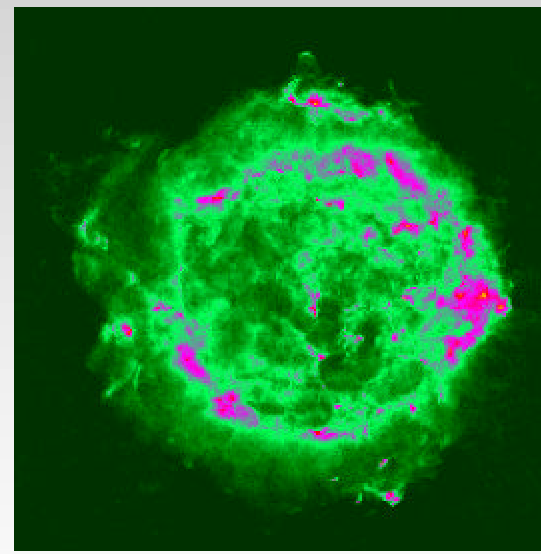
Introduction to Interferometry

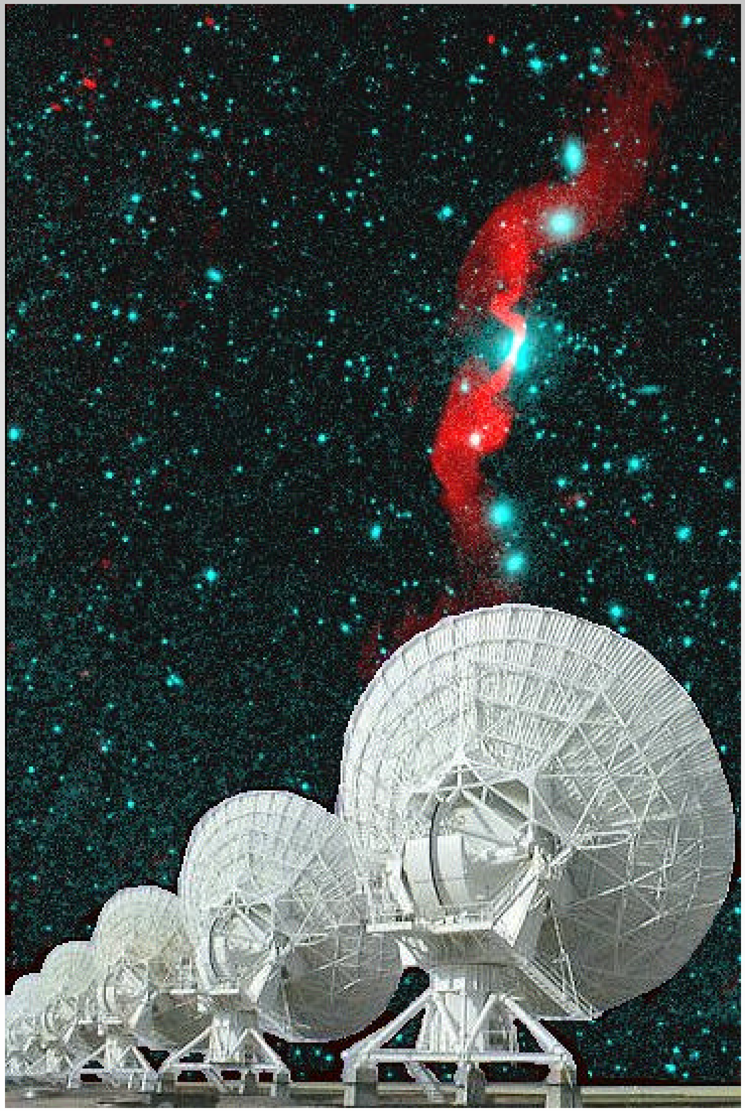


Overview of talk

1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry

Overview

- How do we make images of the radio sky from measurements of the electric field measured by our antennas?



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 arcsec (1/3600 degrees)
- At wavelength 20cm, need Diameter ~ 35km!
- Largest steerable ~ 100m
- Largest fixed ~ 300m

Optics: holes in a mask

- Use smaller antennas to synthesize ~ 35km telescope
- Can fill an area up to ~ 1km

Optics: holes in a mask

- Do not need to fill an area
- VLA D configuration (1km maximum)

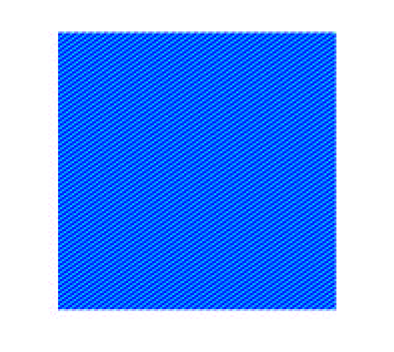
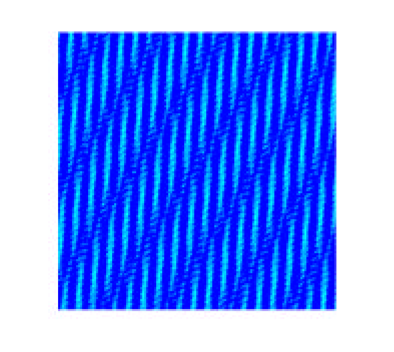
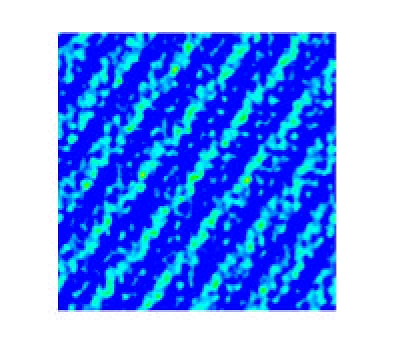
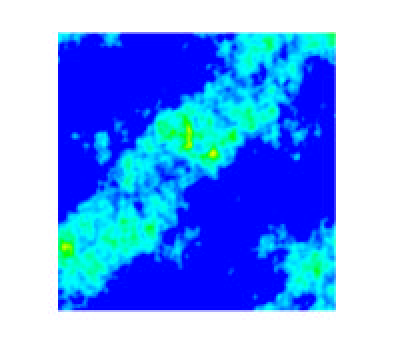
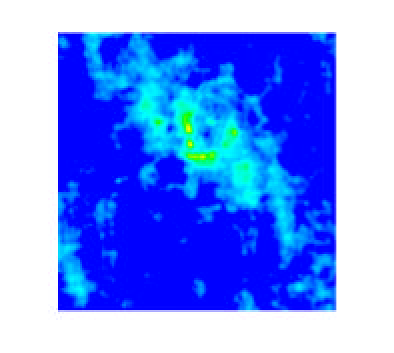
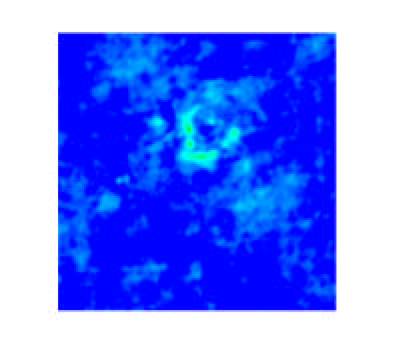
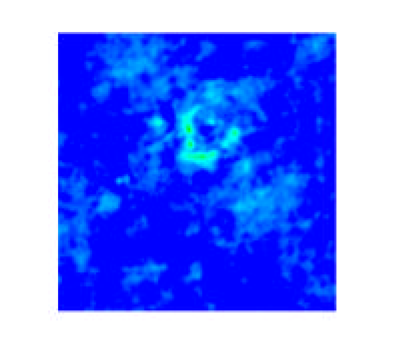
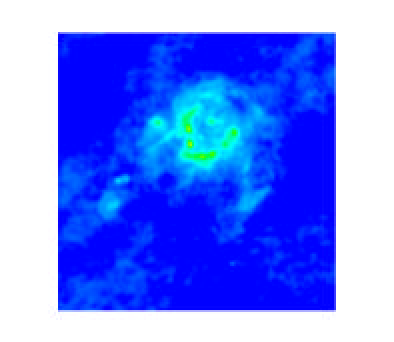
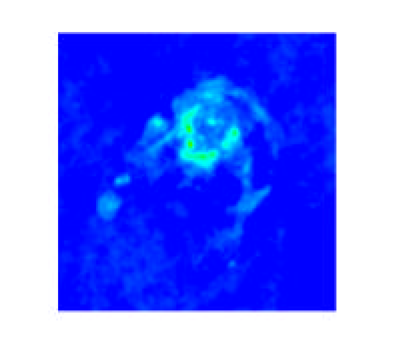
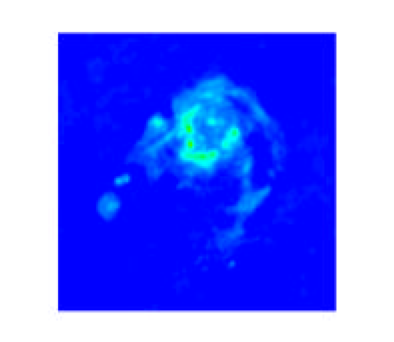
Optics: holes in a mask

- Imagine a lens of *e.g.* a camera
- Can still get an good image even when a mask is placed in front of the len
- How does the image quality change 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 becomes correlated (coherent)
- By measuring correlation in the EM radiation, we can work backwards to determine the properties of the source
- Van Cittert-Zernicke theorem says that
  - *Sky brightness and Coherence function are a Fourier pair*
- Mathematically:

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

Physics: propagation of coherence

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

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

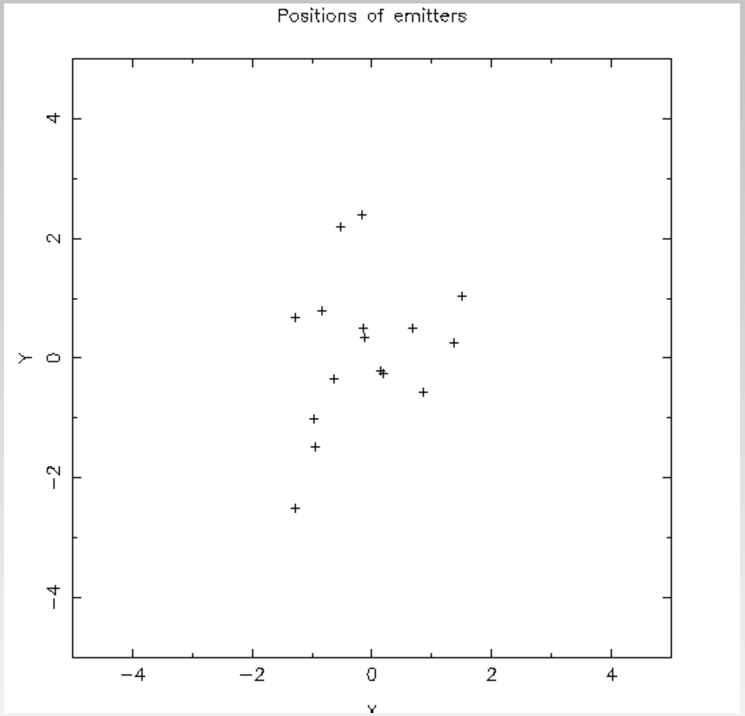
- Correlate voltages from the two receivers

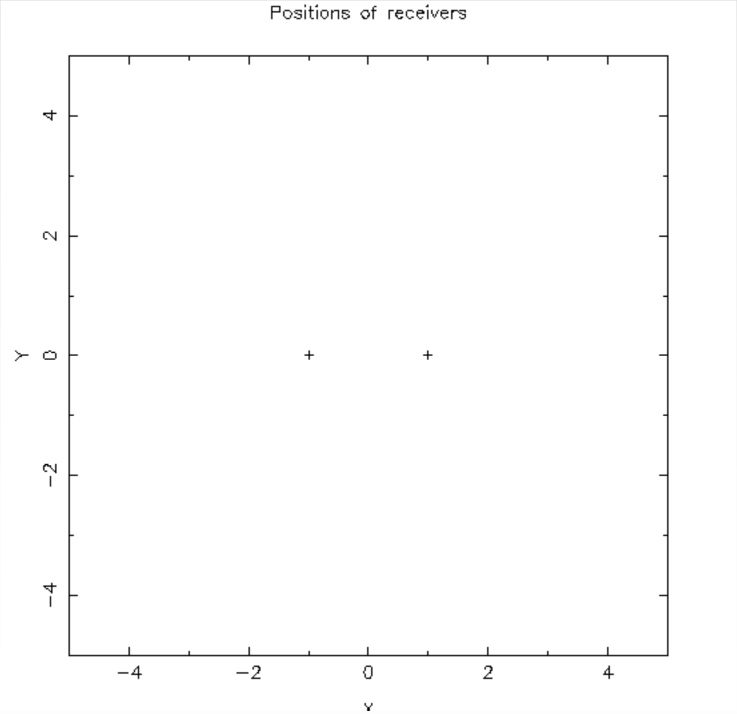
$$\begin{aligned}\langle V_1^r . V_2^r \rangle &= \langle \left(V_a^e . g_1^a + V_b^e . g_1^b\right)\left(V_a^e . g_2^a + V_b^e . g_2^b\right)\rangle \\ &= \langle V_a^e . V_a^e \rangle . g_2^a . g_1^a + \langle V_b^e . V_b^e \rangle . g_2^b . g_1^b \\ &= I_a . g_2^a . g_1^a + I_b . g_2^b . g_1^b\end{aligned}$$

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

Physics: propagation of coherence

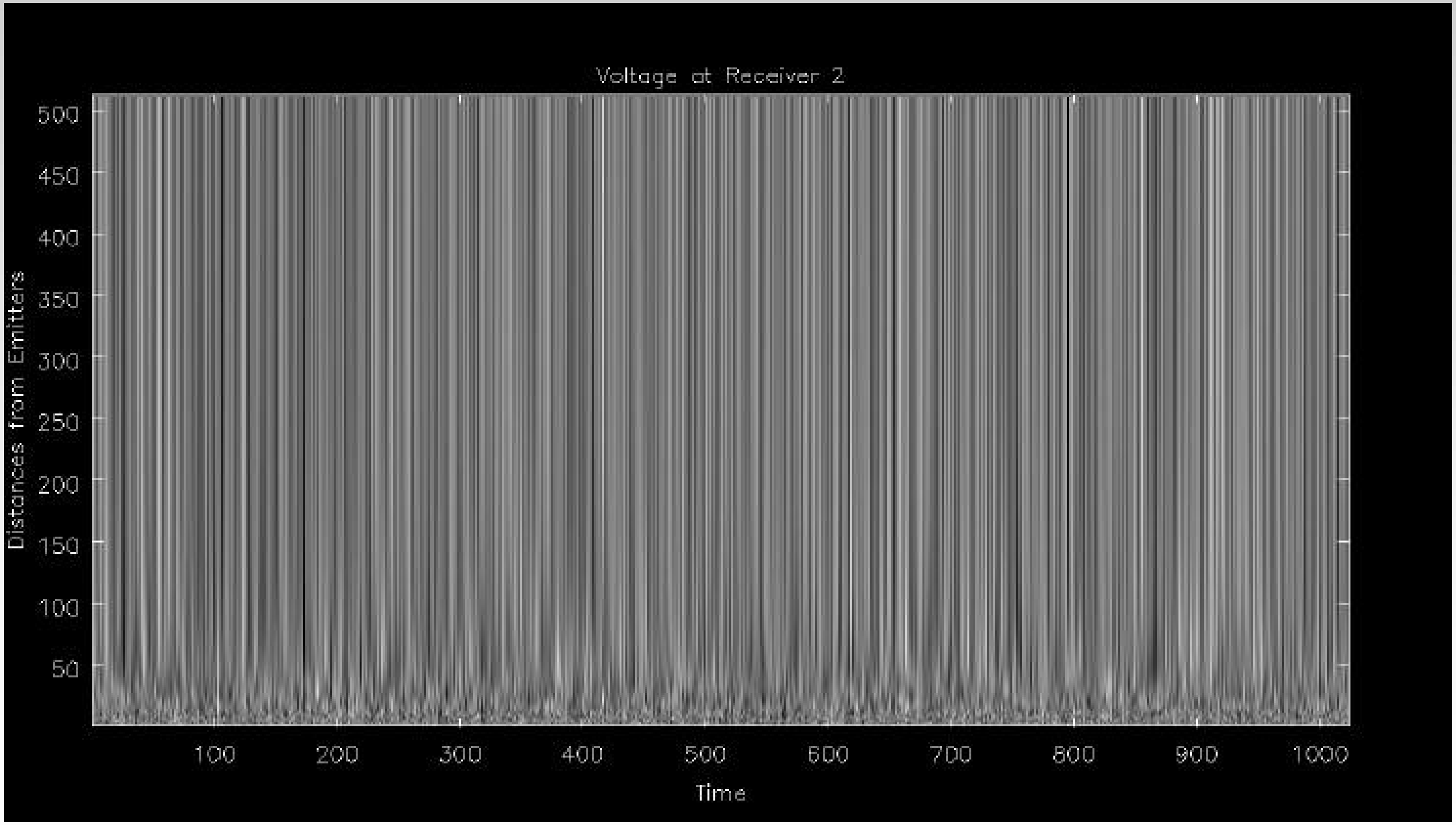
- More complex example
  - Put some emitters in a plane
  - And two receivers in another plane





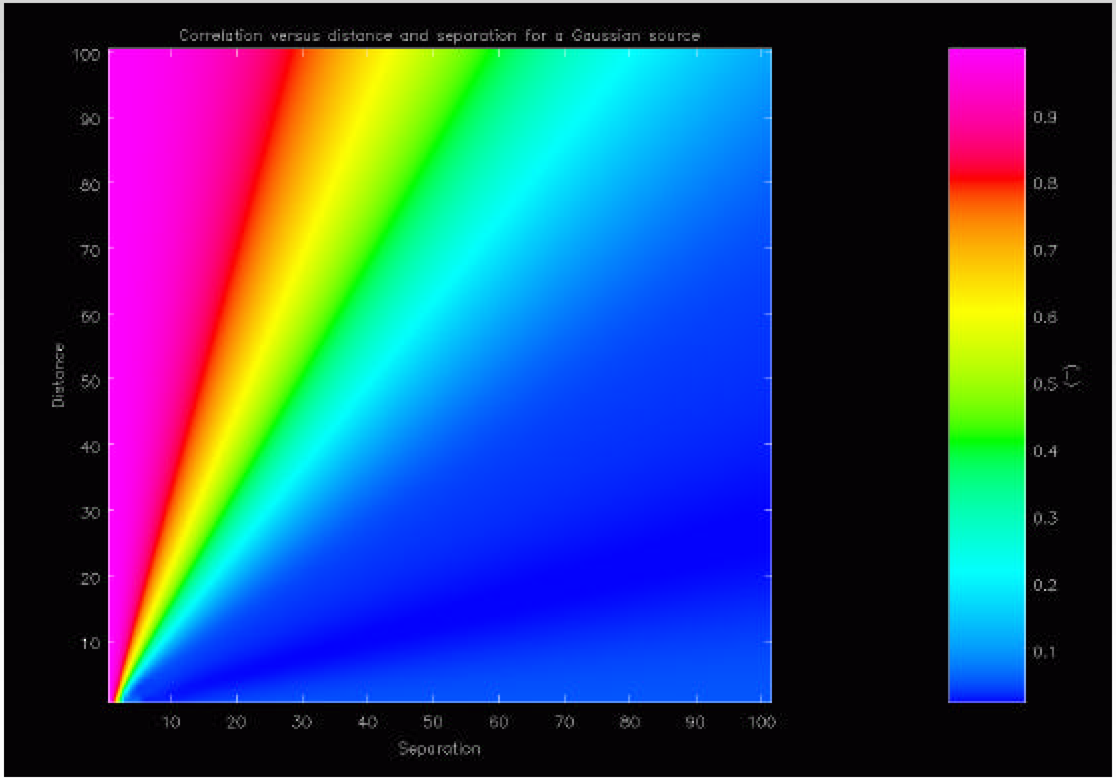
Physics: propagation of coherence

- 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

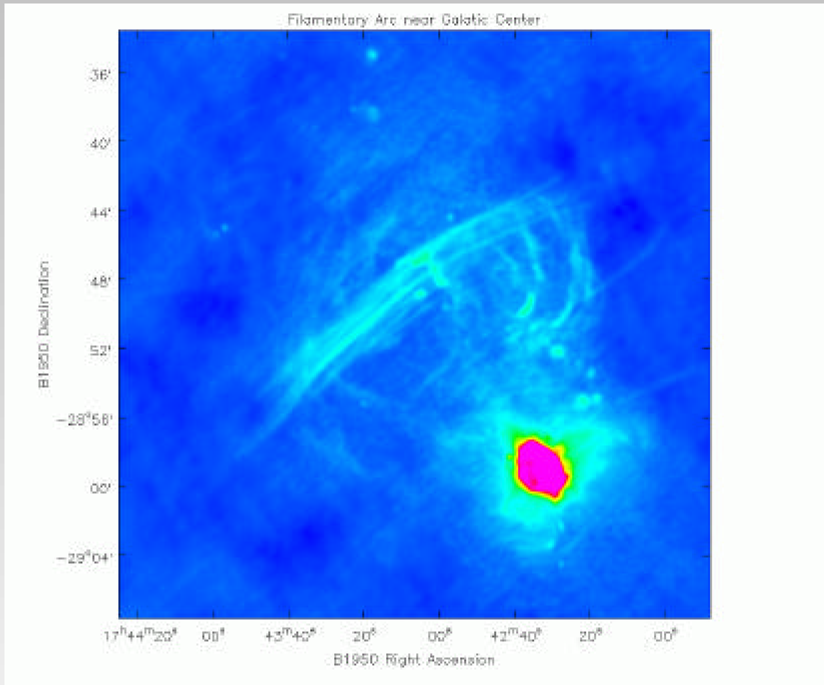


Overview of talk

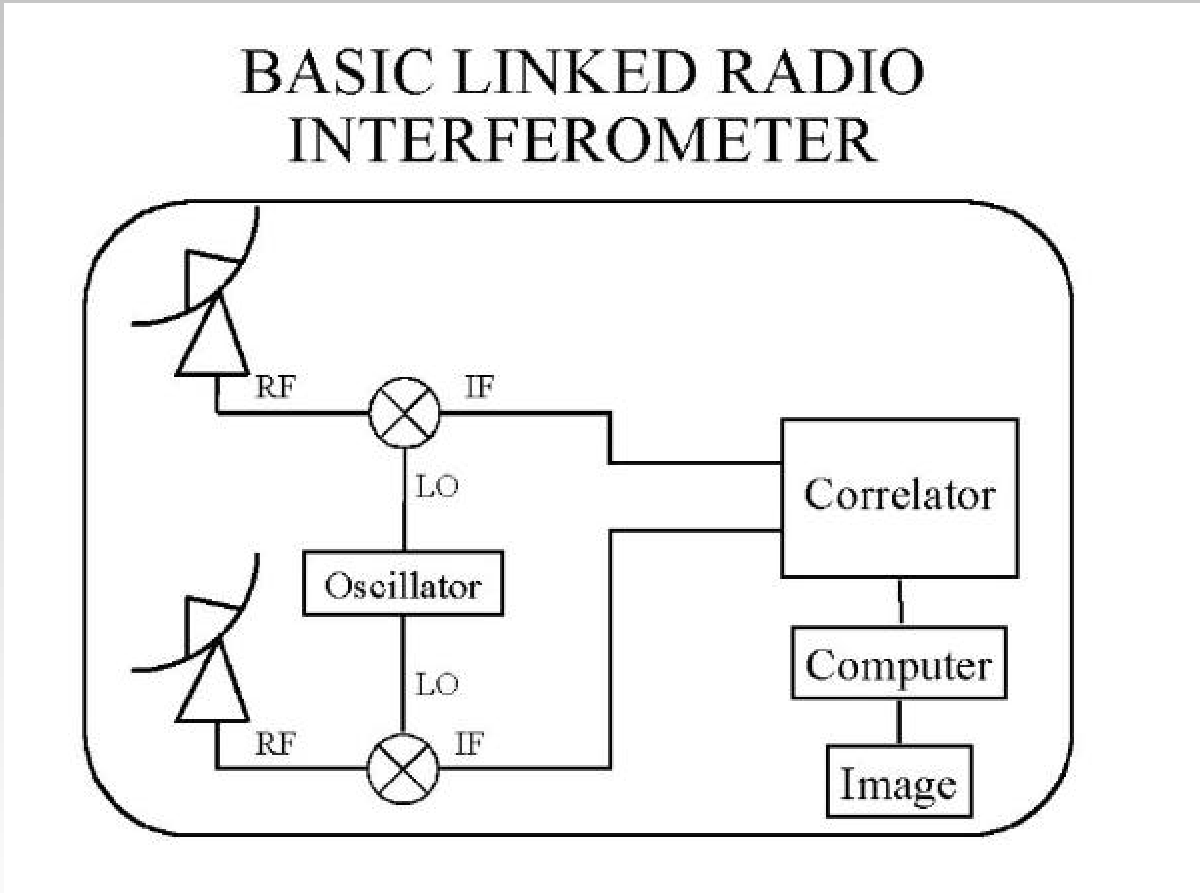
1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry

In practice.......

1. Use many antennas (VLA has 27)
2. Amplify signals
3. Digitize
4. Send to central location
5. Perform cross-correlation
6. Take advantage of earth rotation to fill in “aperture”
7. Inverse Fourier Transform to get an image
8. Correct for limited number of antennas
9. Correct for imperfections in “telescope” e.g. calibration errors
10. Make a beautiful image....

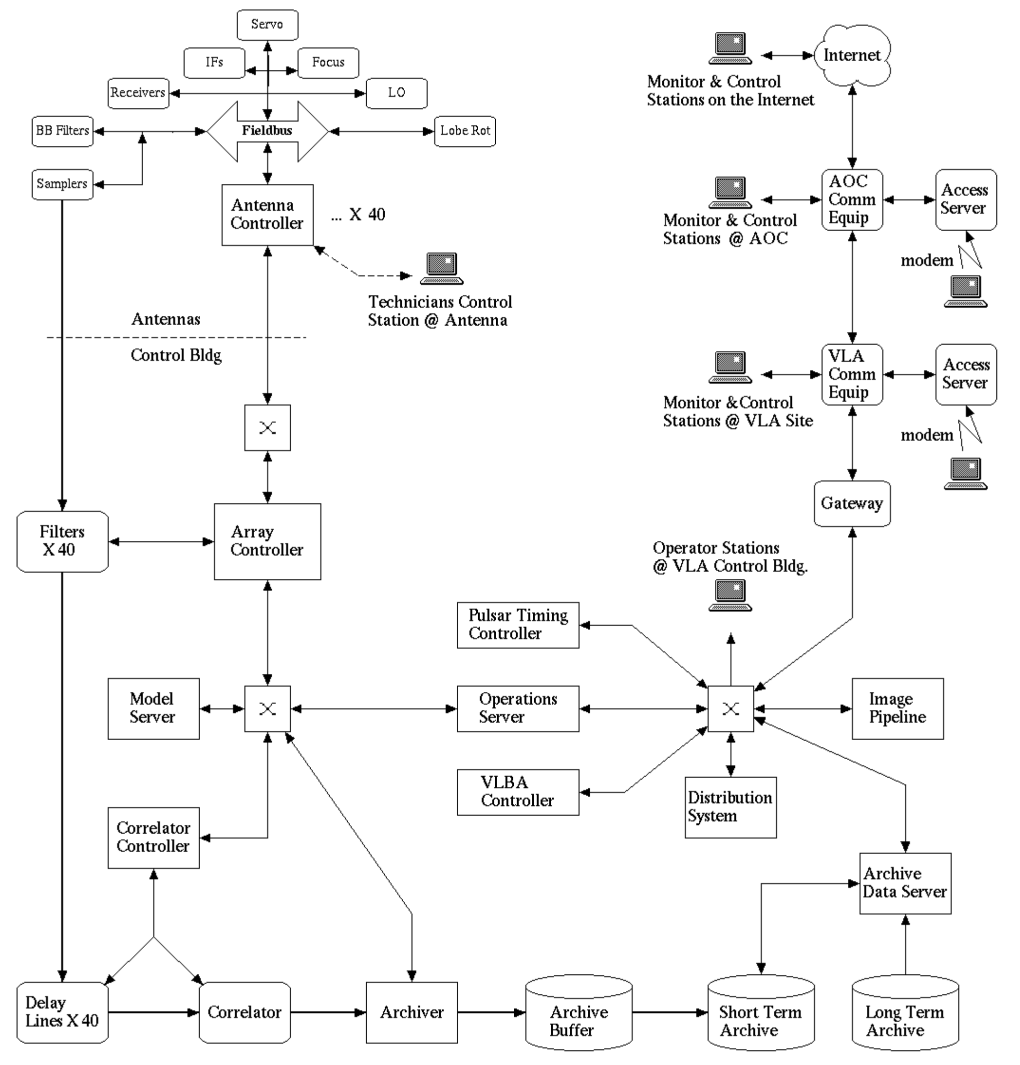


Single interferometer



VLA is much more complex

More information about antennas and electronics in Peter Napier's talk (next)

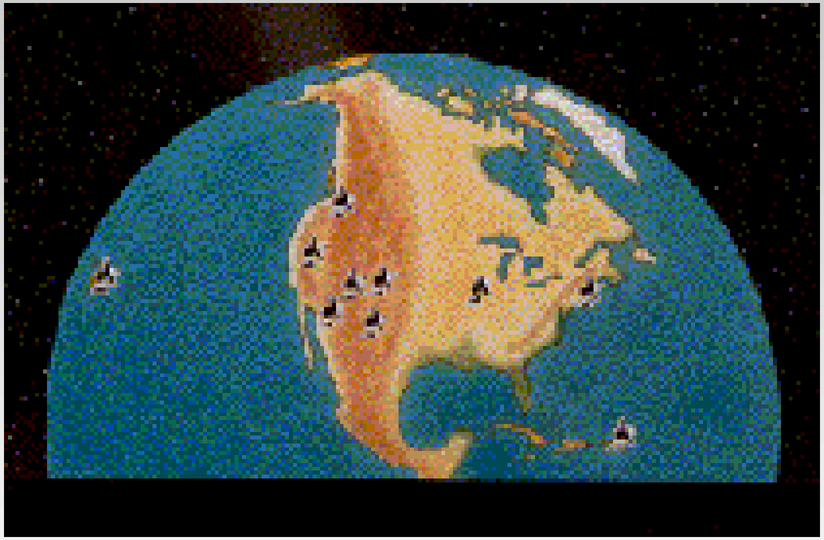


Overview of talk

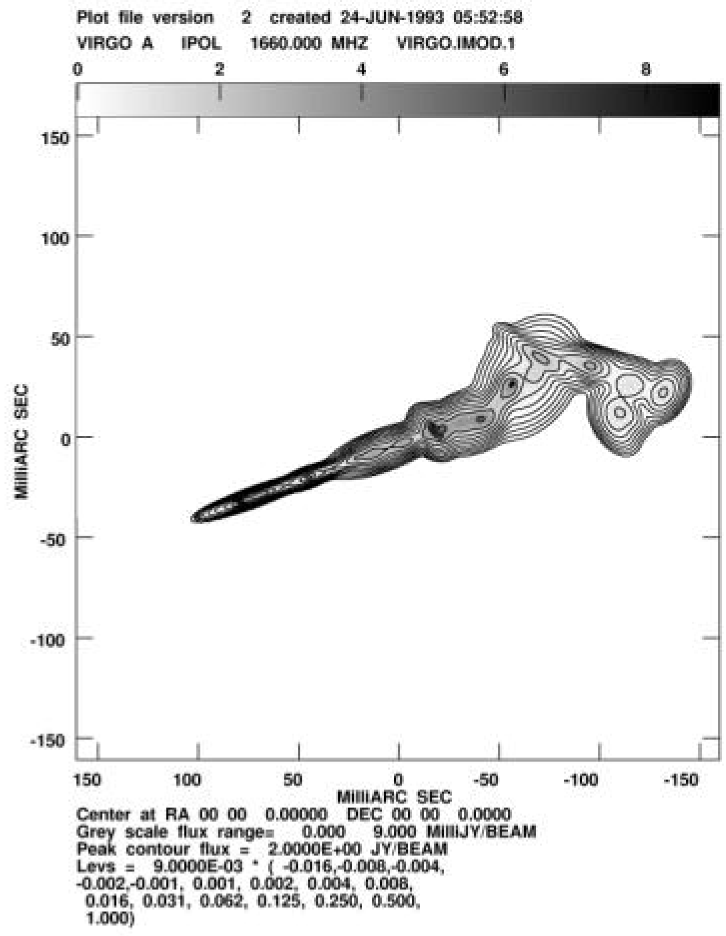
1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry

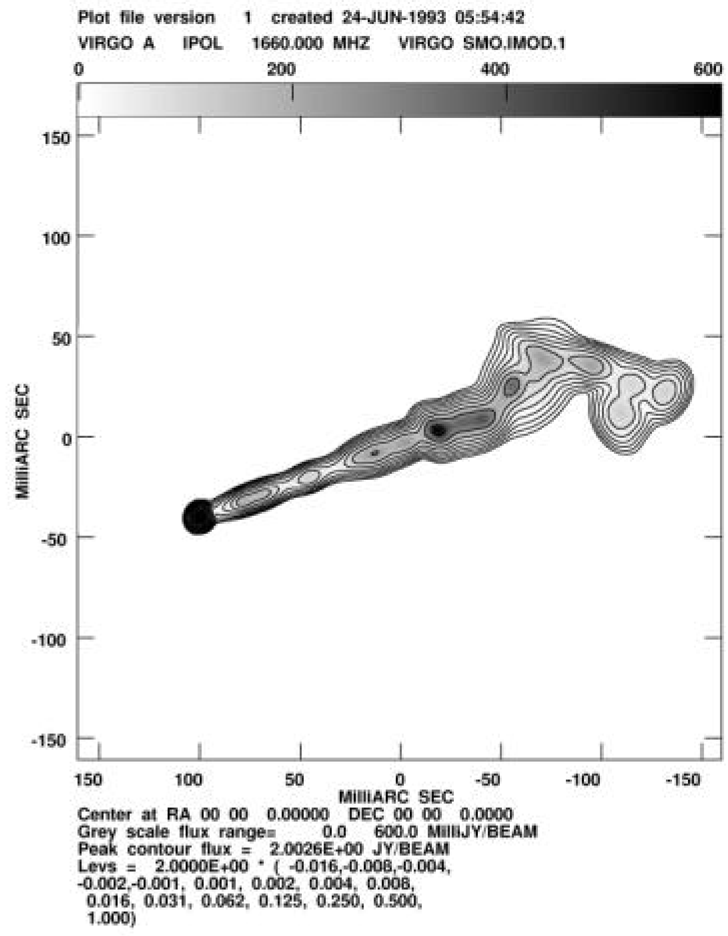
Example of imaging a complex source

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

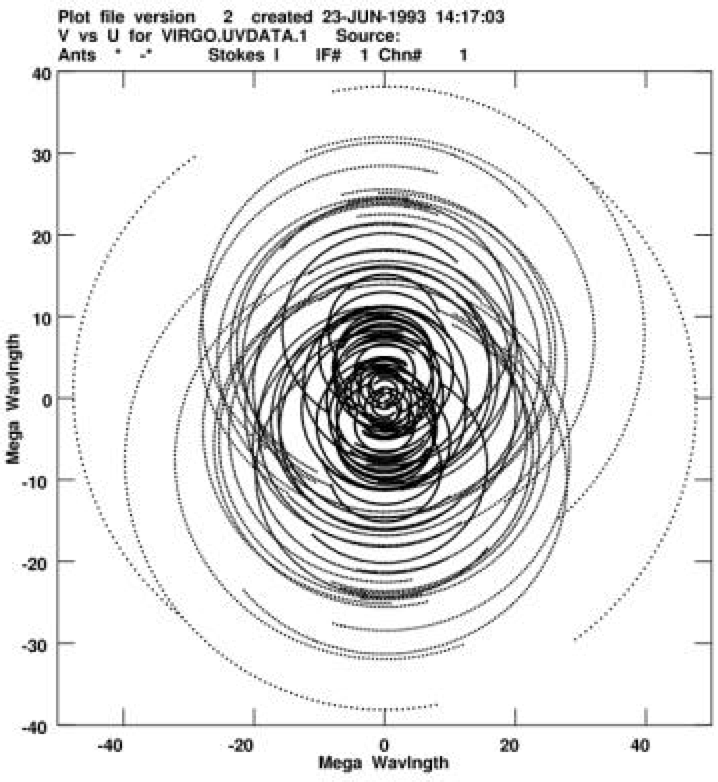


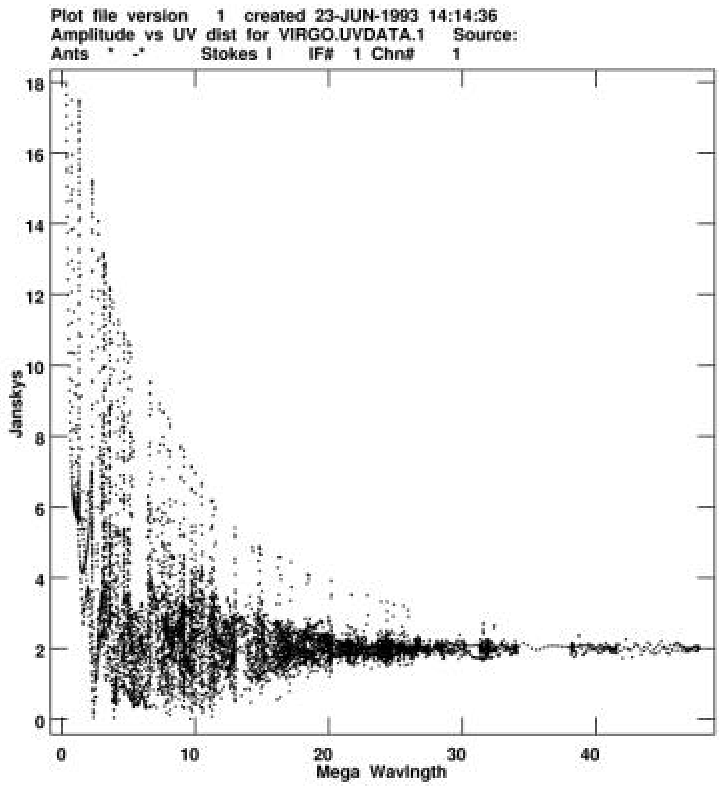
Original and smoothed model



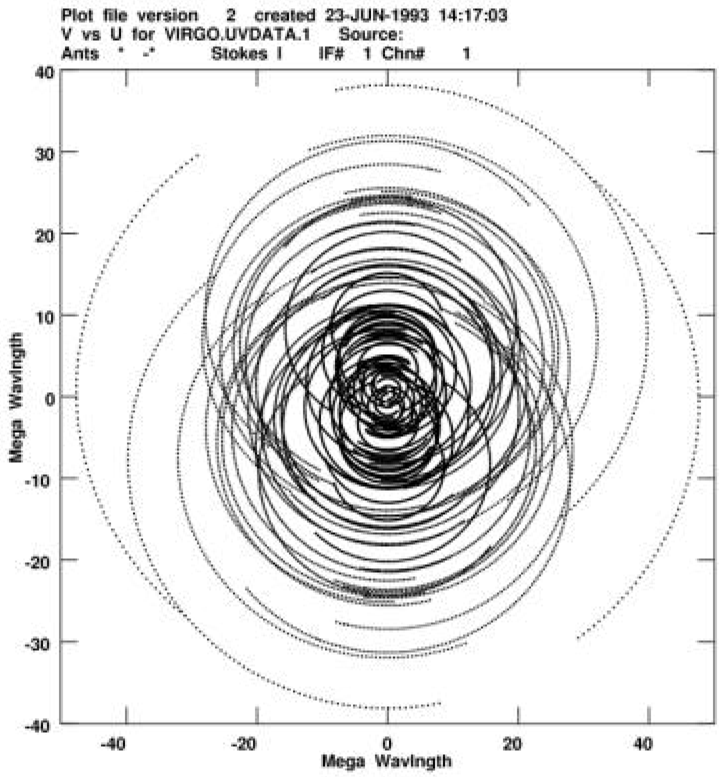


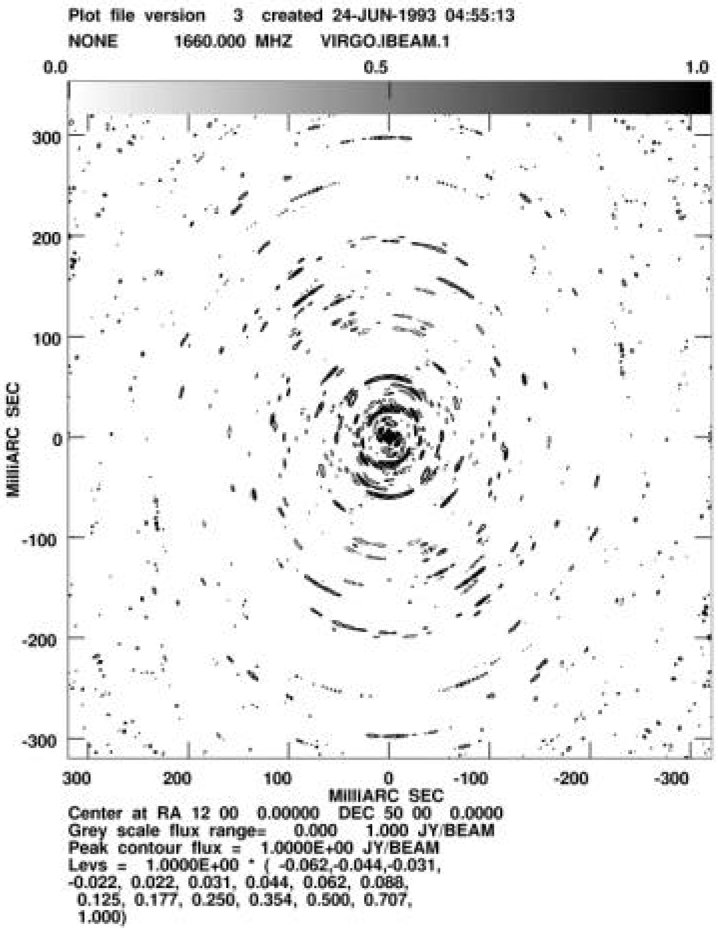
Fourier plane sampling



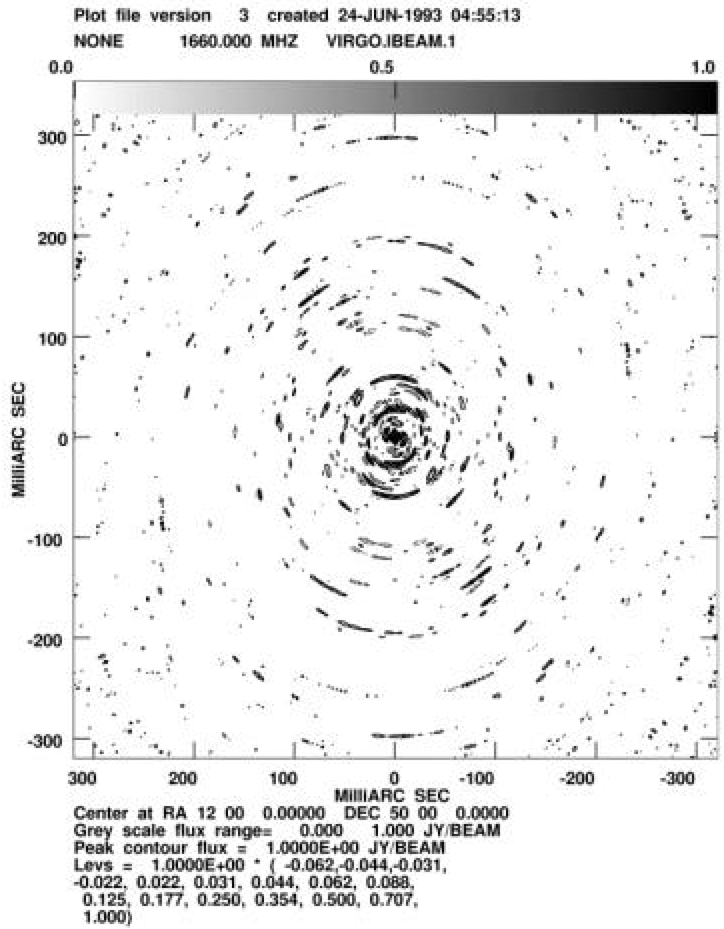


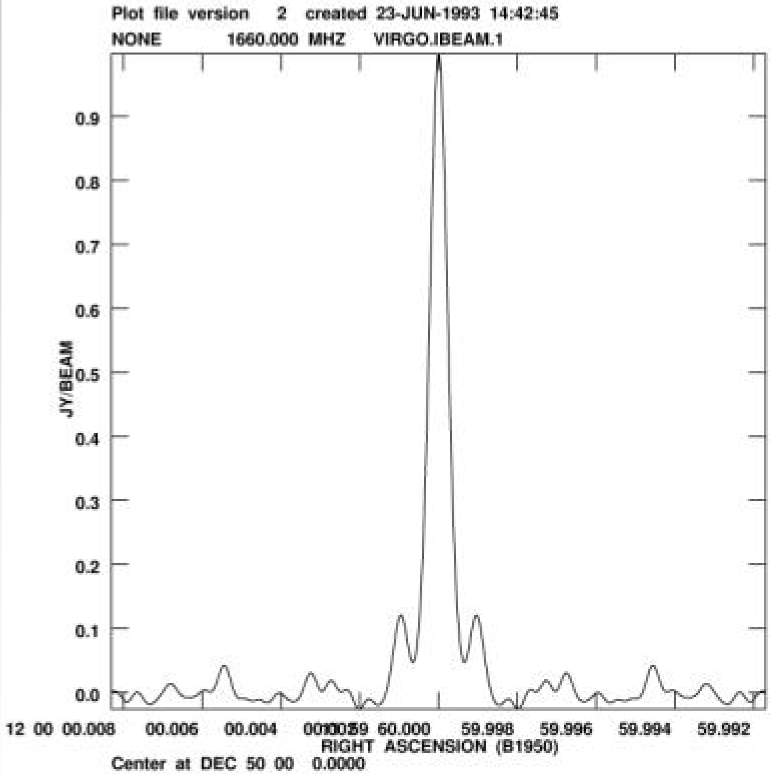
UV Sampling ⇔Point Spread Function



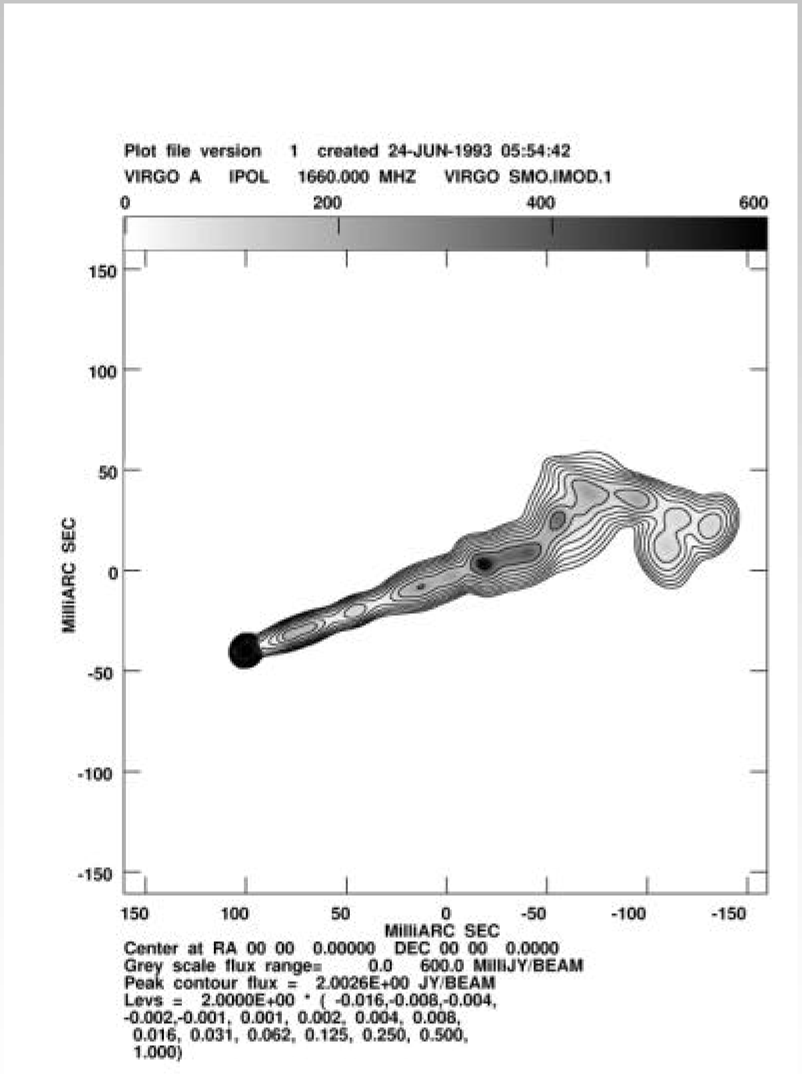


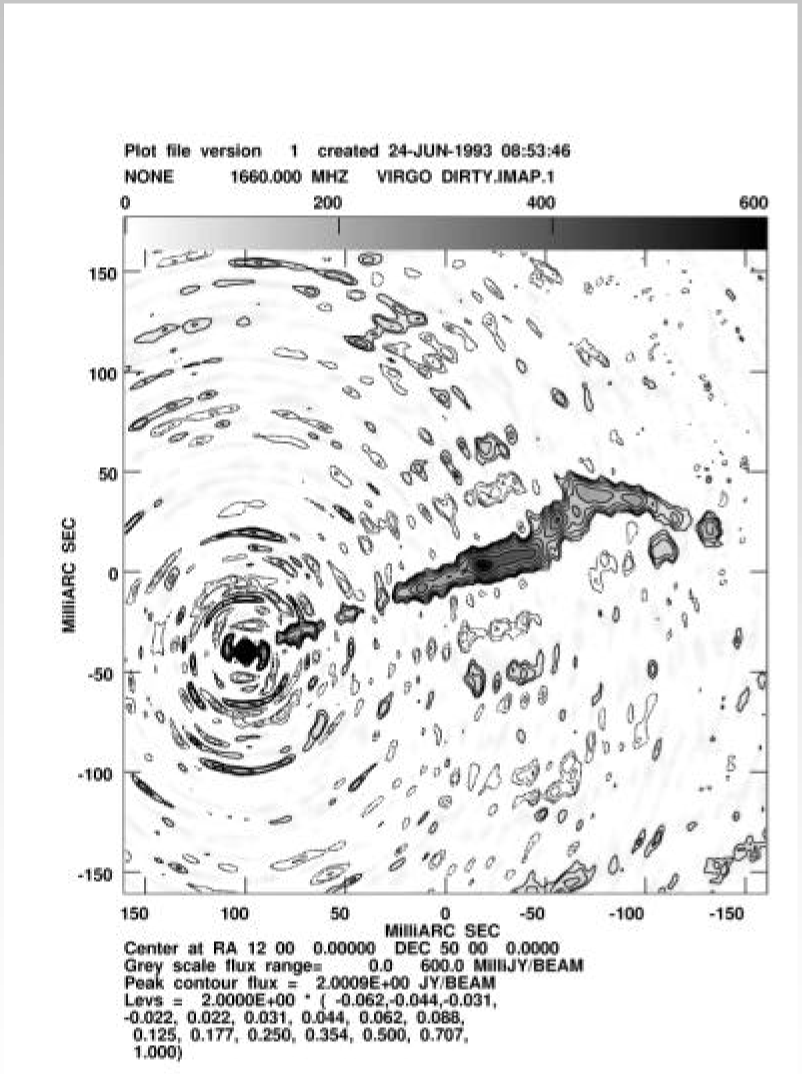
Point Spread Function



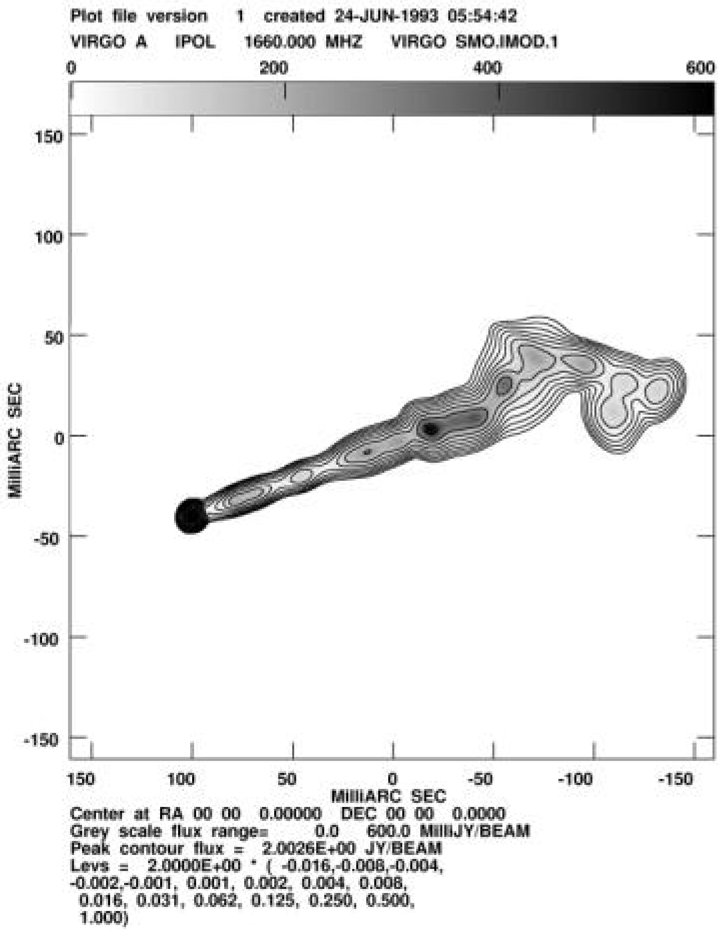


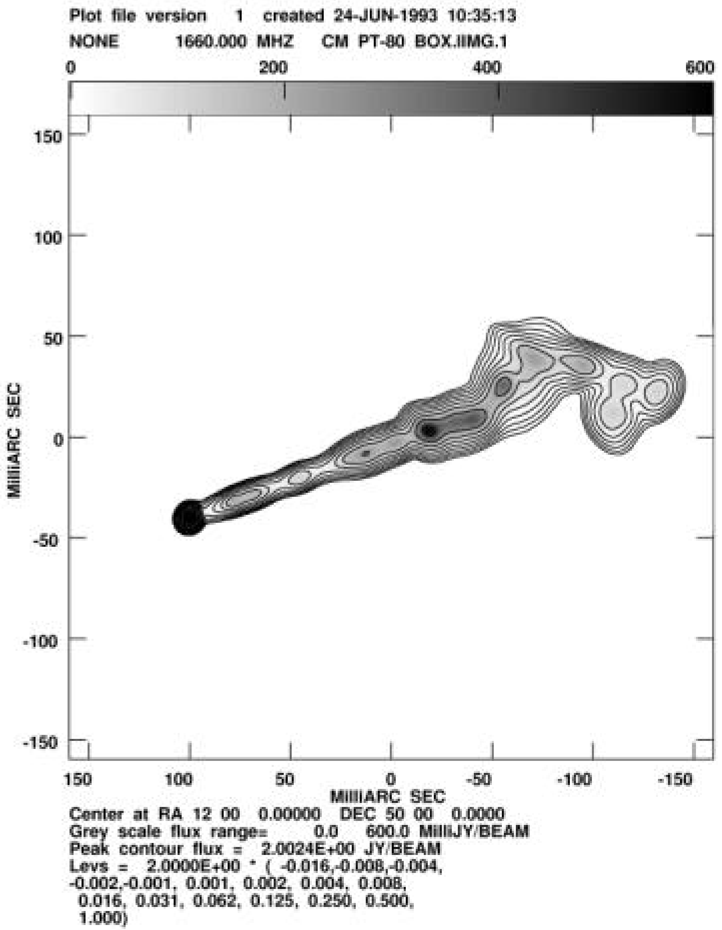
Original model and Dirty image





Original model and best image

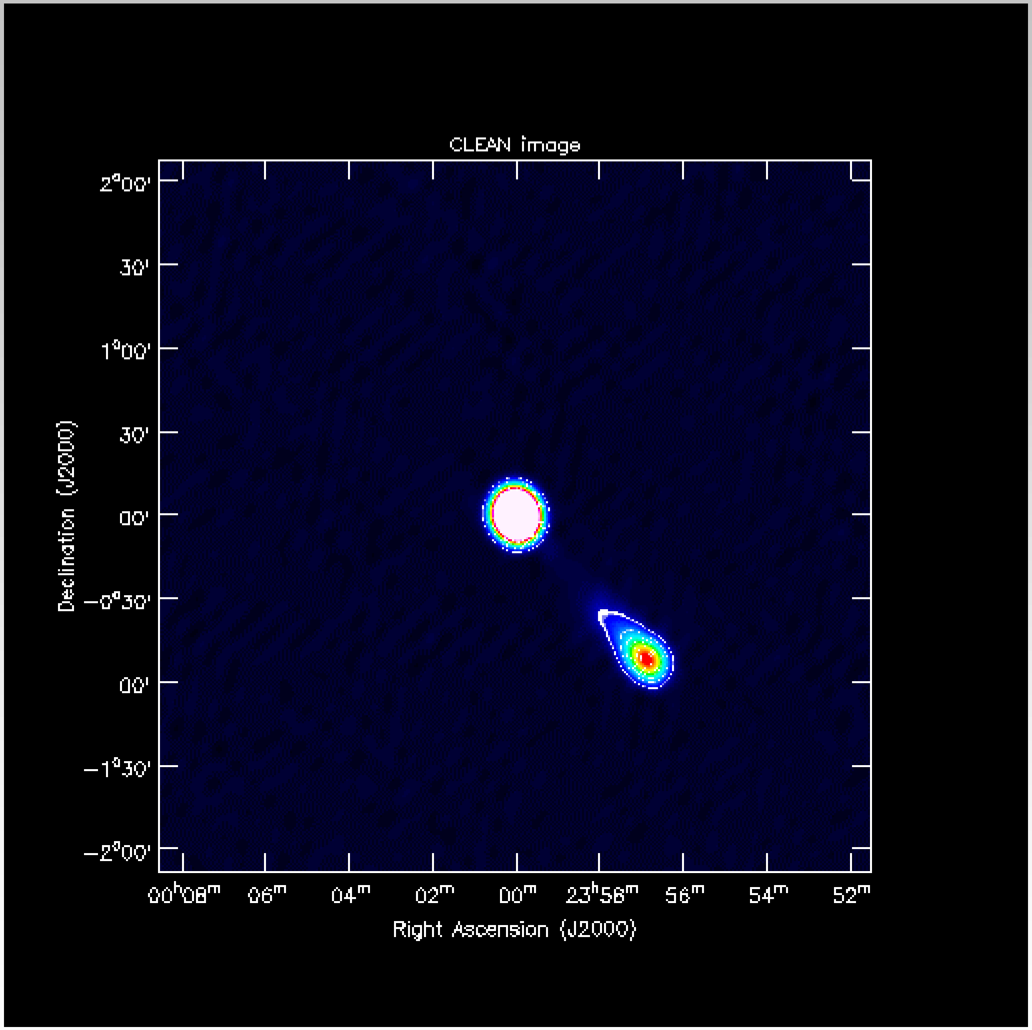




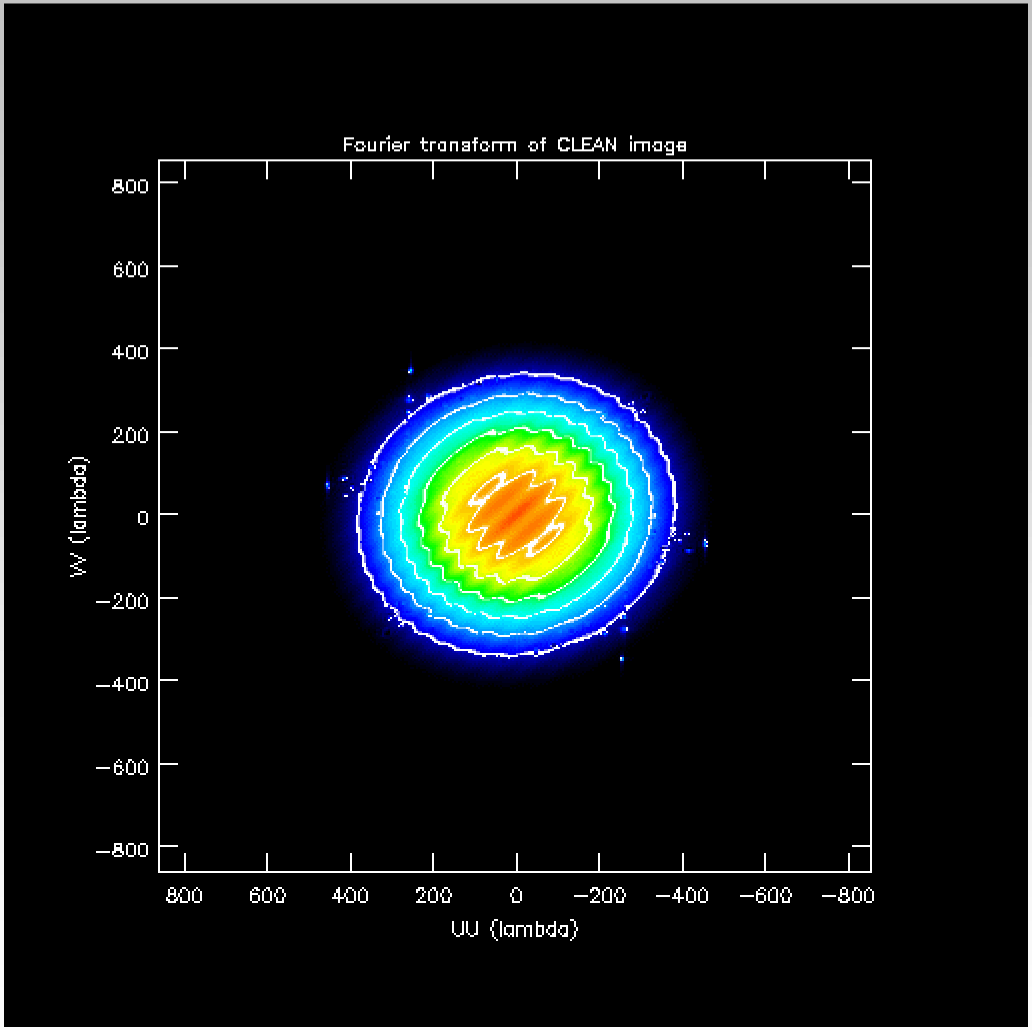
Correcting for limited number of antennas

- Sky is not arbitrarily complex: can exploit this to improve the imaging
  - 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…

Classic CLEAN: 10 iterations, gain=1.0

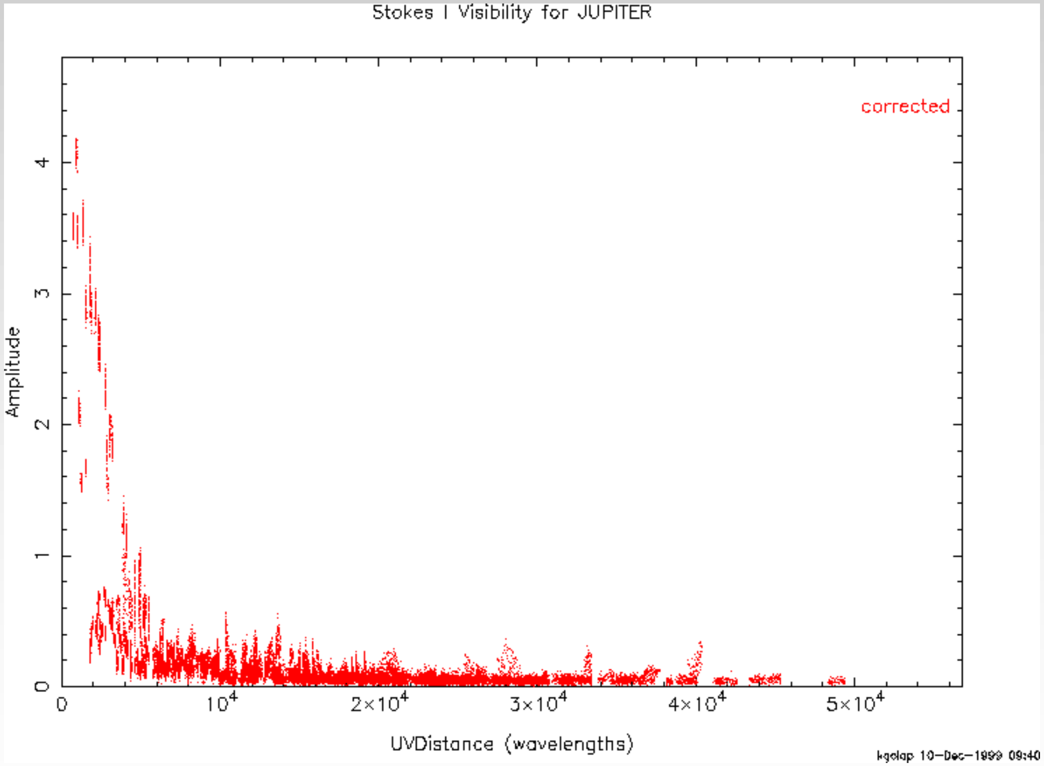


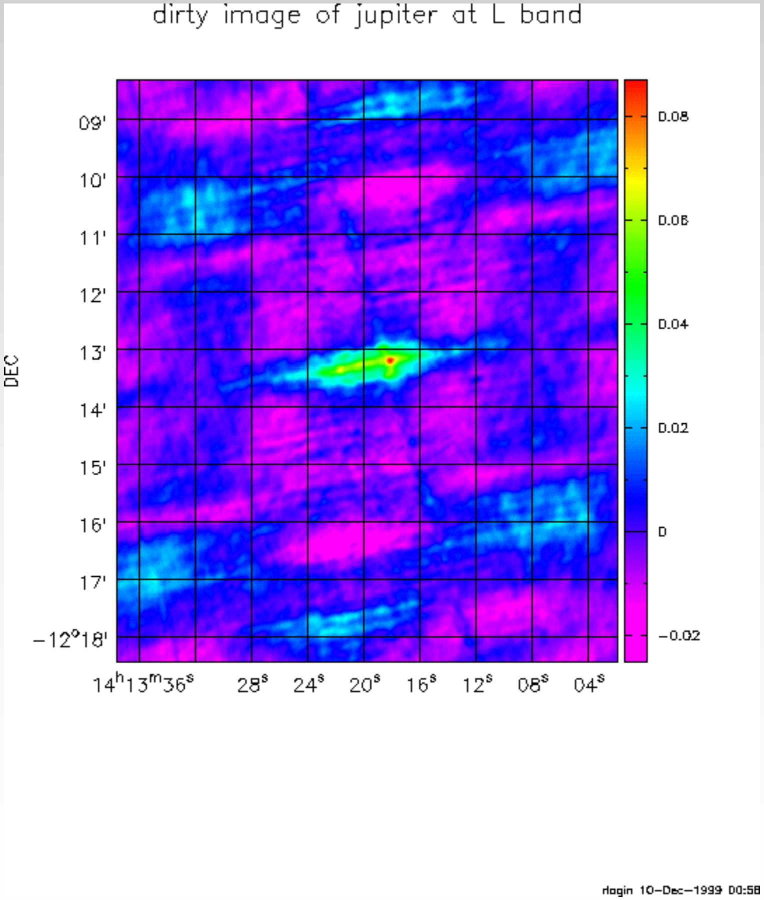
Equivalent aperture of Classic CLEAN



A real example from the VLA

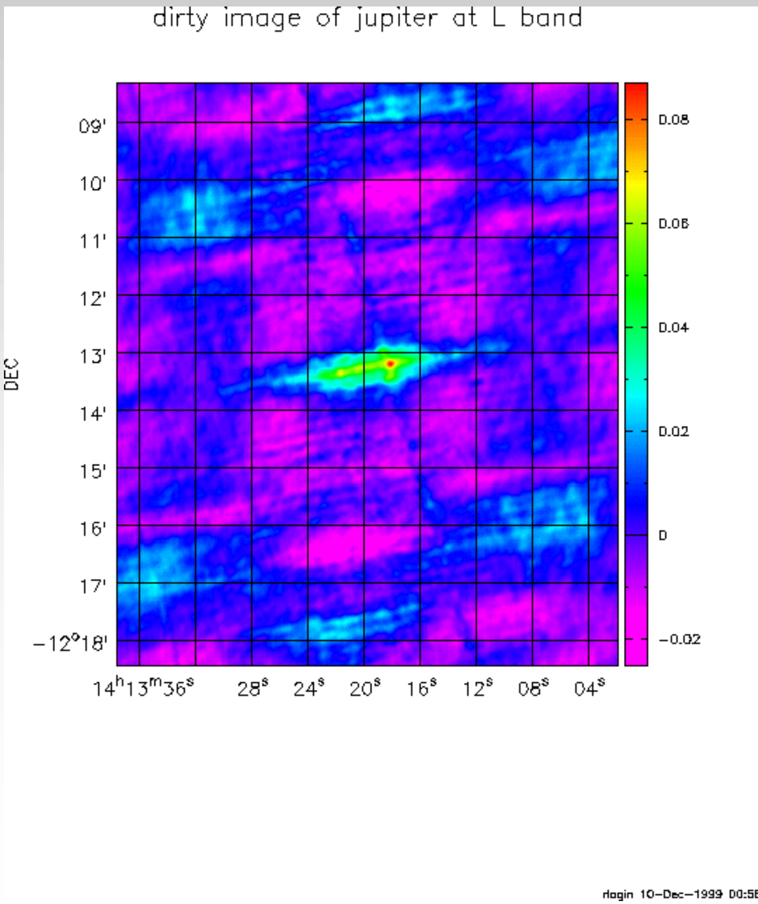
- Sampled correlation function => “Dirty” image

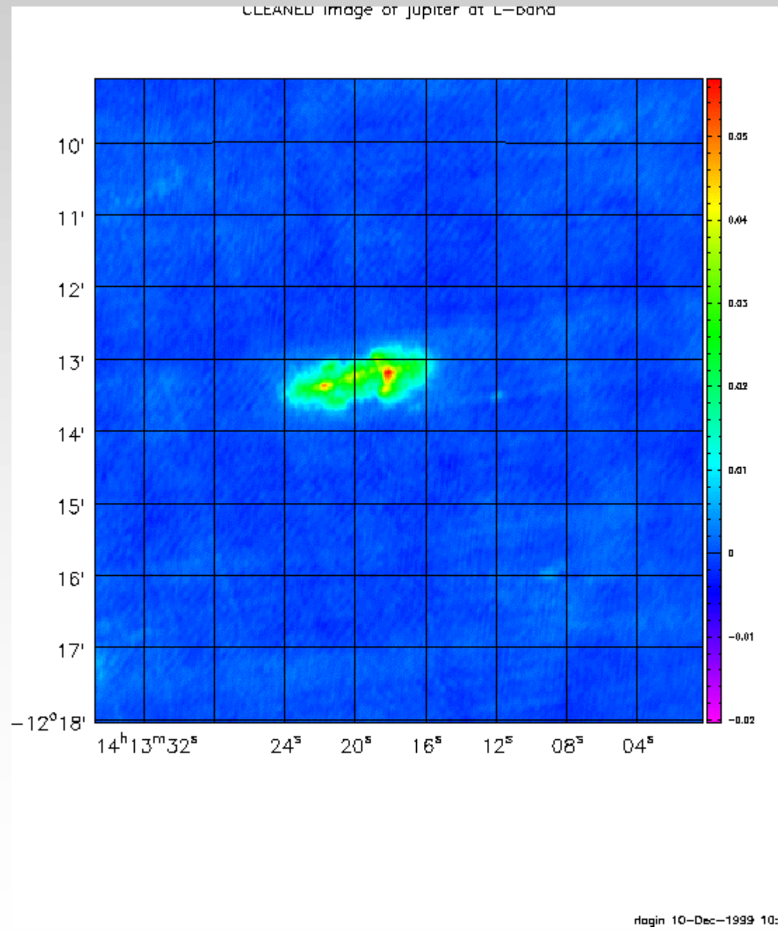




A real example from the VLA

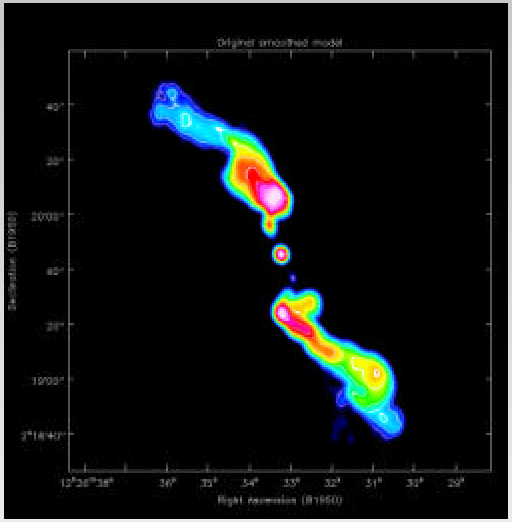
- Effective aperture is filled in and the diffraction patterns vanish



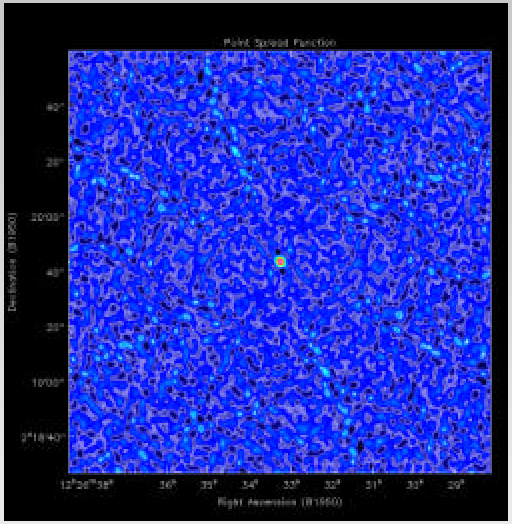


One last synthetic example

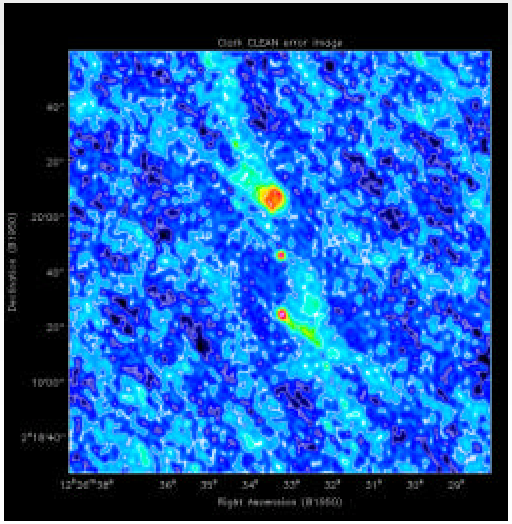
Model



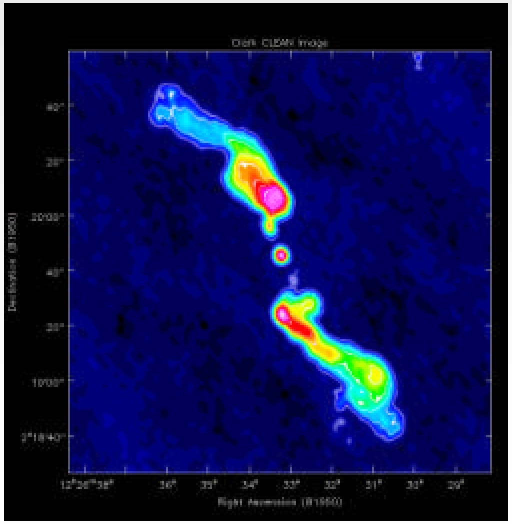
PSF



“Dirty” image



CLEAN image



Overview of talk

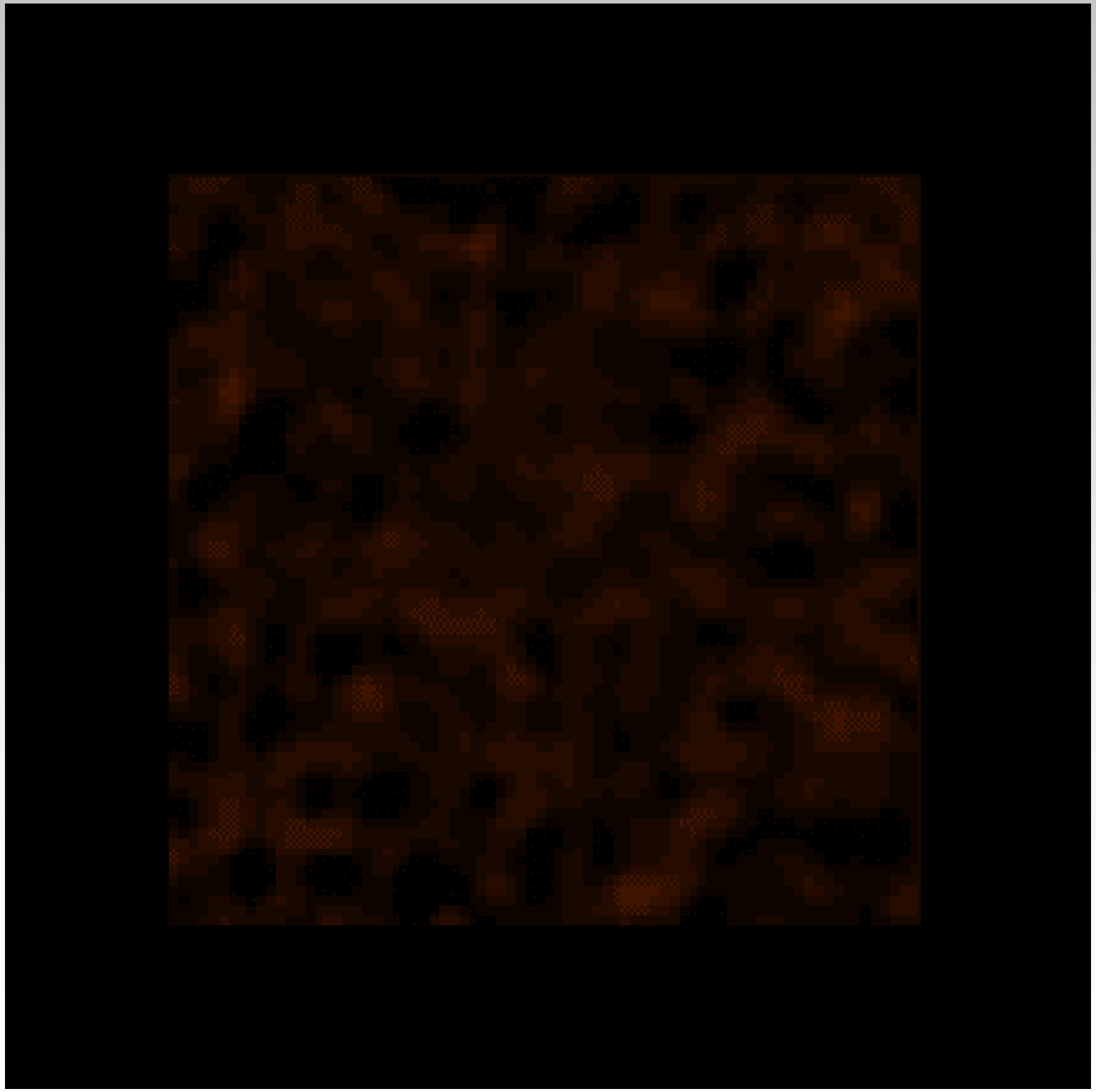
1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry

More things to learn from the radiation

- Polarization of received radiation
  - Measure two radiation states: linear or circular
  - Tells about organization of emitting structures *e.g.* alignment of magnetic fields
- Frequency behavior
  - *Widely spaced* tells about radiation mechanisms
  - *Closely spaced* tells about kinematics via Doppler shift
- More details in following science talks

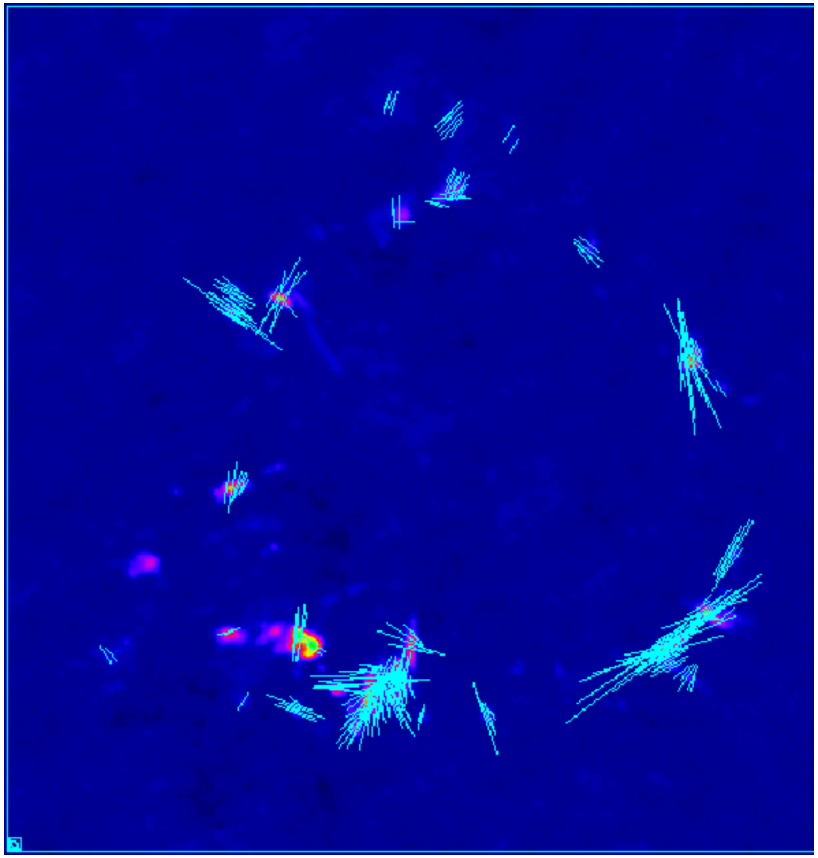
Imaging at different, closely spaced frequencies

- 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



Imaging polarized radiation

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



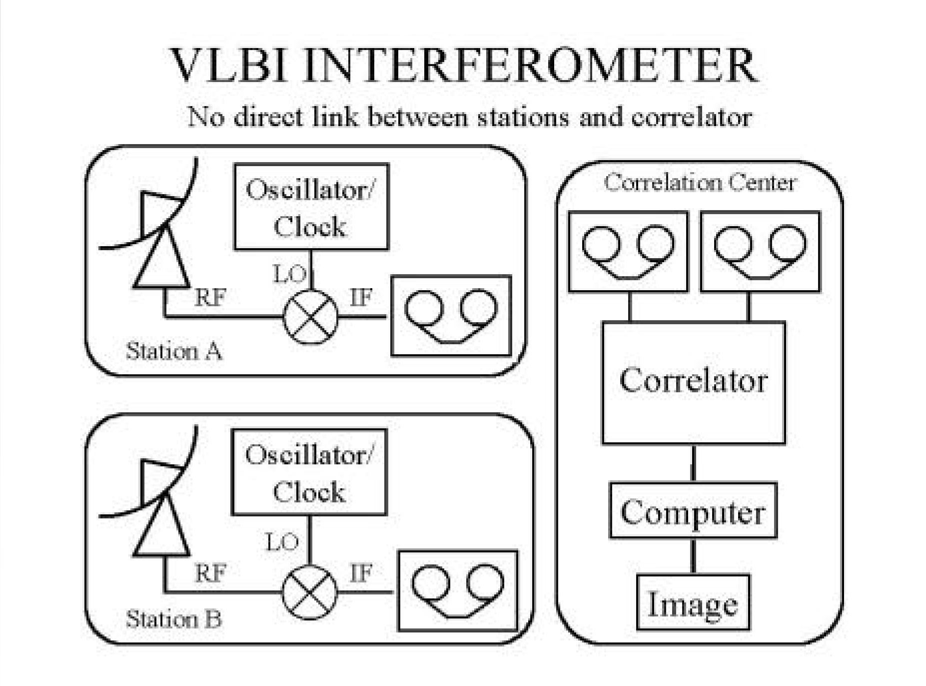
(TX Cam, Mira variable, v=1, J=1-0 SiO maser emission)

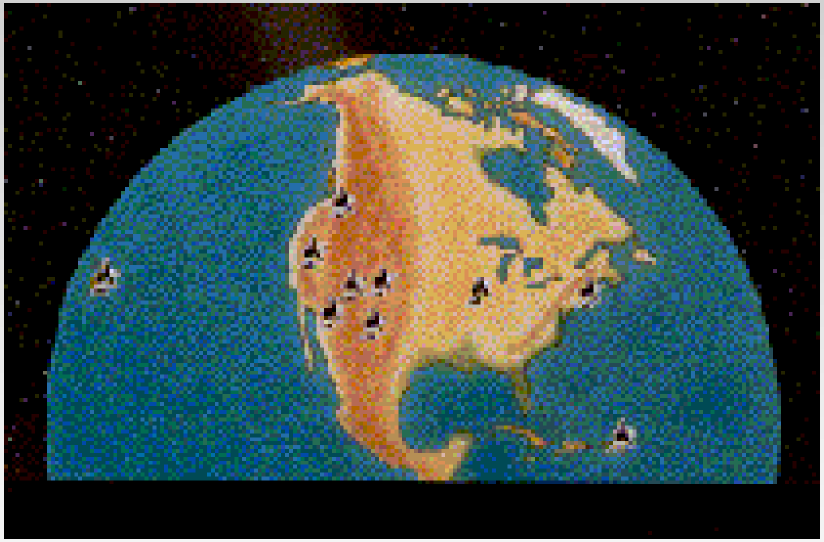
Overview of talk

1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry

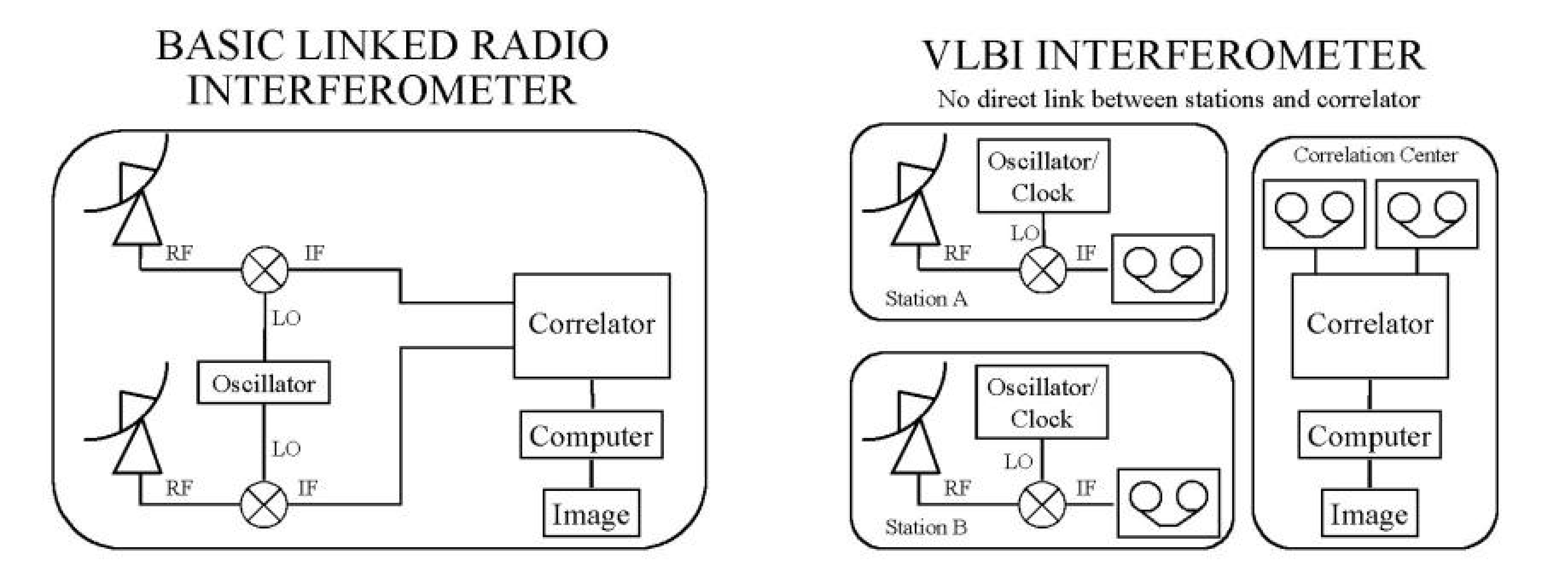
Variations: the Very Long Baseline Array

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



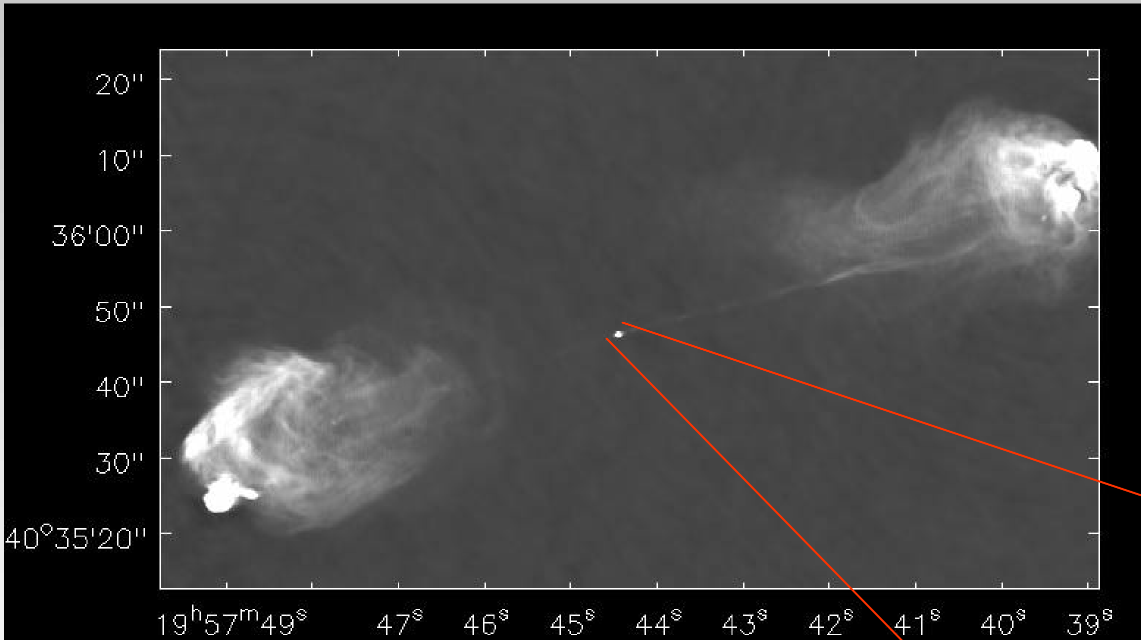


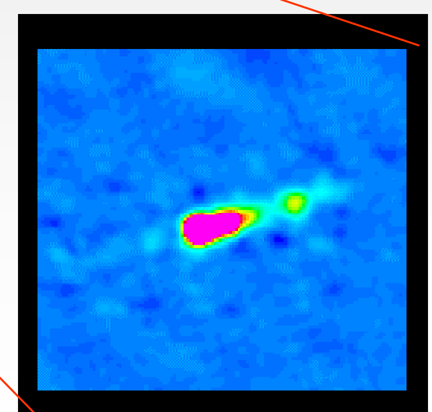
Connected elements versus tape recording



VLA + VLBA

- Zoom lens to reveal inner cores of radio galaxies





VLBA: Time-lapse imaging

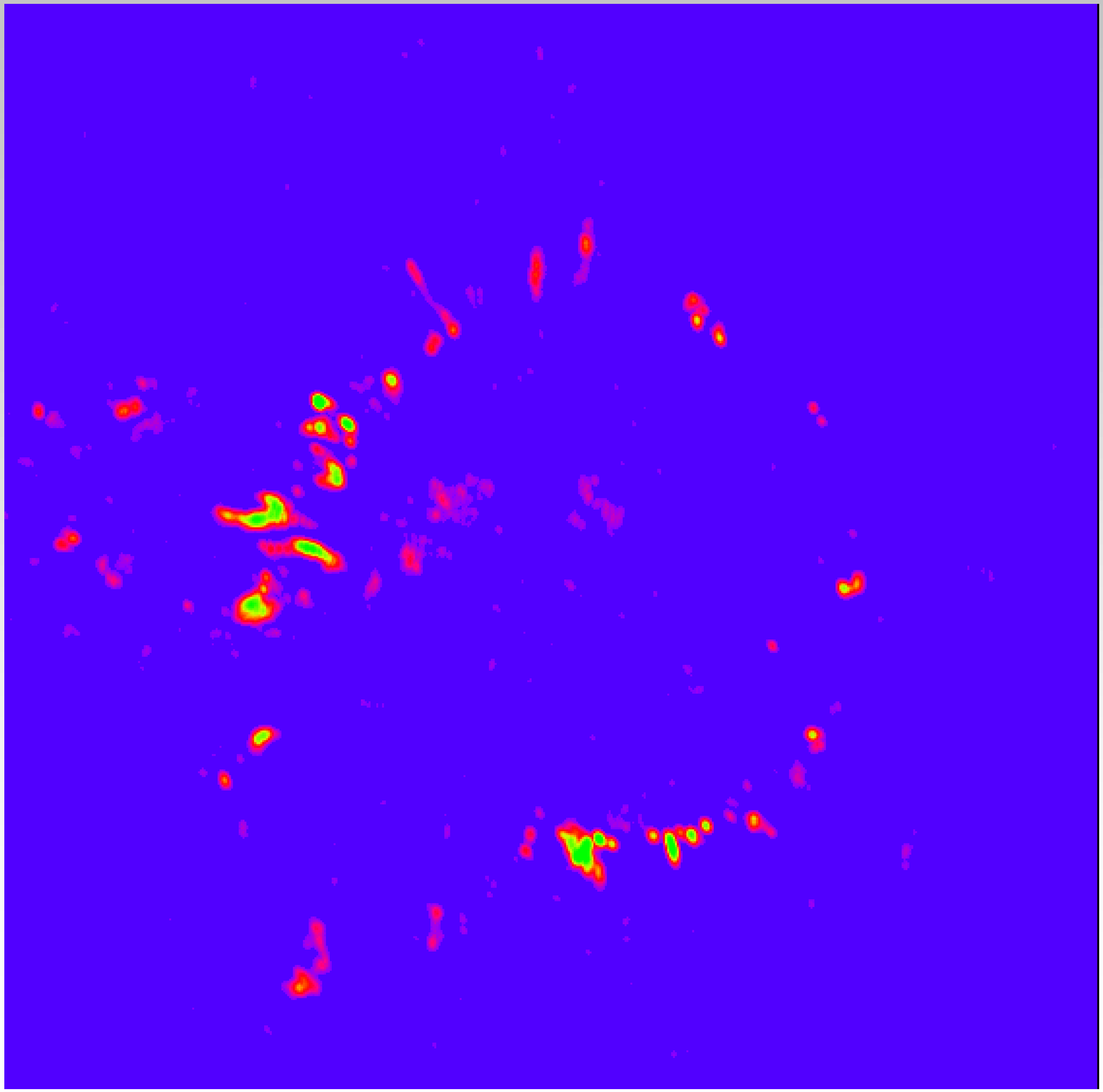
VLBA 22 GHz Observations

of

3C120

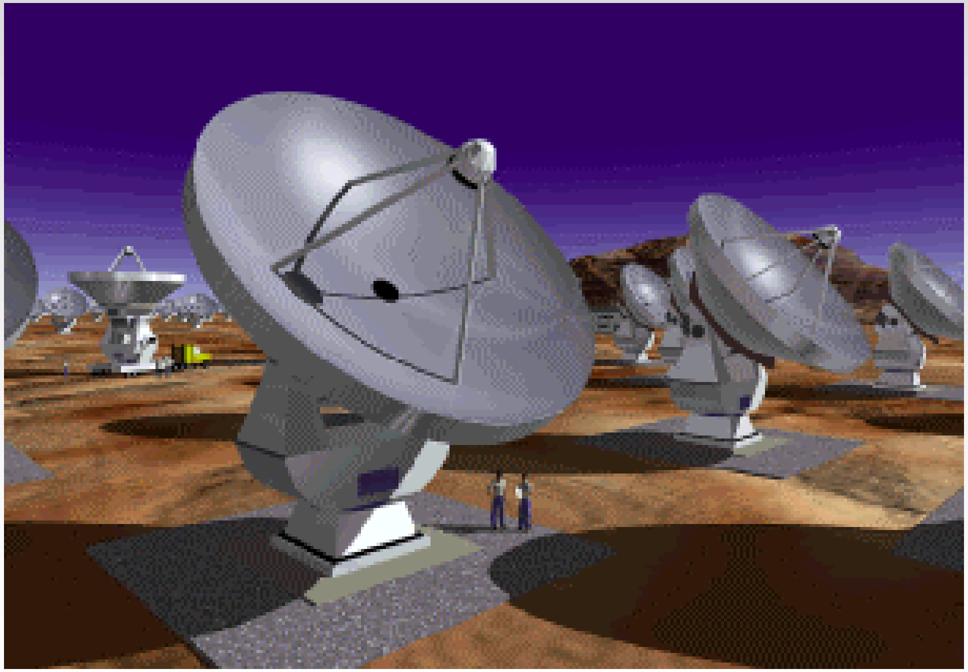
José–Luis Gómez	IAA (Spain)
Alan P. Marscher	BU (USA)
Antonio Alberdi	IAA (Spain)
Svetlana Marchenko–Jorstad	BU (USA)
Cristina García–Miró	IAA (Spain)

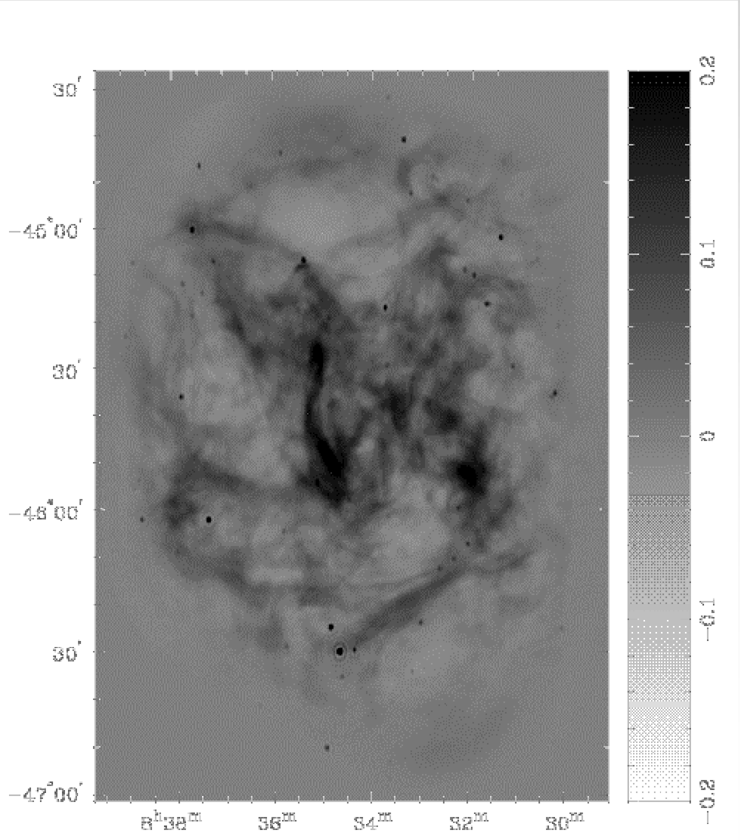
VLBA: Time-lapse imaging



Variations: the Altacama Large Millimeter Array

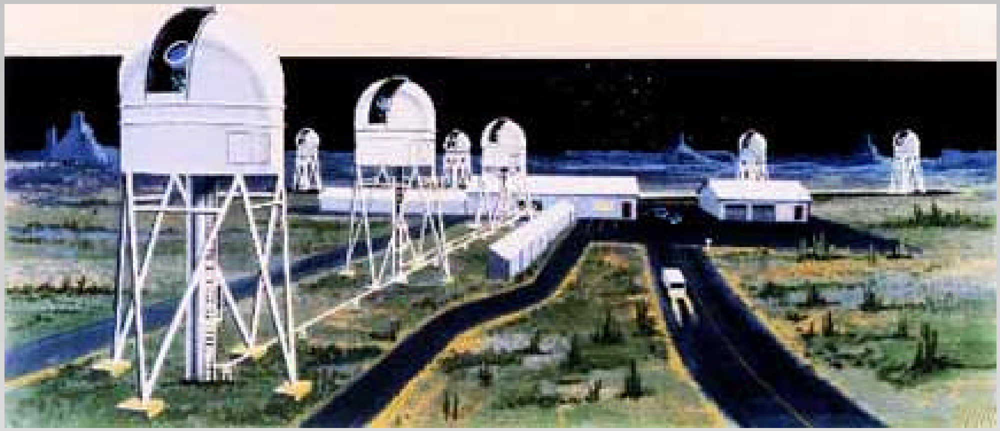
- Observing wavelength short ~ mm
  - Need high, dry site
- Antenna field of view small
  - Must patch together different pointings
  - “Mosaicing”

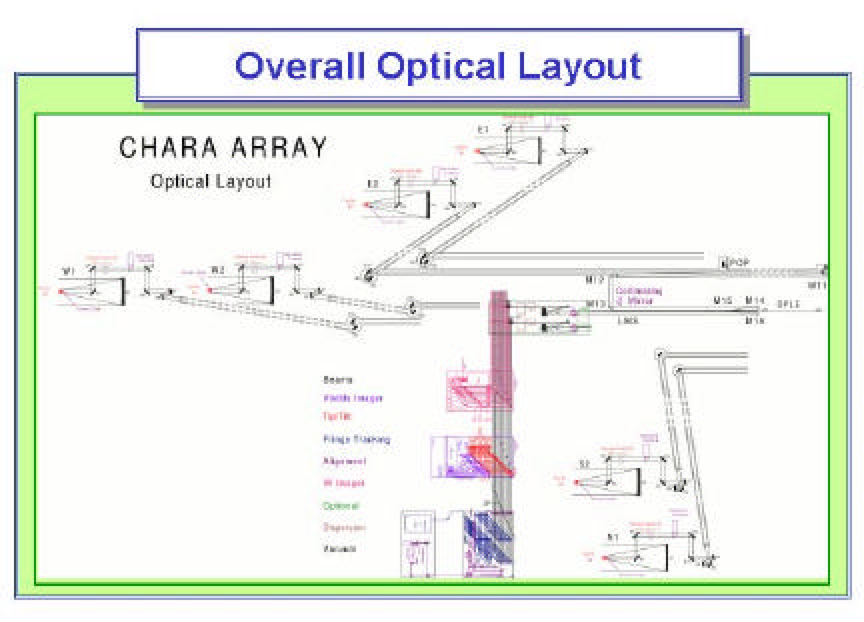


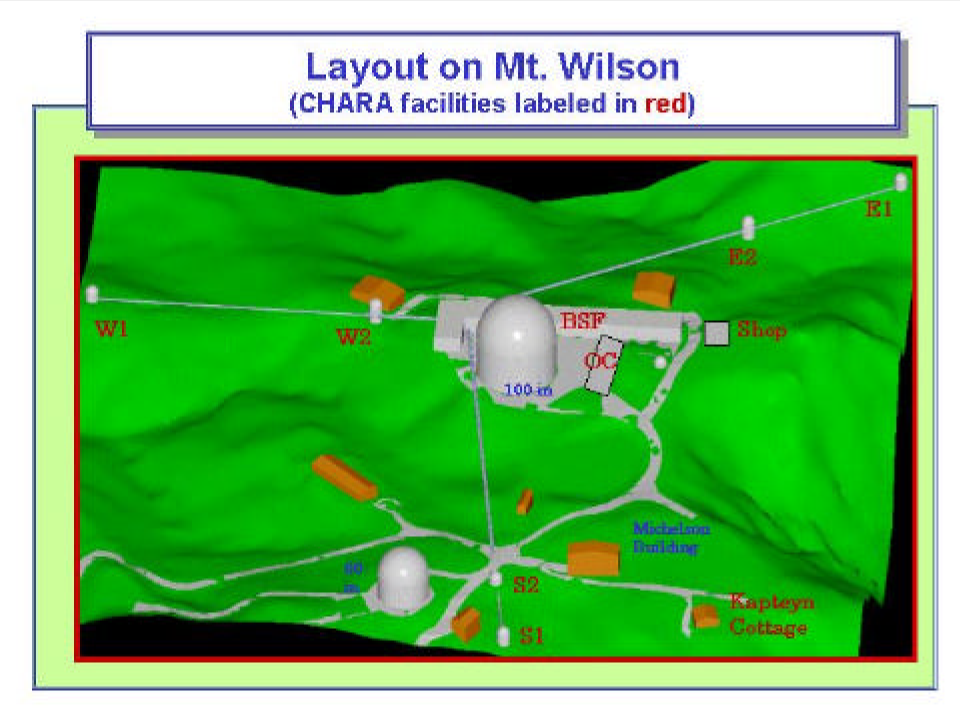


Variations: Optical Interferometry

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







Summary of talk

1. Two ways of understanding interferometery
2. Practical details
3. Some examples
4. Other things to learn from the radiation
5. Variations in interferometry