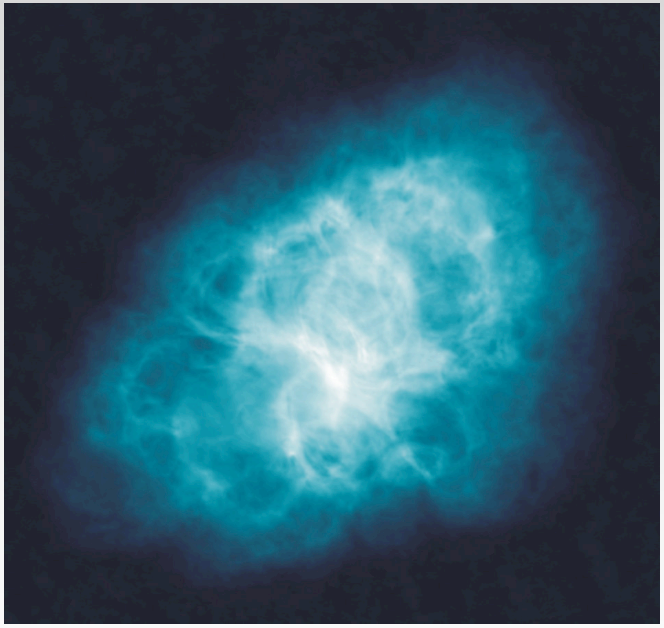
Introduction to Interferometry



Juan M. Usón (NRAO)

12/04/06

Estrellas

El cielo

es el manto acribillado

de la Tierra,

por los agujeros

veo la luz

del universo.

de Tatiana Olavarria

Stars

The sky is Earth’s torn blanket,

through its holes I see the light of the Universe

by Tatiana Olavarria

Important concepts

Coherence

Fringe

Resolution

Interference

uv-plane

Fourier Transform

Imaging: Fourier Inversion

Interferometry: Overview

1. Two ways of understanding interferometry
2. Practical details
3. Some examples
4. Other properties of the radiation
5. Variations in interferometry

Overview

- We make images of the radio sky from measurements of the electric field measured by our antennas

Antennas

Prime focus

(GMRT)

Cassegrain focus

(AT)

Offset Cassegrain

(VLA)

Naysmith

(OVRO)

Beam Waveguide

(NRO)

Dual Offset

(ATA)

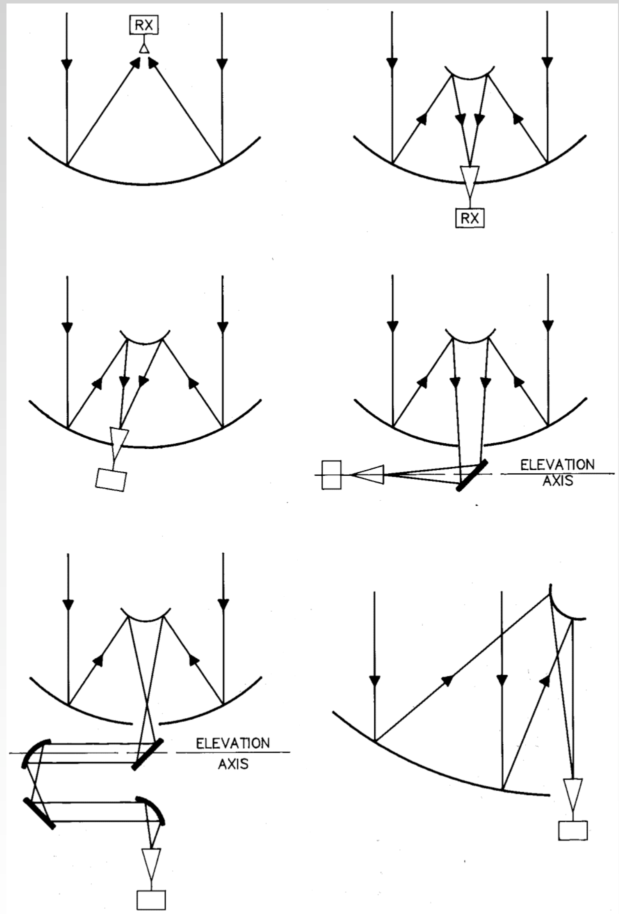
Reflector Types

Prime focus

(GMRT)

Cassegrain focus

(AT)



Offset Cassegrain

(VLA)

Naysmith

(OVRO)

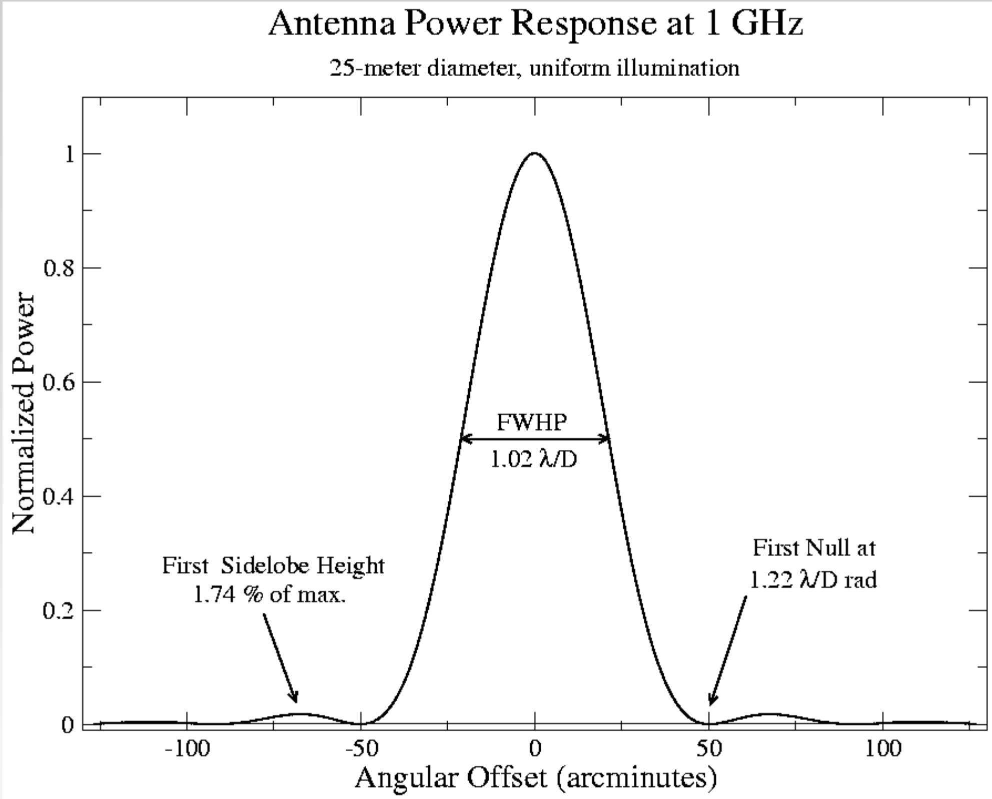
Beam Waveguide

(NRO)

Dual Offset

(ATA)

The Standard Parabolic Antenna

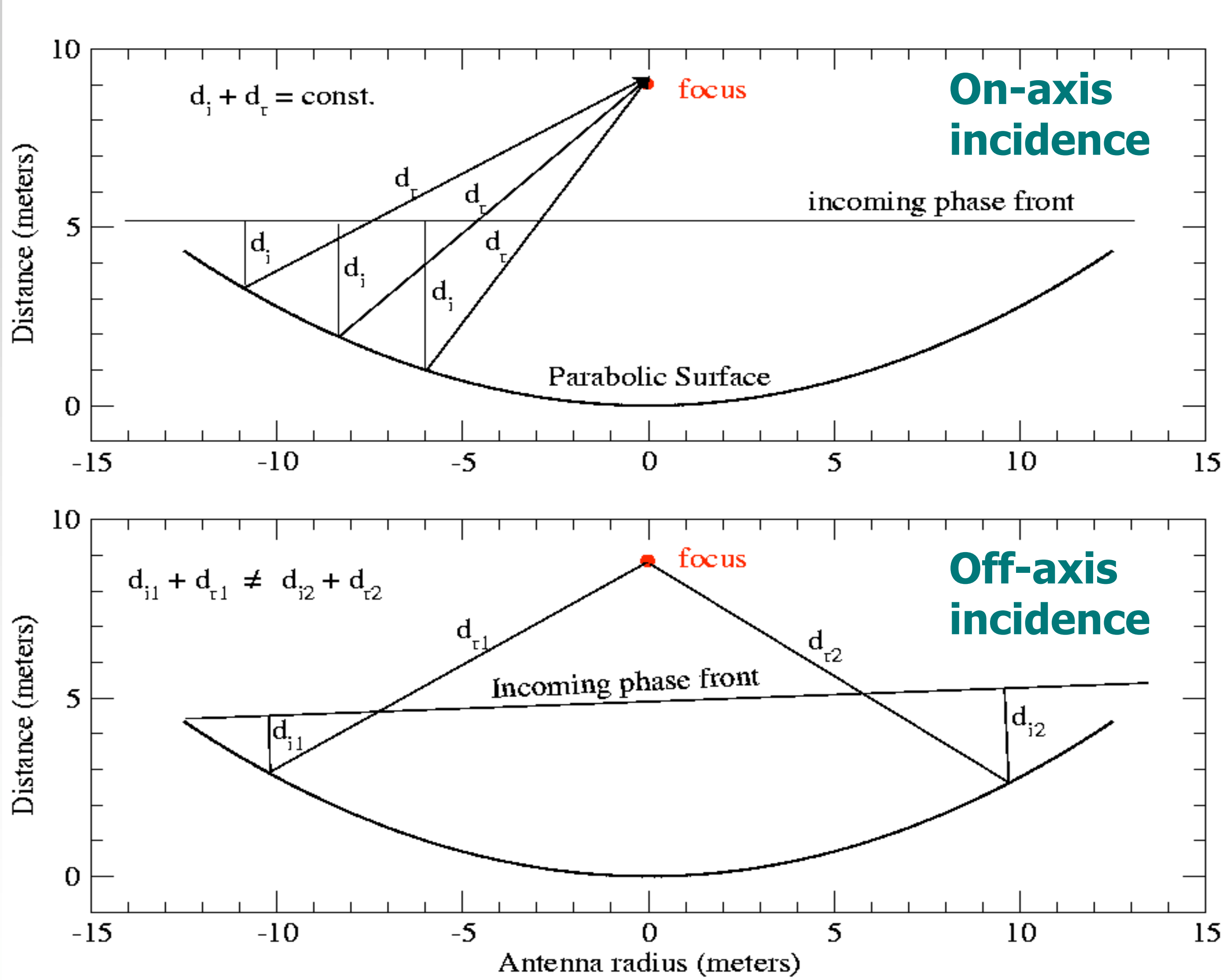


The power response of a uniformly illuminated circular parabolic antenna of 25-meter diameter, at a frequency of 1 GHz.

Origin of the Beam Pattern

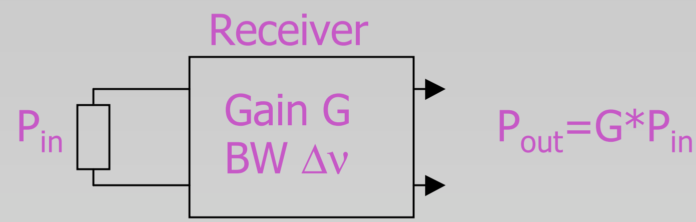
- An antenna's response is a result of coherent phase summation of the electric field at the focus.
- First null will occur at the angle where one extra wavelength of path is added across the full width of the aperture:

$\theta \sim \lambda/D$



Receivers

Matched load
Temp T (K)



Noise Temperature

Rayleigh-Jeans approximation

$P_{in} = \boxed{k_B T\,\Delta\nu}$ k_B = Boltzman's constant ($1.38*10^{-23}$ J / K)

When observing a radio source $T_{total} = T_A + T_{sys}$

Tsys = system noise when not looking at a discrete radio source

T_A = source antenna temperature

$T_A = \eta AS/(2k_B) = K\,S$, S = source flux (Jy)

SEFD = system equivalent flux density

SEFD = Tsys / K (Jy)

EVLA Sensitivities

Band (GHz)	η	T_{sys}	SEFD
1-2	.50	21	236
2-4	.62	27	245
4-8	.60	28	262
8-12	.56	31	311
12-18	.54	37	385
18-26	.51	55	606
26-40	.39	58	836
40-50	.34	78	1290

Two ways of understanding interferometry

- Optics
  - Put a mask over an aperture: still works ~ fine
  - More holes allow more information through
  - Distribution of holes affects quality of image
  - Image quality improves as number of holes in mask increases

- Physics
  - Radio sources emit random signals: noise but no signal
  - Correlation of voltage far from the source contains information about the source
  - Measure spatial correlation function of voltages at antennas
  - Derive image of sky from sampled correlation function

Optics: holes in a mask

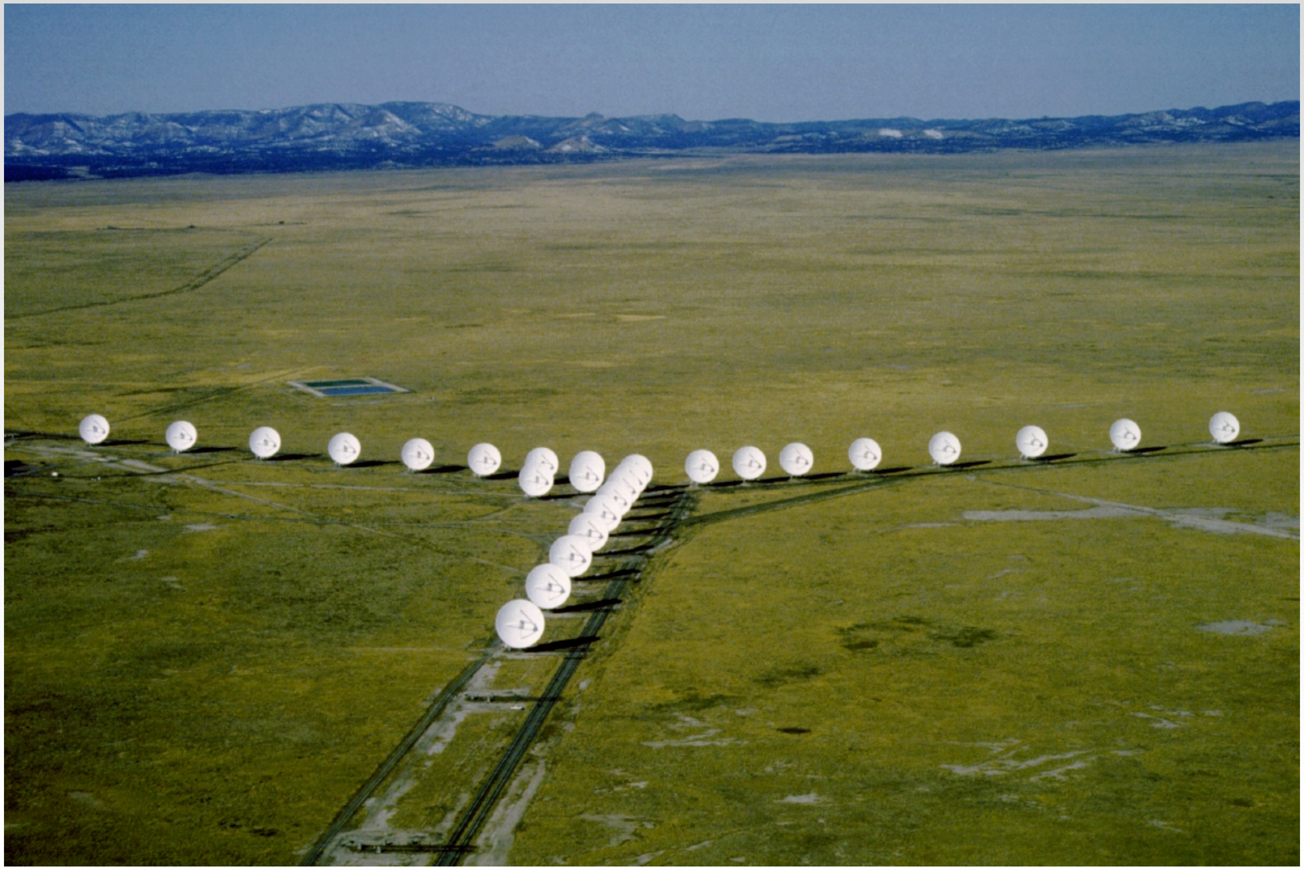
- Build a big reflector lens
- Measure power on the focal plane: get an image of the radio sky

Optics: holes in a mask

- Resolution ~ wavelength / diameter
- Optical telescope has resolution ~ 1 arcsecond
- At a wavelength of 20cm, we need a diameter ~ 35km!
- Largest steerable radiotelescope has D ~ 100m
- Largest fixed radiotelescope has D ~ 300m

Optics: holes in a mask

- We do not need to fill the area!
- Example: VLA D configuration (1km maximum distance)



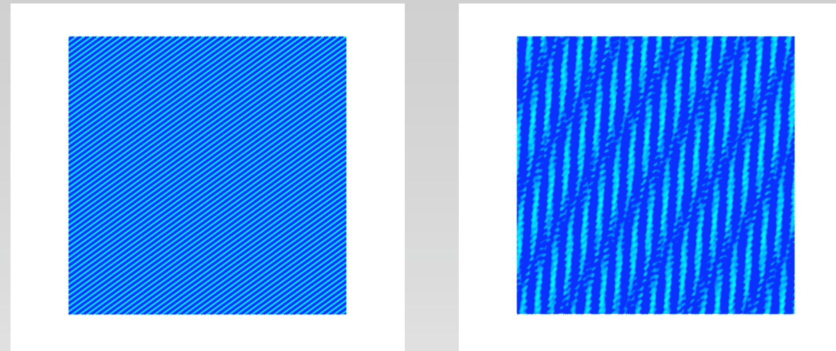
Optics: holes in a mask

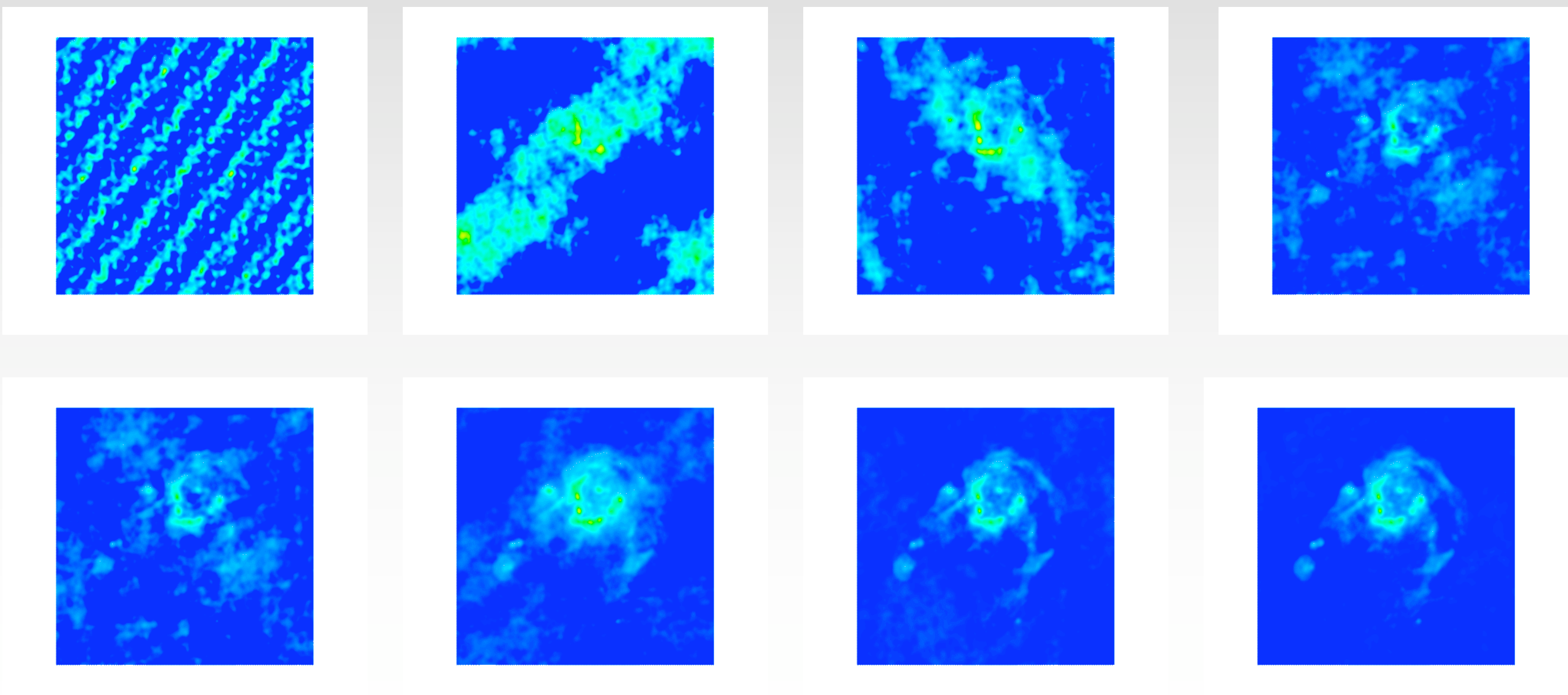
- Imagine the lens of a camera
- Still get a good image even with a mask in front of the lens
- But the image quality changes with the number of holes
- Demonstration
  - Choose a representative image of a source
  - Add holes to a mask
  - Start with two holes and double in every additional frame

Optics: holes in a mask

Double number of holes from frame to frame:

- 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024





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
- Van Cittert-Zernicke theorem states that the
  - *Sky brightness and Coherence function are a Fourier pair*
- Mathematically:

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

Physics: propagation of coherence

- Simplest example
  - Put two emitters (a,b) in a plane
  - And two receivers (1,2) in another plane

$$V_1^r = V_a^e.g_1^a + V_b^e.g_1^b$$
$$V_2^r = V_a^e.g_2^a + V_b^e.g_2^b$$

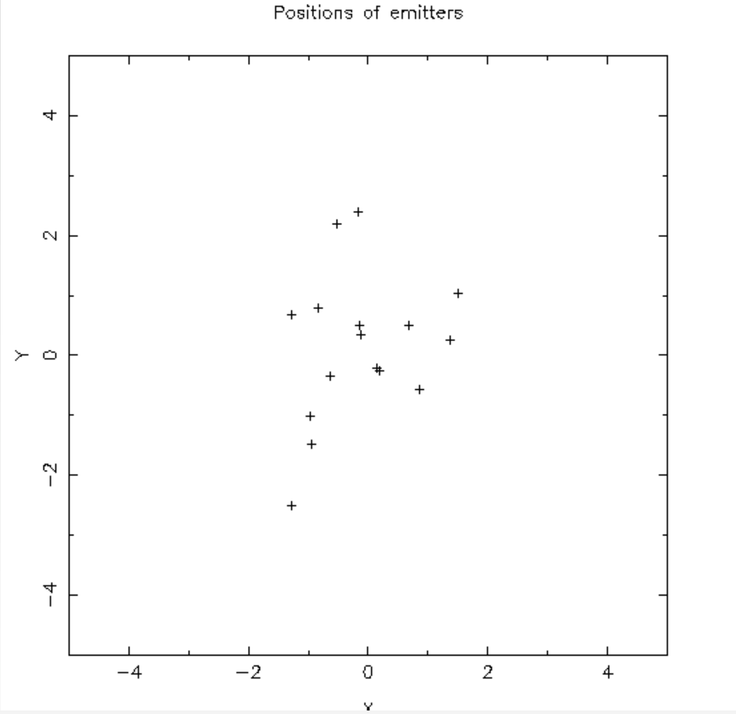
- Correlate voltages from the two receivers

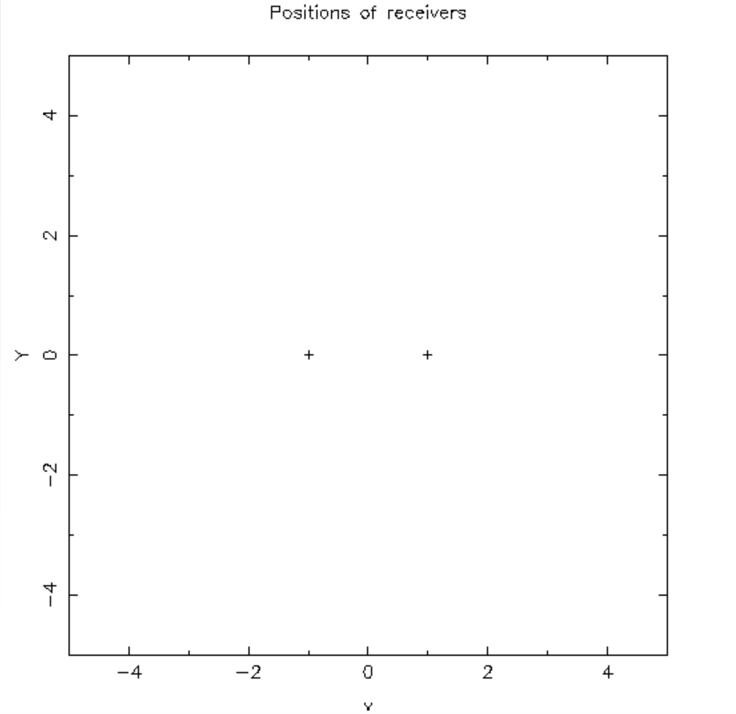
$$\begin{aligned}\langle V_1^r.V_2^r\rangle &= \langle\left(V_a^e.g_1^a + V_b^e.g_1^b\right)\left(V_a^e.g_2^a + V_b^e.g_2^b\right)\rangle \\ &= \langle V_a^e.V_a^e\rangle.g_2^a.g_1^a + \langle V_b^e.V_b^e\rangle.g_2^b.g_1^b \\ &= I_a.g_2^a.g_1^a + I_b.g_2^b.g_1^b\end{aligned}$$

- Correlation contains information about the source *I*
- Can move receivers around to untangle information in *g's*

Physics: propagation of coherence

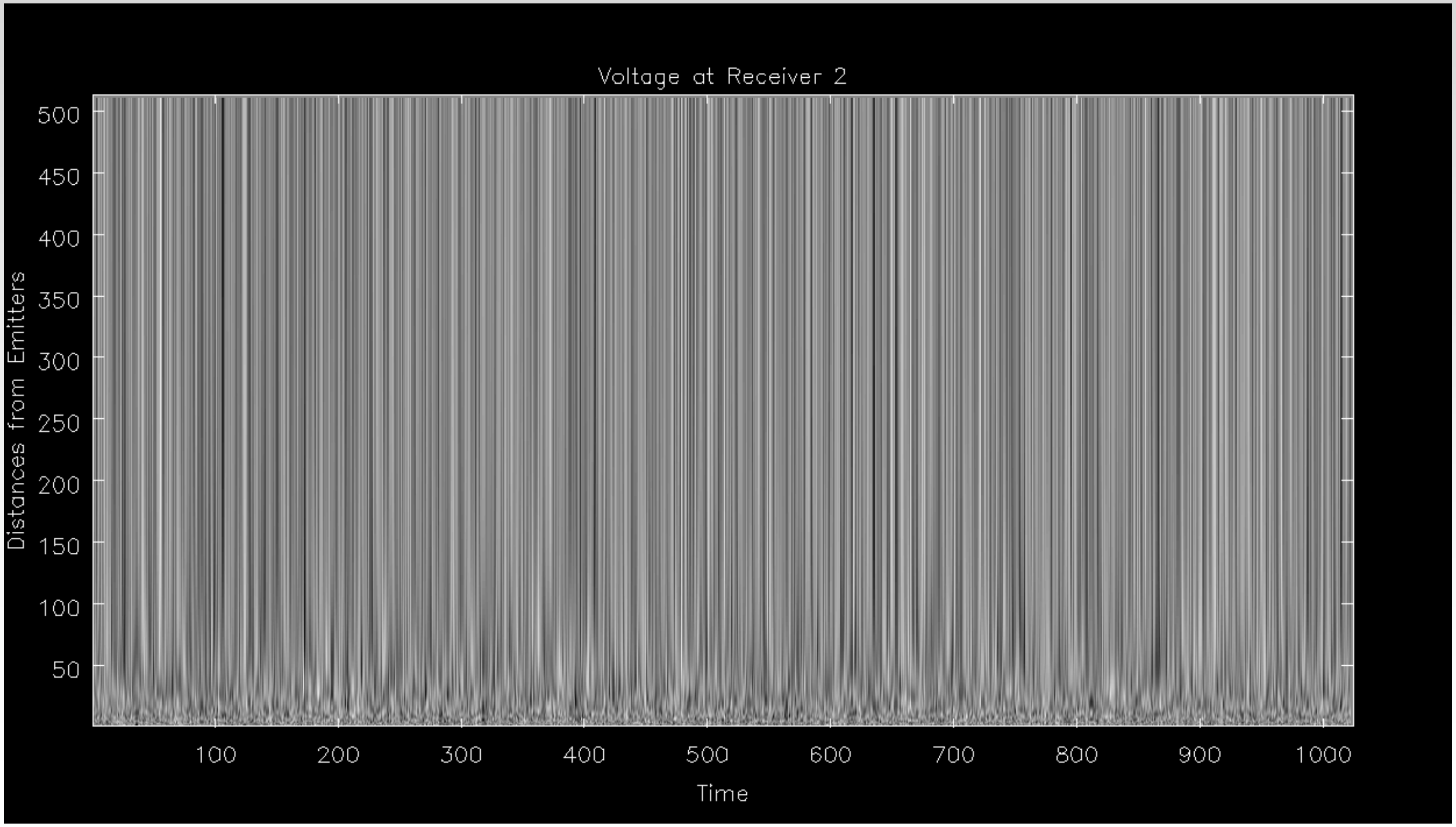
- More complex example
  - Put some emitters in a plane
  - And two receivers in another plane





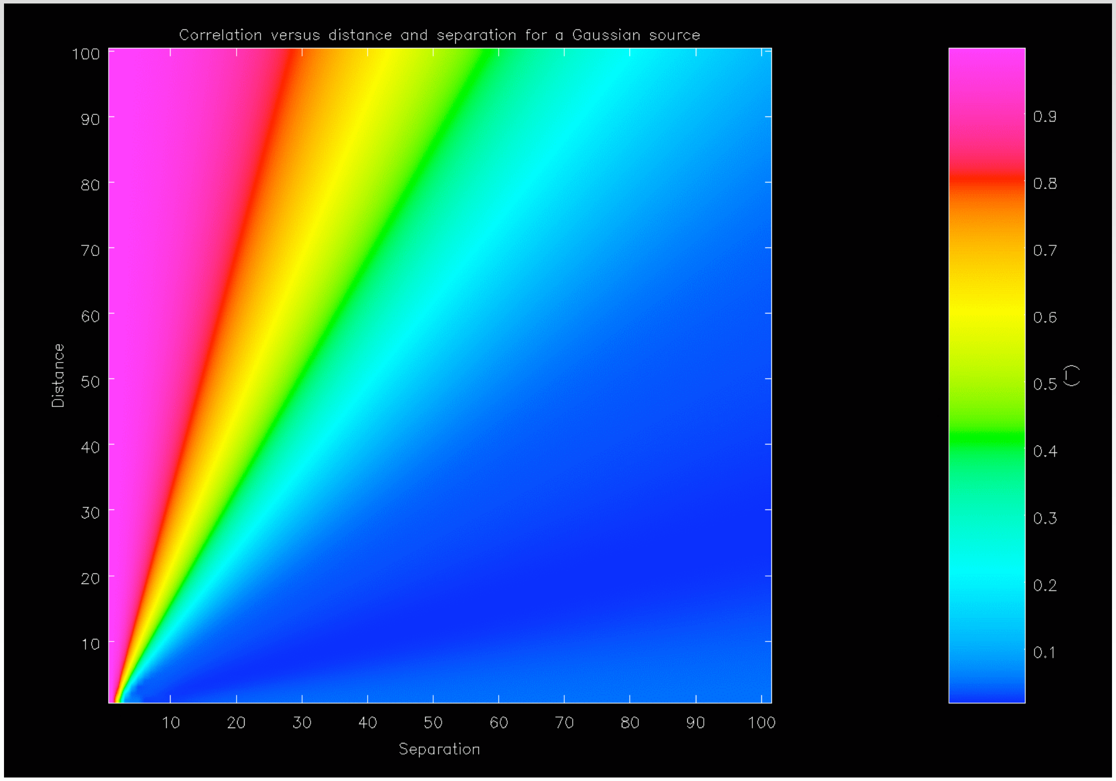
Physics: propagation of coherence

- Look at the electric fields at the two receivers as we move the receivers away from the emitters



Physics: propagation of coherence

- Another example: Gaussian (bell) shaped source a few meters in width
- Follow coherence function away from the source



Overview of talk

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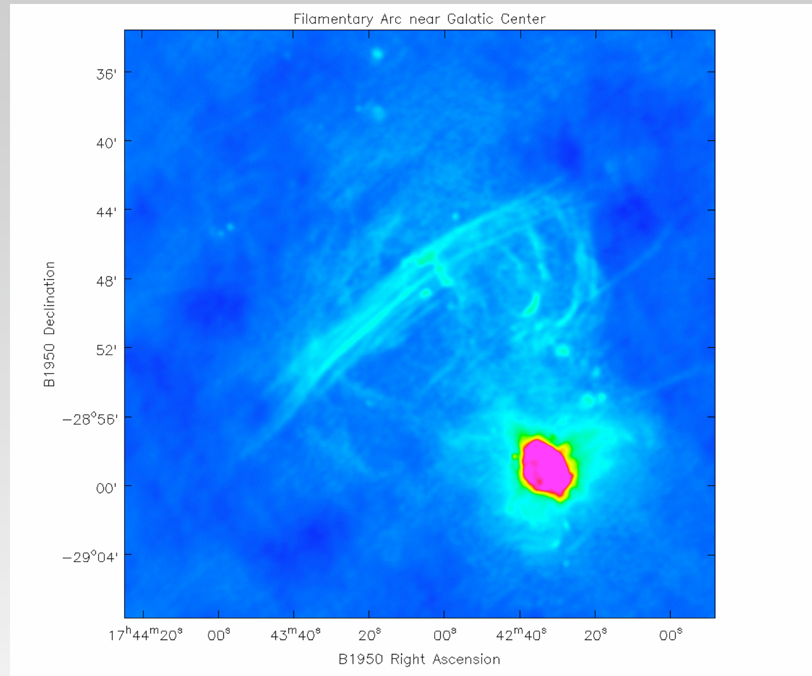
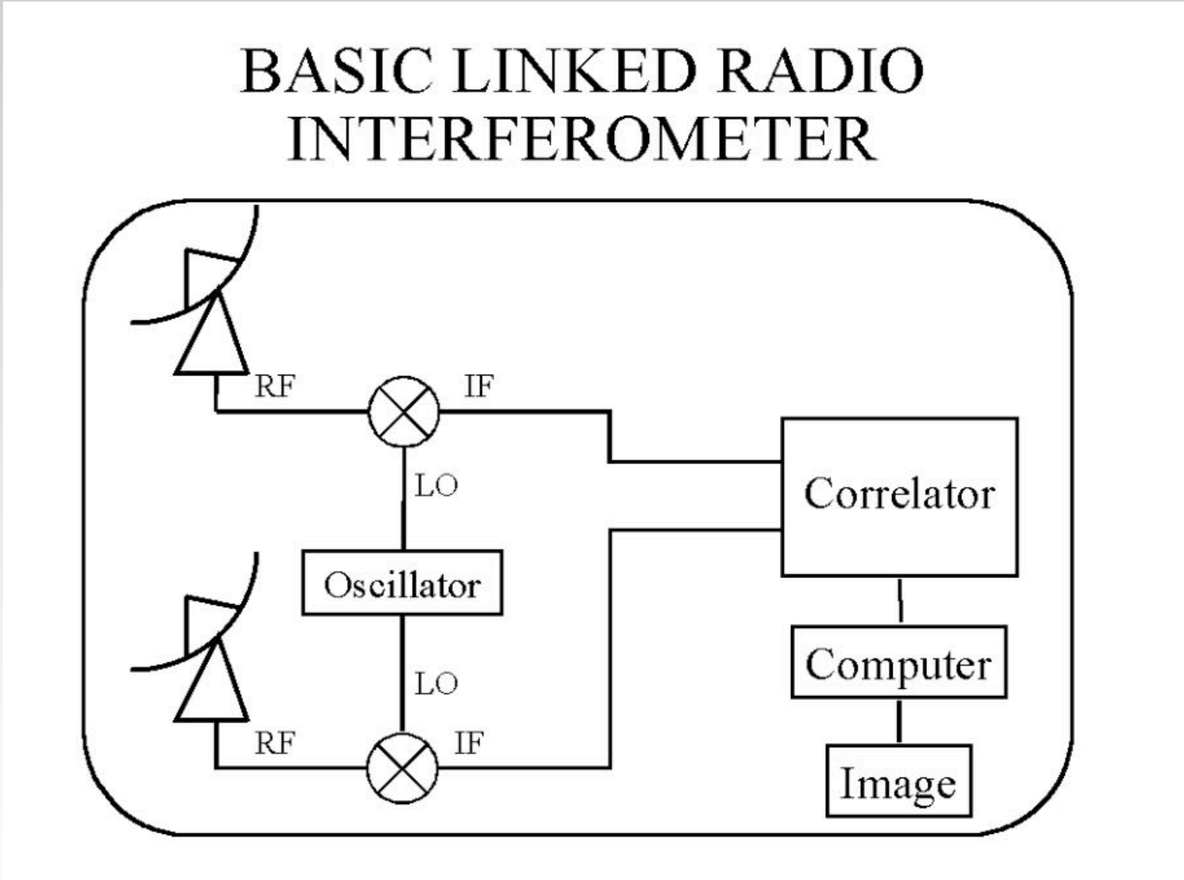
2. Practical details
3. Some examples
4. Other properties of the radiation
5. Variations in interferometry

In practice…

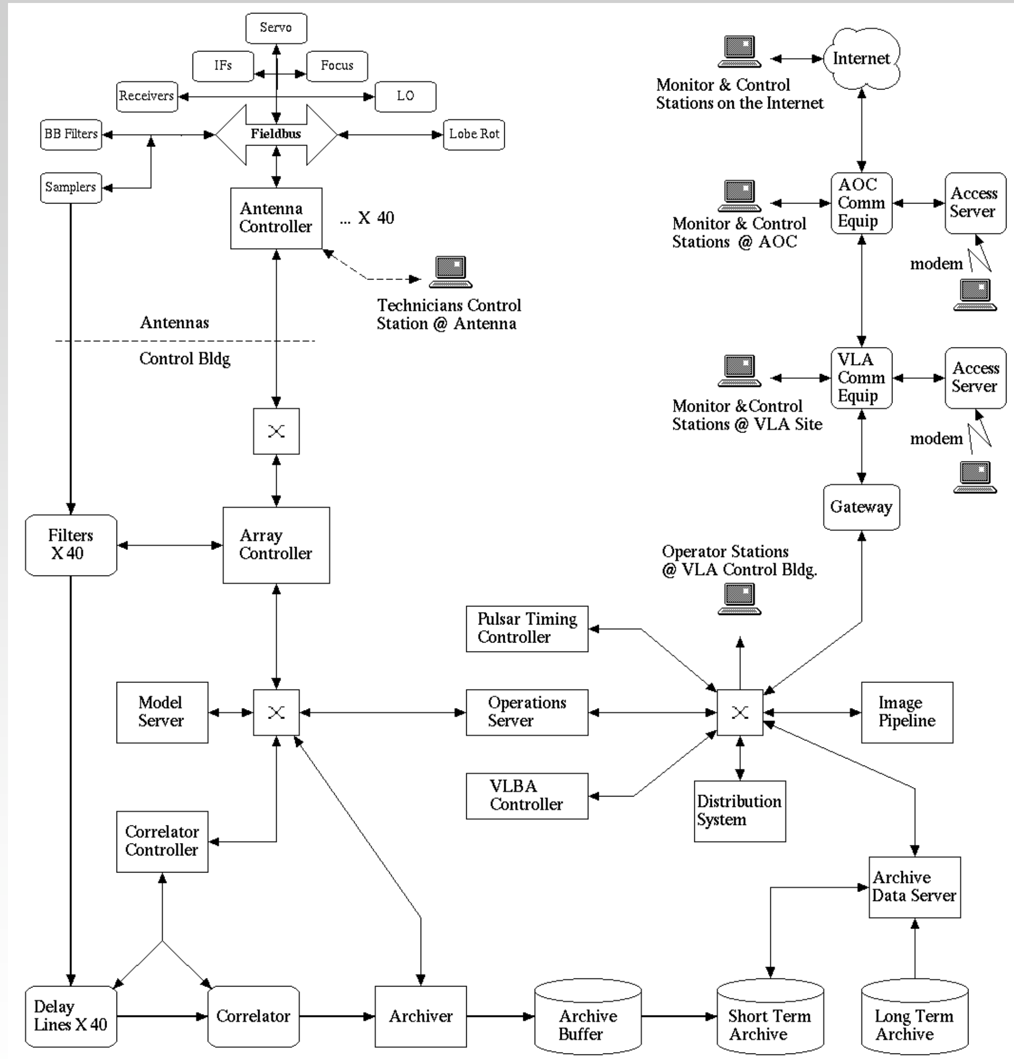
1. Use many antennas (VLA has 27)
2. Amplify signals
3. Sample and digitize
4. Send to central location
5. Perform cross-correlation
6. Earth rotation fills the "aperture"
7. Inverse Fourier Transform gets image
8. Correct for limited number of antennas
9. Correct for imperfections in the "telescope" e.g. calibration errors
10. Make a beautiful image…



Single interferometer



The VLA is much more complex



(ALMA will be even more...)

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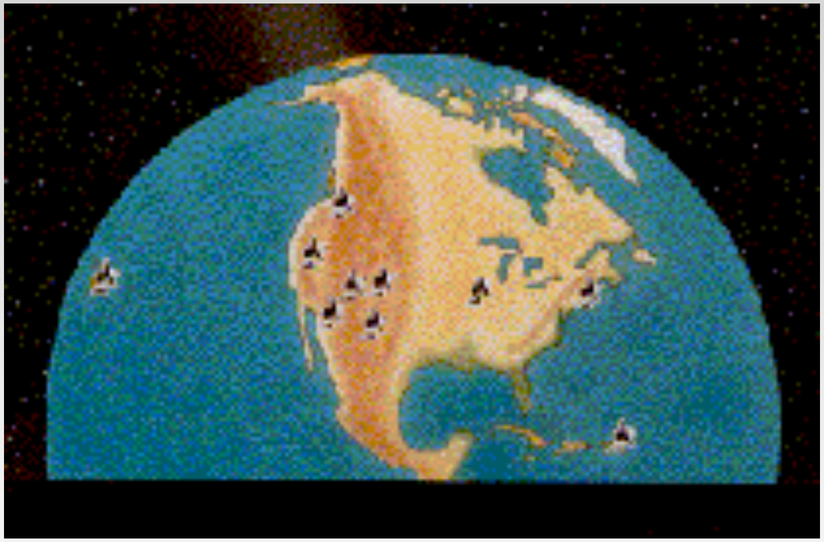
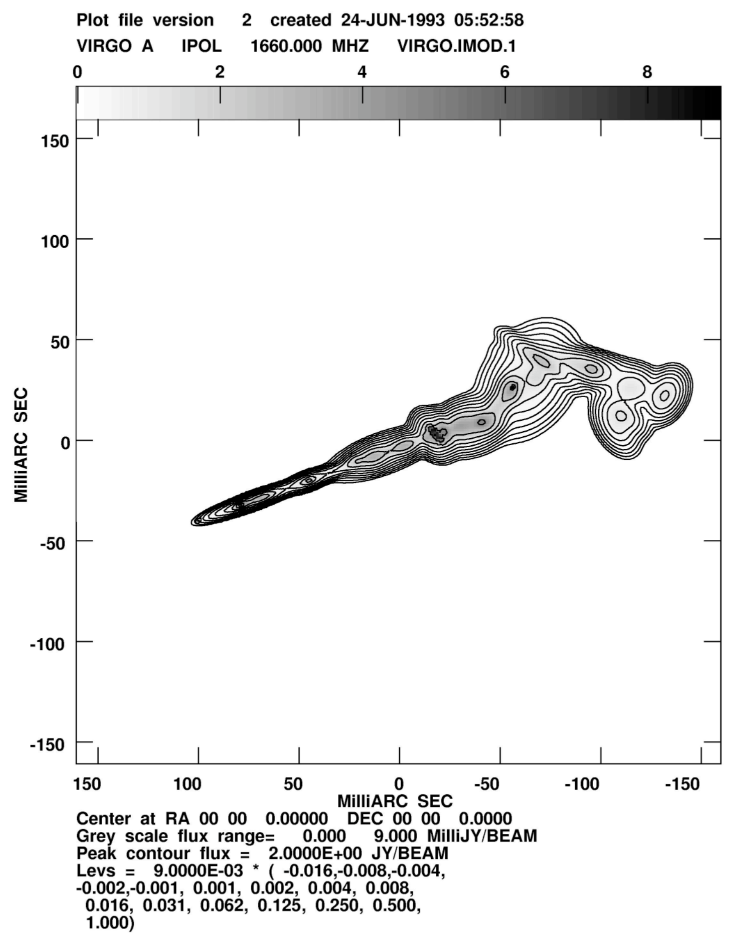
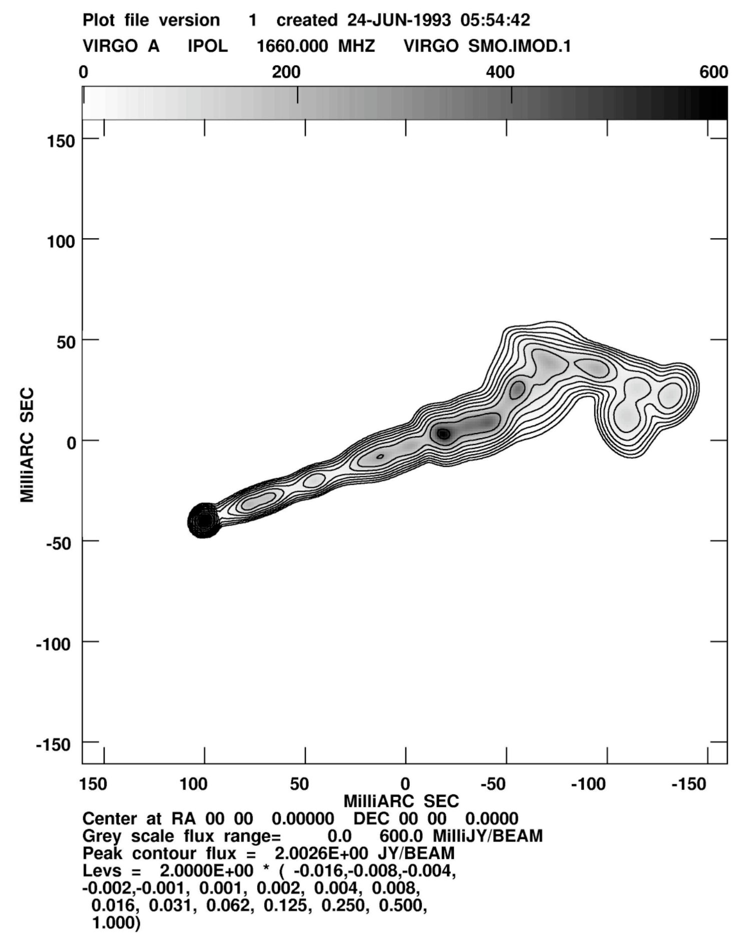
Example of imaging a complex source

- VLBA simulated observations of M87-like jet source
- Will show
  - UV coverage
  - Correlation function
  - Point Spread Function
  - “Dirty” image
  - Best Clean image

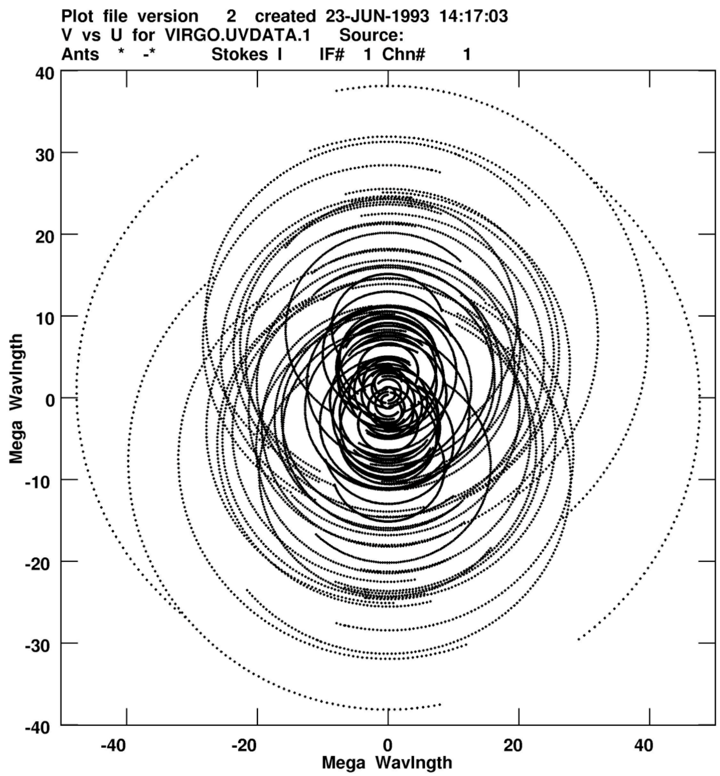


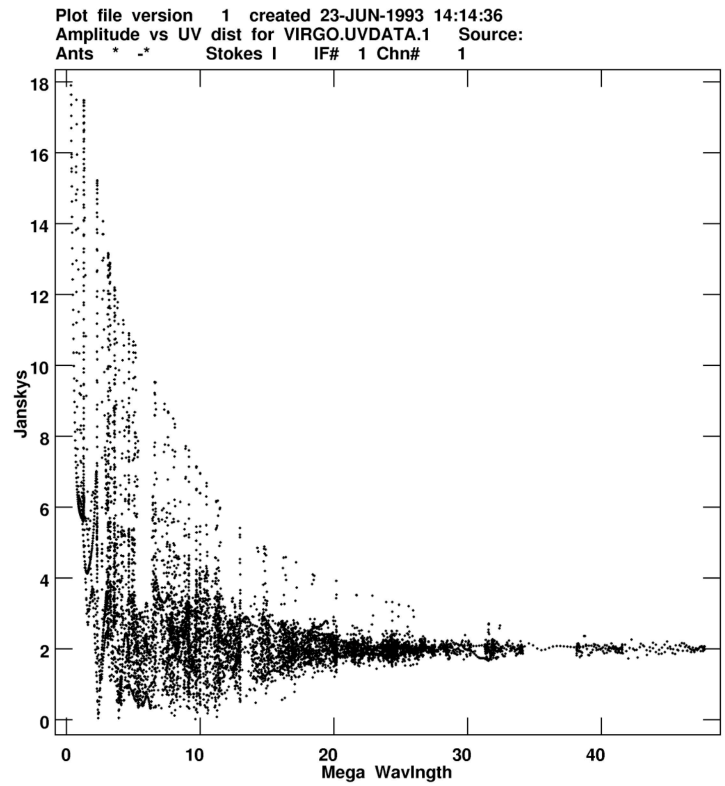
Original and smoothed model



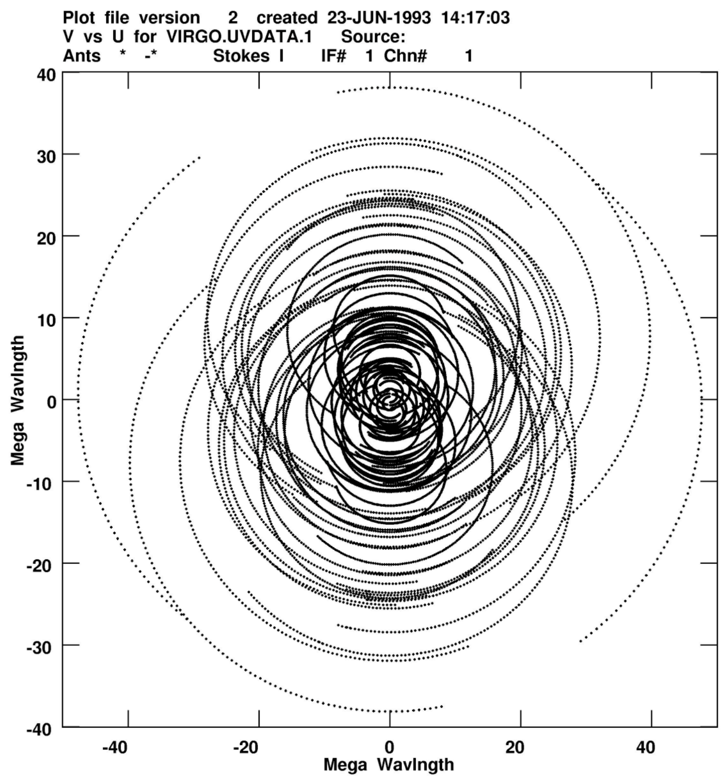


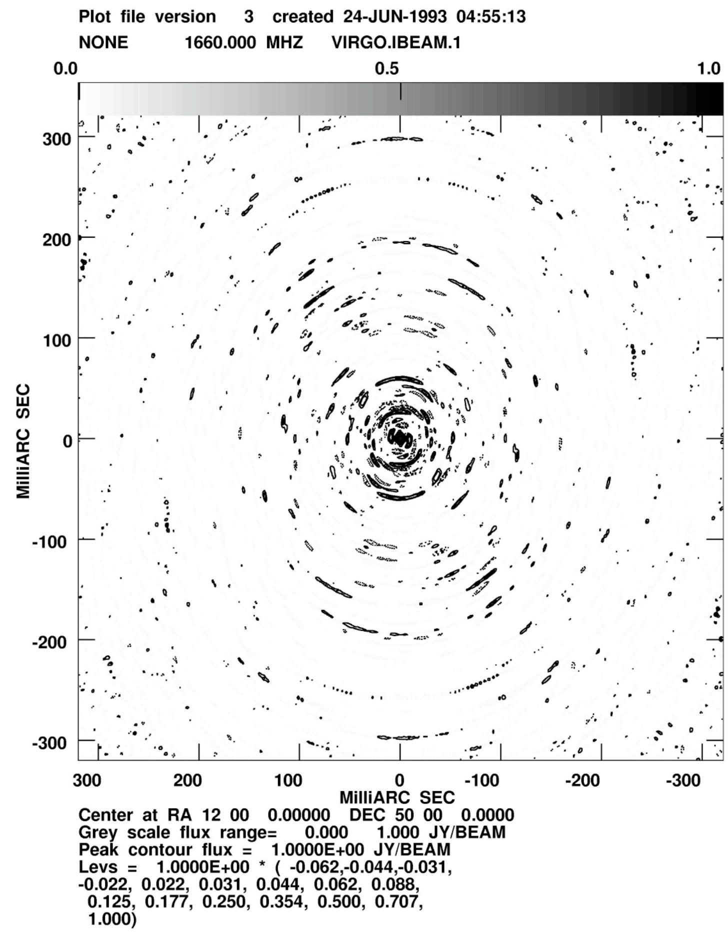
Fourier plane sampling



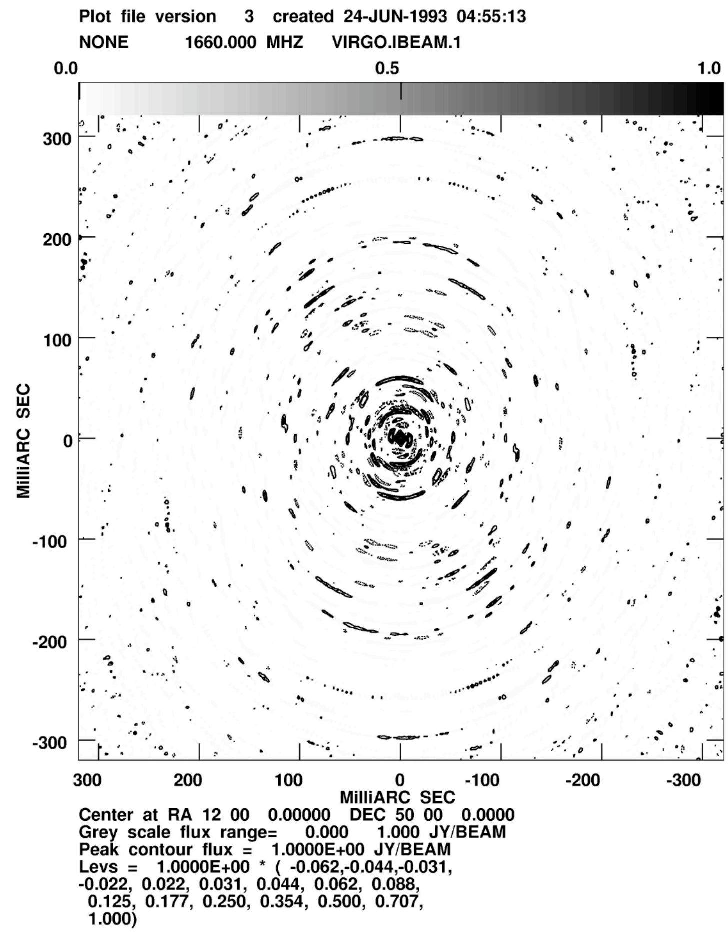


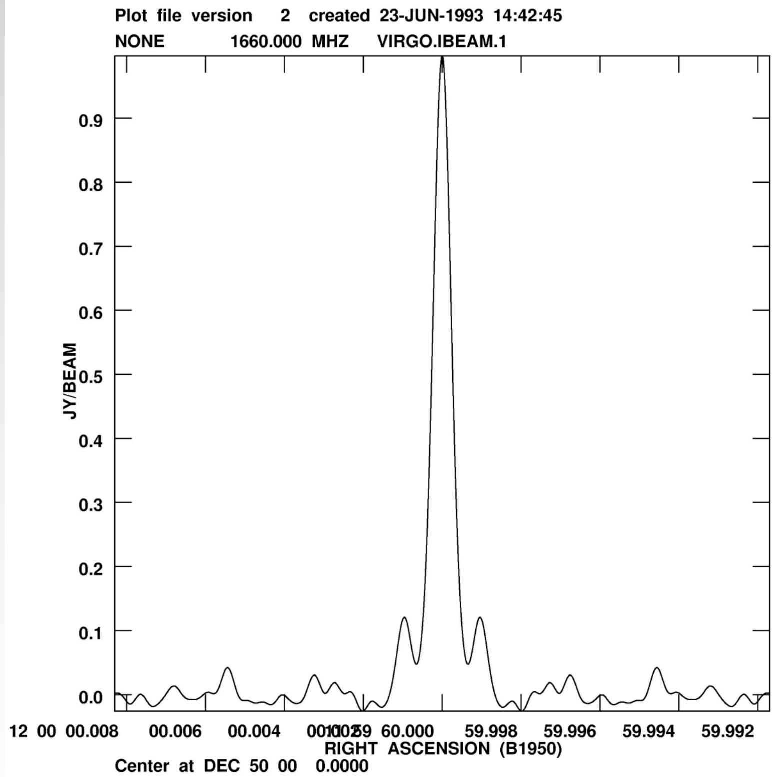
UV Sampling ⇔ Point Spread Function



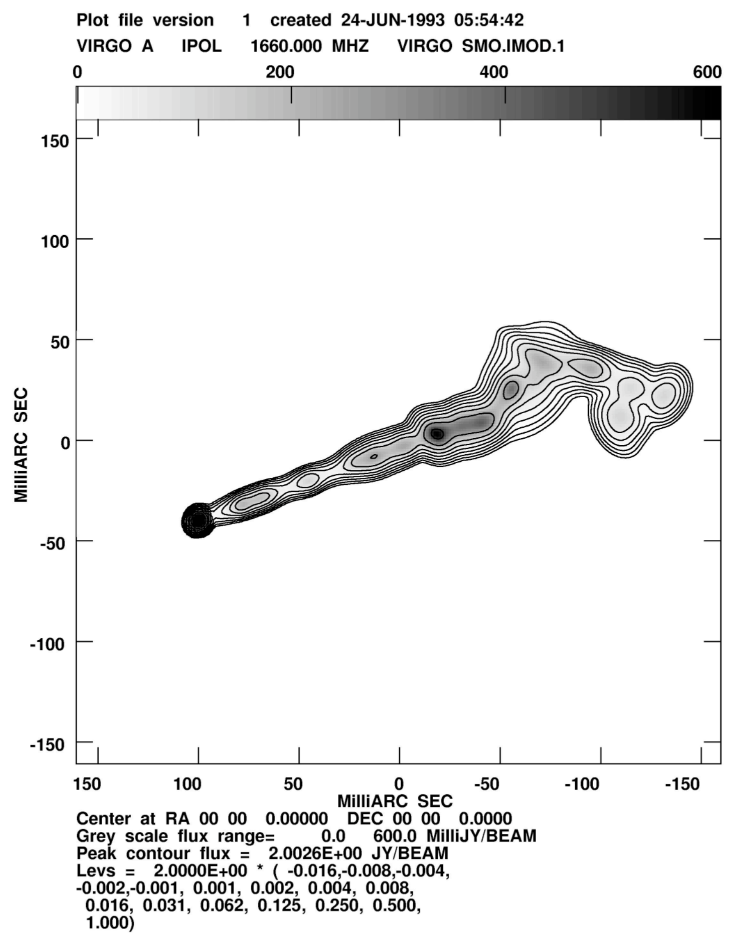


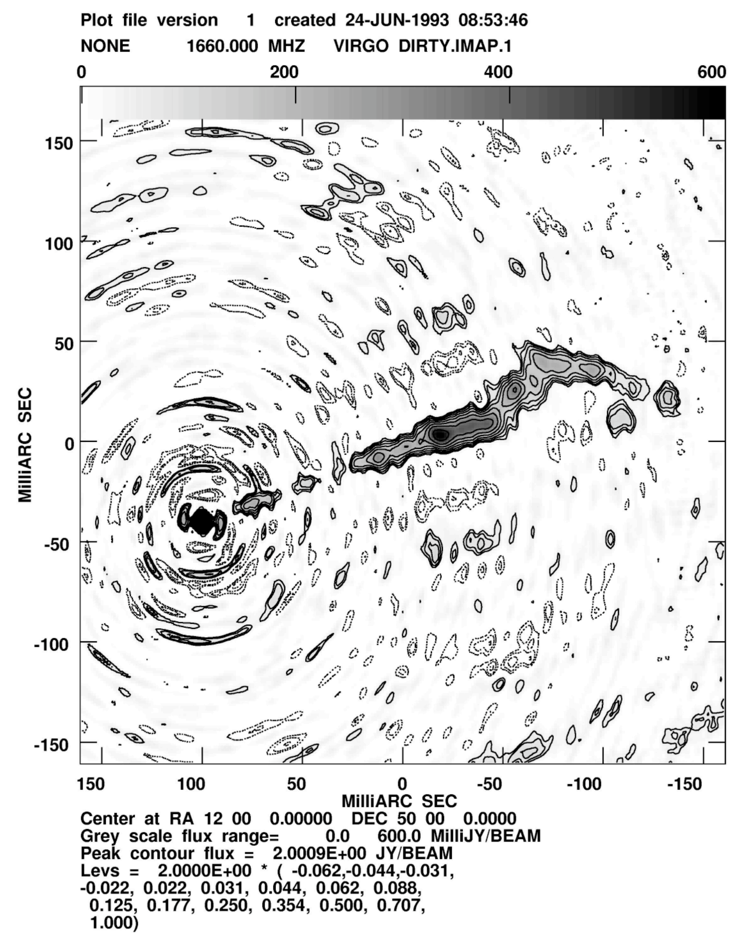
Point Spread Function



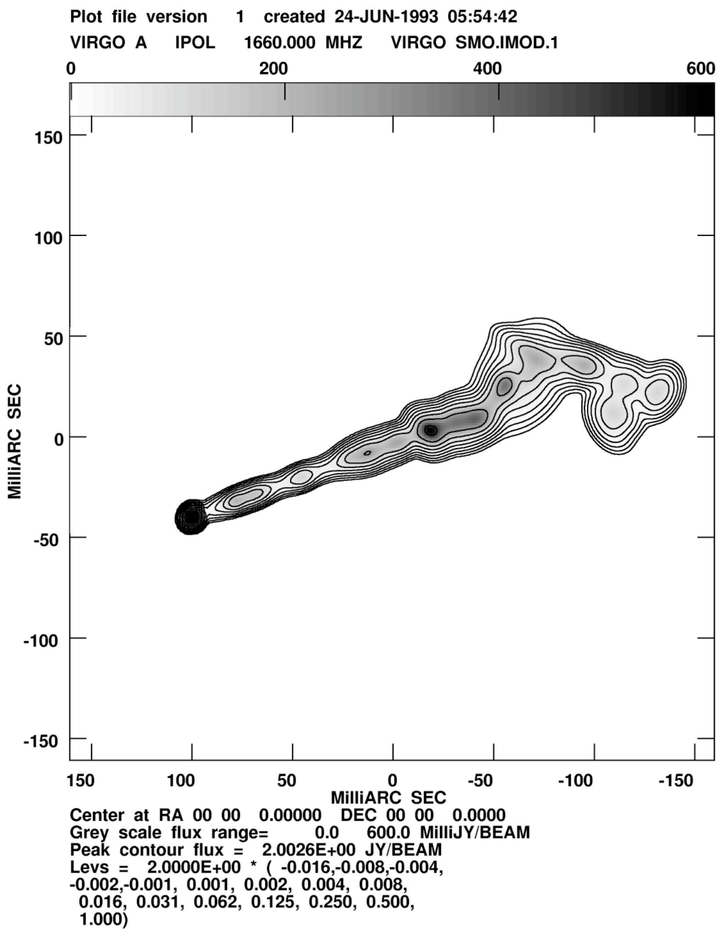


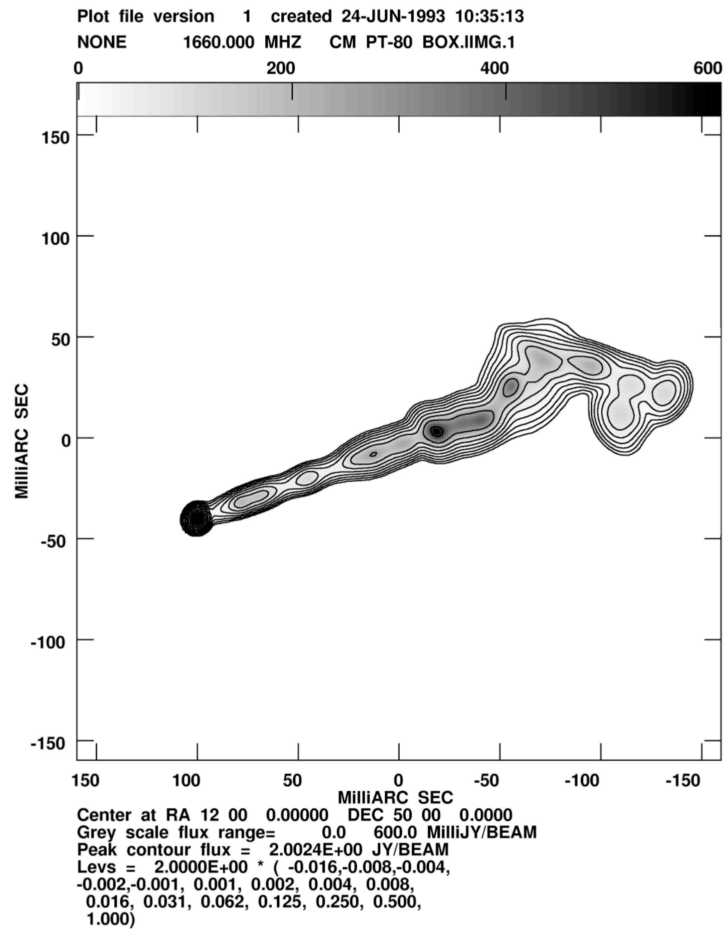
Original model and Dirty image





Original model and best image



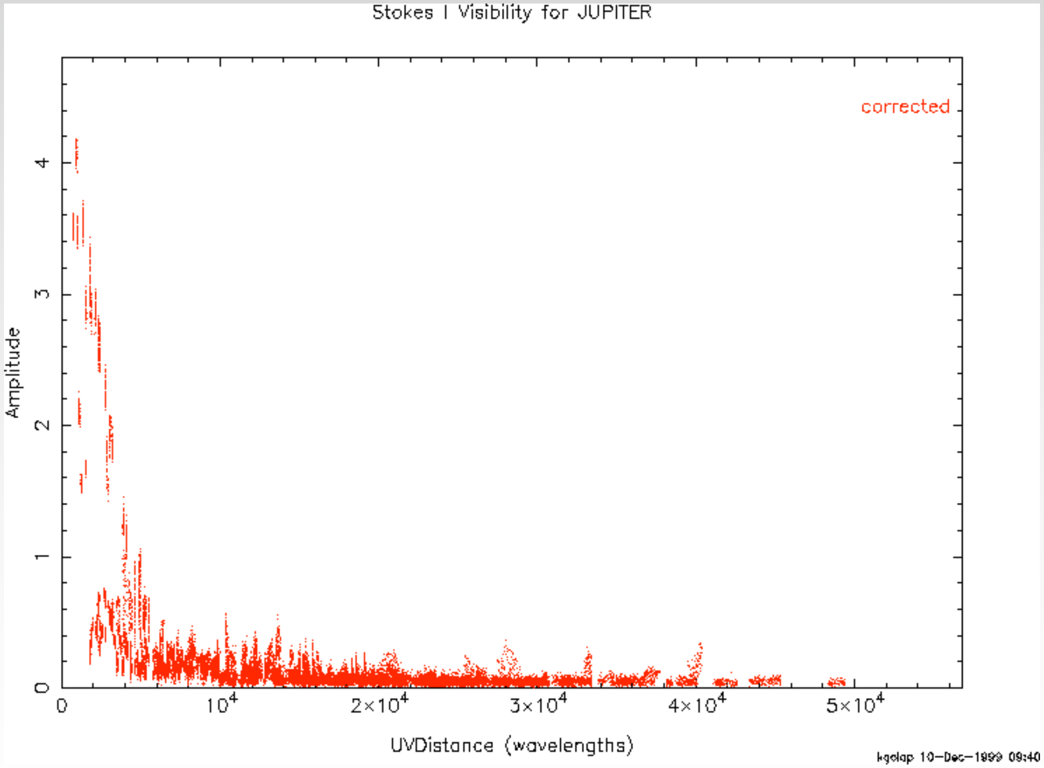


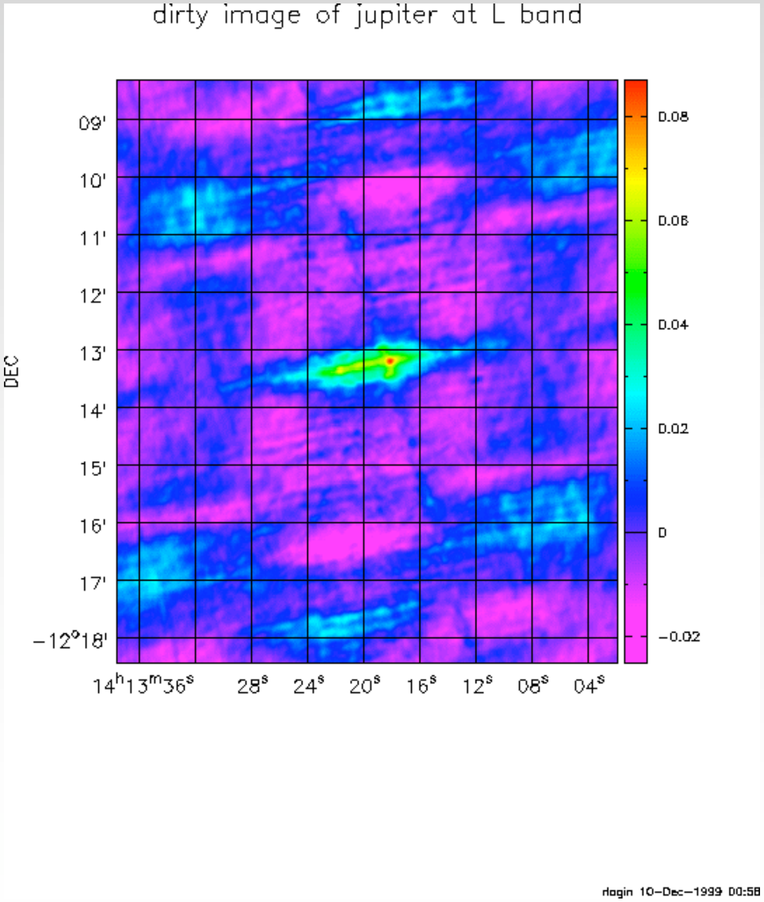
Correcting for limited number of antennas

- Sky is not too complex: can exploit this to improve the image
  - CLEAN:
    - sky is composed of point sources on a dark sky
    - sky is composed of resolved sources of known extent on a dark sky
  - Multi-scale CLEAN:
    - sky is composed of smooth, limited extent blobs on a dark sky
  - Maximum Entropy Method:
    - sky is smooth and positive
  - Non-negative least squares:
    - sky is non-negative and compact
  - Hybrid algorithms:
    - Some combination of the above...

A real example from the VLA

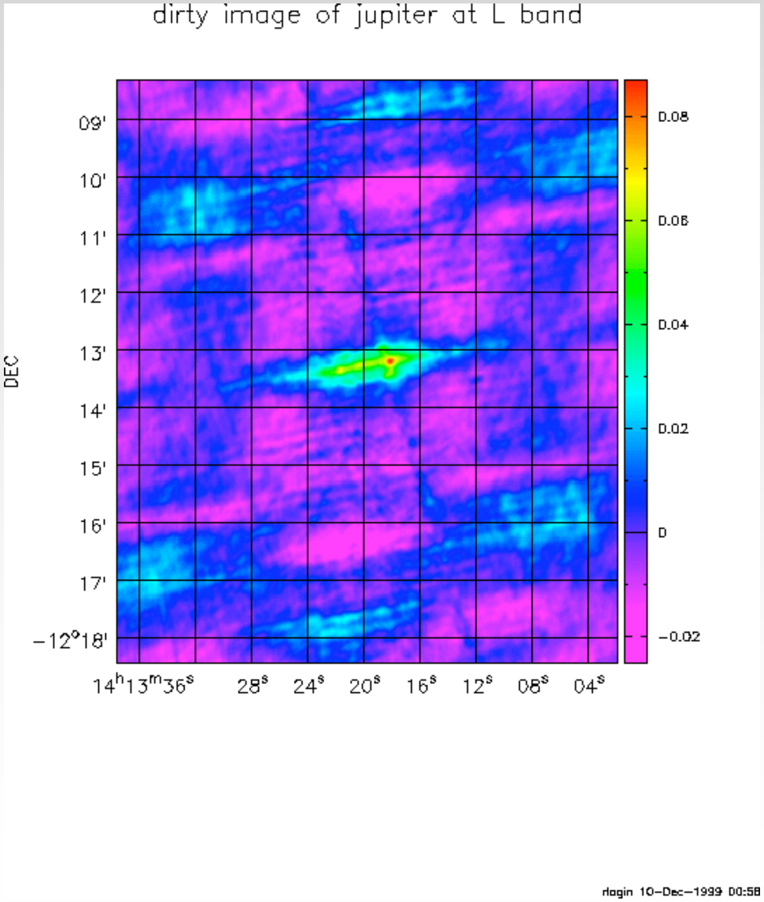
- Sampled correlation function => “Dirty” image

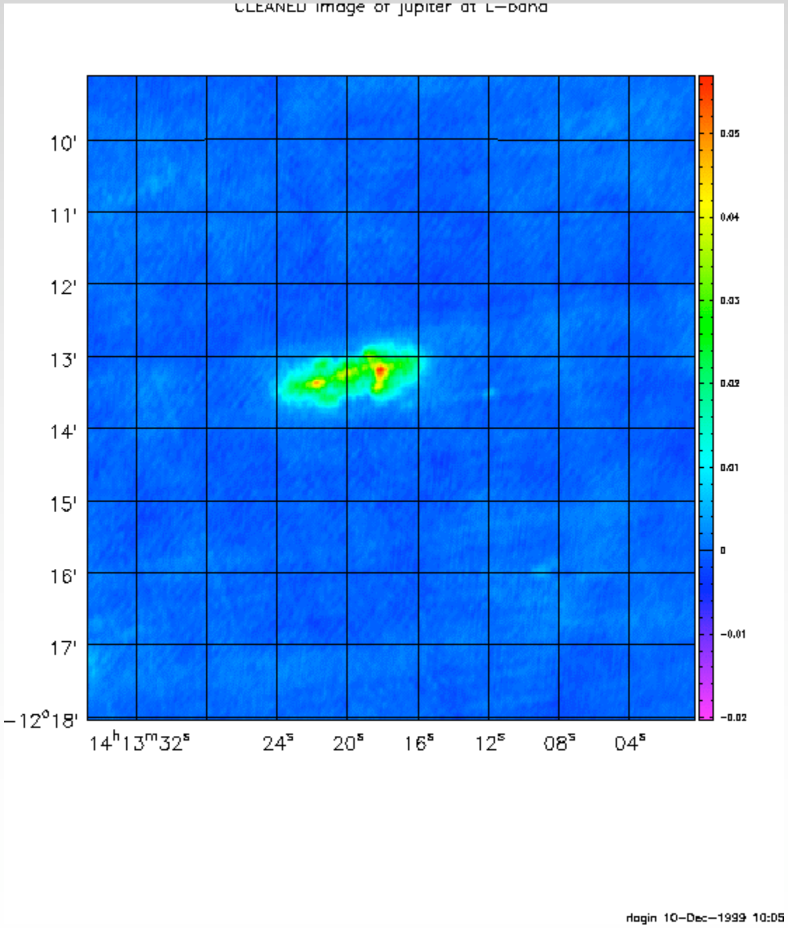




A real example from the VLA

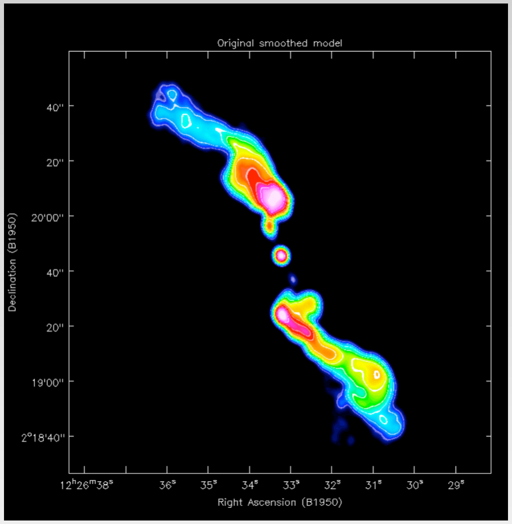
- Effective aperture is filled in and the diffraction patterns vanish

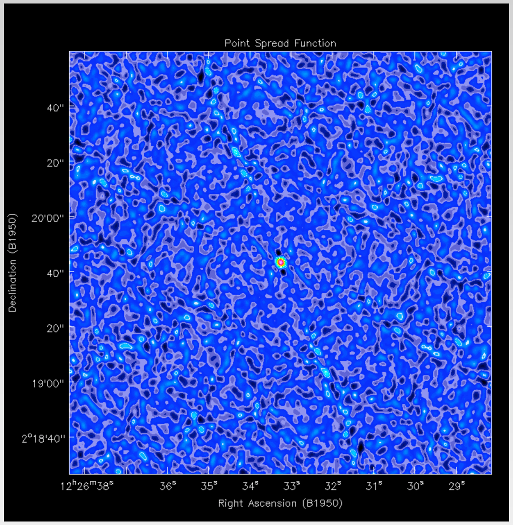




Another synthetic example

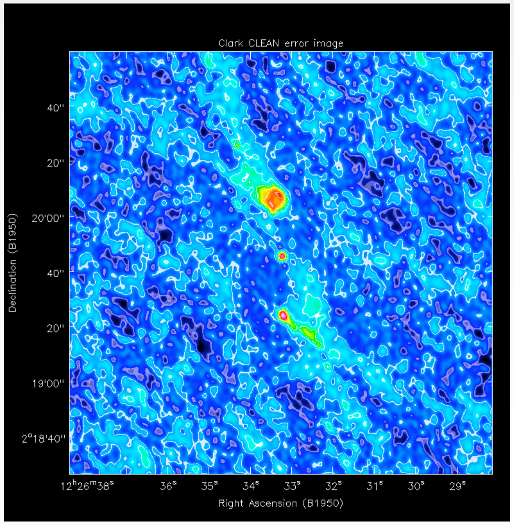
Model

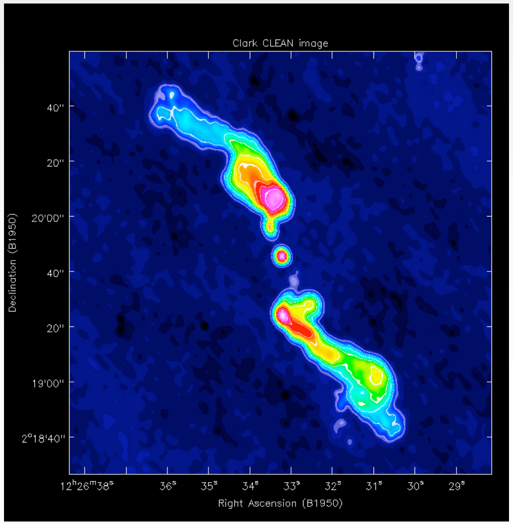




PSF

"Dirty" image





CLEAN image

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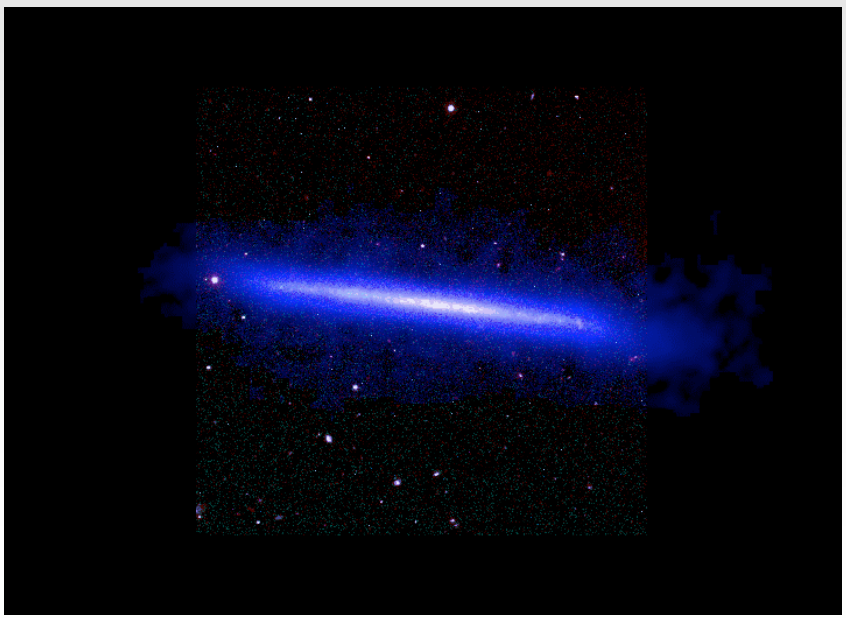
5. Variations in interferometry

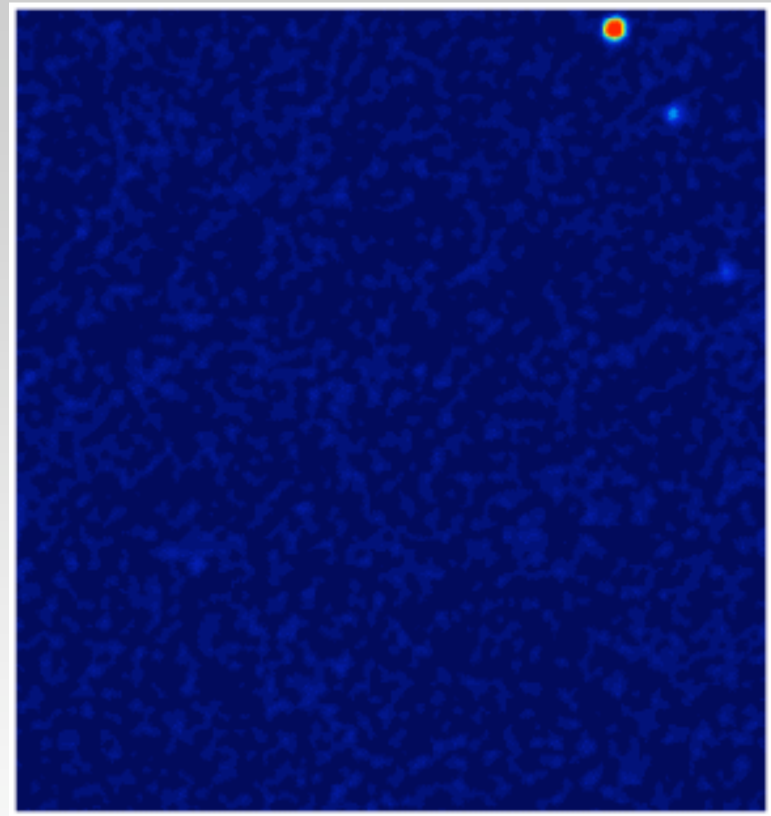
Other properties of the radiation

- Polarization of received radiation
  - Measure two radiation states: linear or circular
  - Tells us about the organization of emitting structures, *e.g.* alignment of magnetic fields
- Frequency behavior
  - *Widely spaced* tells us about radiation mechanisms
  - *Closely spaced* tells us about kinematics through the Doppler shift of spectral lines
- More examples will be shown by my colleagues

Imaging at different, closely spaced frequencies

- Spectral line image of a spiral galaxy
- Shows emission in the hyperfine transition of Hydrogen
- Associate velocity (line of sight only) with each point
- Determine kinematics of galaxy from rotation curve

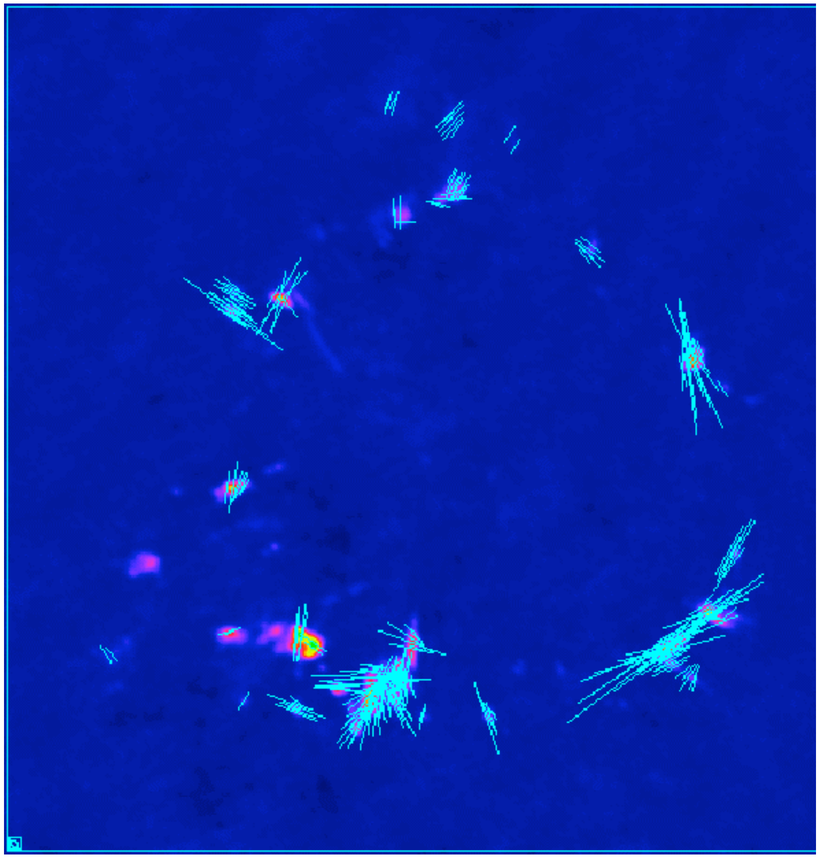




Superthin galaxy UGC7321

Imaging polarized radiation

- Radiation from sources is often polarized
- Measure degree and orientation of polarization



(TX Cam, Mira variable, v=1, J=1-0 SiO maser emission)

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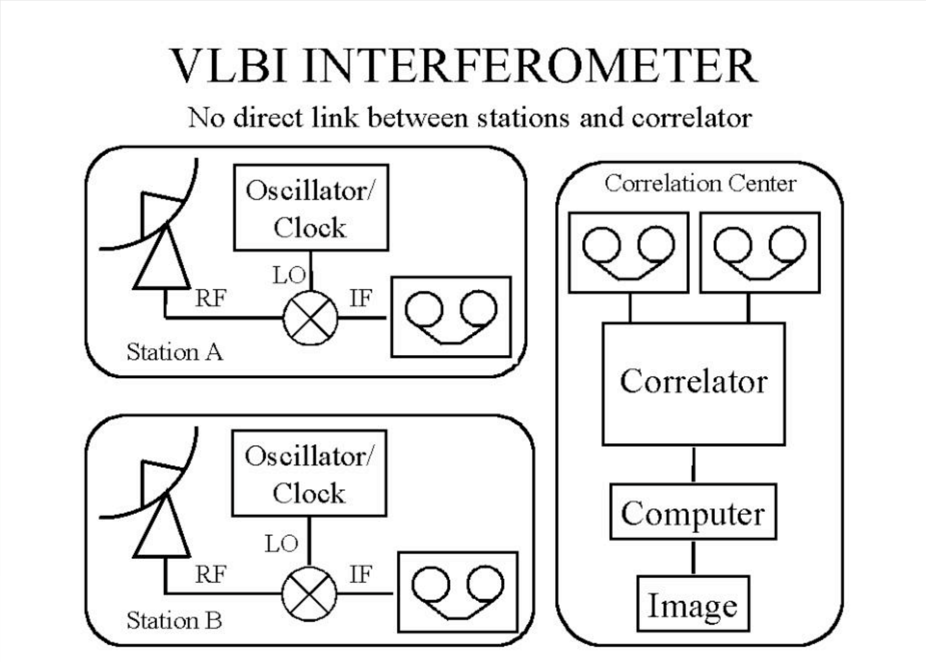
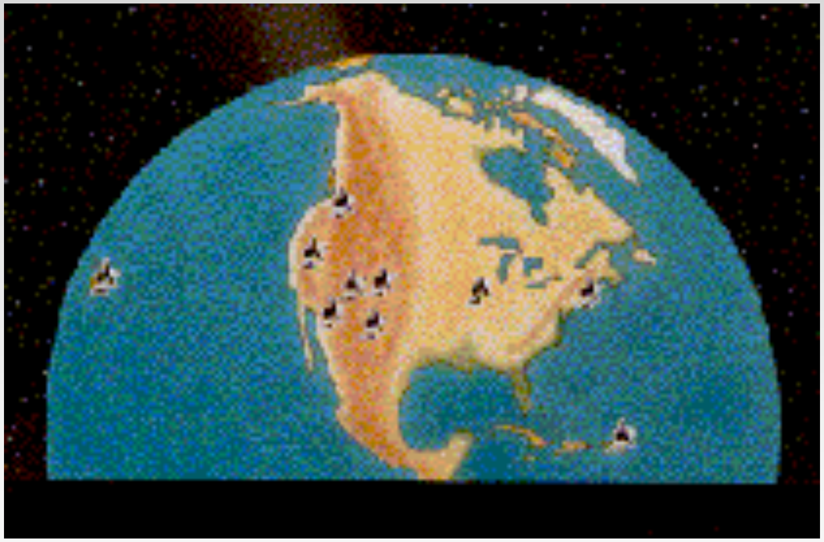
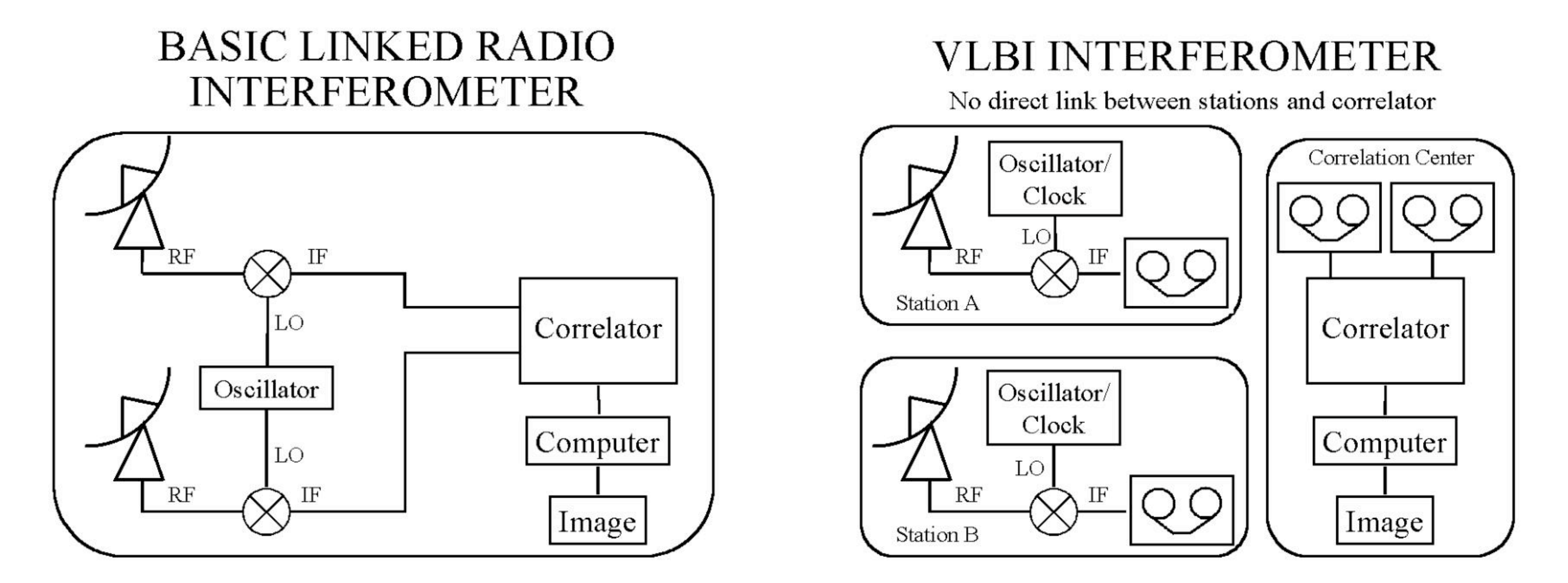
Variations: the Very Long Baseline Array

- Antennas very far apart
  - resolution very high: milli-arcsecs
- Very Long Baseline Interferometry
- Record signals on tape



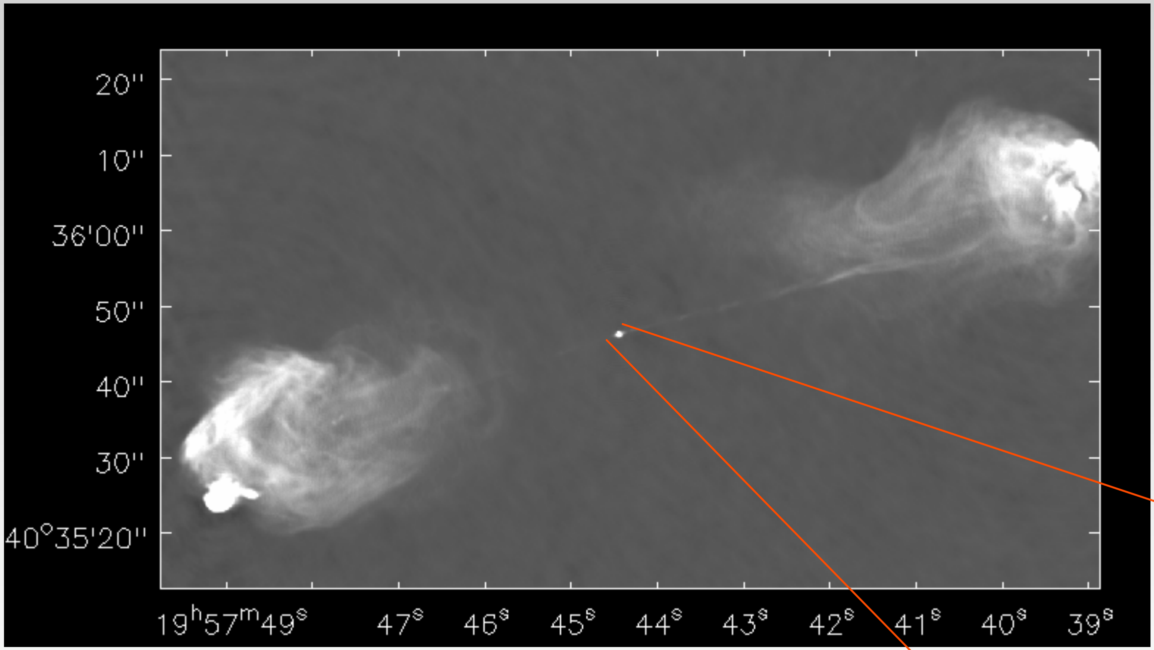


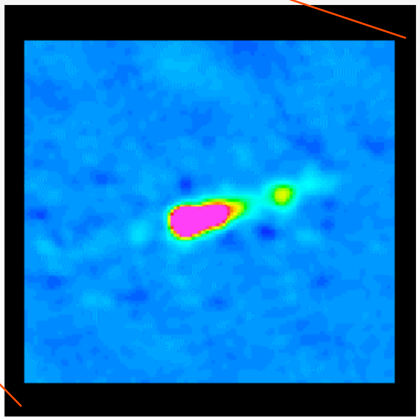
Connected elements versus tape recording



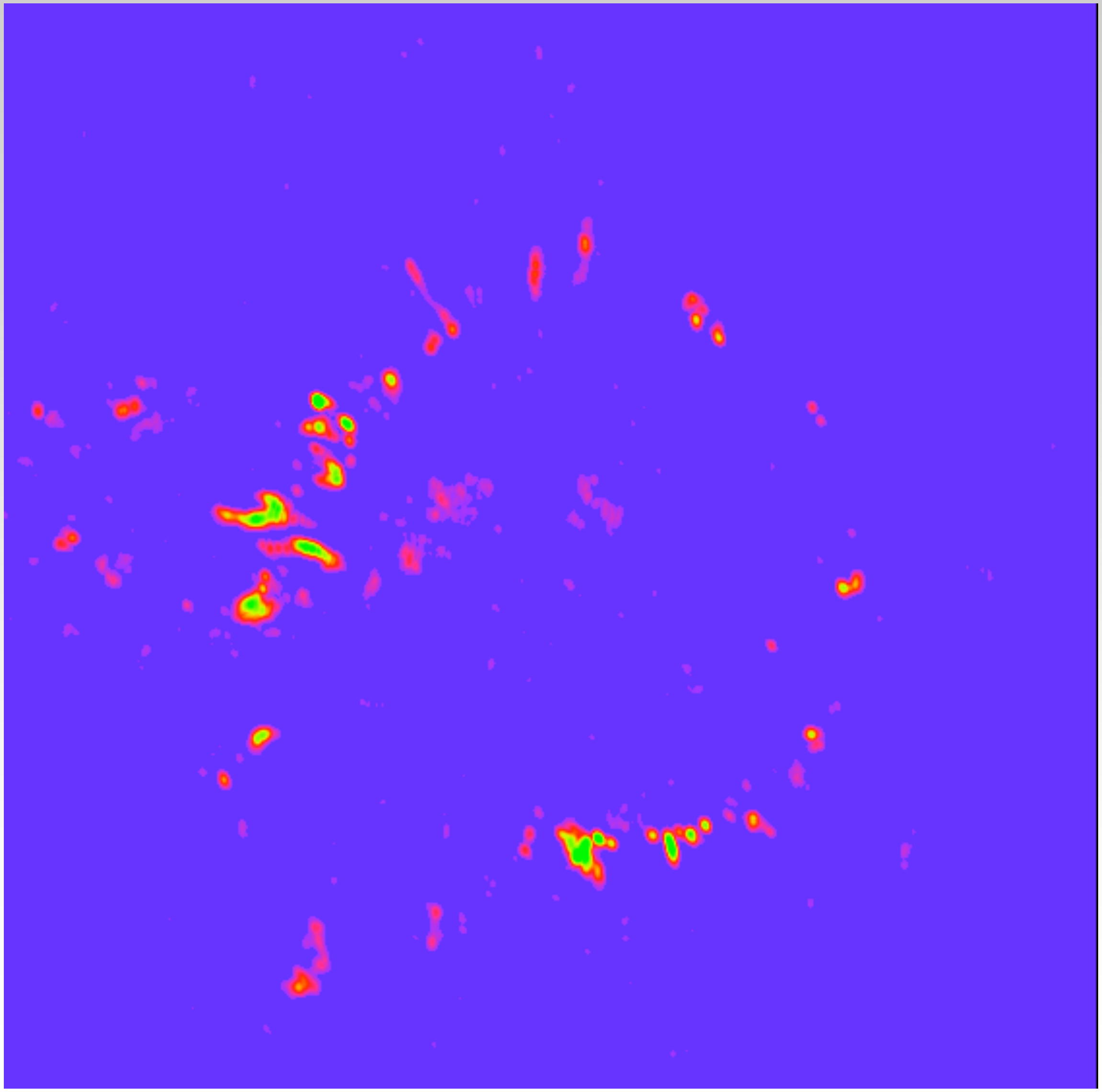
VLA + VLBA

- Zoom lens to reveal inner cores of radio galaxies



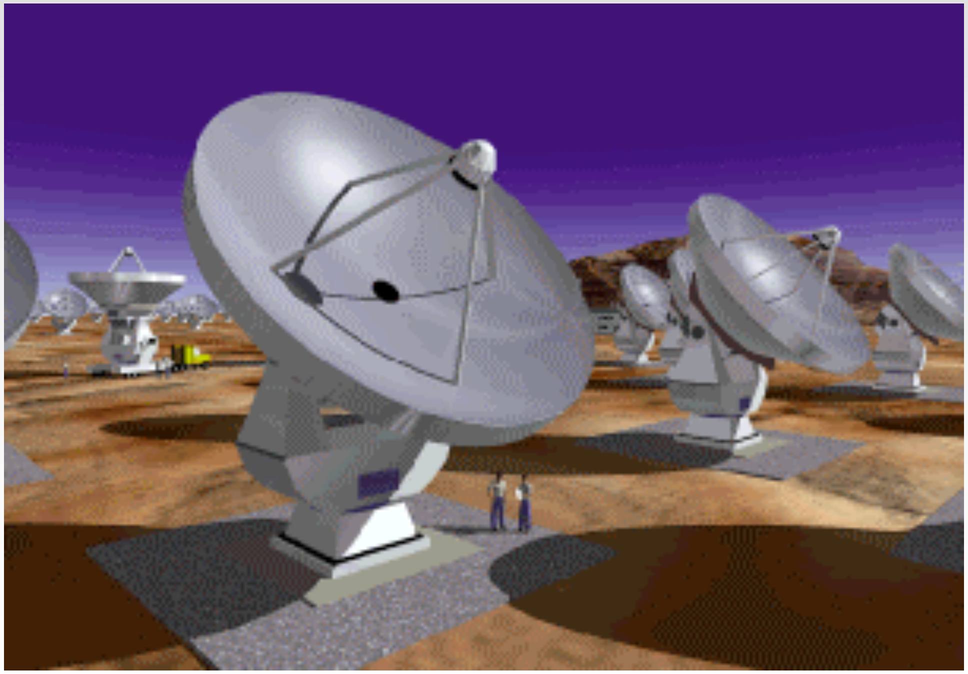


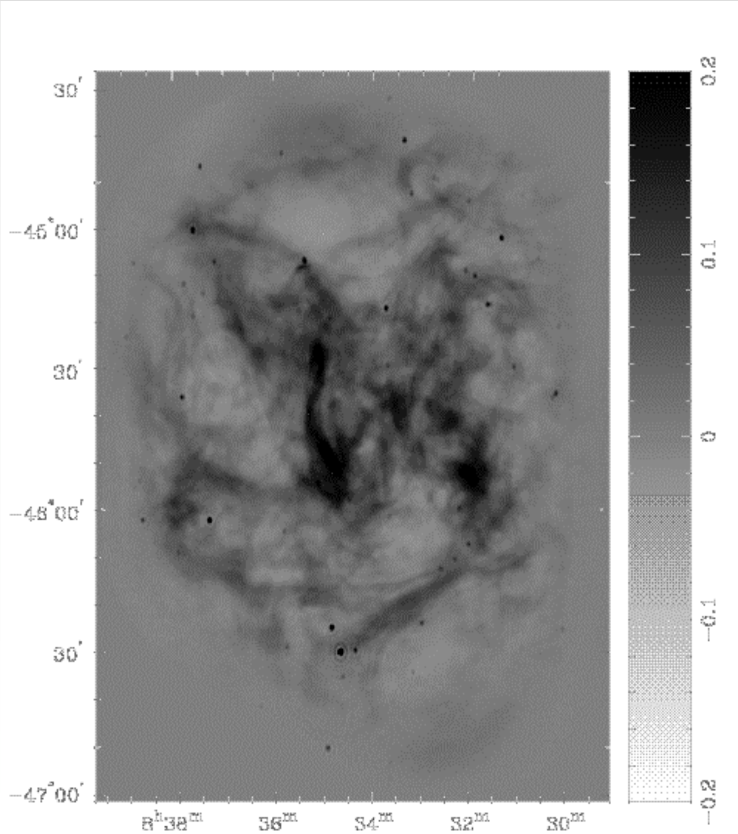
VLBA: Time-lapse imaging



Variations: the Altacama Large Millimeter Array

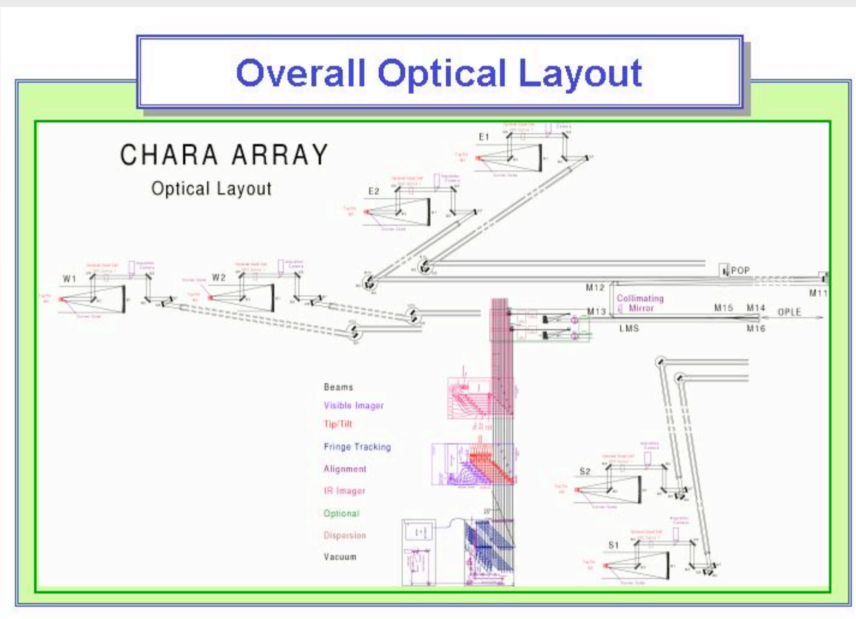
- Observing wavelength short ~ mm
  - Need high, dry site
- Antenna field of view small
  - Must patch together different pointings
  - "Mosaicing"

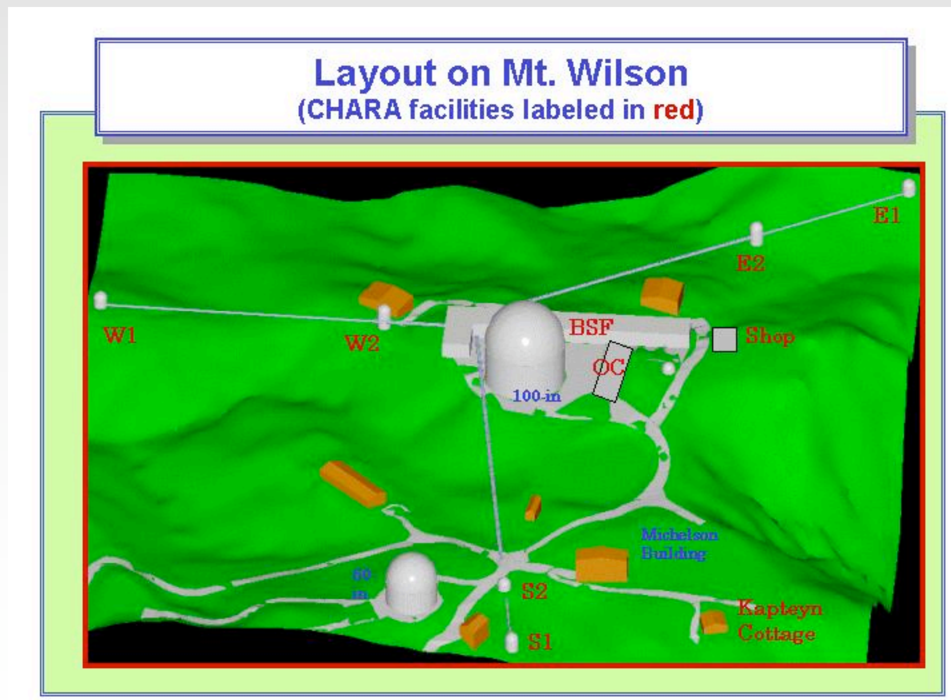




Variations: Optical Interferometry

- Observe at optical or infra-red
- Very difficult technically
  - Tolerances tiny
  - Signals very weak
  - Stars twinkle
- First arrays now coming online





Acknowledgements and references

Acknowledgements:

Based on a talk by Tim Cornwell. I have benefited from discussions with Ron Ekers. Some slides adapted from Peter Napier and Rick Perley.

References:

Interferometry and Synthesis in Radio Astronomy (2nd Edition) by A. R. Thompson, J. M. Moran & G. W. Swenson, Wiley (2001)

Synthesis Imaging in Radio Astronomy II. Eds. G. B. Taylor, C. L. Carilli & R. A. Perley, ASP Conference Series vol. 180 (1999)

Lectures of the 10th Synthesis Imaging Summer School (2006): http://www.aoc.nrao.edu/events/synthesis/2006/lectures/

De cada una.

De cada estrella en el cielo pende

Un hilo de hielo hasta la Tierra…

(de un poema de Alicia Salinas)

From each one.

From each star hangs

an icy thread down to Earth…

(from a poem by Alicia Salinas)