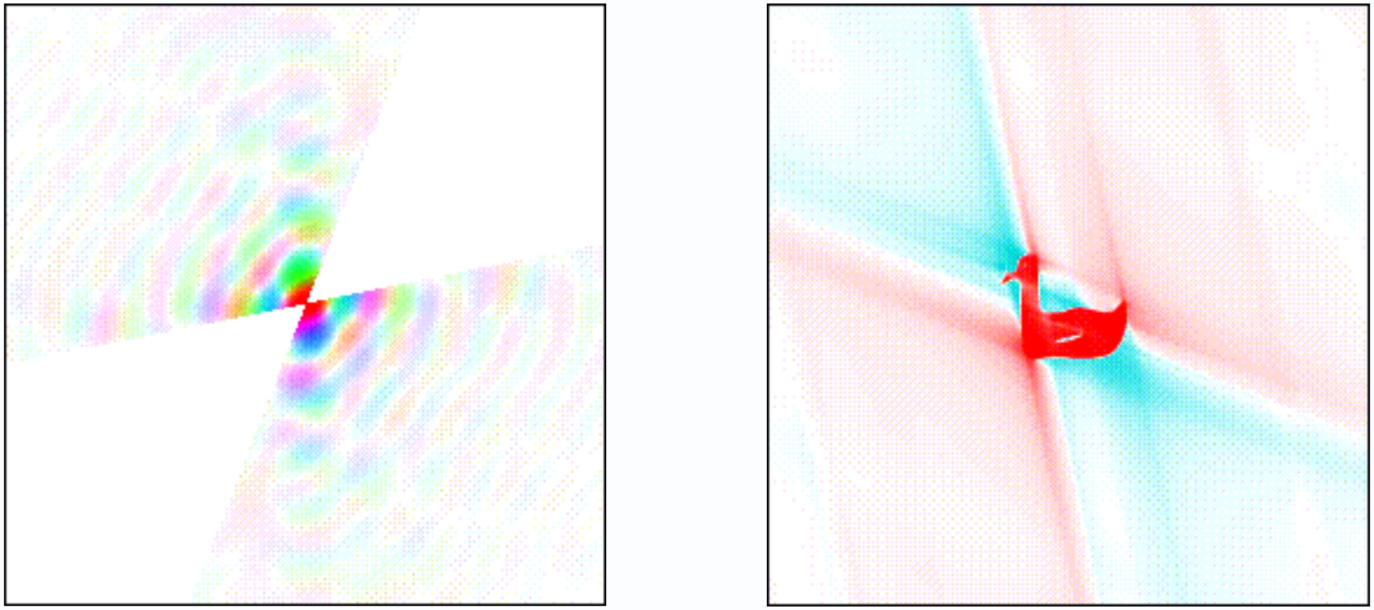
Fourier Transform examples



If we only have the high resolution terms of the diffraction pattern, we see only the edges of the duck

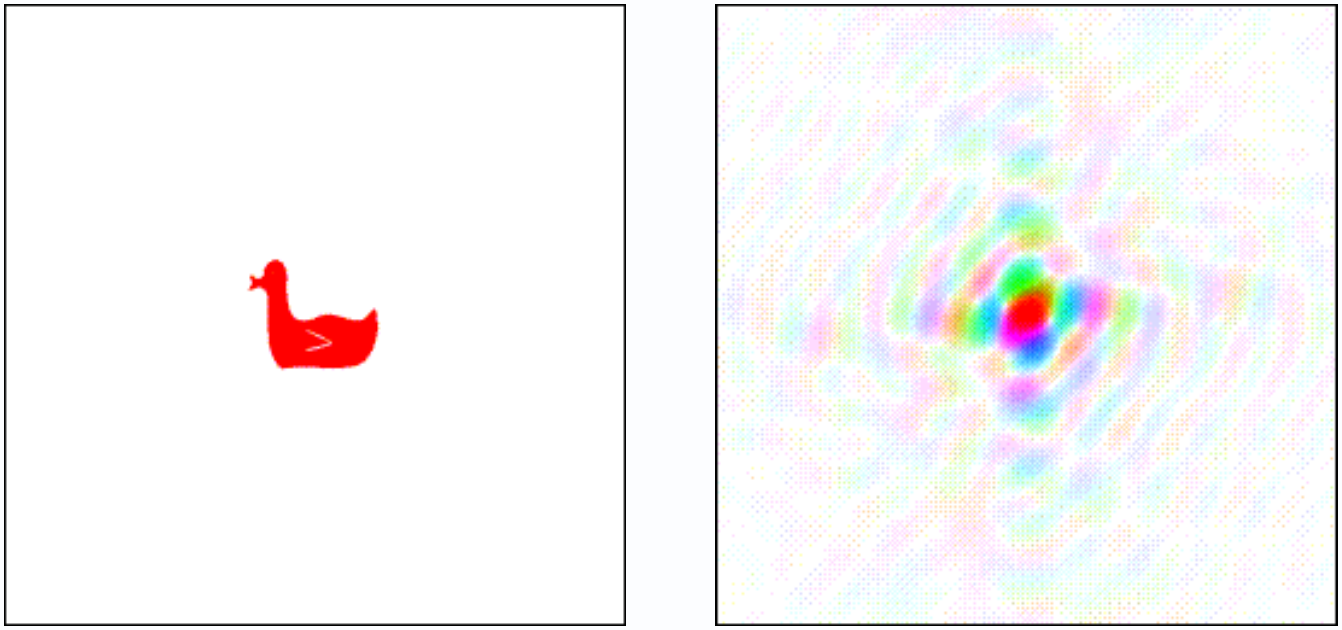
Do not omit your low resolution data. Collect it and use it!

Fourier Transform examples

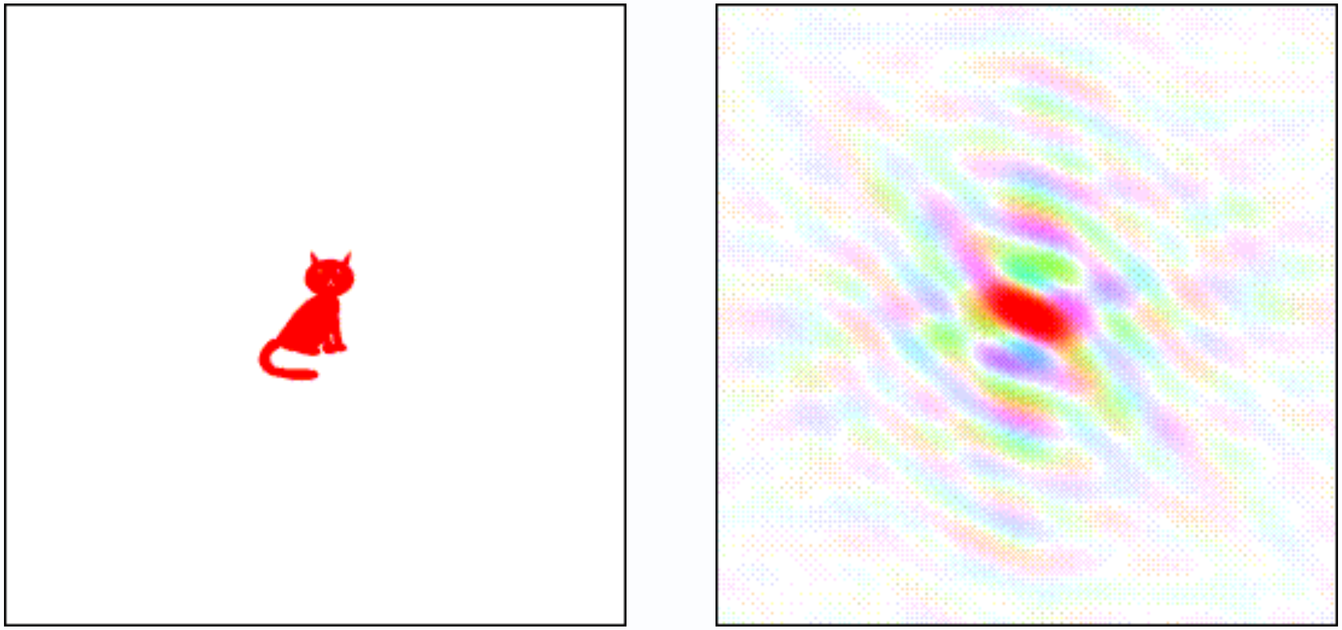


If a segment of data is missing, features perpendicular to that segment will be blurred.

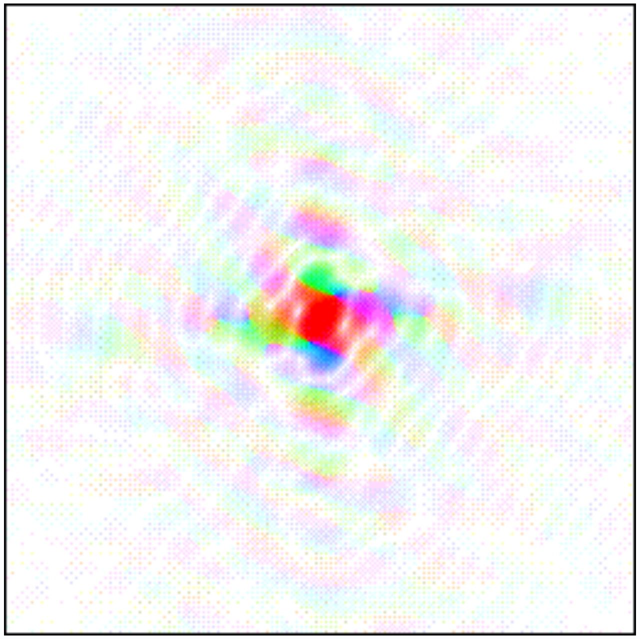
The duck and its FT



A cat and its FT



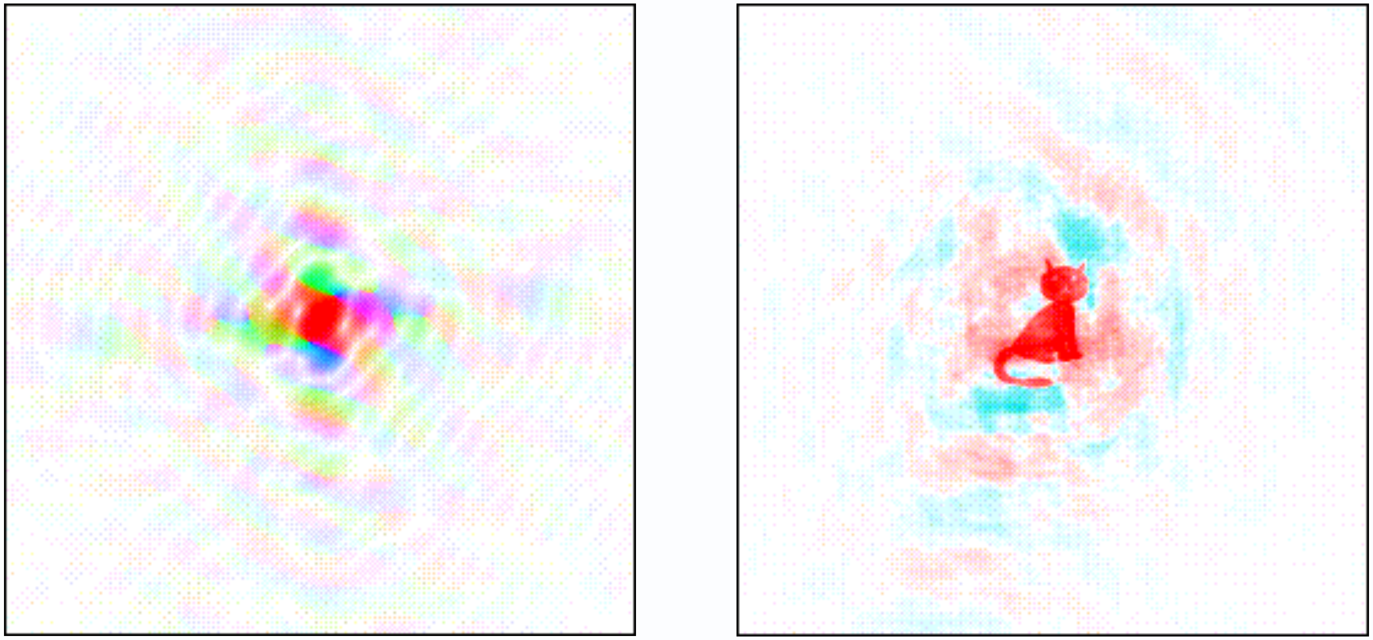
Fourier Transform examples



FT = ?

Let us combine the magnitudes from the Duck transform with the phases from the Cat transform.

Fourier Transform examples



Let us combine the magnitudes from the Duck FT with the phases from the Cat FT.

The image which contributed the phases is still visible, whereas the image which contributed the magnitudes has gone!

“Anthropomorphism” in Astronomy

Snake

- ApJ 443, 638 (1995); ApJ, 462, 768 (1996)

Kookaburra

- ApJ 561,L187 (2001)

Rabbit

- ApJ 515, 712 (1999)

Duck

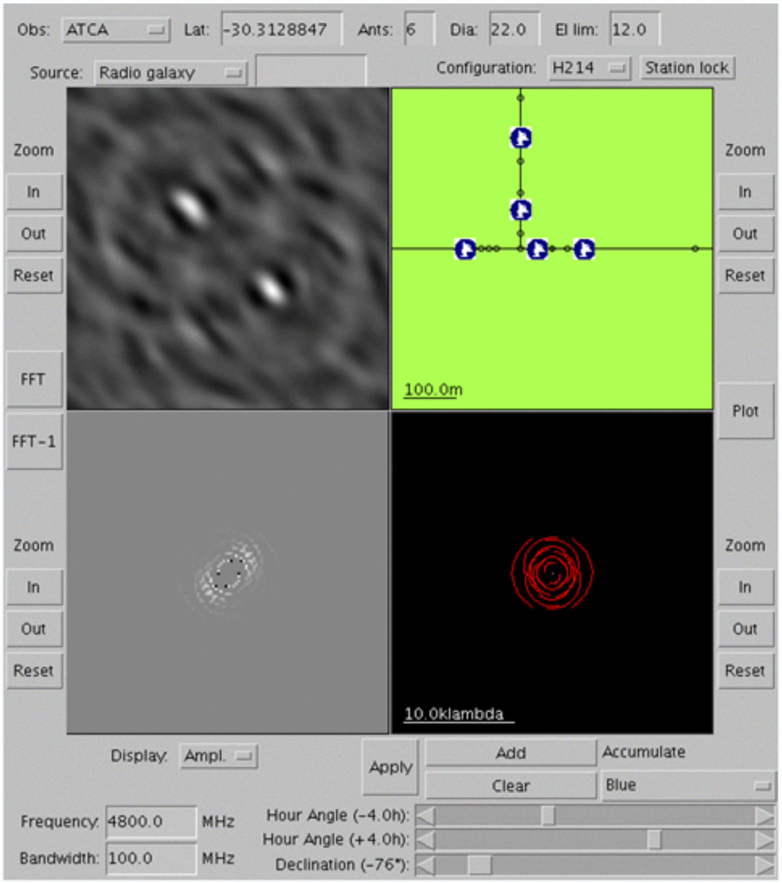
- ApJ 573, L111 (2002); ApJ 652,1523 (2006)

CaT

- MNRAS 393, 846 (2009)

VRI

- VRI, the virtual radio interferometer
    - Type vri in searchbox on ATNF website or the URL link below
    - Lets you experiment with Fourier transforms and ATCA configurations



Obs: ATCA
Lat: -30.3128847
Ants: 6
Dia: 22.0
El lim: 12.0
Source: Radio galaxy
Configuration: H214
Display: Ampl.
Frequency: 4800.0 MHz
Bandwidth: 100.0 MHz
Hour Angle (-4.0h):
Hour Angle (+4.0h):
Declination (-76°):

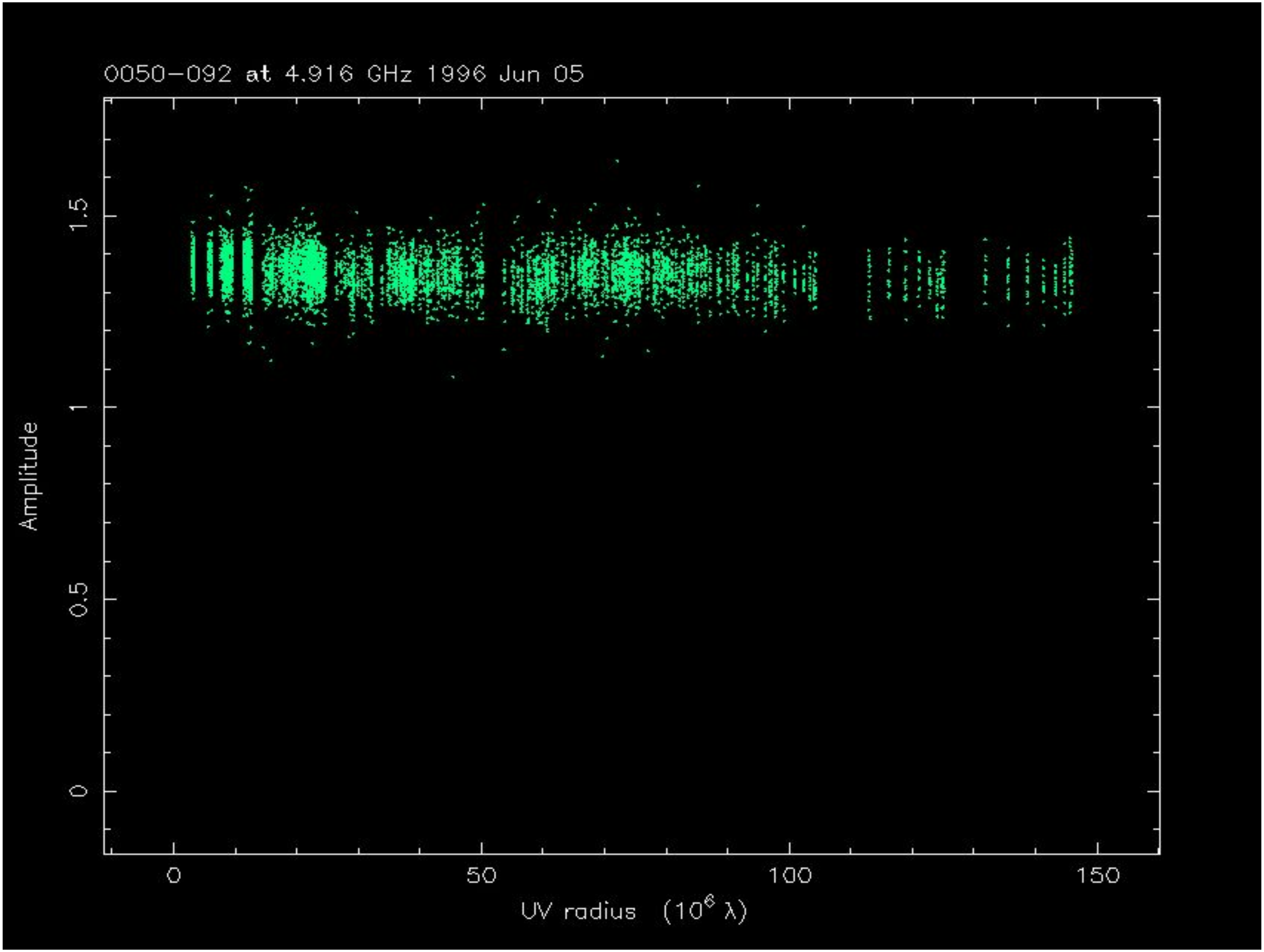
http://www.narrabri.atnf.csiro.au/astronomy/vri.html

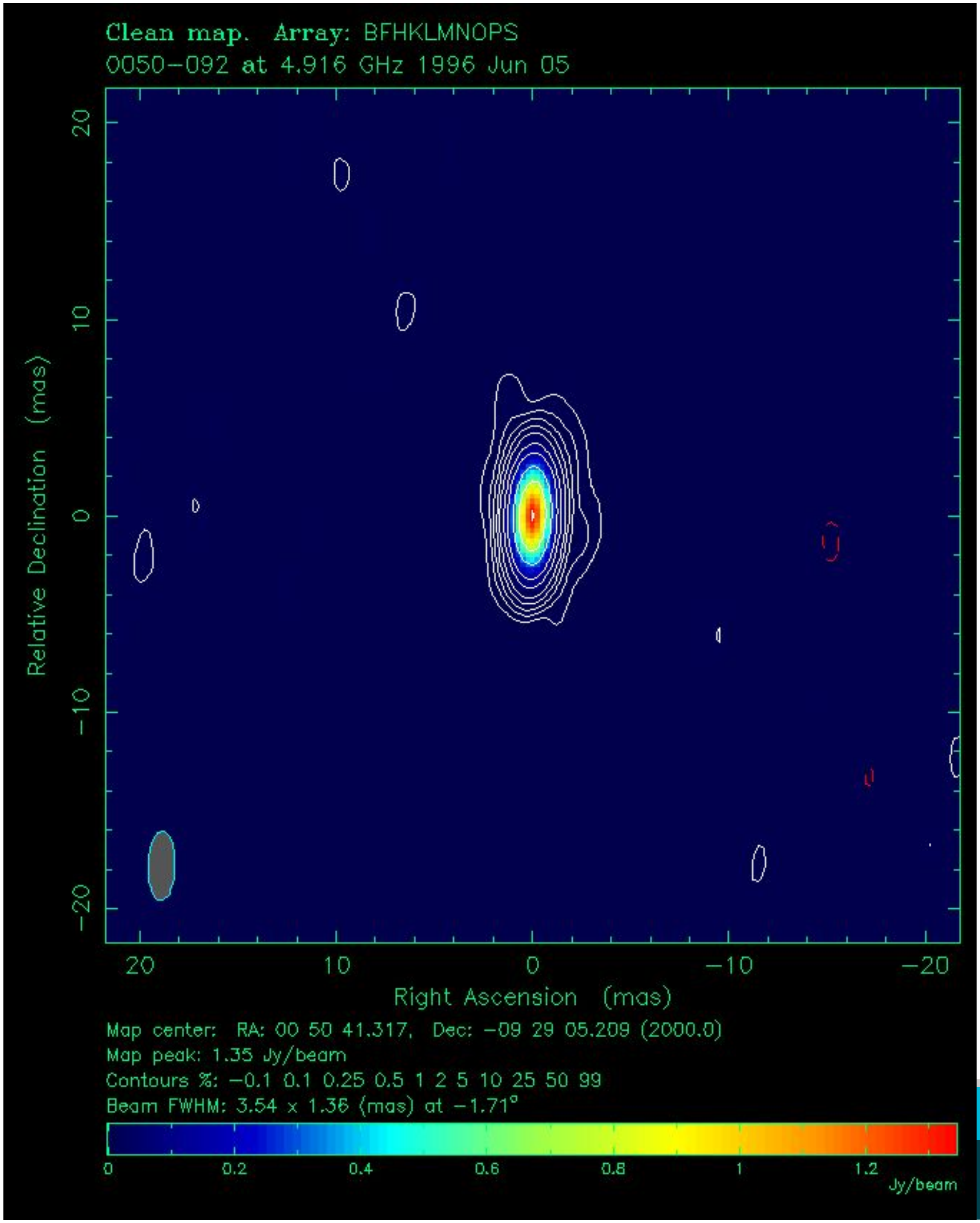
Some examples

Now let's do some Fourier Transforms in our head!

The following examples show the amplitude of the correlated flux density as a function of (u,v) radius projected onto the u-axis.

The Fourier Transforms of these visibilities (amplitude and phase) gives the source structure


0050-092 at 4.916 GHz 1996 Jun 05
Amplitude
0
0.5
1
1.5
0
50
100
150
UV radius (10^6 λ)



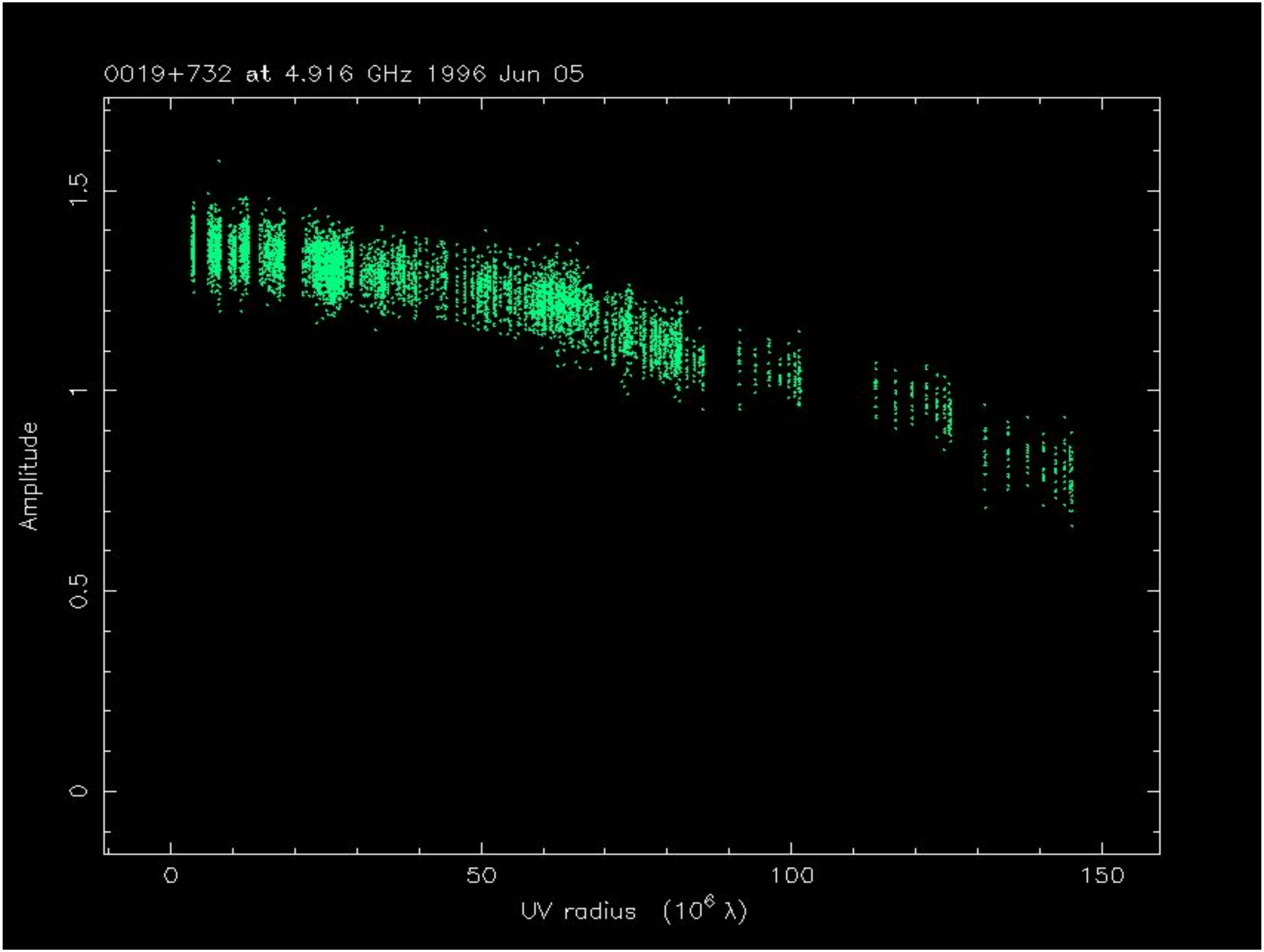
A point source
(at this resolution)

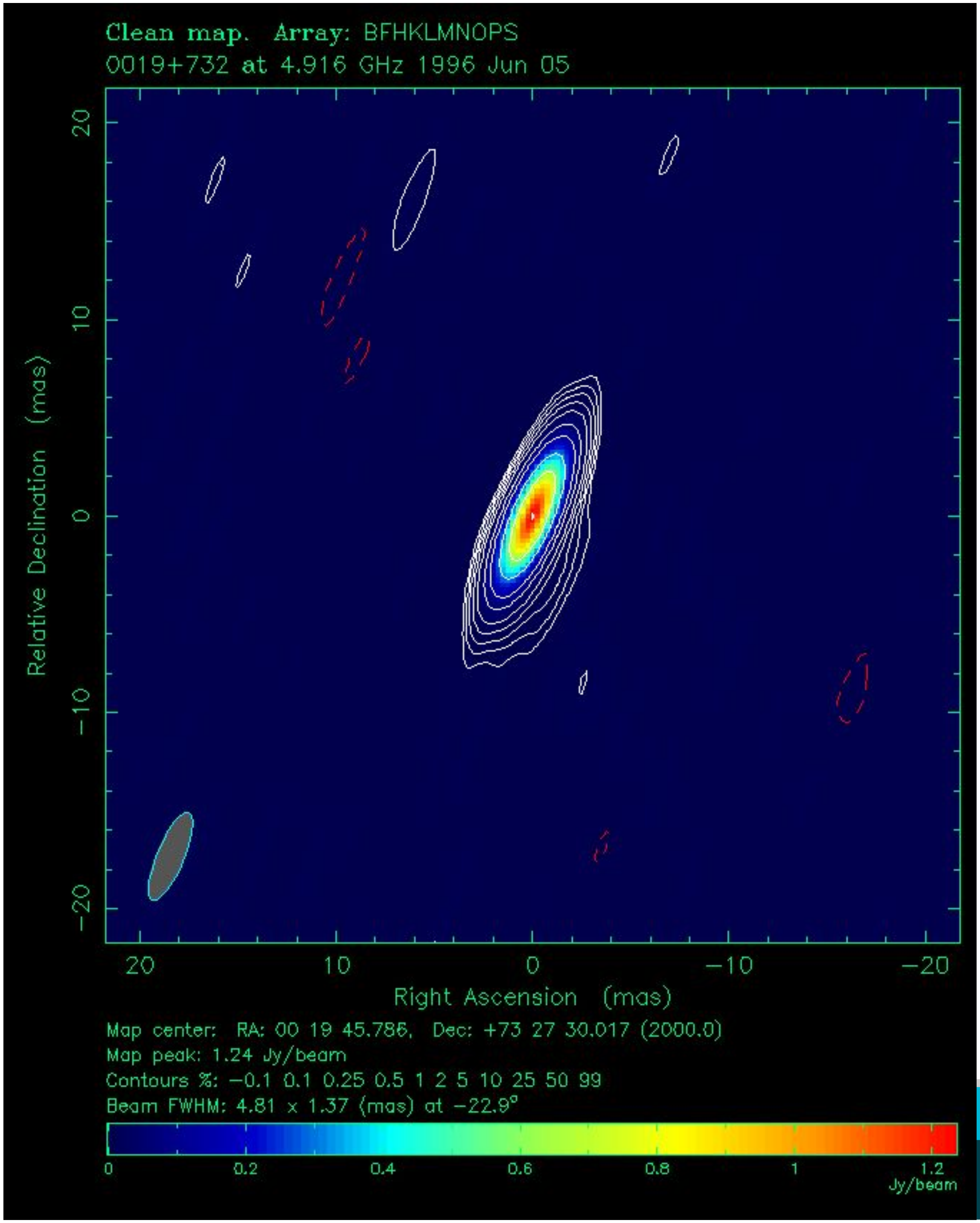
Map peak 1.35 Jy/beam

Model-fit:
1.35 Jy
a < 0.6 mas
b < 0.2 mas

a & b are semi-major and semi-minor axes of a gaussian fit

Fomalont et al. (2000), ApJS, 131, 95
http://www.vlba.nrao.edu/astro/obsprep/sourcelist/6cm/

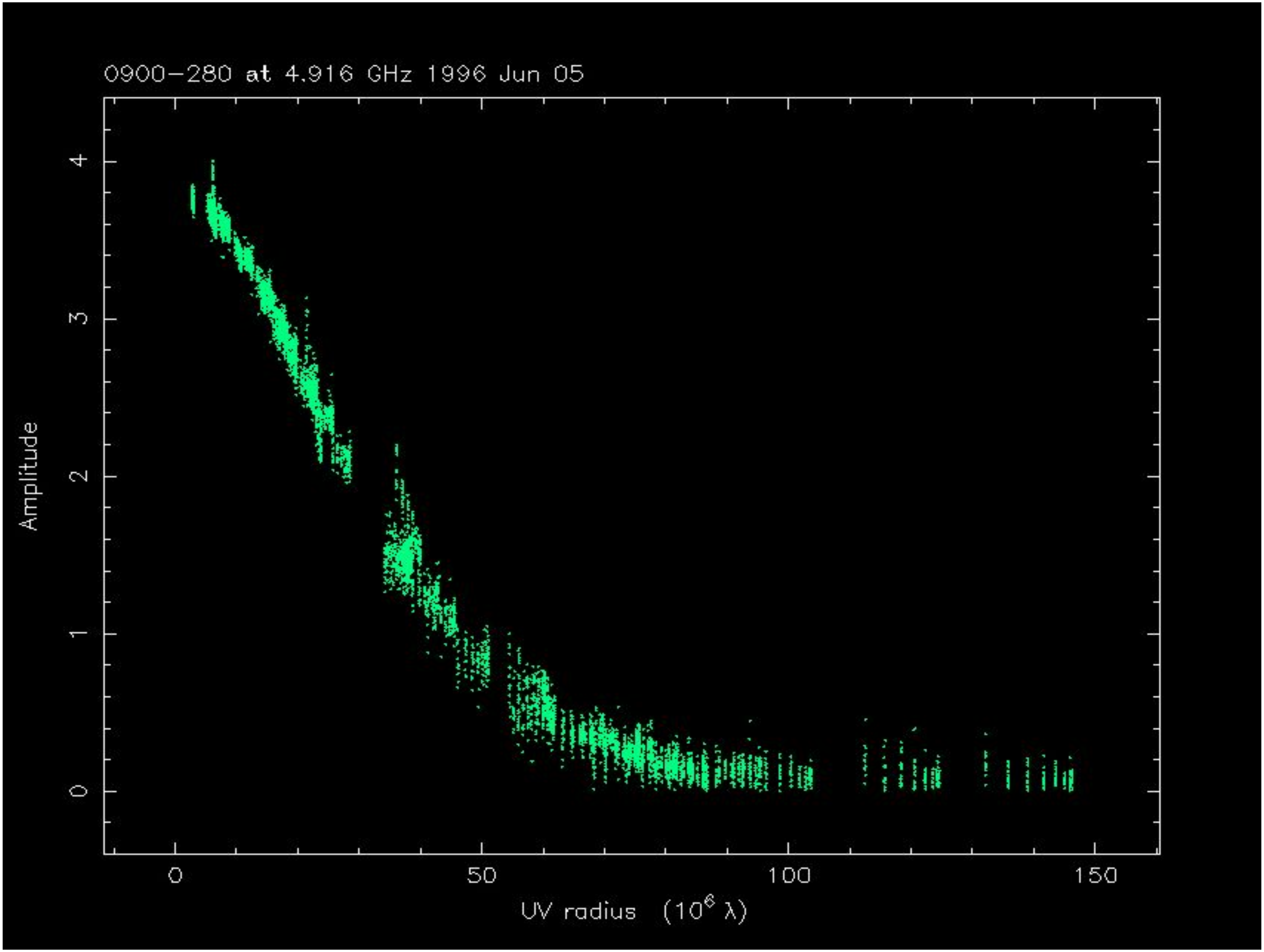

0019+732 at 4.916 GHz 1996 Jun 05
Amplitude
0
0.5
1
1.5
UV radius (10^6 λ)
0
50
100
150

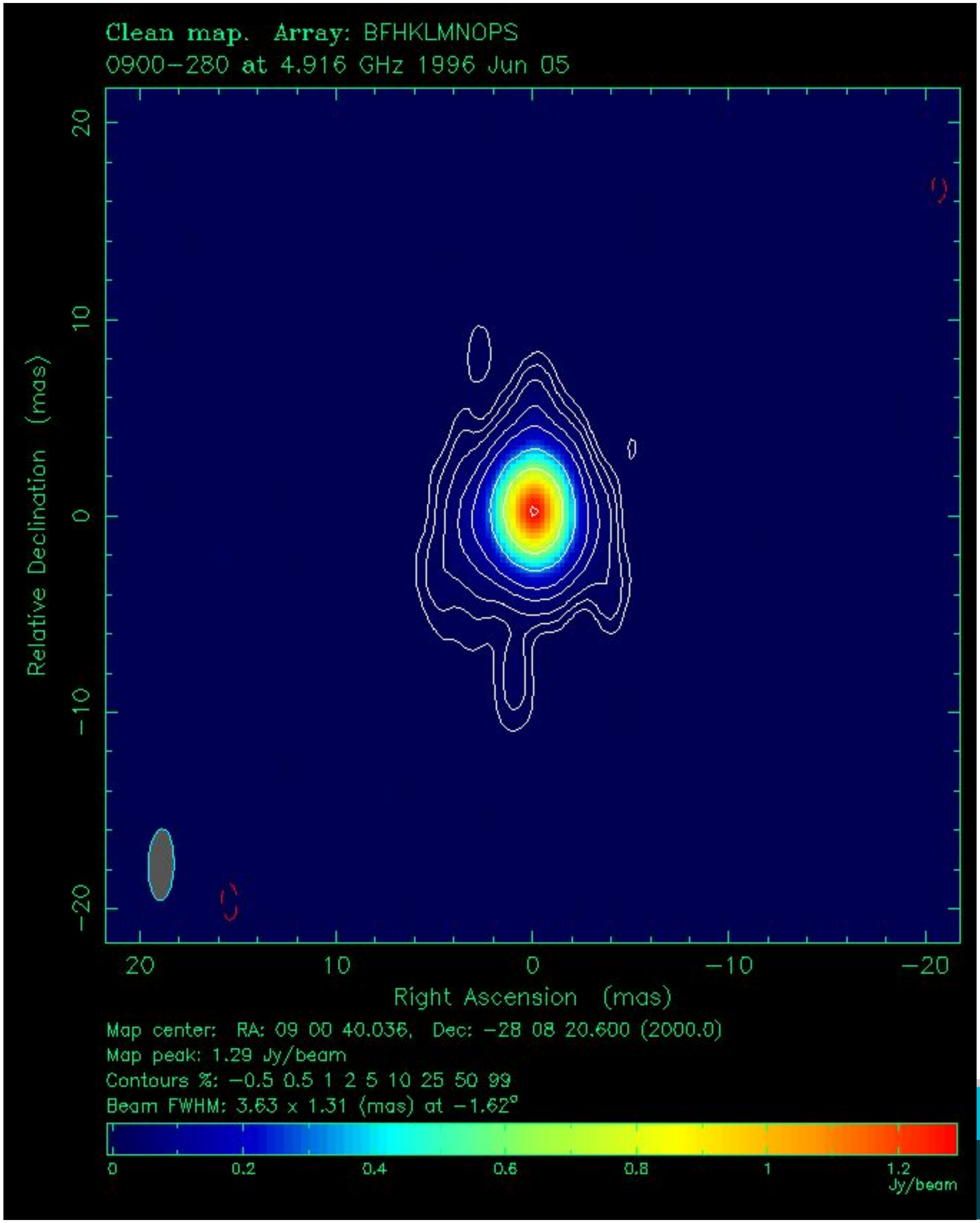


Partially resolved

Map peak 1.24 Jy/beam

Model:
1.33 Jy
a = 0.7 mas
b < 0.3 mas

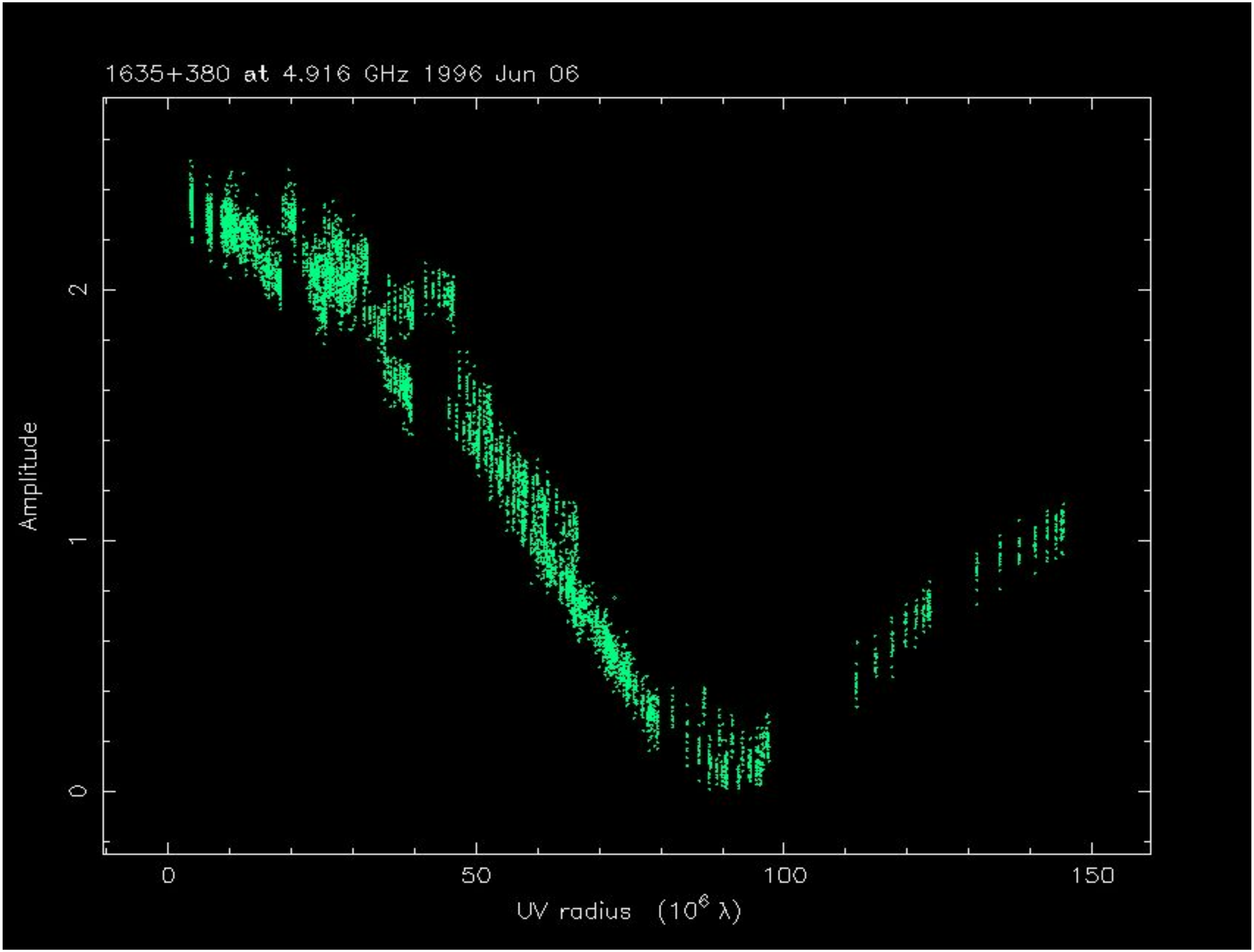

0900−280 at 4.916 GHz 1996 Jun 05
Amplitude
0
1
2
3
4
0
50
100
150
UV radius (10^6 λ)

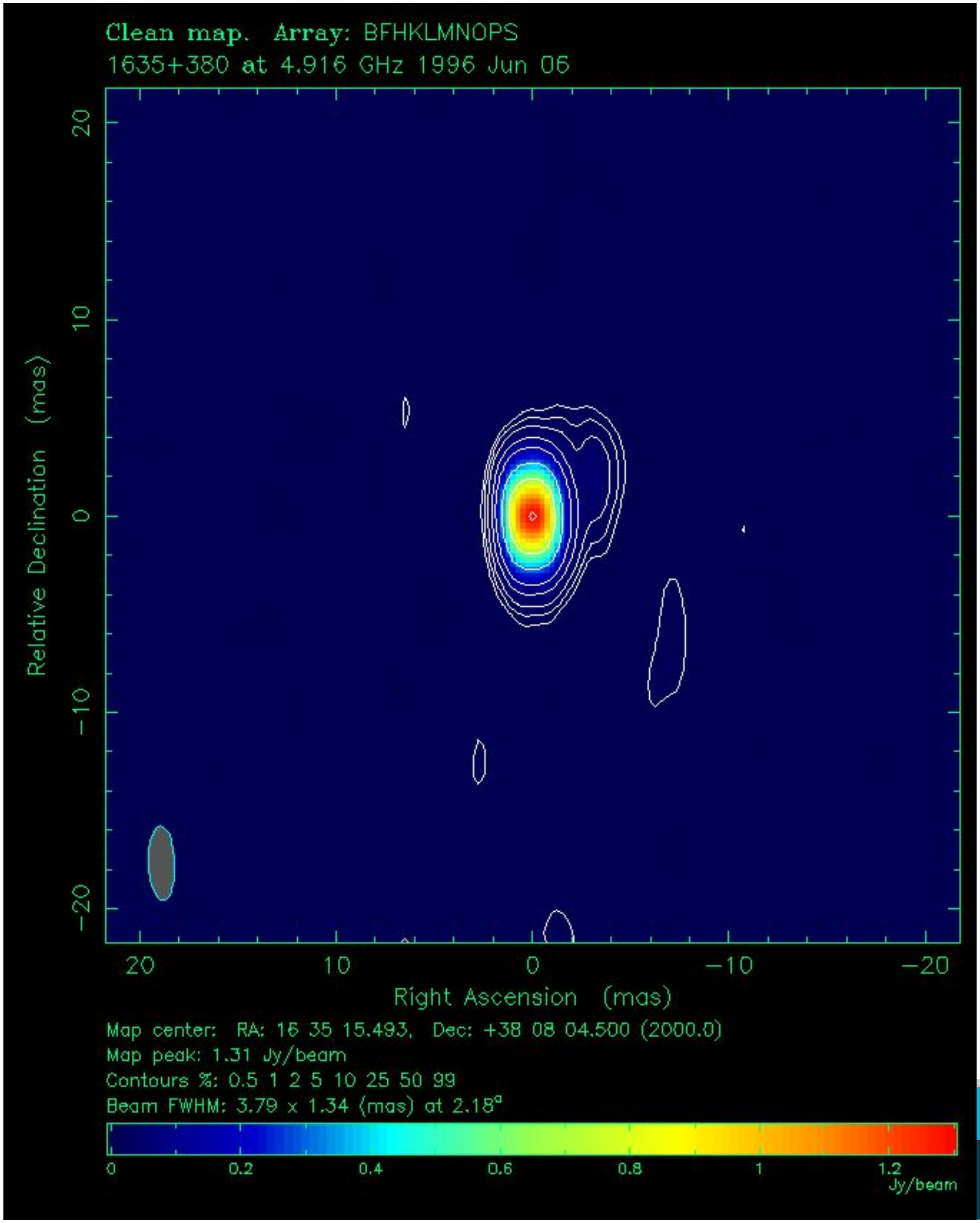


Resolved out on longest baselines

Map peak 1.3Jy/beam

Model:
3.7 Jy
a = 2.8 mas
b = 1.9 mas


1635+380 at 4.916 GHz 1996 Jun 06
Amplitude
0
1
2
0
50
100
150
UV radius (10^6 λ)

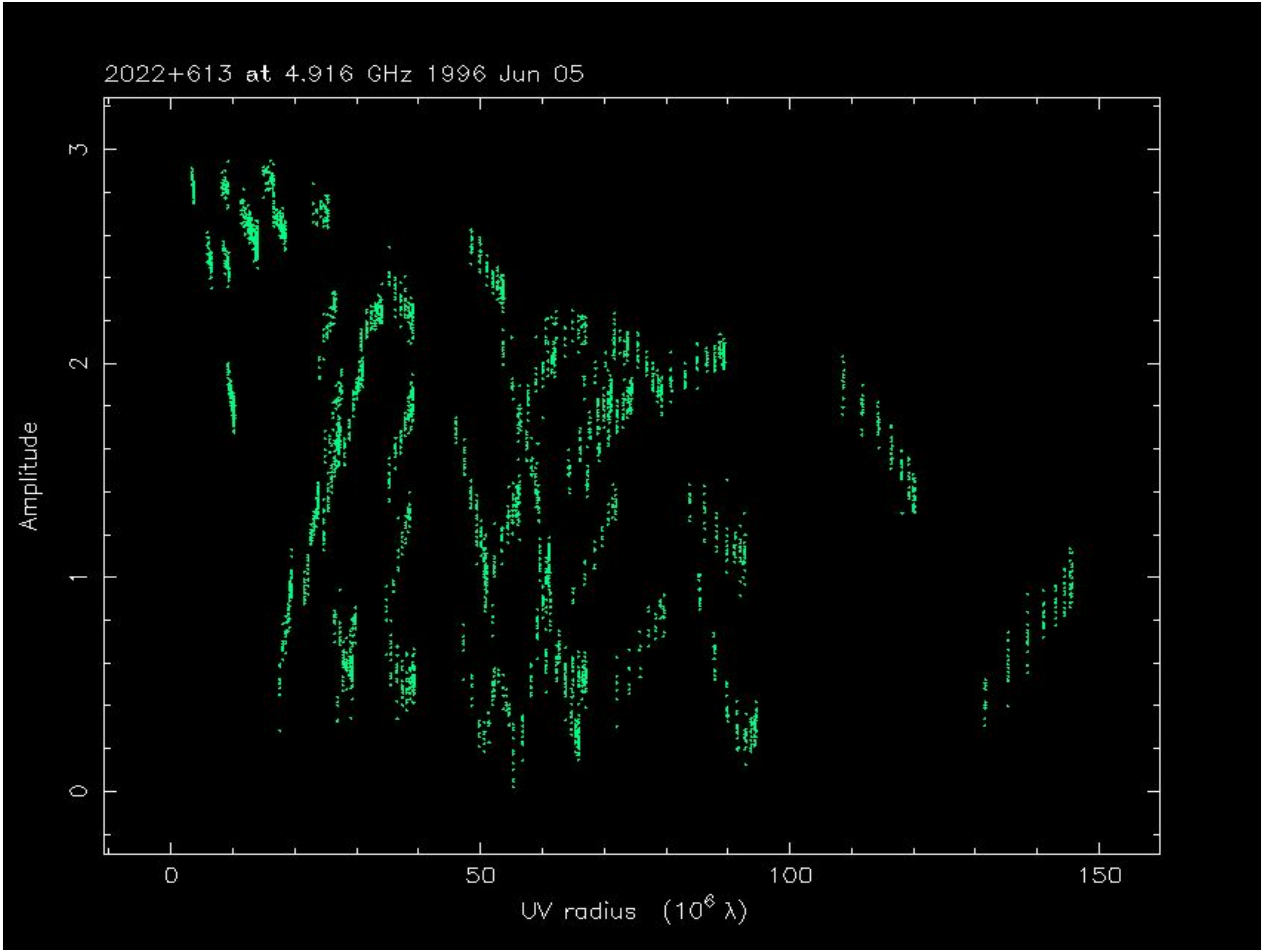


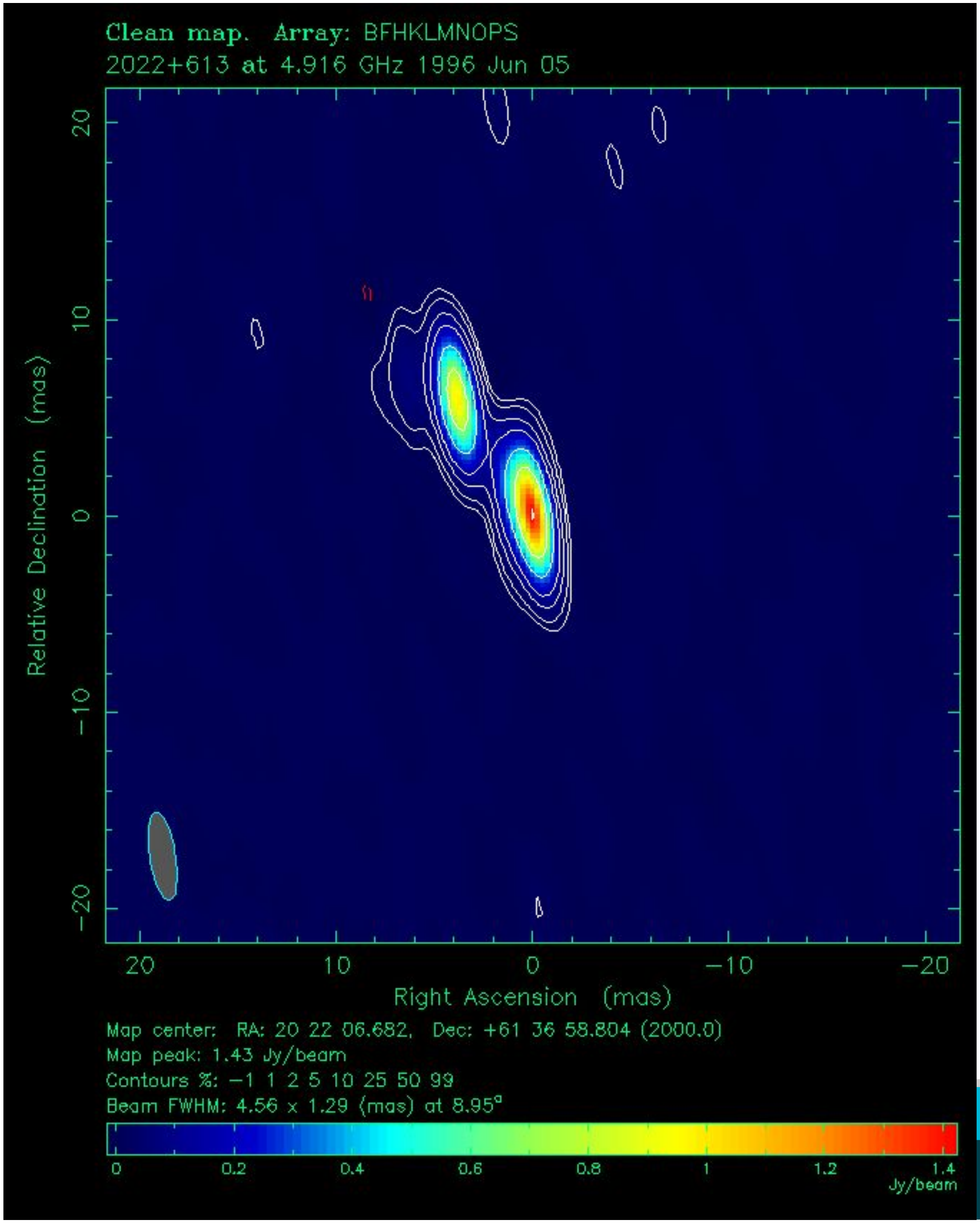
A close double

Map peak 1.3 Jy/beam

Model:
(i) 1.4 Jy
    a = 0.9 mas
    b < 0.3 mas
(ii) 0.8 Jy
    a < 0.7 mas
    b < 0.3 mas

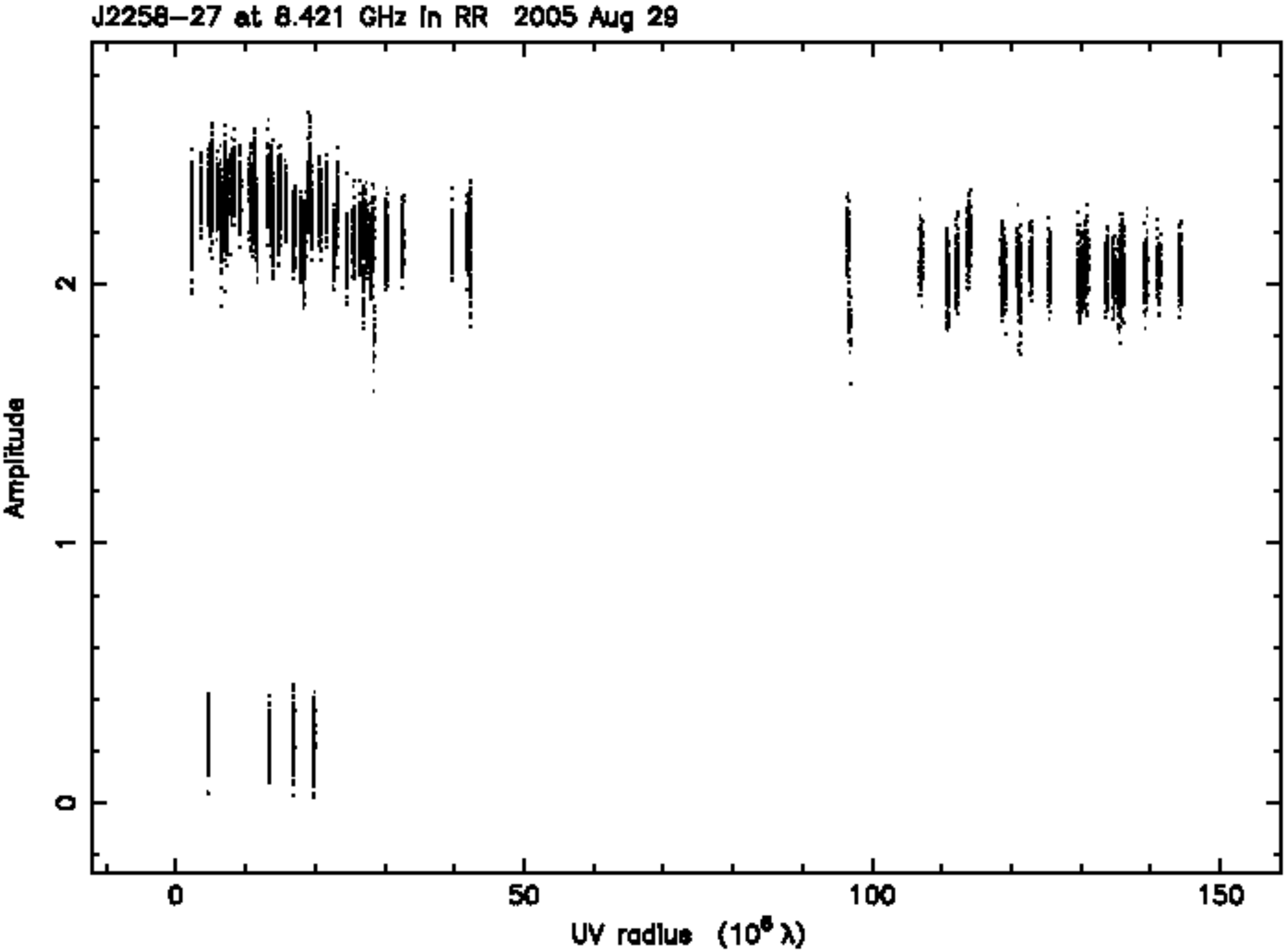
Separation 1.1 mas


2022+613 at 4.916 GHz 1996 Jun 05
Amplitude
0
1
2
3
UV radius (10^6 λ)
0
50
100
150



Impossible to do the FT in your head in this case – the source is more complex and the visibilities are not projected on the best axis to infer the structure.

Sometimes it is necessary to image the source
with software!


J2258-27 at 8.421 GHz in RR 2005 Aug 29
Amplitude
0
1
2
0
50
100
150
UV radius (10^6 λ)

Answer

This was a trick question: the low amplitude points at small (u,v) distances need to be flagged, or edited out in this case, and probably arise because one antenna was late slewing to the source. With those points edited out, the source appears to be dominated by a point source, but with some lower level extended structure visible on the shortest baselines.

A real-life example

C
4"

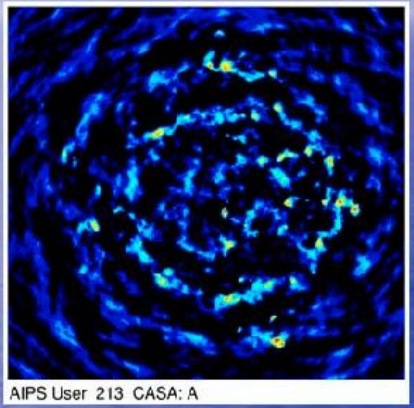
D
15"

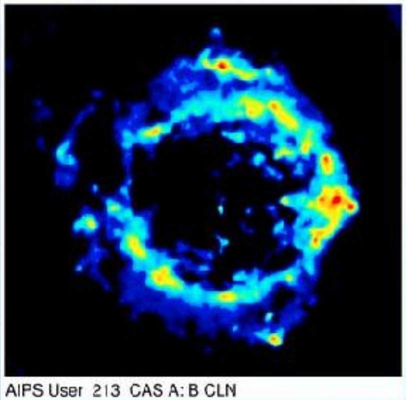
Courtesy Michael Rupen

Cas A: four VLA configurations

A

0.3"



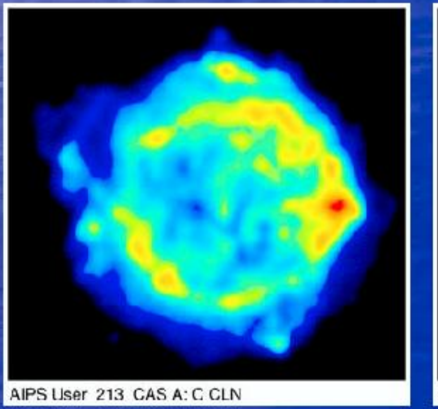


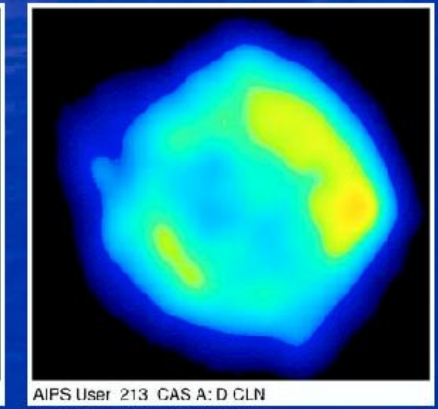
B

1.3"

C

4"



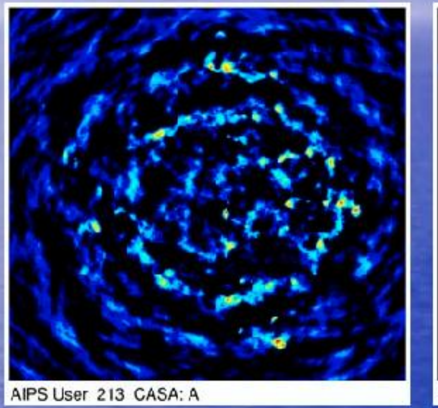


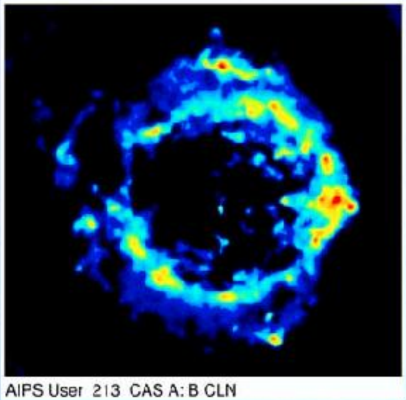
D

15"

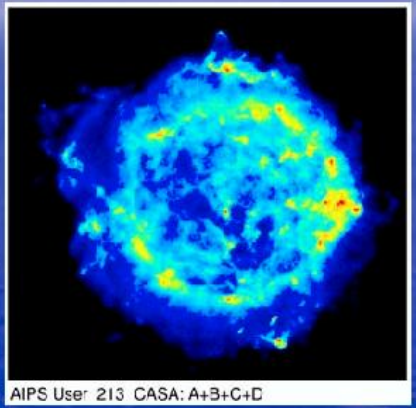
Cas A: four VLA configurations

A
0.3"

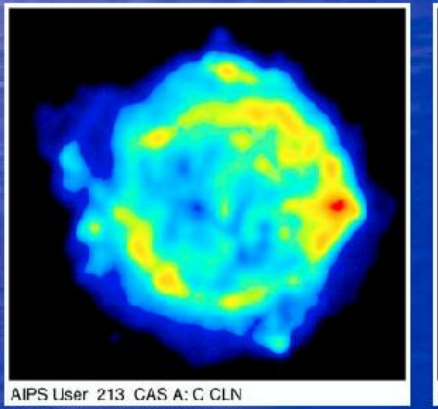

AIPS User 213 CASA: A

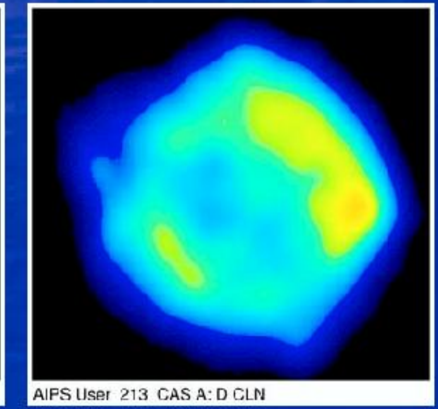

AIPS User 213 CAS A: B CLN

B
1.3"


AIPS User 213 CASA: A+B+C+D

C
4"


AIPS User 213 CAS A: C CLN

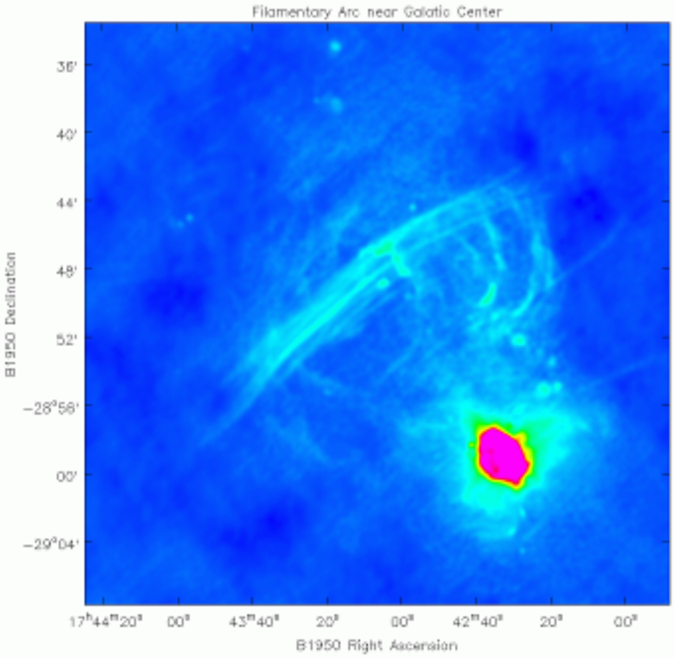

AIPS User 213 CAS A: D CLN

D
15"

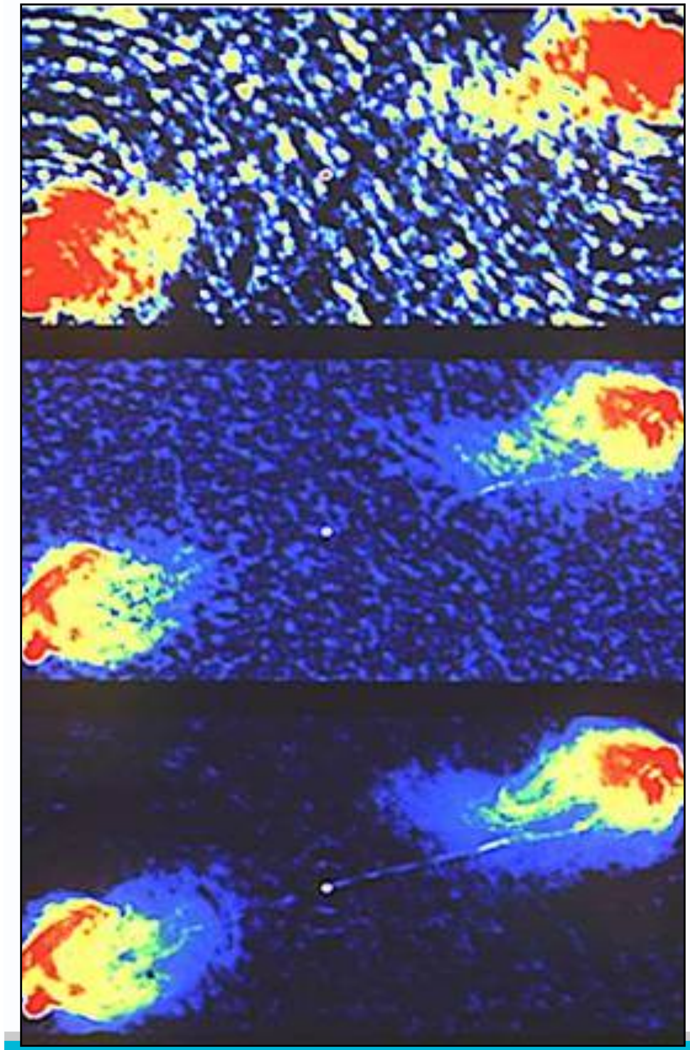
A+ B+ C+ D
0.3" +
total flux

In practice…

1. Use an array
2. Amplify signals
3. Sample and digitize
4. Send to central location
5. Perform cross-correlation
6. Earth rotation fills the “aperture”
7. Inverse Fourier Transform gets image
8. Correct for limited number of antennas
9. Correct for imperfections in the “telescope” e.g. calibration errors
10. Make a beautiful image



Cygnus A



← Raw data

VLA continuum

← Deconvolution

correcting for gaps between telescopes

← Self Calibration

adaptive optics

Conclusions

- Synthesis imaging is a powerful tool
- Each baseline samples a spatial frequency of the source structure
- As the earth rotates, an E-W array sweeps out a 2-D (u,v) coverage
- You don't have to do Fourier Transforms in your head (but in simple cases it can be helpful to know you can)

Thank you

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