Astronomical Observing Techniques

Lecture 8: Fringes, Damned Fringes and Interferometry

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Overview

1. Basic Principle
2. Main Components
3. 1D Imaging and Fringes
4. Fringe Tracking
5. 2D Imaging
6. Fundamental Considerations
7. Radio Interferometers
8. Sub-mm Interferometers

Cygnus A at 6 cm with VLA

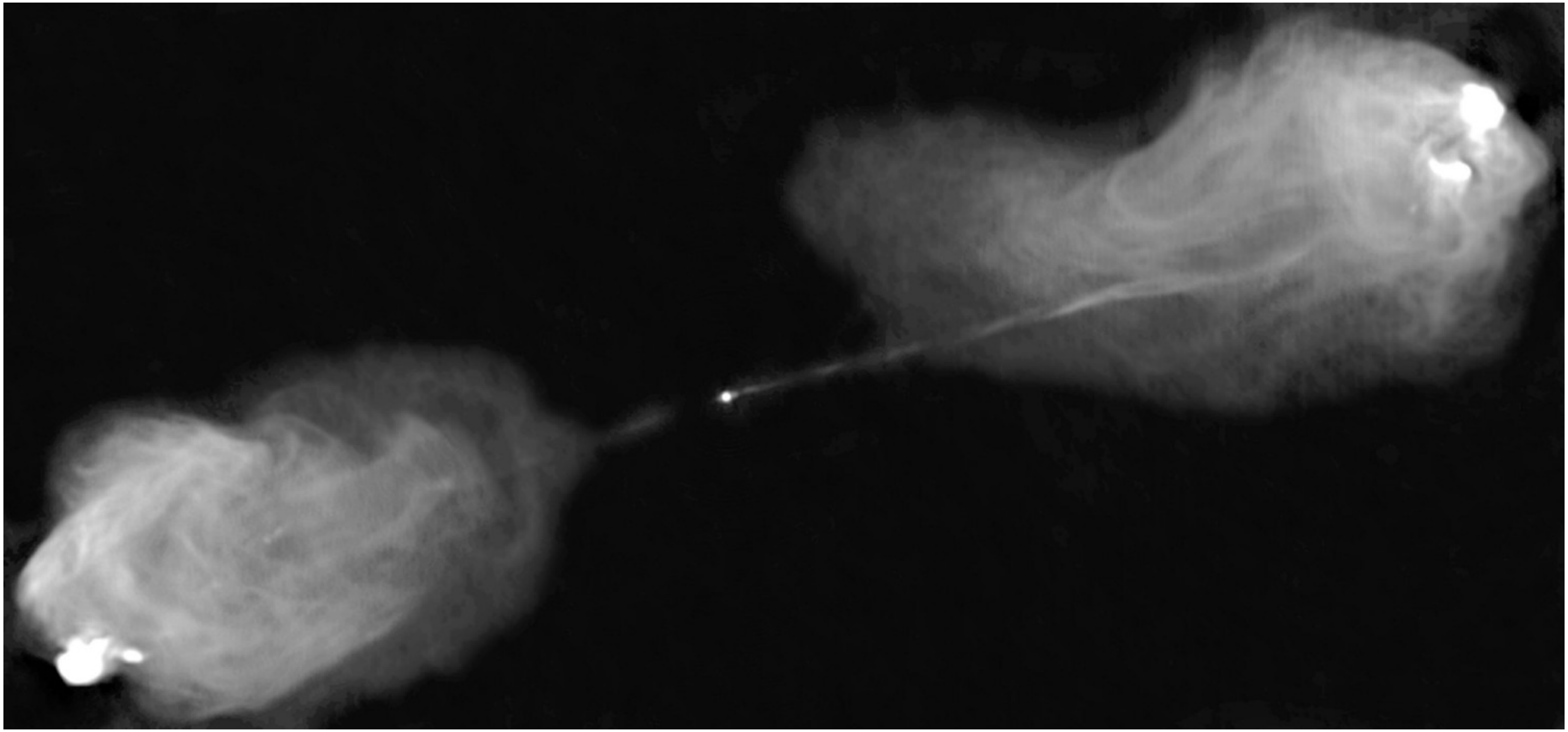
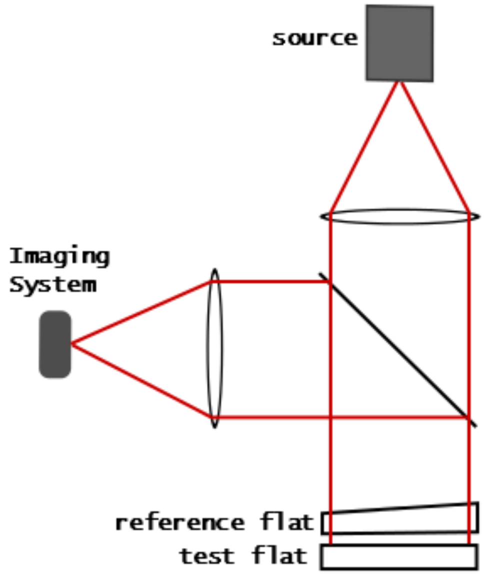


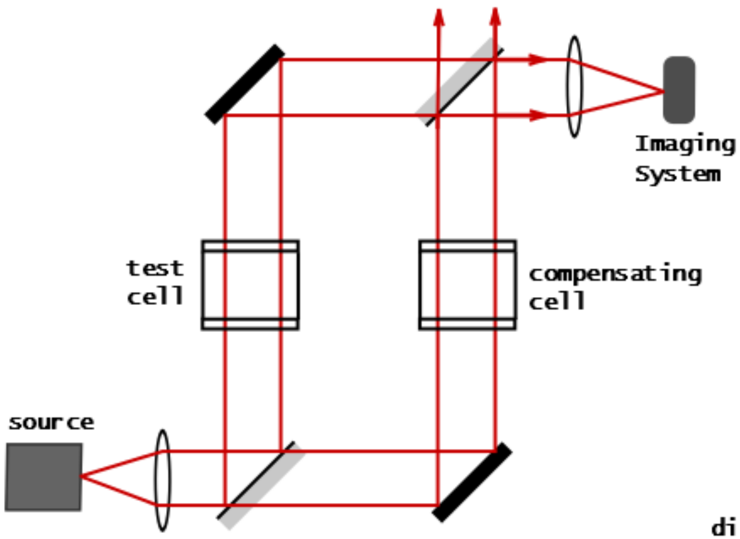
Image courtesy of NRAO/AUI

Interferometers

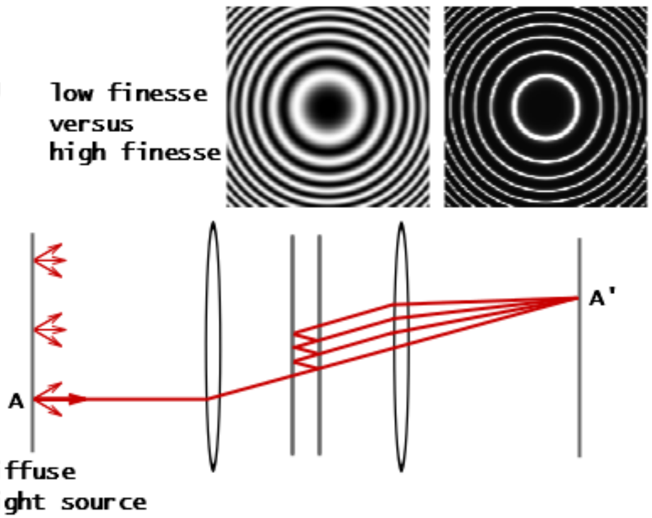
- General principle: Coherently combine two (or more) beams.
- Angular resolution determined by interference
- Interference does not require continuous aperture (e.g. Young’s double slit experiment)
- Hippolyte Fizeau (1868): basic concept of stellar interferometry



Fizeau



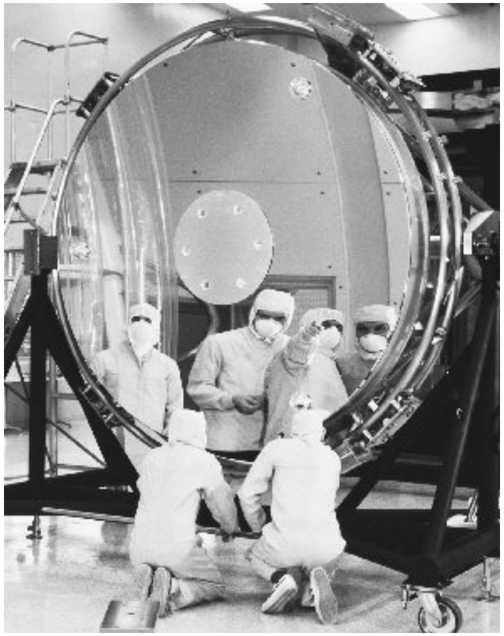
Mach Zehnder



Fabry Perot

Goal: Increase Angular Resolution

$D = D_{tel}$

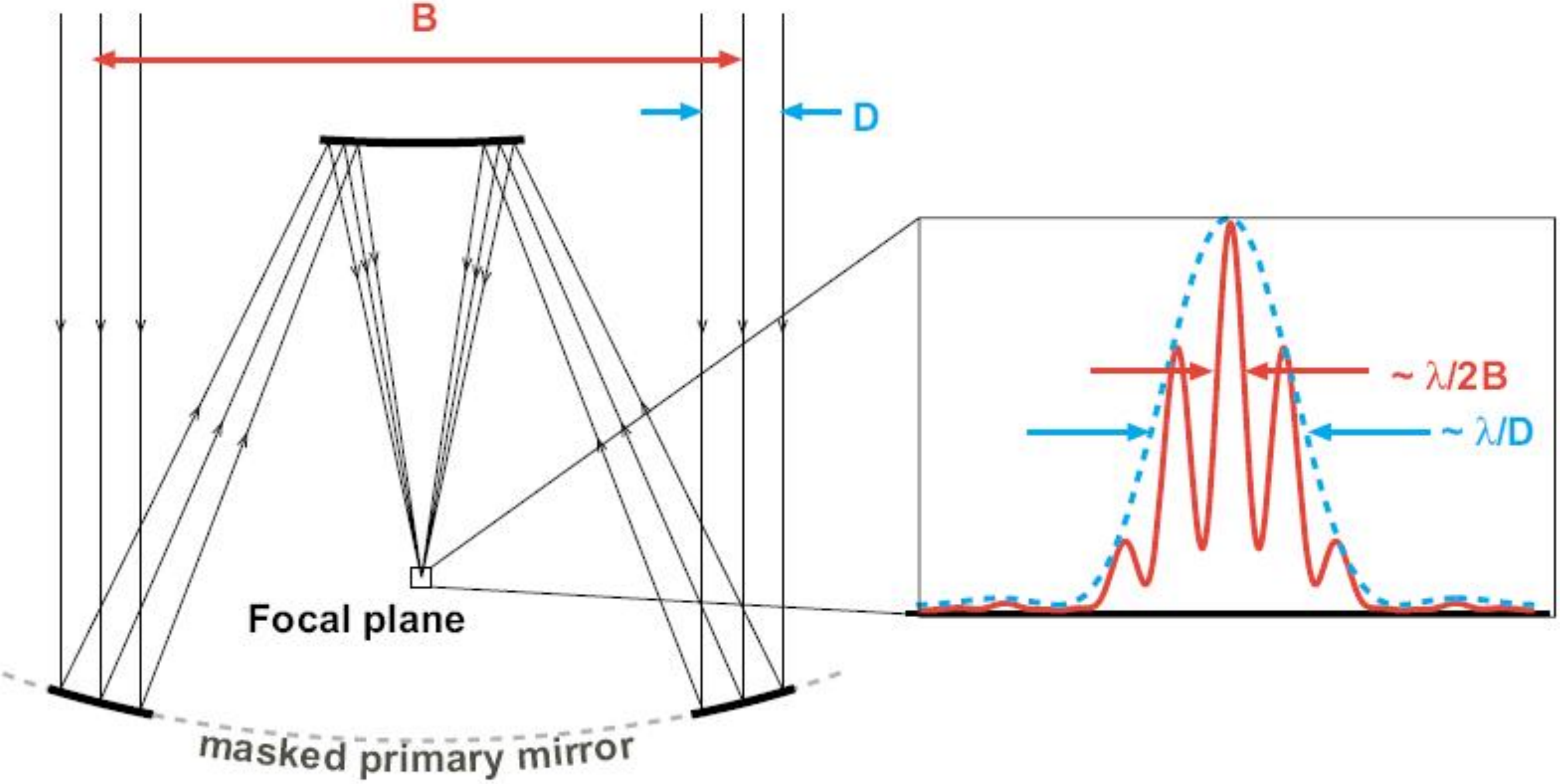


$D = d_{baseline} + D_{telescope}$

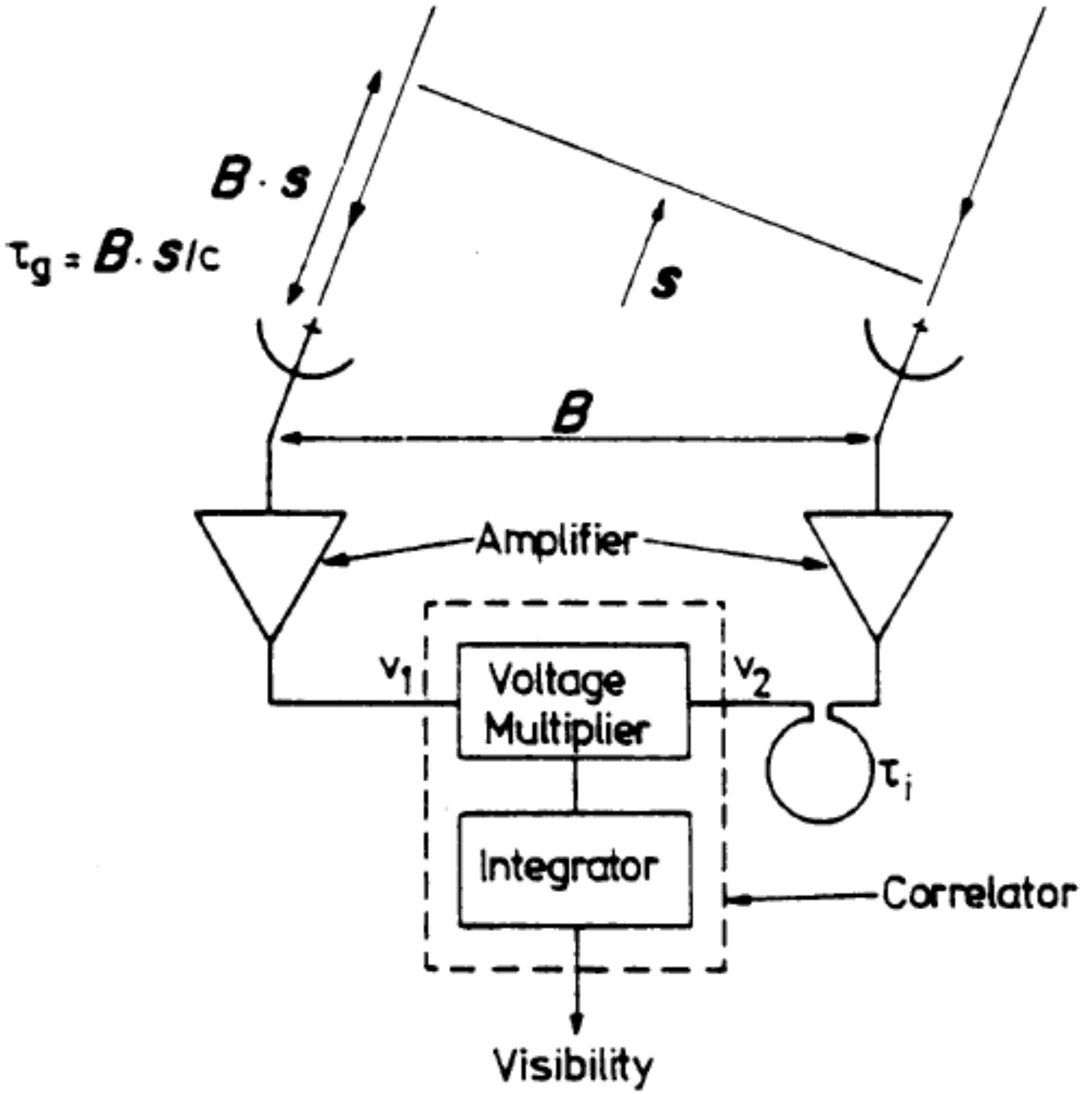
- angular resolution of 1.22λ/D only applies to filled aperture
- interferometer resolution is $\lambda/2(D_{baseline}+D_{telescope})$

PSF of Masked Aperture

Interferometry is like masking a giant telescope:

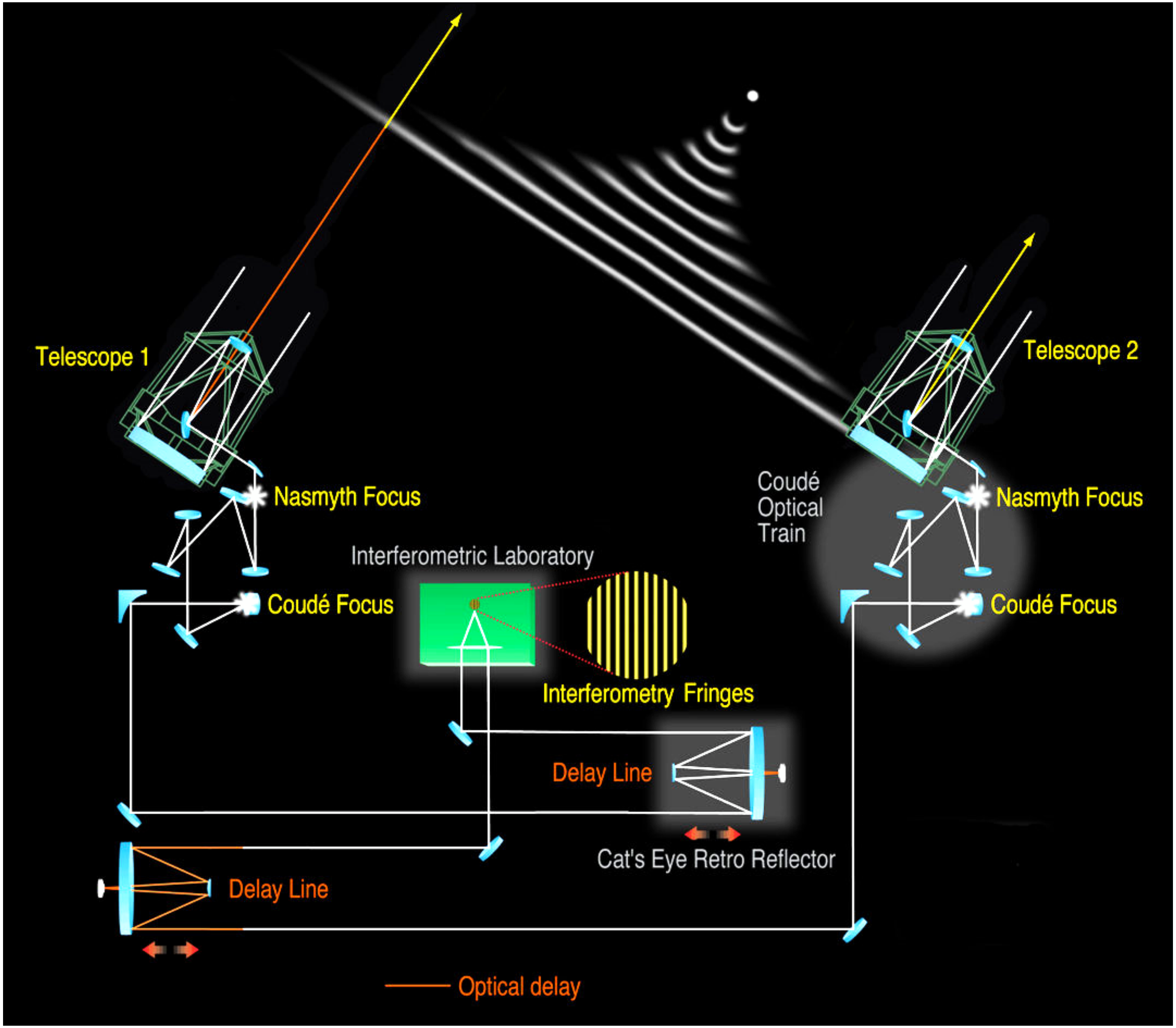


Basic Principle of Radio Interferometry



- Radio heterodyne receiver output retains phase information of incoming signal
- Adjustable signal delay
- Correlator: average product of two signals

Basic Principle of Optical Interferometry



Telescopes

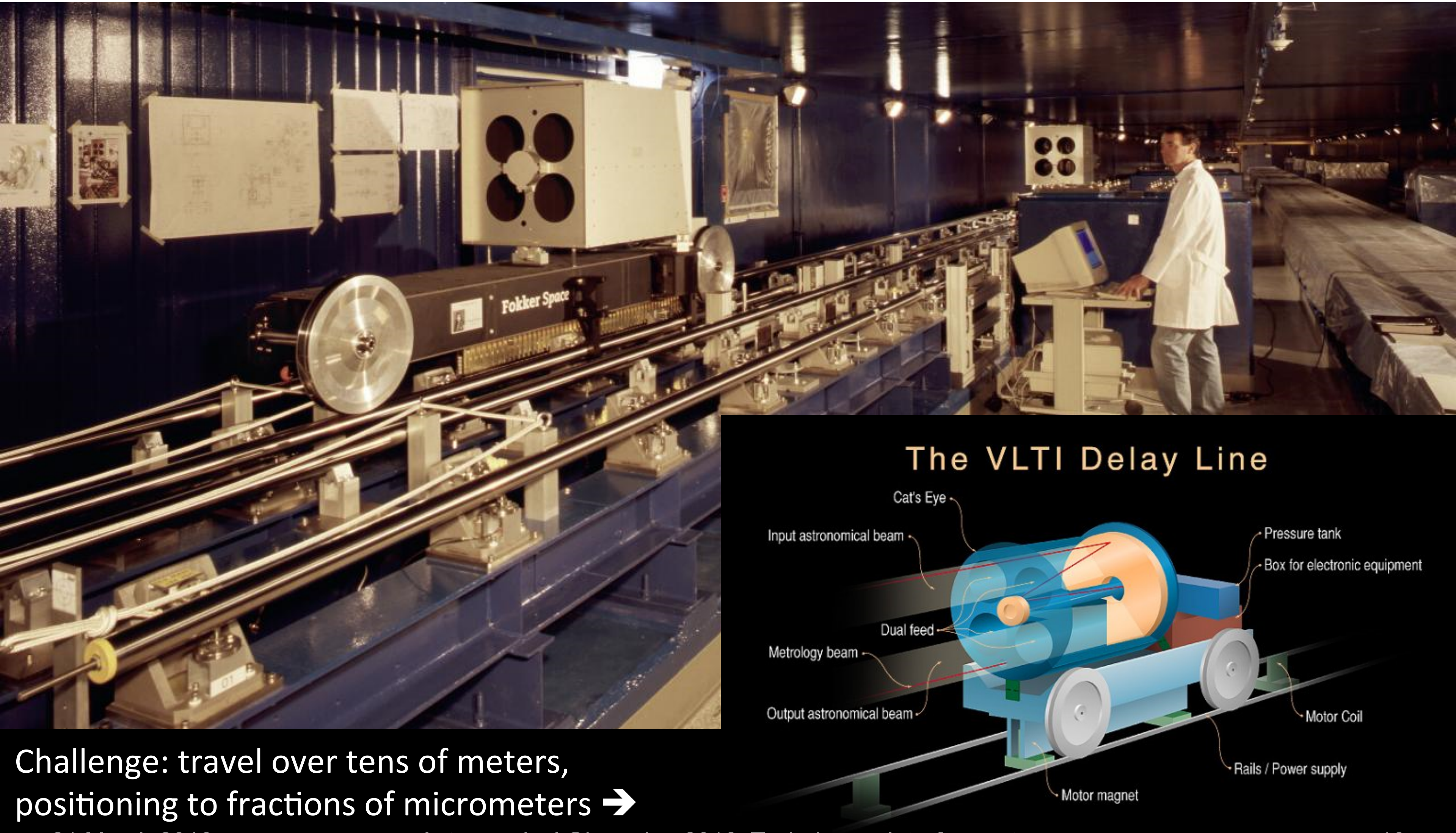
An optical interferometer typically consists of *n* telescopes of similar type and characteristics

Keck interferometer (Hawaii) ↑

← VLTI (Paranal)

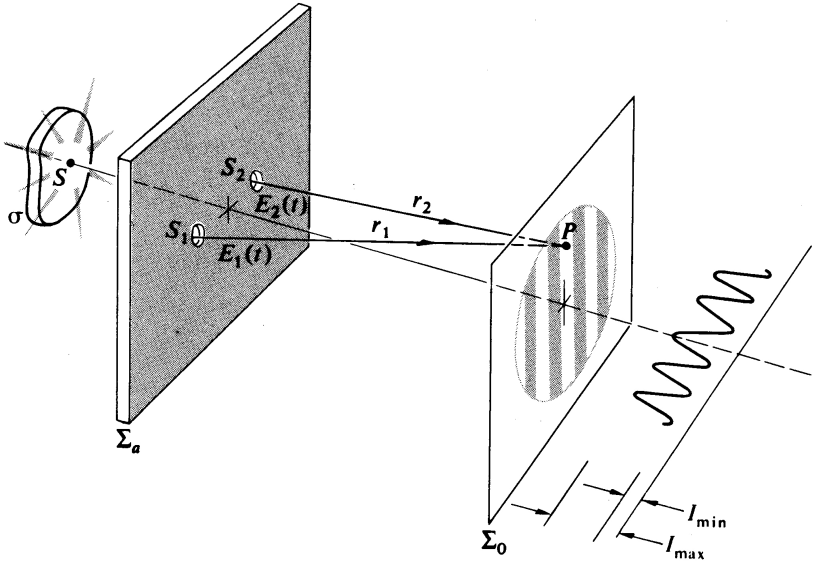
Delay Lines

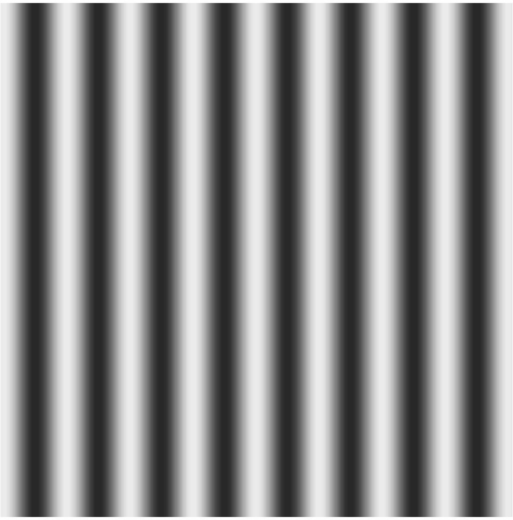
Compensate optical path difference between telescopes (depends on object location on sky)



Challenge: travel over tens of meters, positioning to fractions of micrometers ➔ dynamic range of > 10^9 !

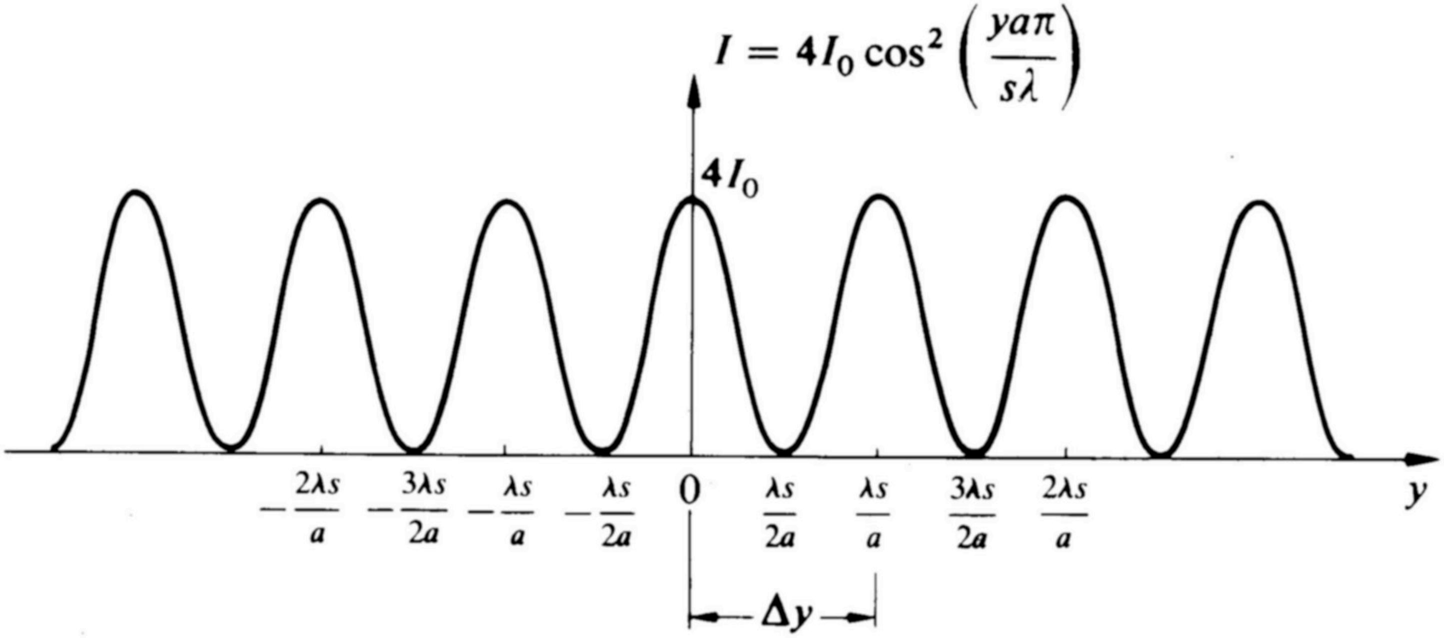
Young’s Double Slit Experiment





- monochromatic wave
- infinitely small pinholes
- source S generates fields
  - $E(r_1,t) = E_1(t)$ at S_1
  - $E(r_2,t) = E_2(t)$ at S_2
- two spherical waves from pinholes interfere on screen
- electrical field at P is $E_P(t)=c_1E_1(t-t_1)+c_2E_2(t-t_2)$ $t_1=r_1/c$, $t_2=r_2/c$
- $r_{1,2}$: path lengths from $S_{1,2}$ to P
- propagators $c_{1,2}=i/\lambda$

Fringes from Monochromatic Point Source



- irradiance as a function of the y-coordinate of the fringes in observation plane Σ_O
- irradiance vs. distance distribution is Point-Spread Function (PSF) of ideal two-element interferometer

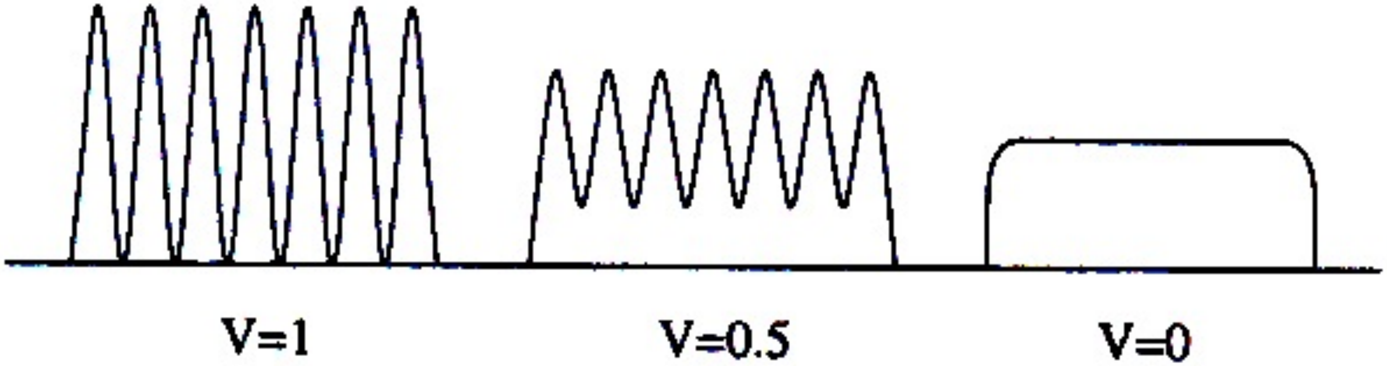
Fringe Visibility – Definition

Fringe visibility defined as $$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Van-Cittert Zernike theorem: Visibility is the absolute value of the Fourier transform of the object's brightness distribution

If dark regions in fringe pattern go to zero V = 1 → object is "unresolved"

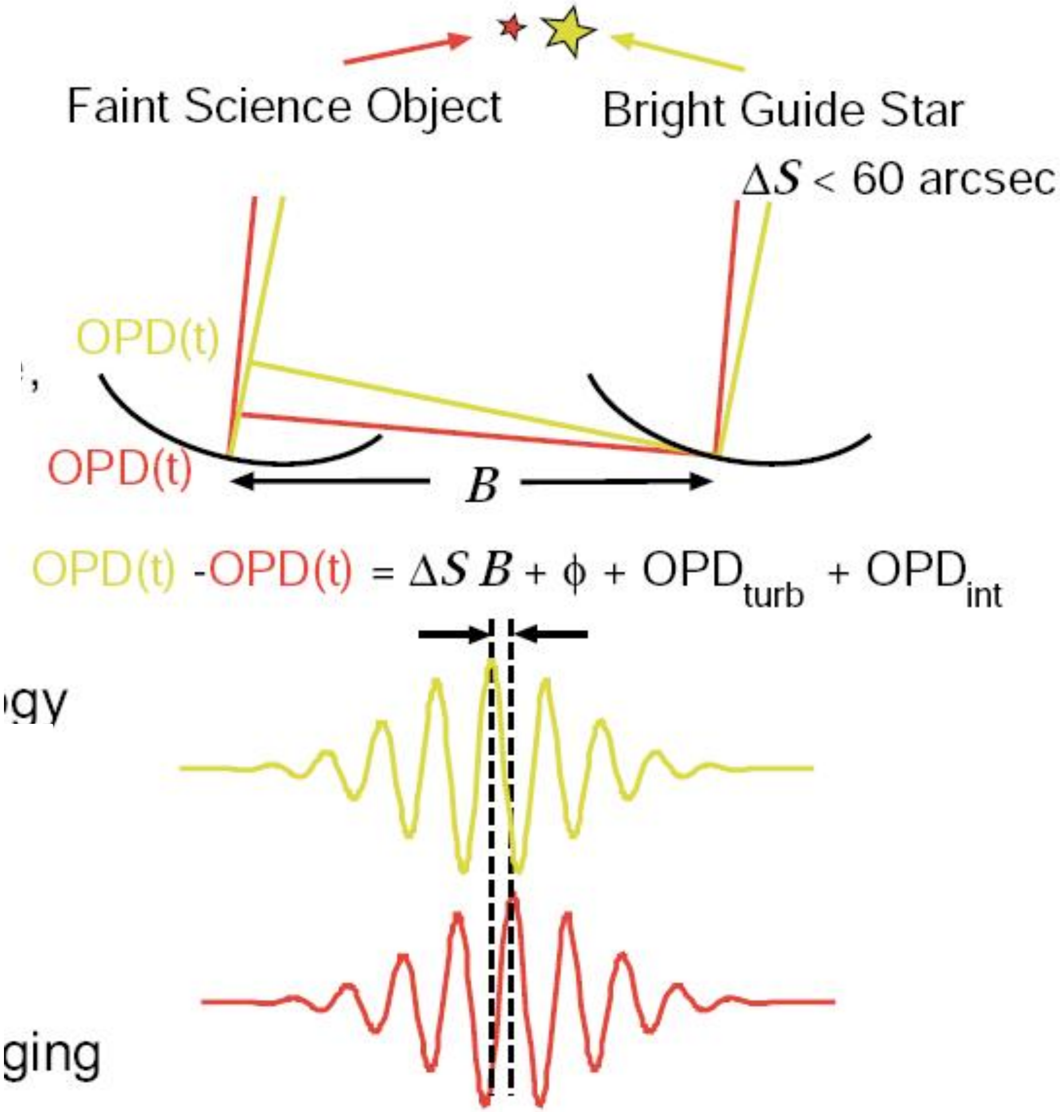
If V = 0 then there are no fringes → object is completely "resolved"



Fringe Tracking (Co-Phasing)

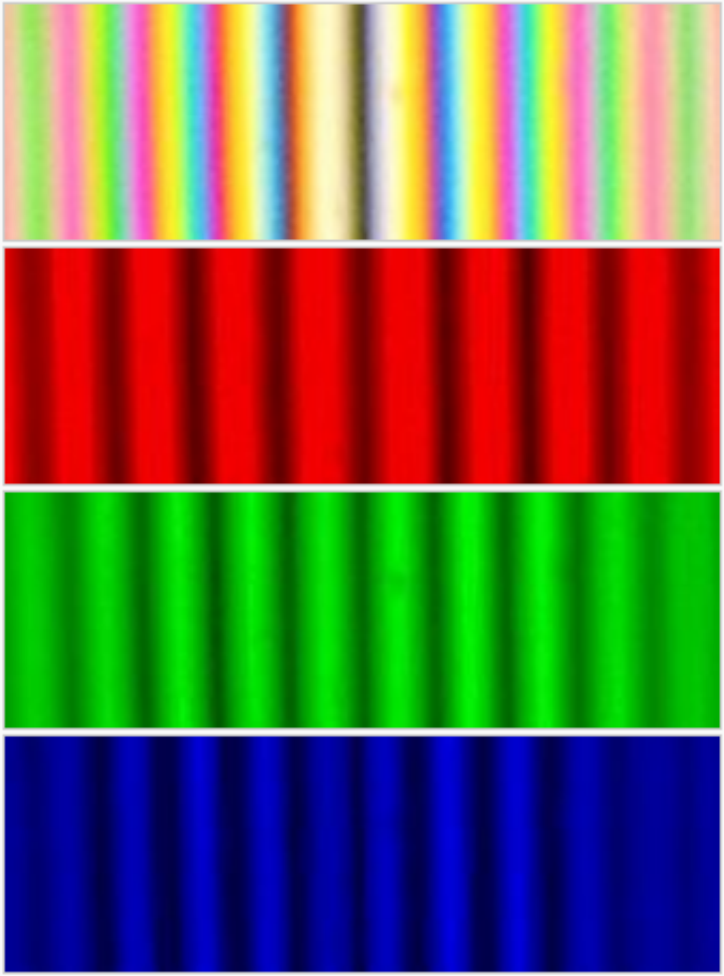
Fringes have to be actively tracked; requires tracking fluctuations within small fraction of wavelength in real-time

Example: ESO’s FINITO scans center of fringe packet in H band with high speed and sends a co-phasing signal to the VLTI delay lines; FINITO operates on two channels, i.e. tracks three baselines.



White Light Fringes

- Use of white light (= typical astronomical signal) will result in a pattern of colored fringes
- *The term white light fringe refers to the central fringe*
- The central fringe representing equal path length may be light or dark depending on the number of phase inversions experienced by the two beams as they traverse the optical system



Above: White light Interferogram, **Below**: Red-, Green- and Blue channels of the White light interferogram shown above

Closure Phase (1)

Fringe visibility tells one component of the objects Fourier transform = amplitude of the fringes

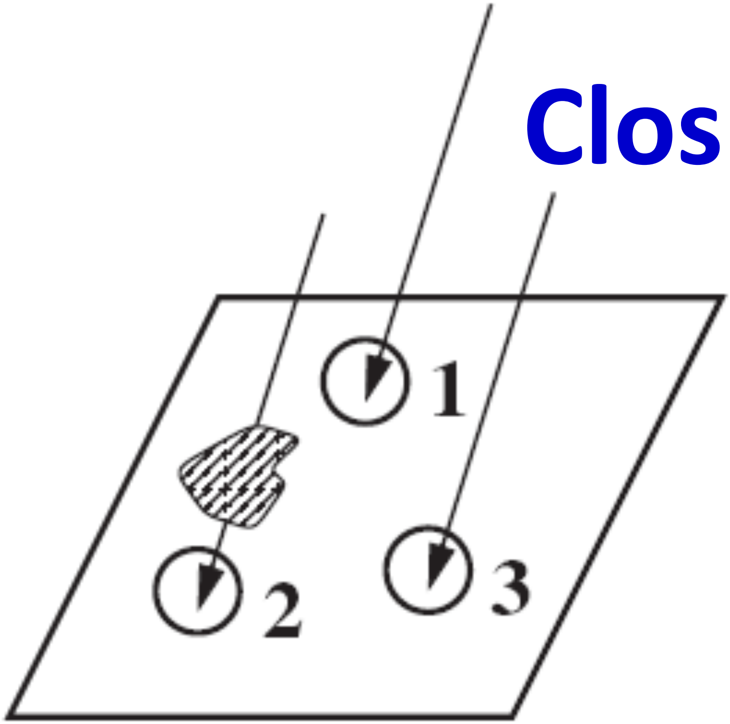
The phase is determined by the position of the fringes.

Problem: due to atmospheric turbulence (which changes the optical path length), the fringes move constantly forward and backward.

Idea: use three telescopes → three sets of fringes: (1-2), (2-3), (1-3)
In all three sets the fringes move, but not independently!

→ this information is called closure phase (or self-calibration in aperture synthesis imaging – the standard technique in radio interferometry) and can be used to cancel out phase error terms.

Closure Phase (2)



Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	=	$\Phi_o(1\text{-}2)$	+	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	=	$\Phi_o(2\text{-}3)$	+	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	=	$\Phi_o(3\text{-}1)$	+	$[\phi(1)-\phi(3)]$

$$\text{Closure Phase (1-2-3)} = \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$$

Error terms cancel out!

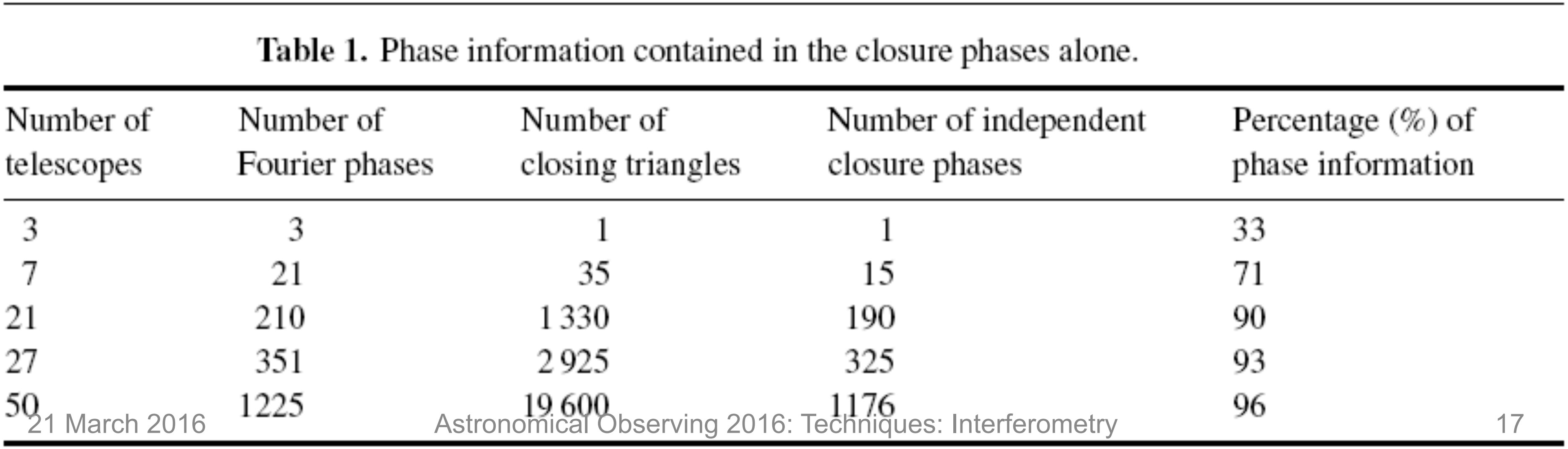


Table 1. Phase information contained in the closure phases alone.

Number of telescopes	Number of Fourier phases	Number of closing triangles	Number of independent closure phases	Percentage (%) of phase information
3	3	1	1	33
7	21	35	15	71
21	210	1 330	190	90
27	351	2 925	325	93
50	1225	19 600	1176	96

(Radio) Aperture Synthesis

The limited information about the structure of a source provided by a two element interferometer can be expanded by moving the telescopes to change the baselines.

Even better: use N telescopes and combine their outputs: N telescopes provide N(N-1)/2 baselines. Each baseline adds a new Fourier component (or fringe spacing)*)*

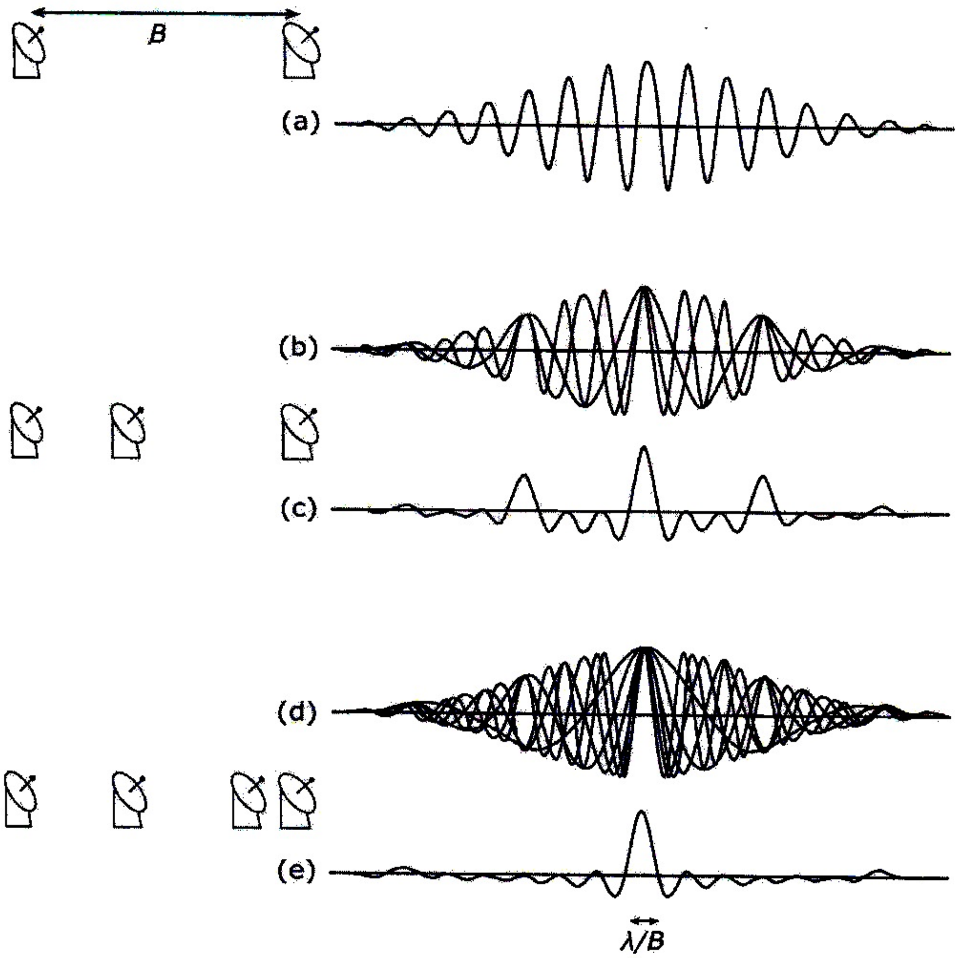
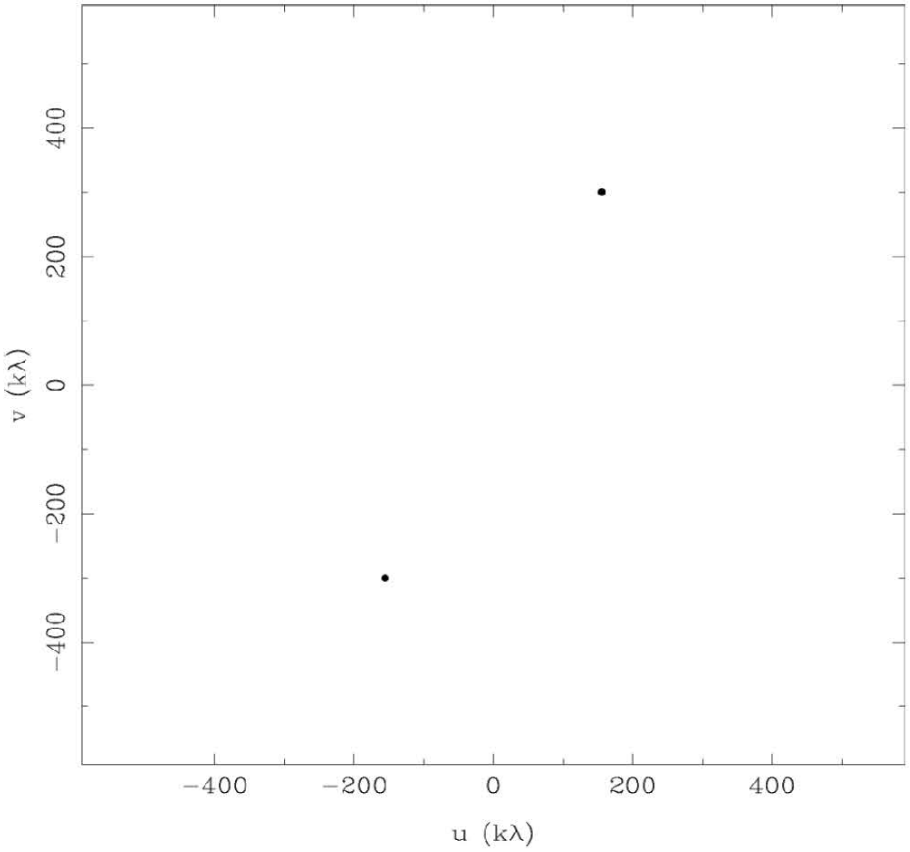
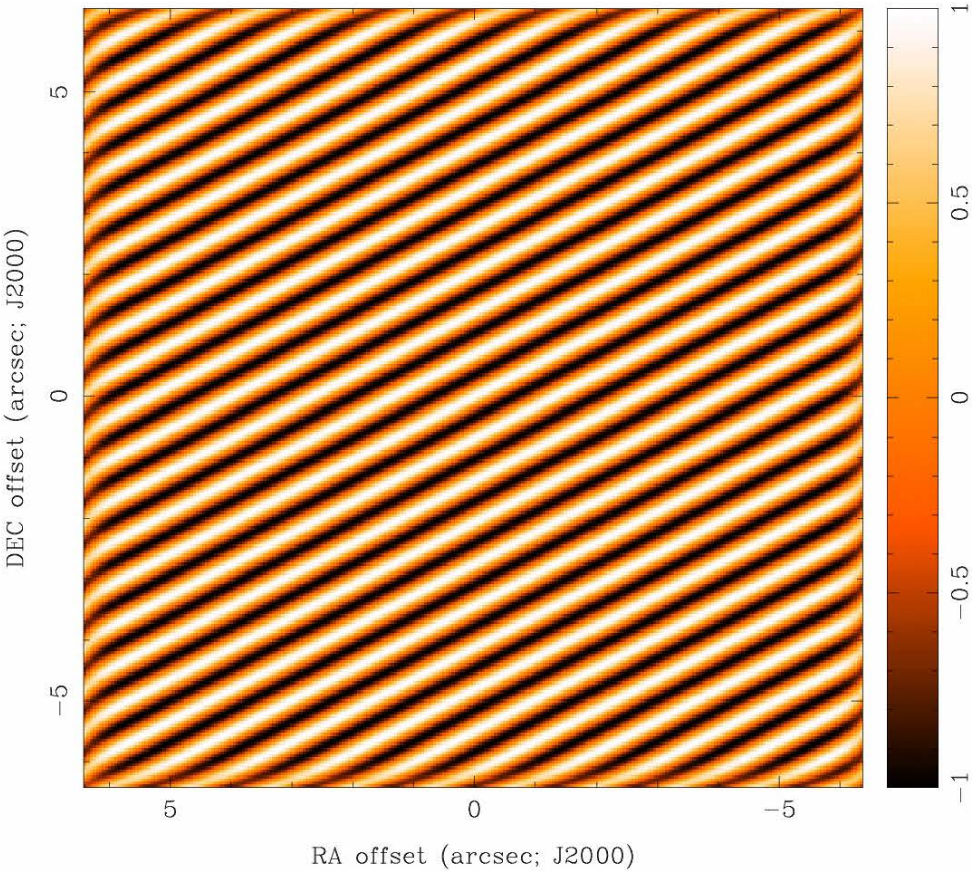


Figure 9.2. Improvement in field pattern quality (the images are the autocorrelation) with increasing number of interferometer baselines. Based on Condon and Ransom (2010).

Dirty Beam Shape and N Antennas

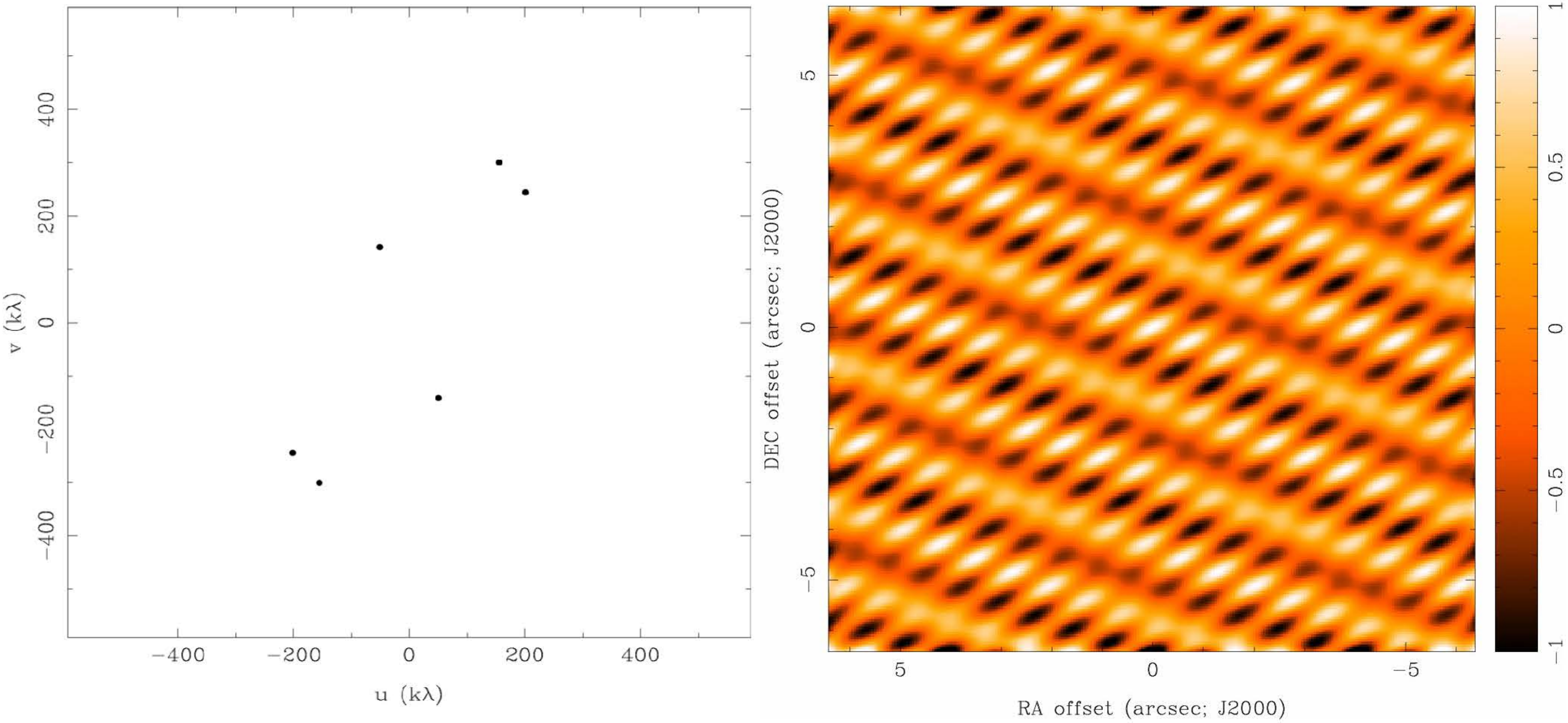
2 Antennas





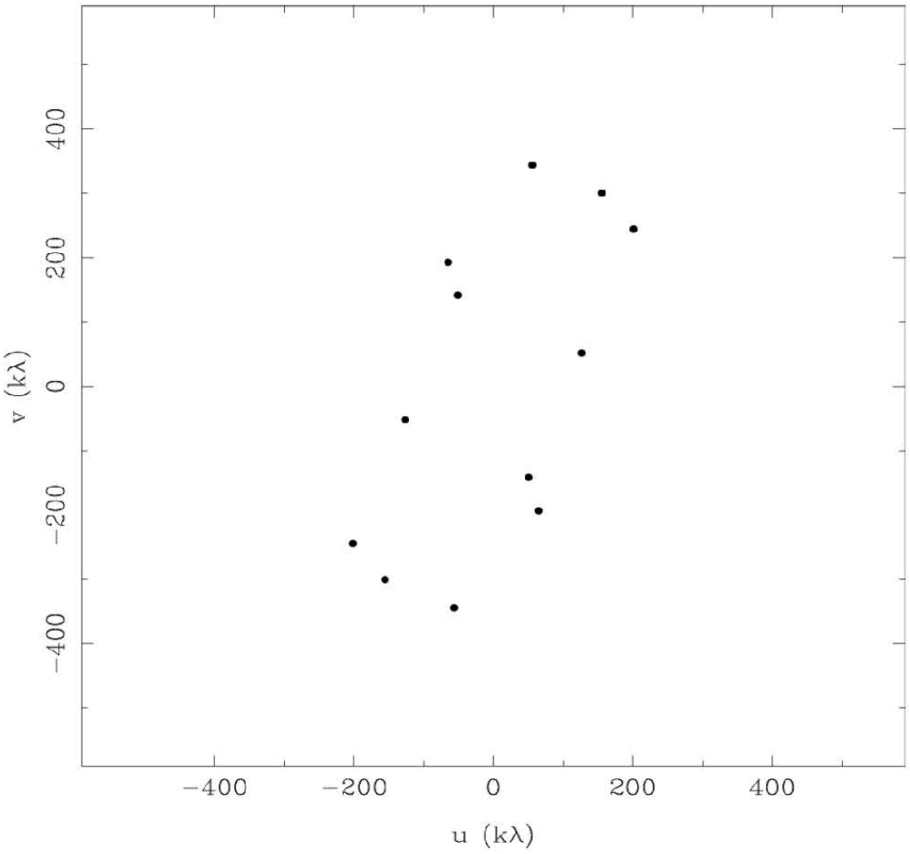
Dirty Beam Shape and N Antennas

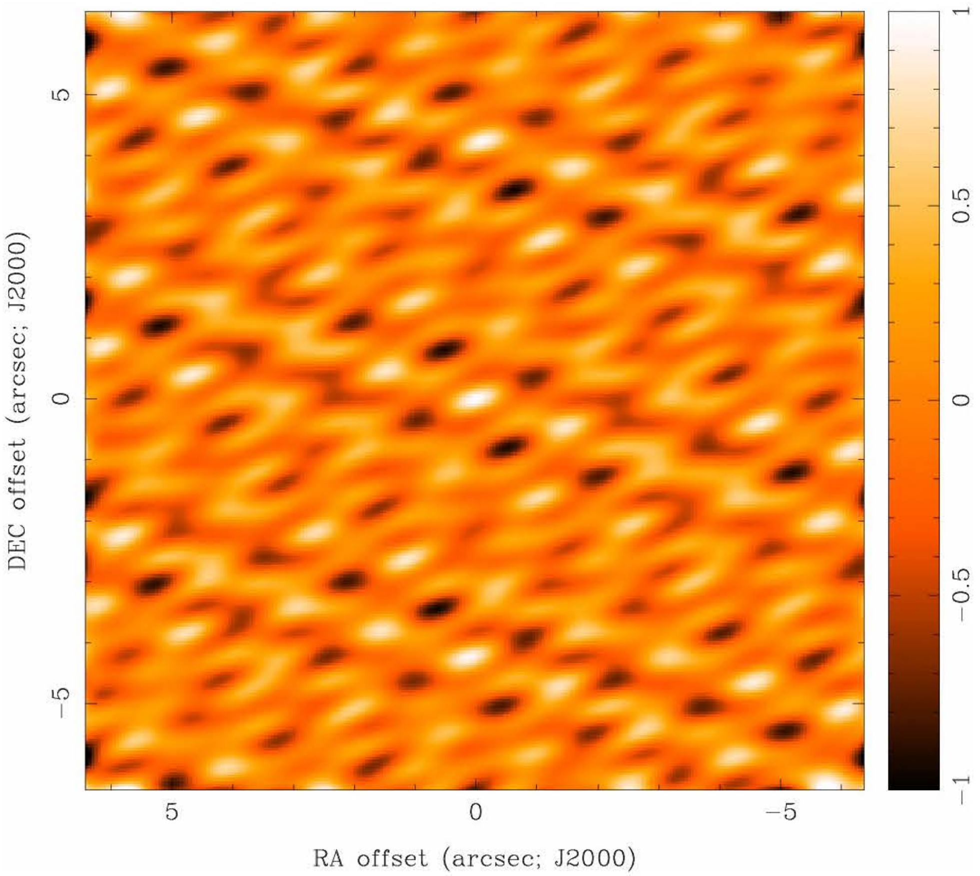
3 Antennas



Dirty Beam Shape and N Antennas

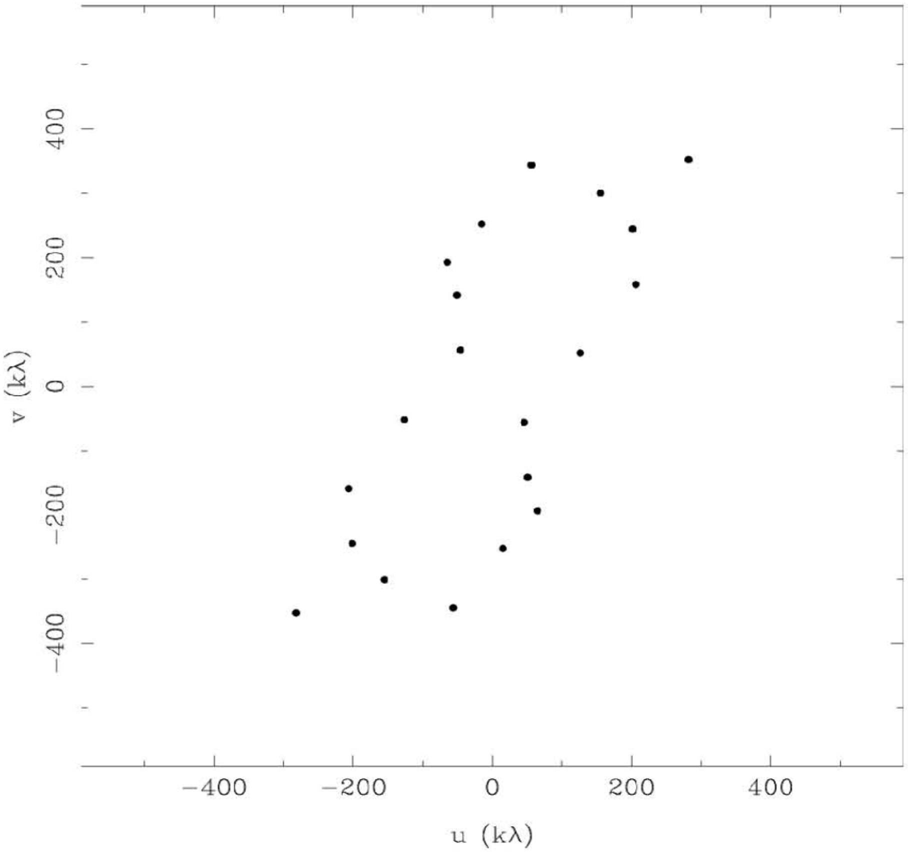
4 Antennas

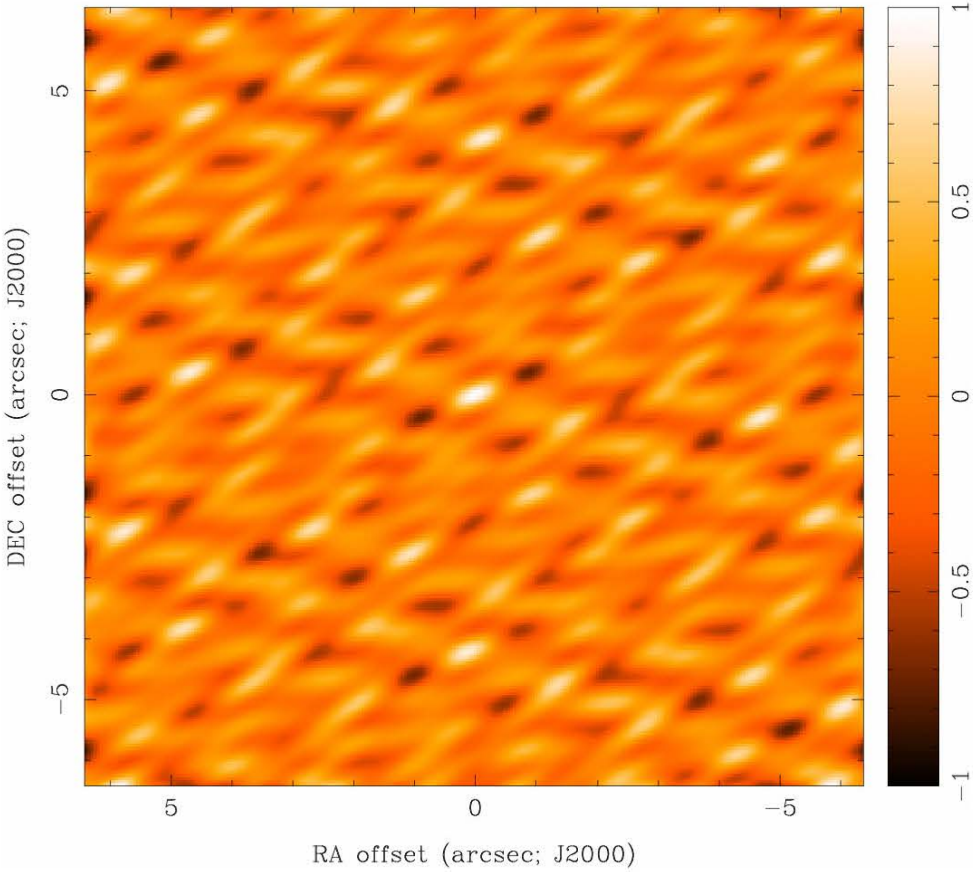




Dirty Beam Shape and N Antennas

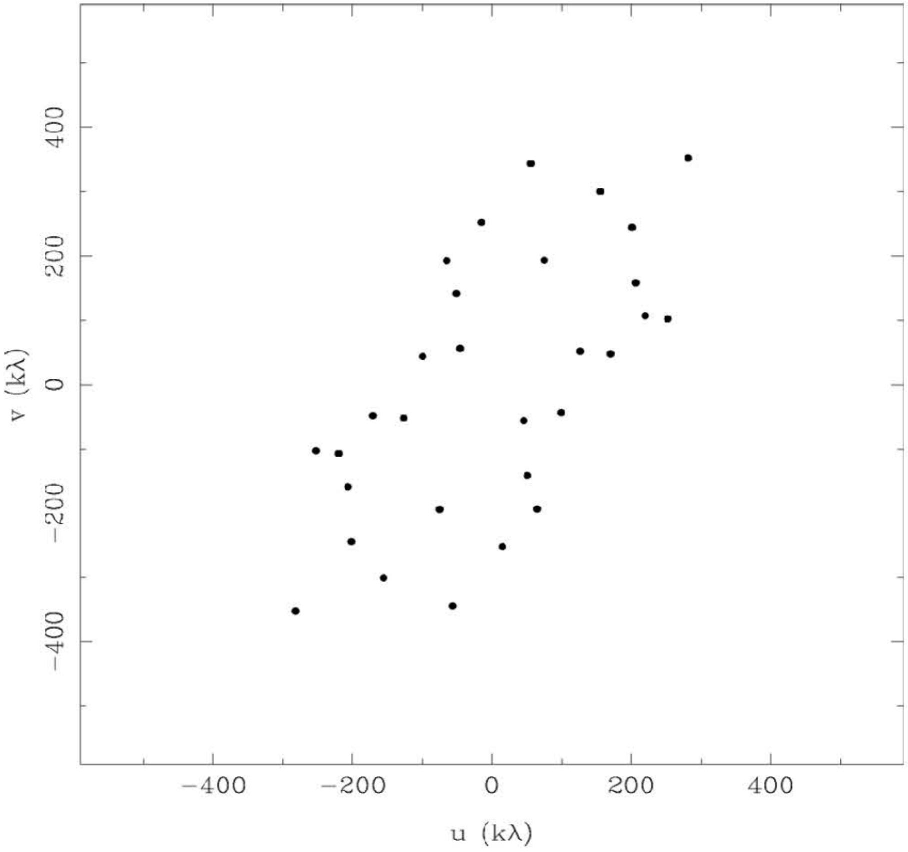
5 Antennas

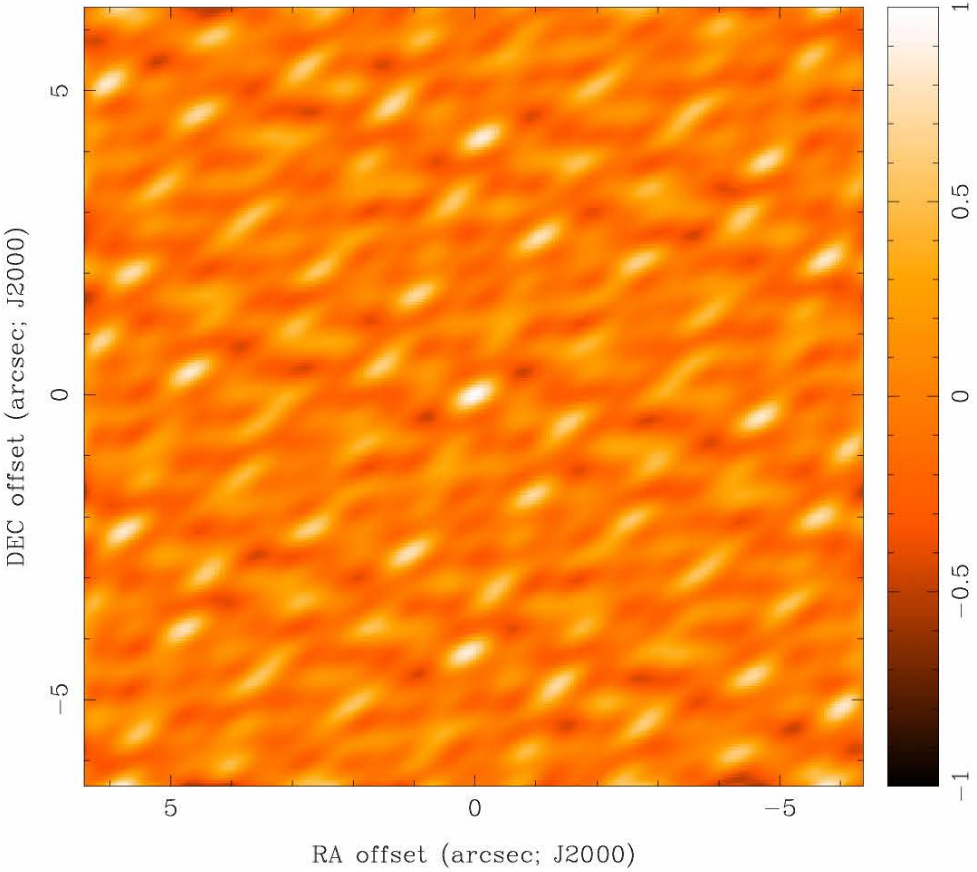




Dirty Beam Shape and N Antennas

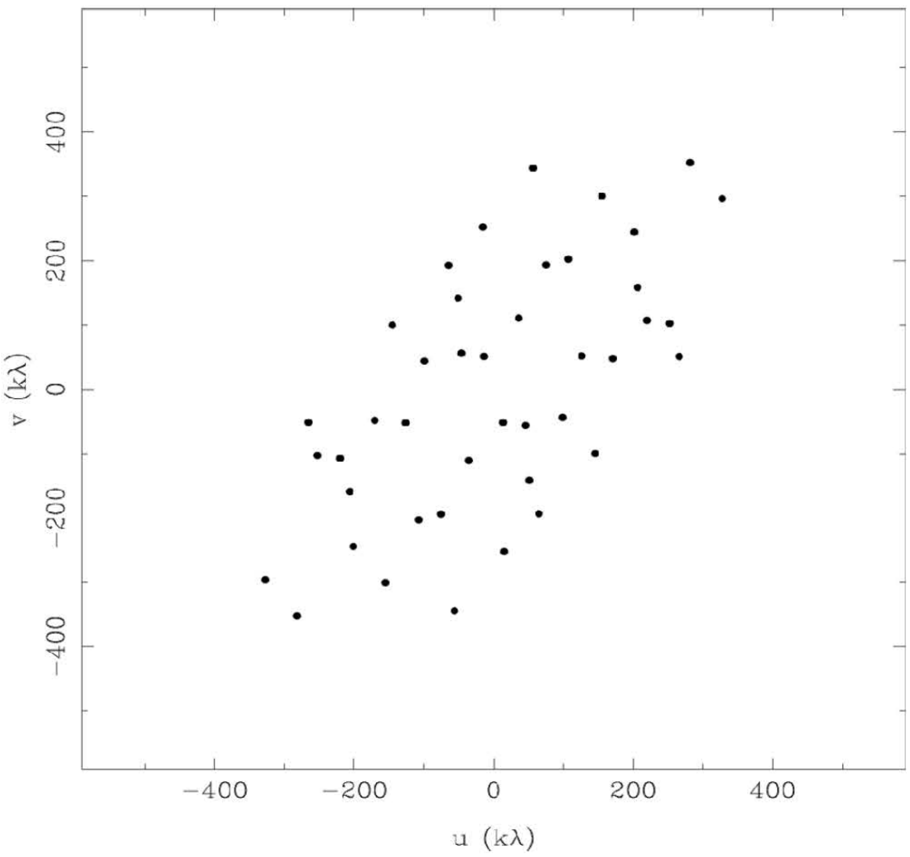
6 Antennas

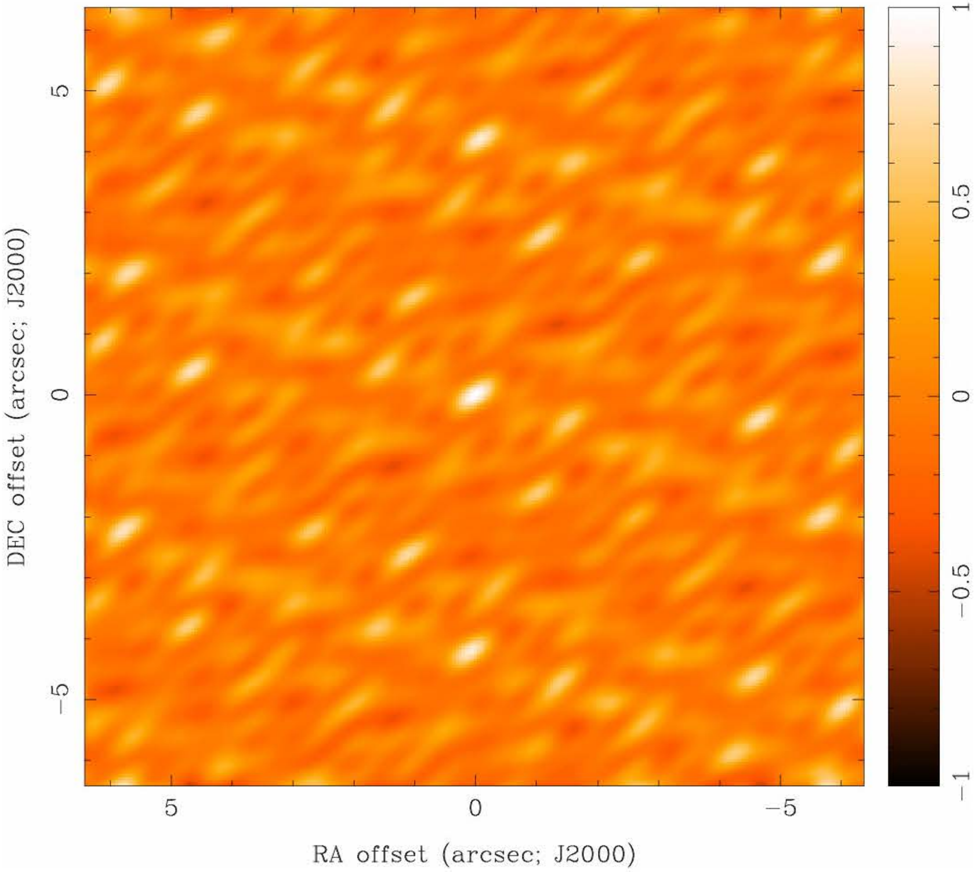




Dirty Beam Shape and N Antennas

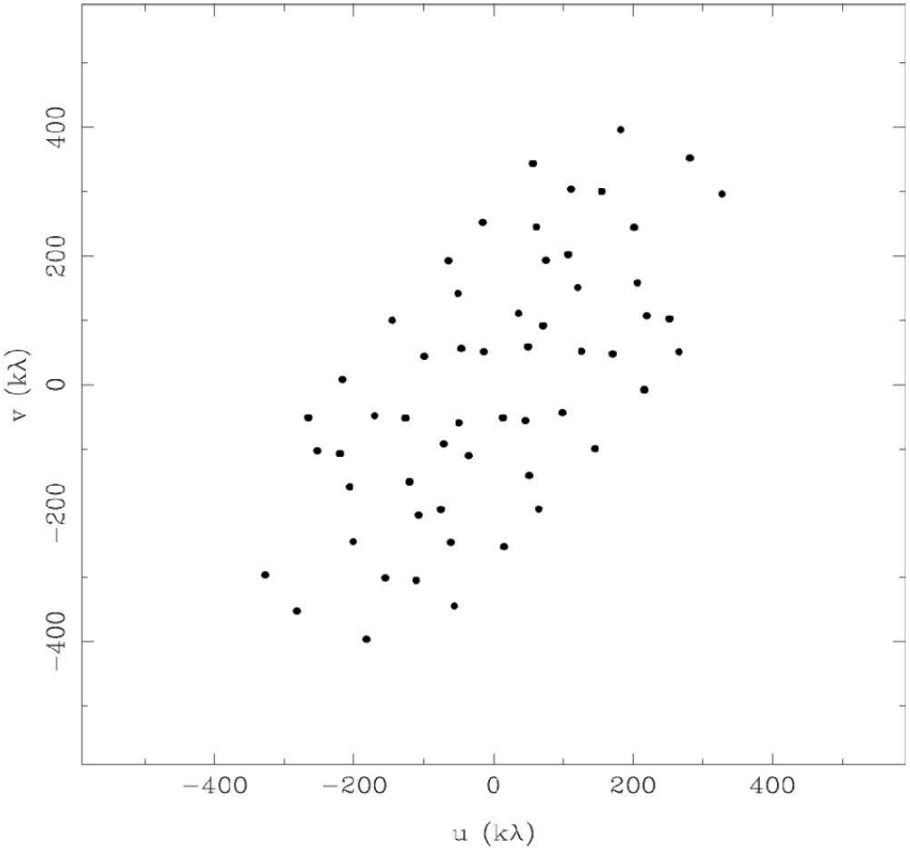
7 Antennas

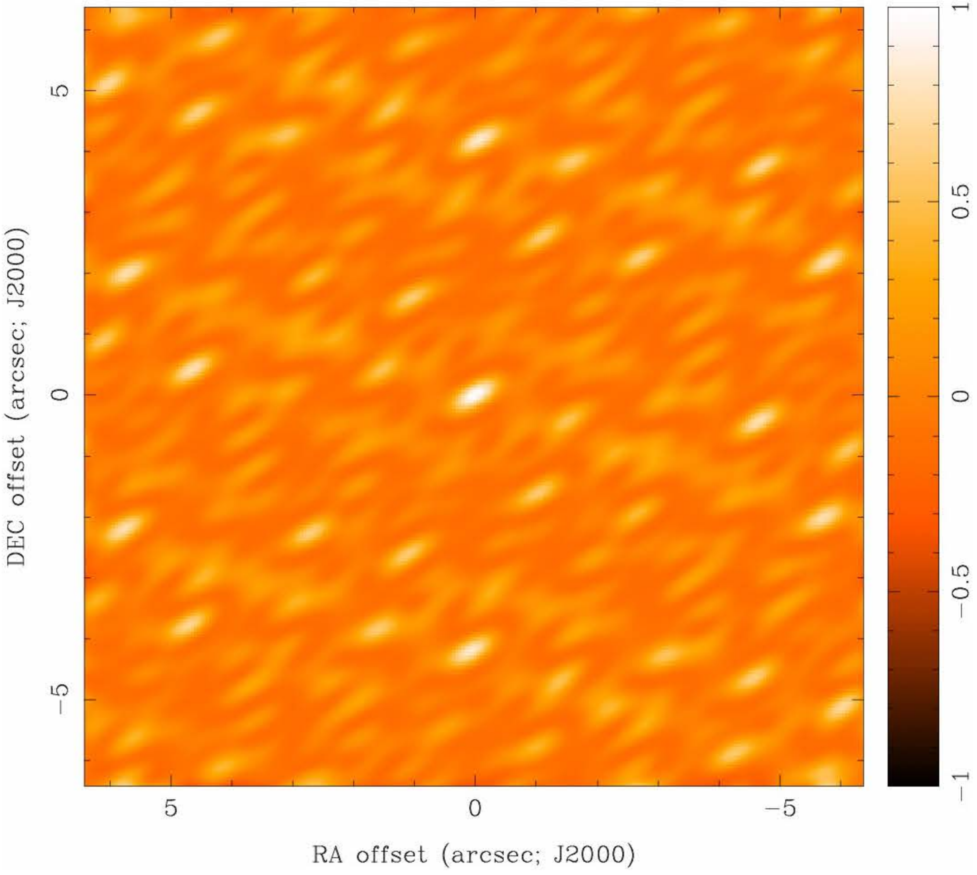




Dirty Beam Shape and N Antennas

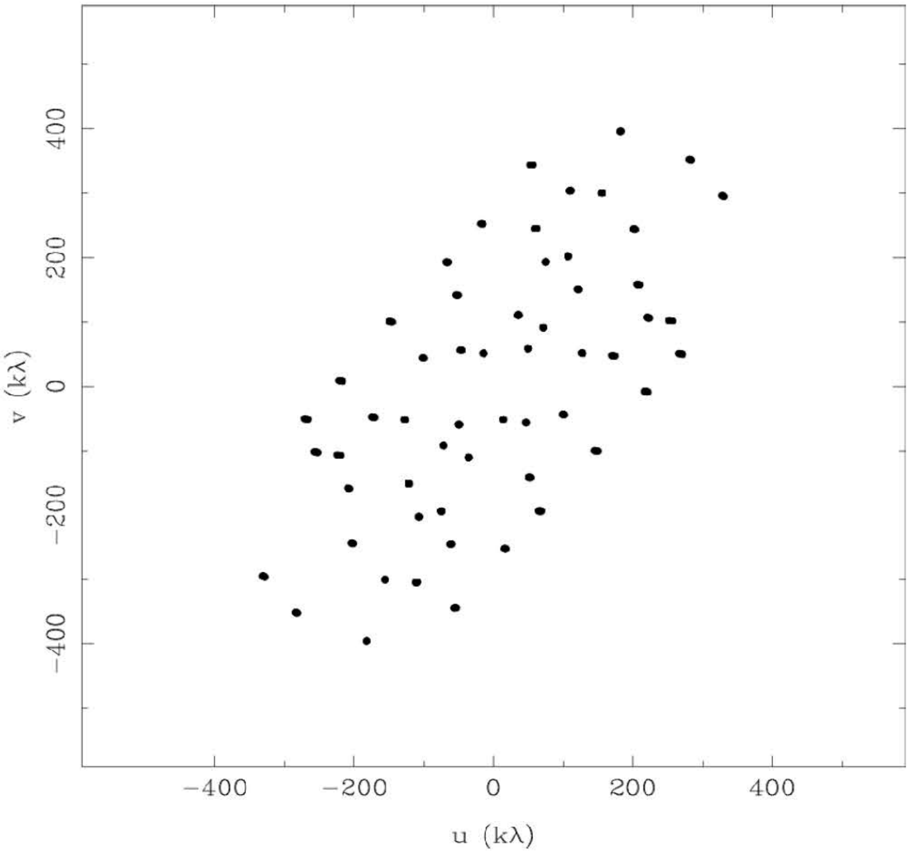
8 Antennas

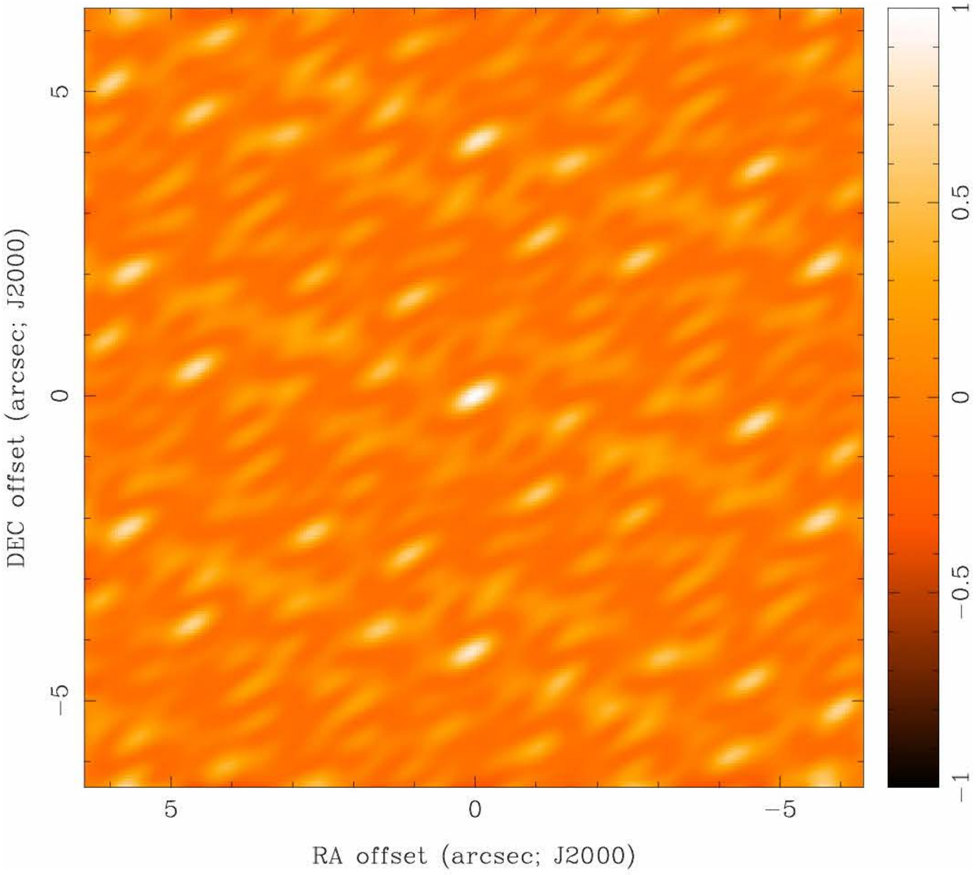




Dirty Beam Shape and N Antennas

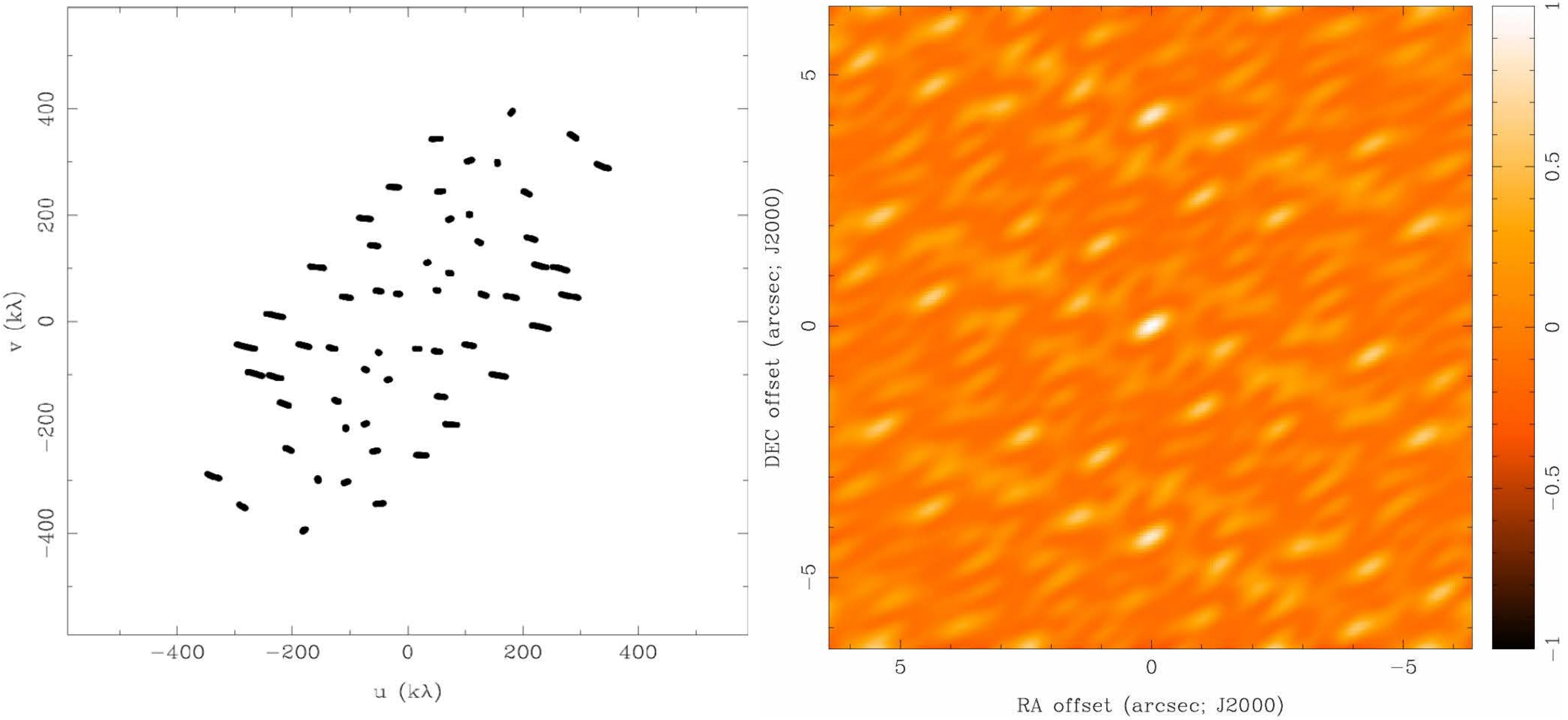
8 Antennas x 6 Samples





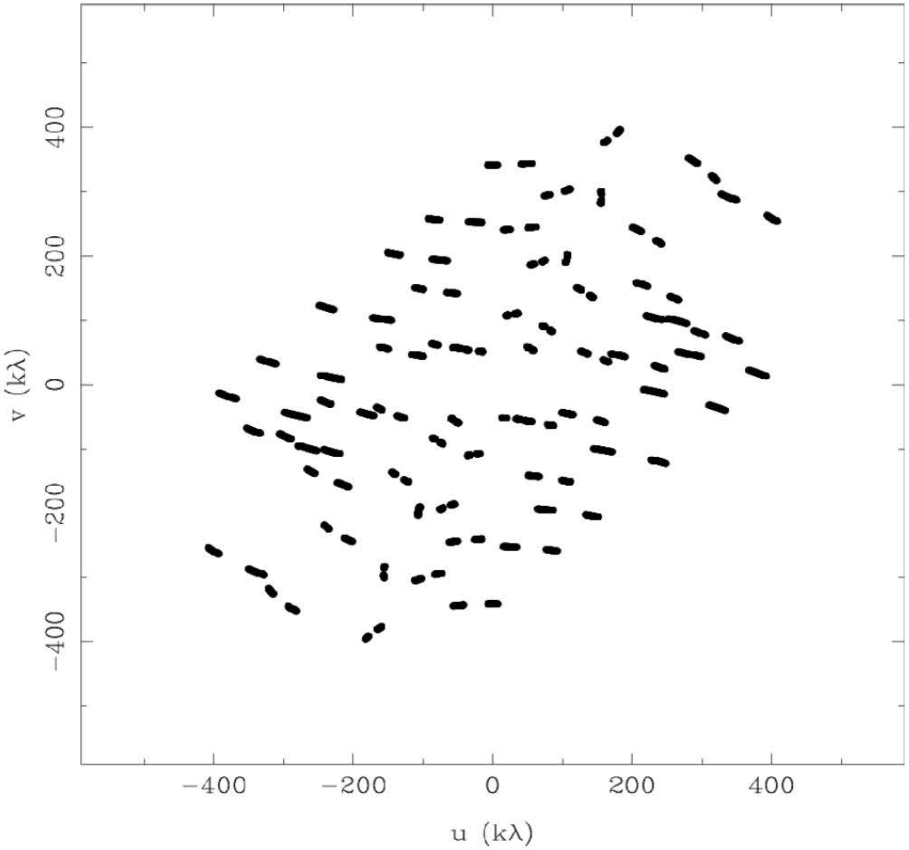
Dirty Beam Shape and N Antennas

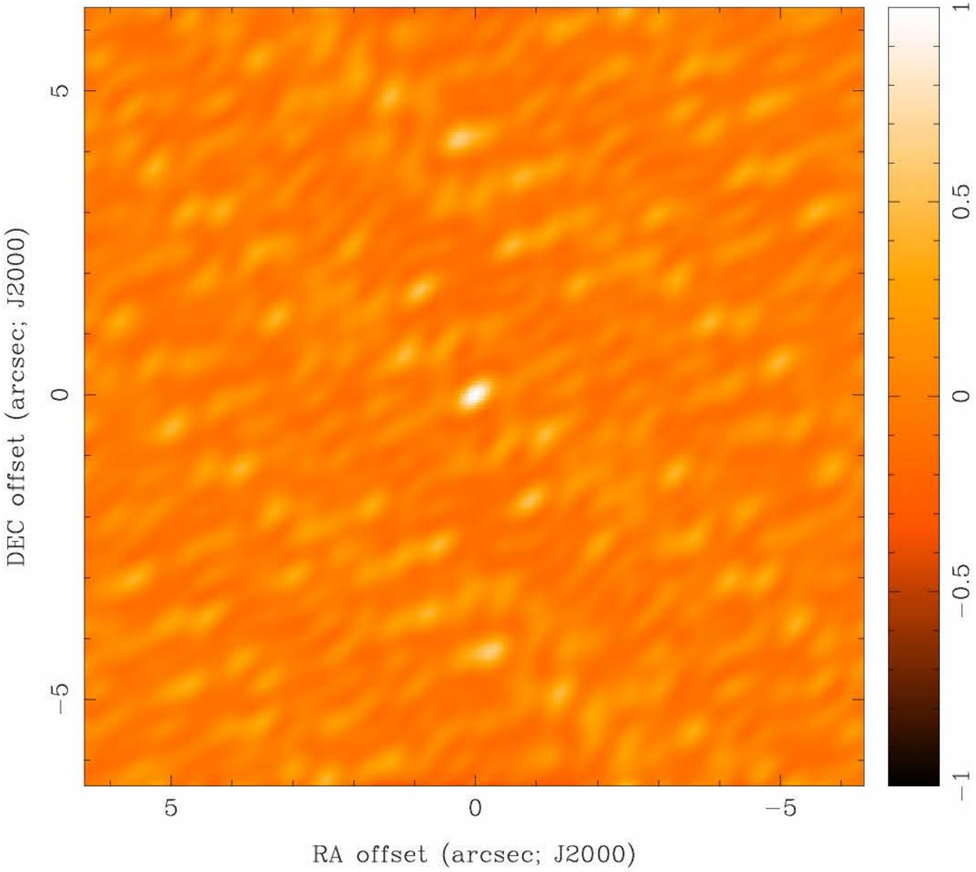
8 Antennas x 30 Samples



Dirty Beam Shape and N Antennas

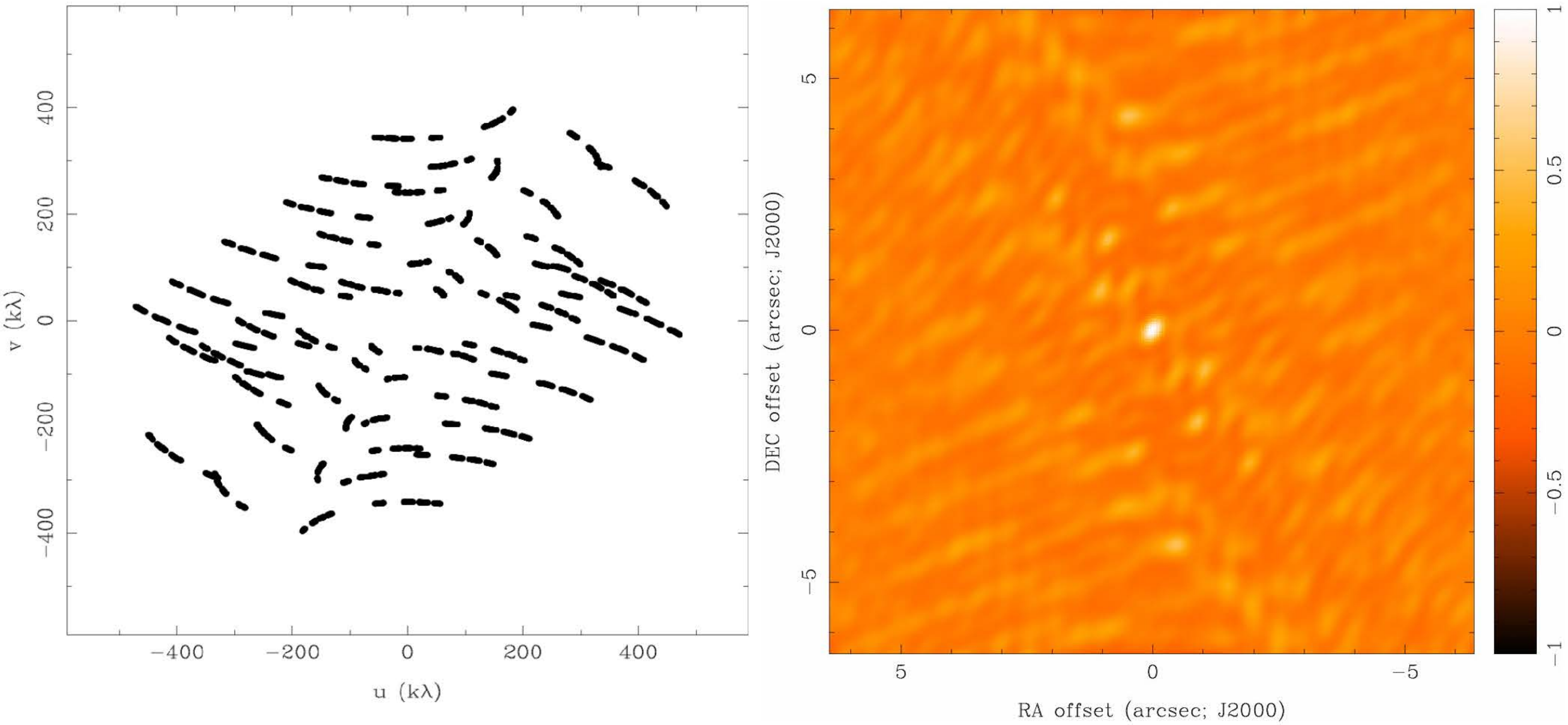
8 Antennas x 60 Samples





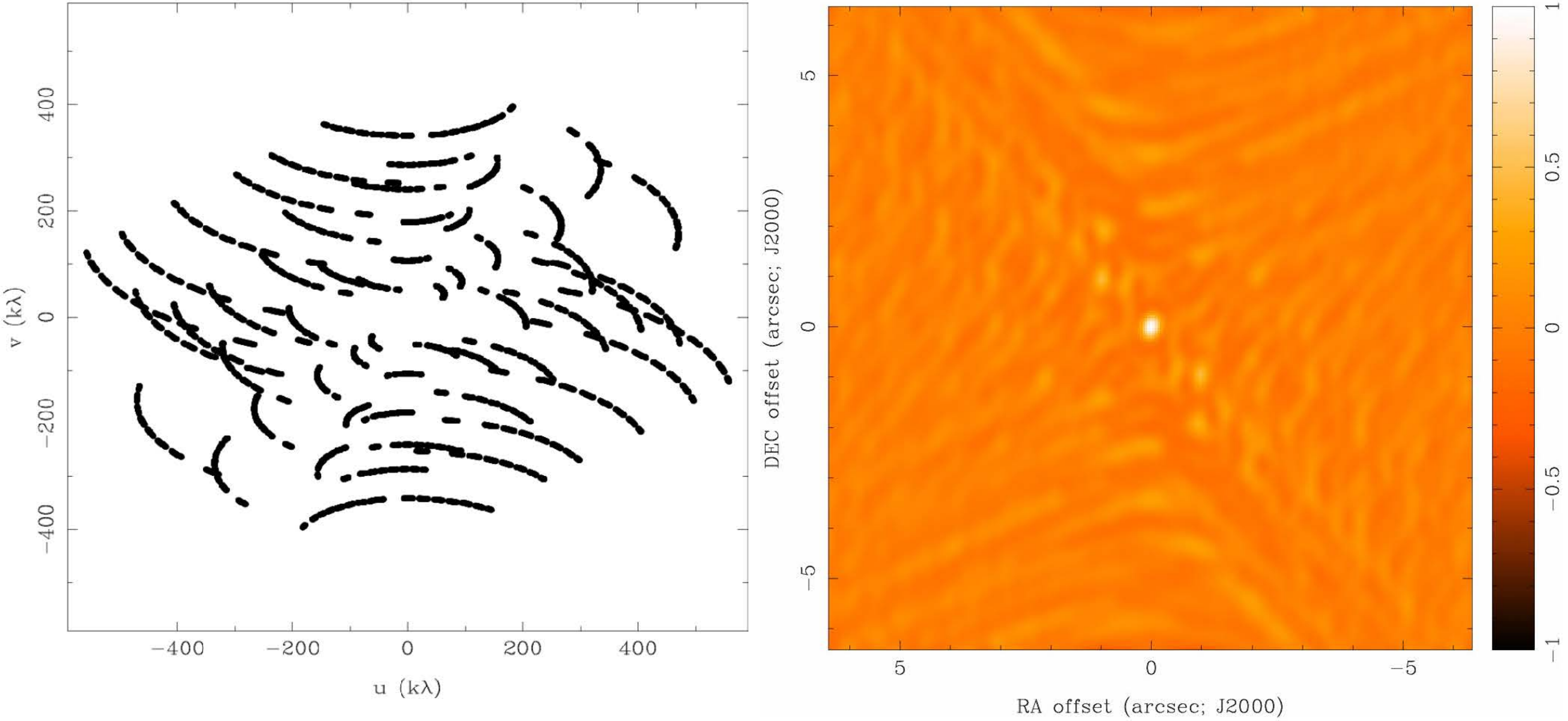
Dirty Beam Shape and N Antennas

8 Antennas x 120 Samples



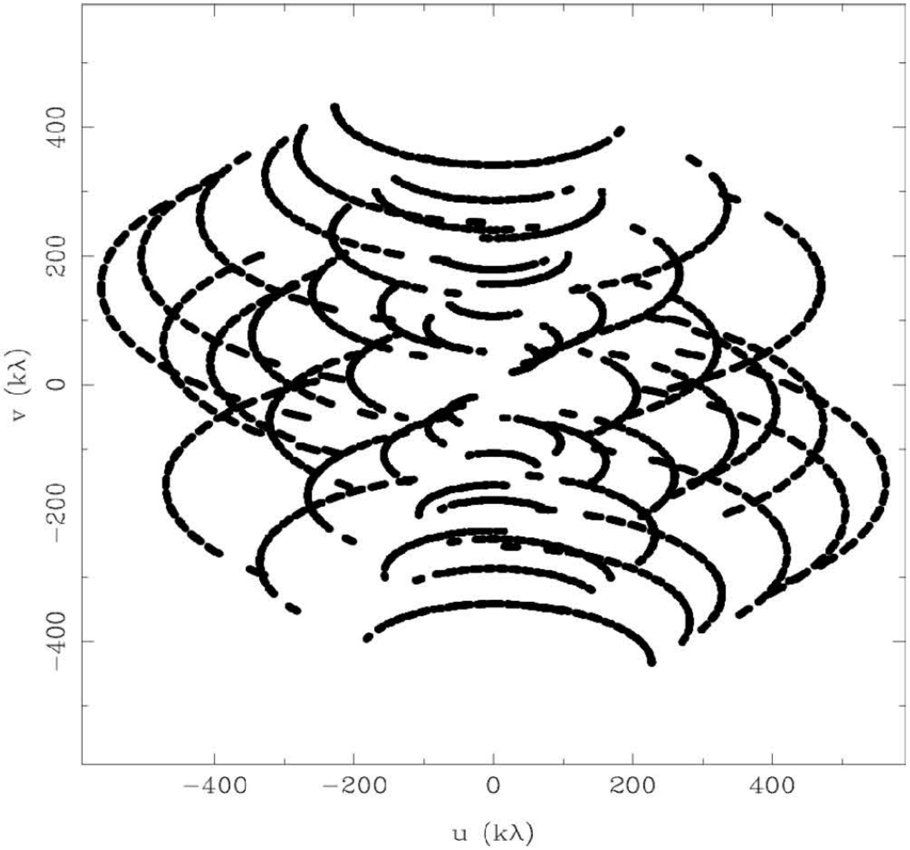
Dirty Beam Shape and N Antennas

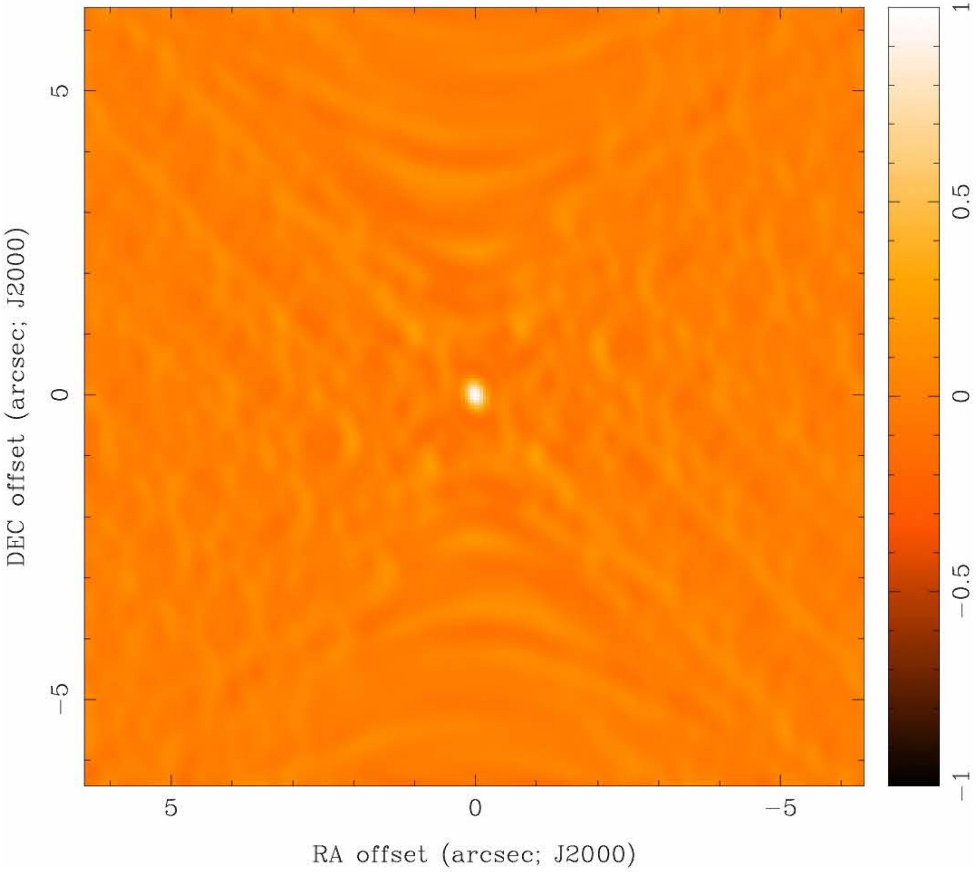
8 Antennas x 240 Samples



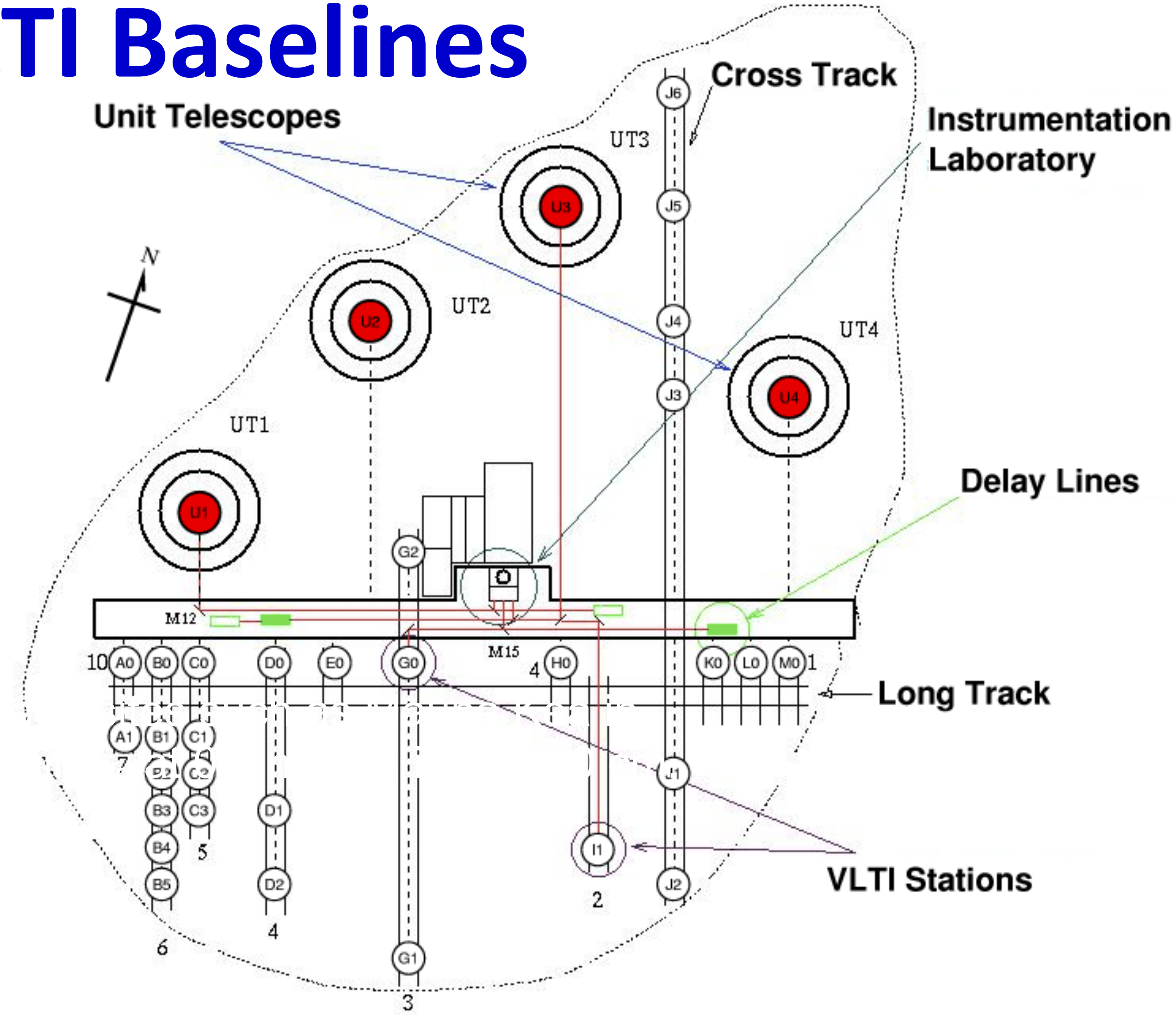
Dirty Beam Shape and N Antennas

8 Antennas x 480 Samples





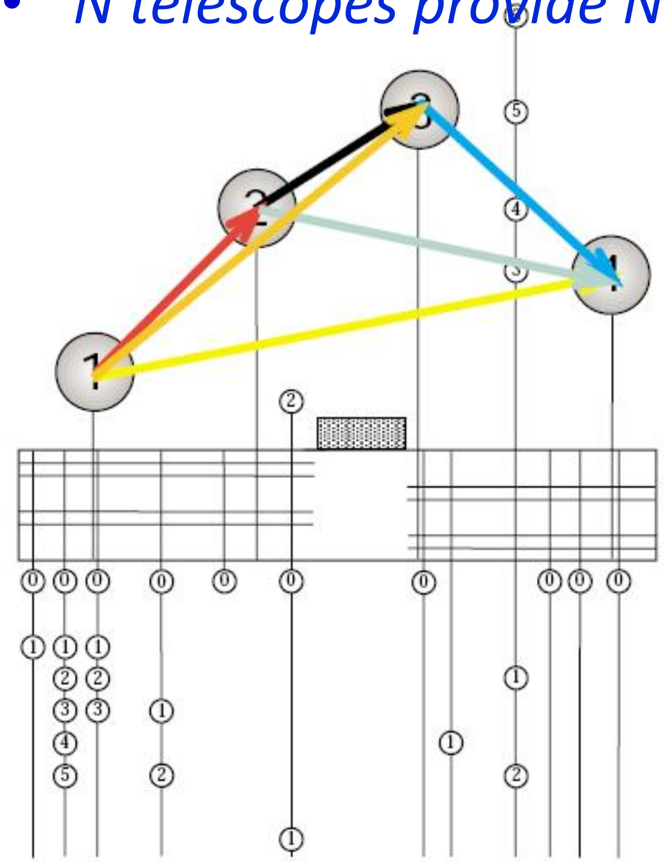
Optical: VLTI Baselines

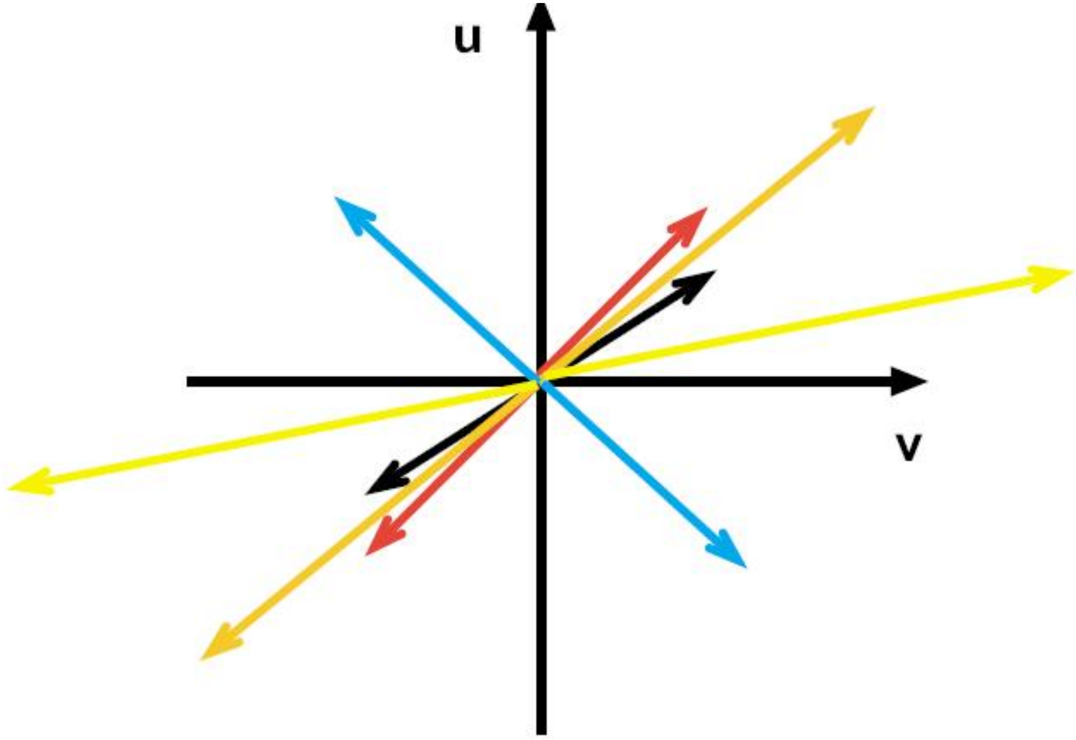


The three ATs move on rails between the thirty observing stations above the holes that provide access to the underlying tunnel system. The light beams from the individual telescopes are guided towards the centrally located, partly underground Interferometry Laboratory

Baseline Coverage (1)

- Smooth reconstruction of object's intensity distribution requires good coverage of (u,v) plane
- *N telescopes provide N(N-1)/2 baselines*

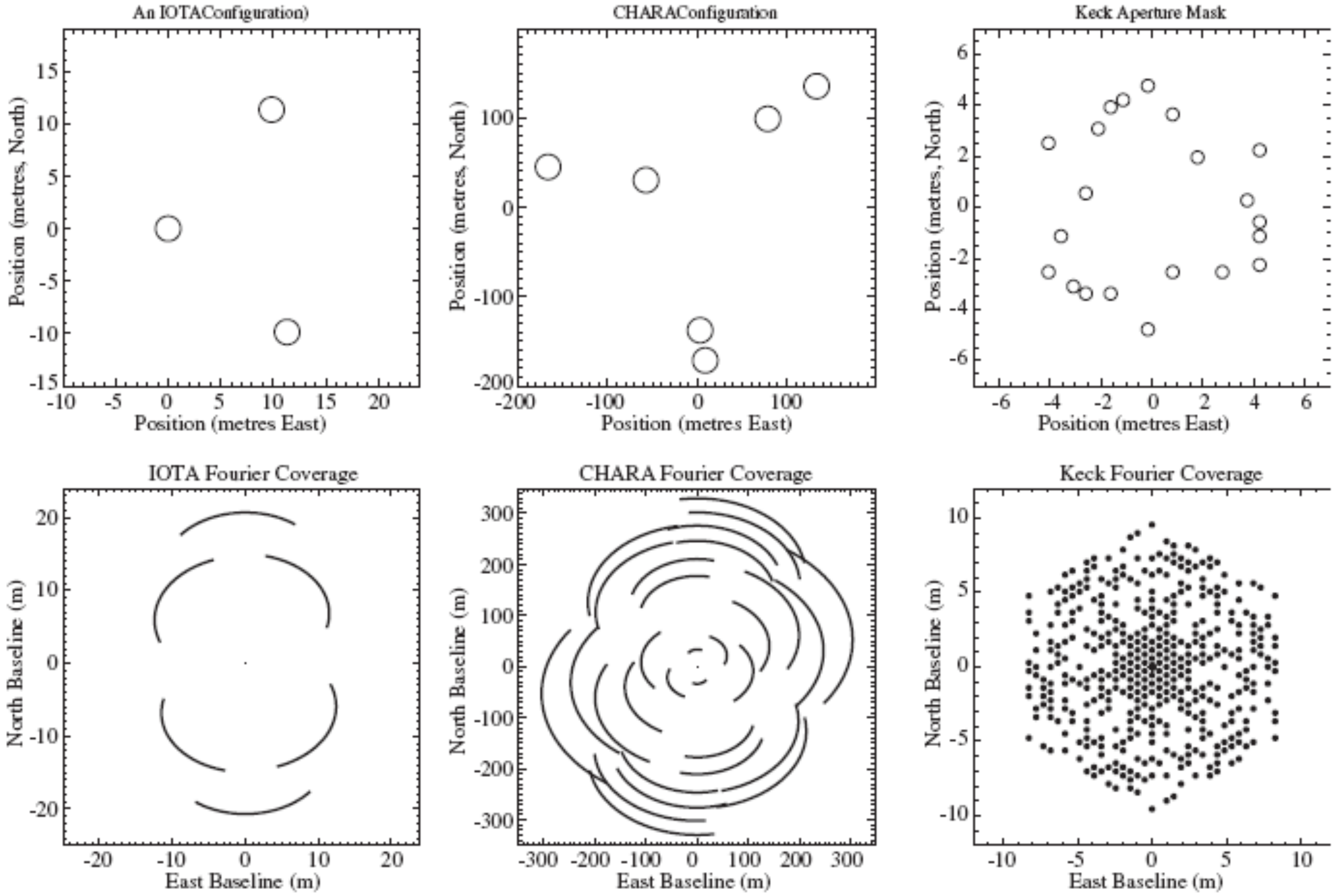




Note: This is the uv-plane for an object at zenith.
In general, the projected baselines have to be used.

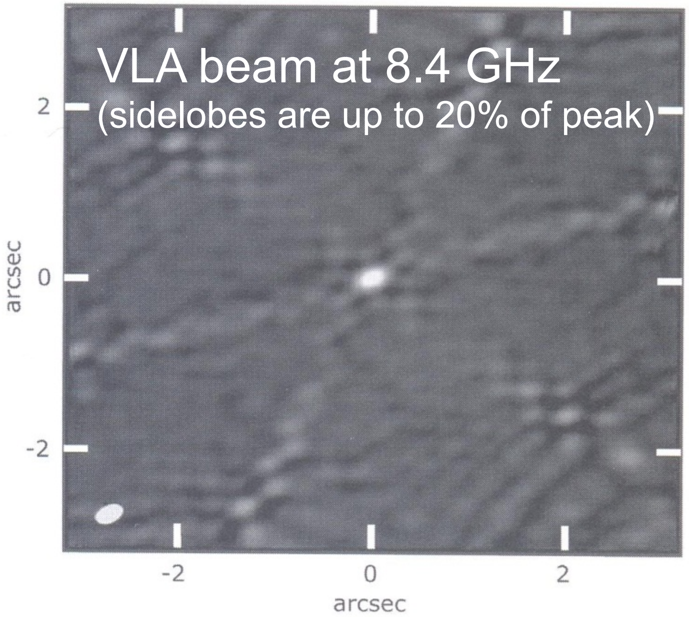
Baseline Coverage (2)

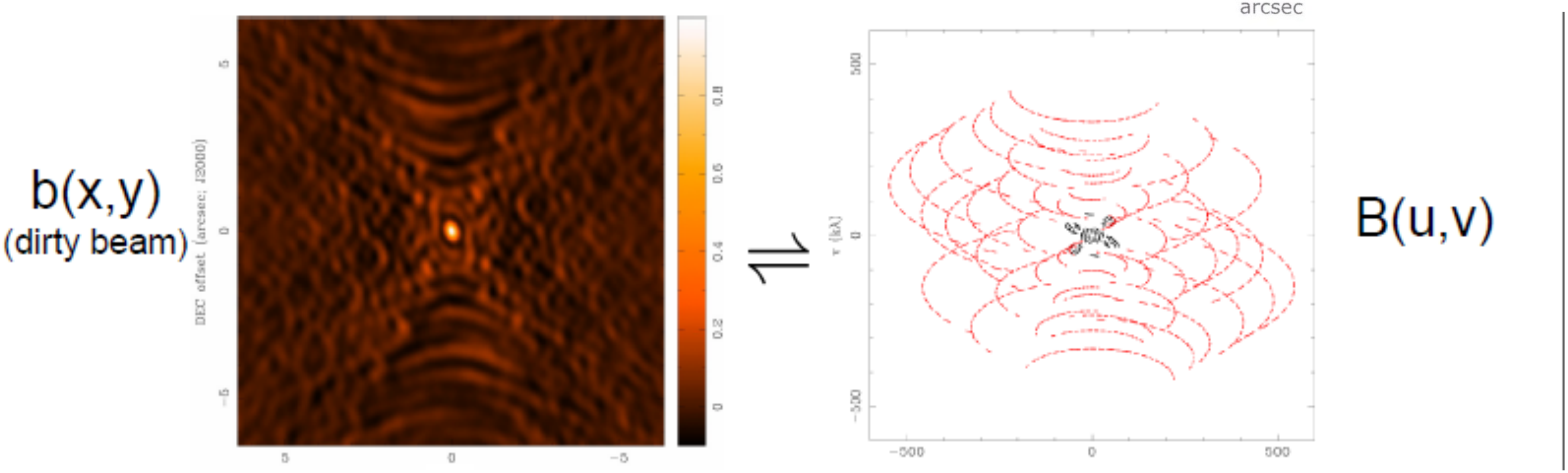
Earth's rotation helps to fill (u,v) plane. *Example: source at 45˚ declination, observed for 3 hr both before and after transit.*



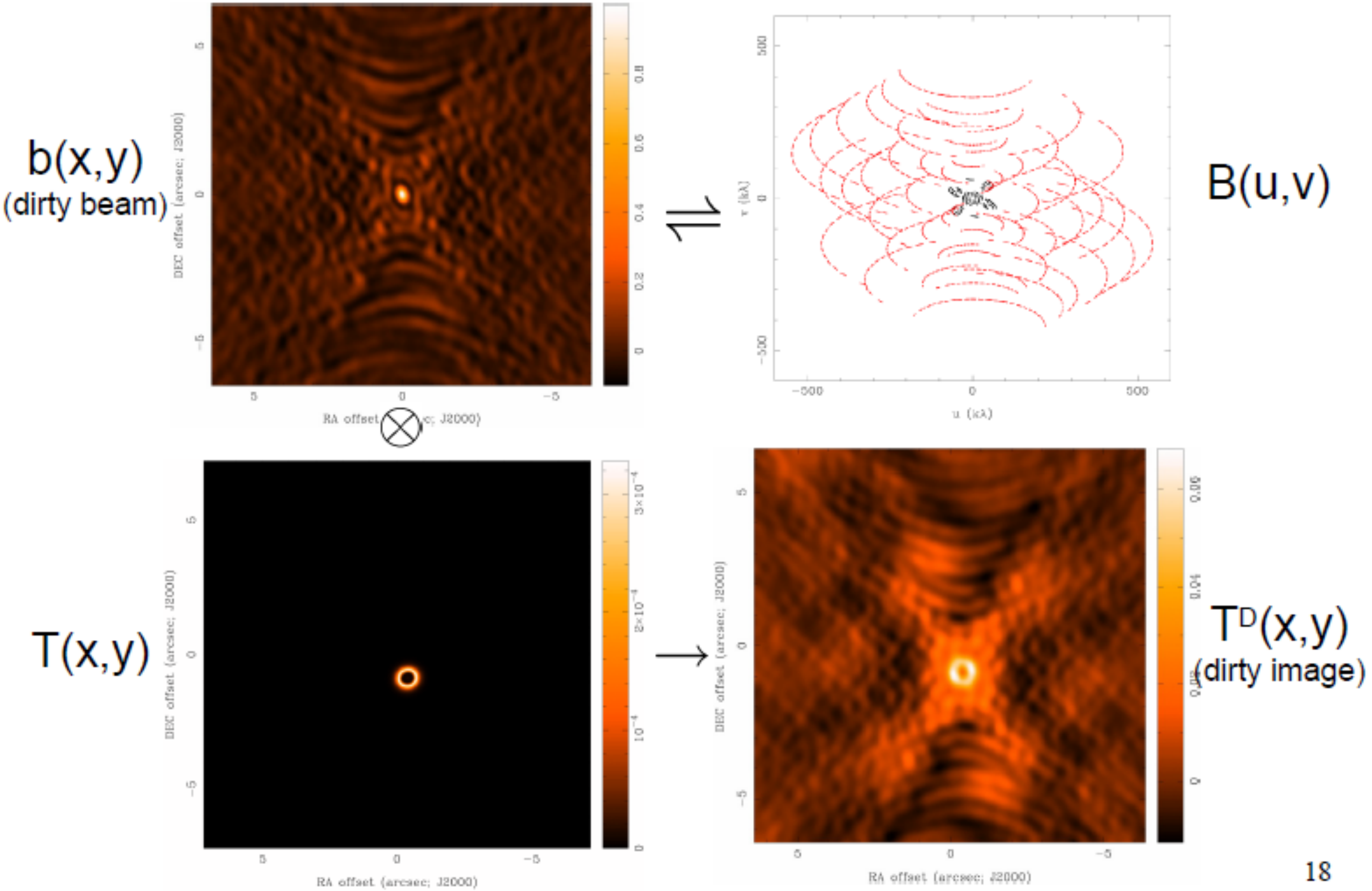
Dirty Beam and Dirty Image (1)

- interferometer array leave gaps in u,v-plane
- non-deal PSF: dirty beam
- dirty beam makes dirty image





Dirty Beam and Dirty Image (2)



b(x,y)
(dirty beam)

$\rightleftharpoons$

B(u,v)

$\otimes$

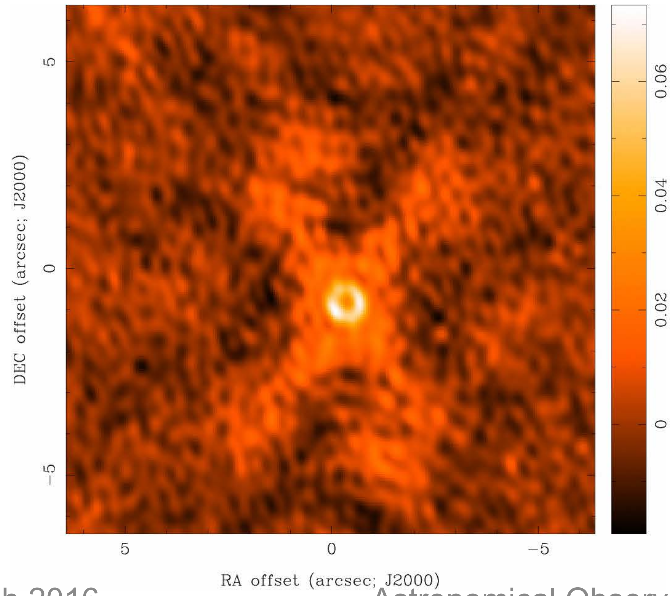
T(x,y)

$\rightarrow$

$T^D(x,y)$
(dirty image)

Deconvolution

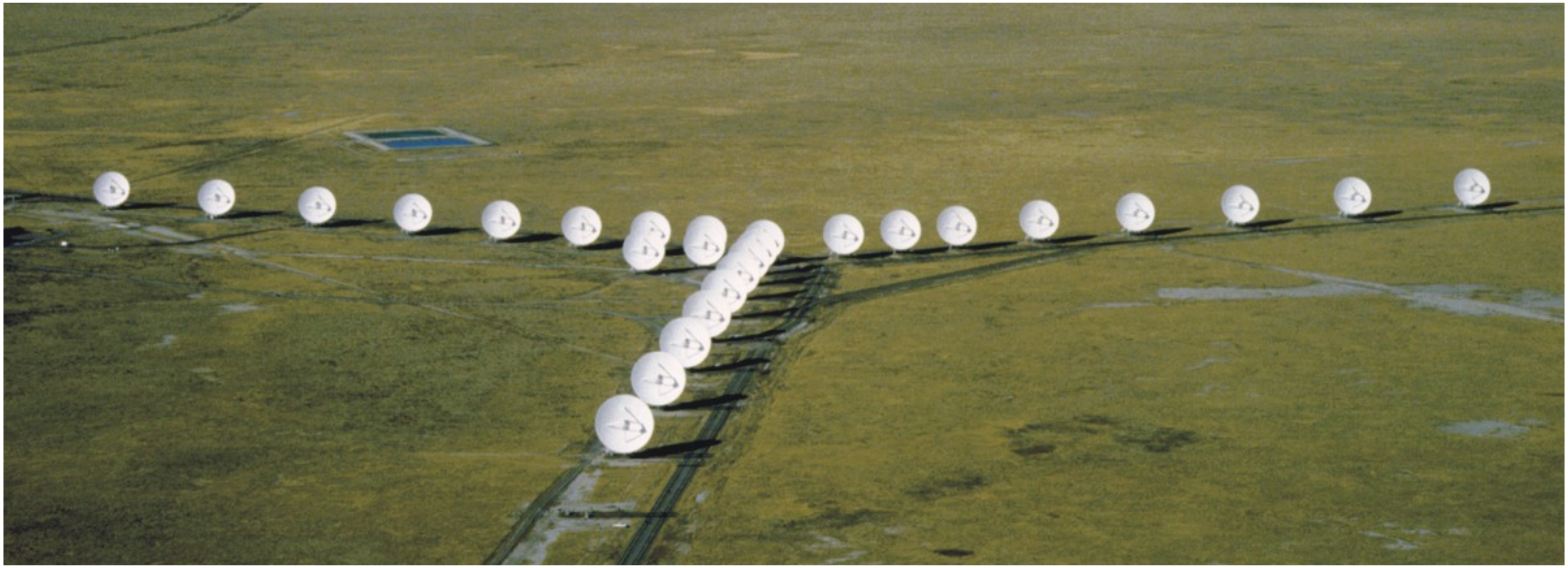
- difficult to do science with dirty image
- deconvolve b(x,y) from T^D(x,y) to recover T(x,y)
- information is missing and noise is present -> difficult problem


dirty image


“CLEAN” image

Very Large Array VLA

- Y-shaped array, 27 telescopes on railroad tracks
- 25-m diameter, San Augustin Plains, New Mexico
- configurations spanning 1.0, 3.4, 11, and 36 km



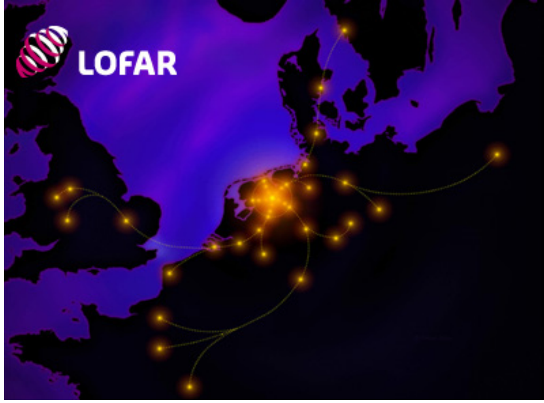
Australia Telescope Compact Array ATCA

Six 22 m telescopes on an east-west baseline

Westerbork

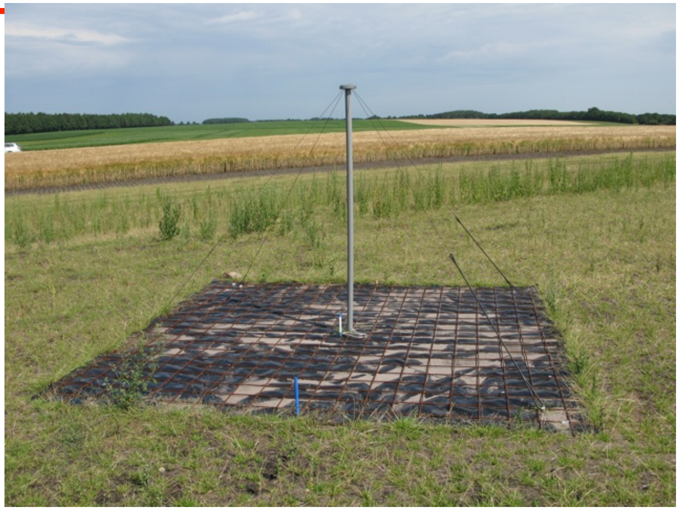
- Westerbork Synthesis Radio Telescope (WSRT)
- 14 telescopes
- 25-m diameter
- East-west baseline
- 3 km in length
- effective collecting area of a 92 m dish

LOFAR in the Netherlands



LOw Frequency ARray uses two types of low-cost antennas:

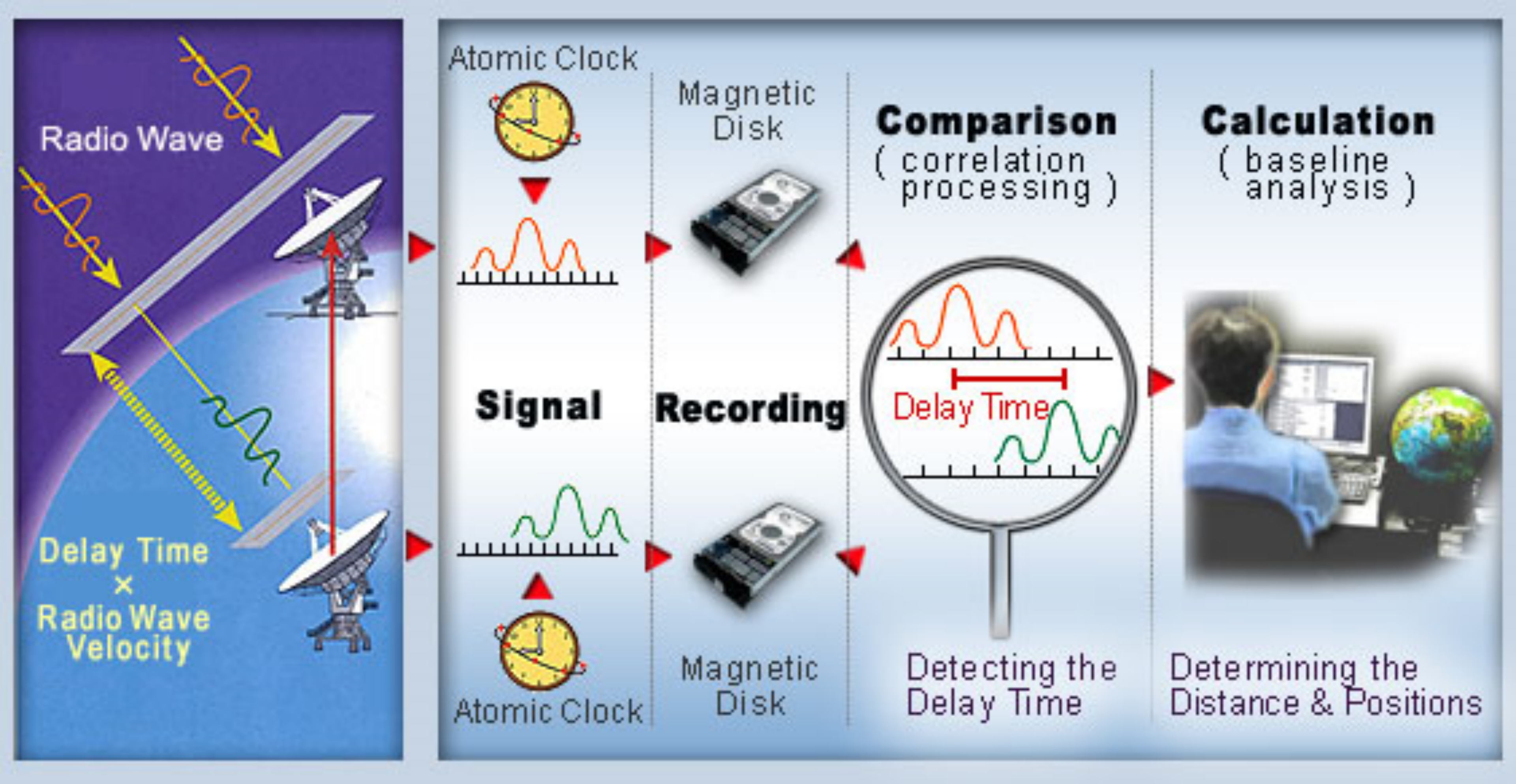
- Low Band Antenna (10-90 MHz)
- High Band Antenna (110-250 MHz)



Antennae are organized in 36 stations over ~100 km. Each station contains 96 LBAs and 48 HBAs

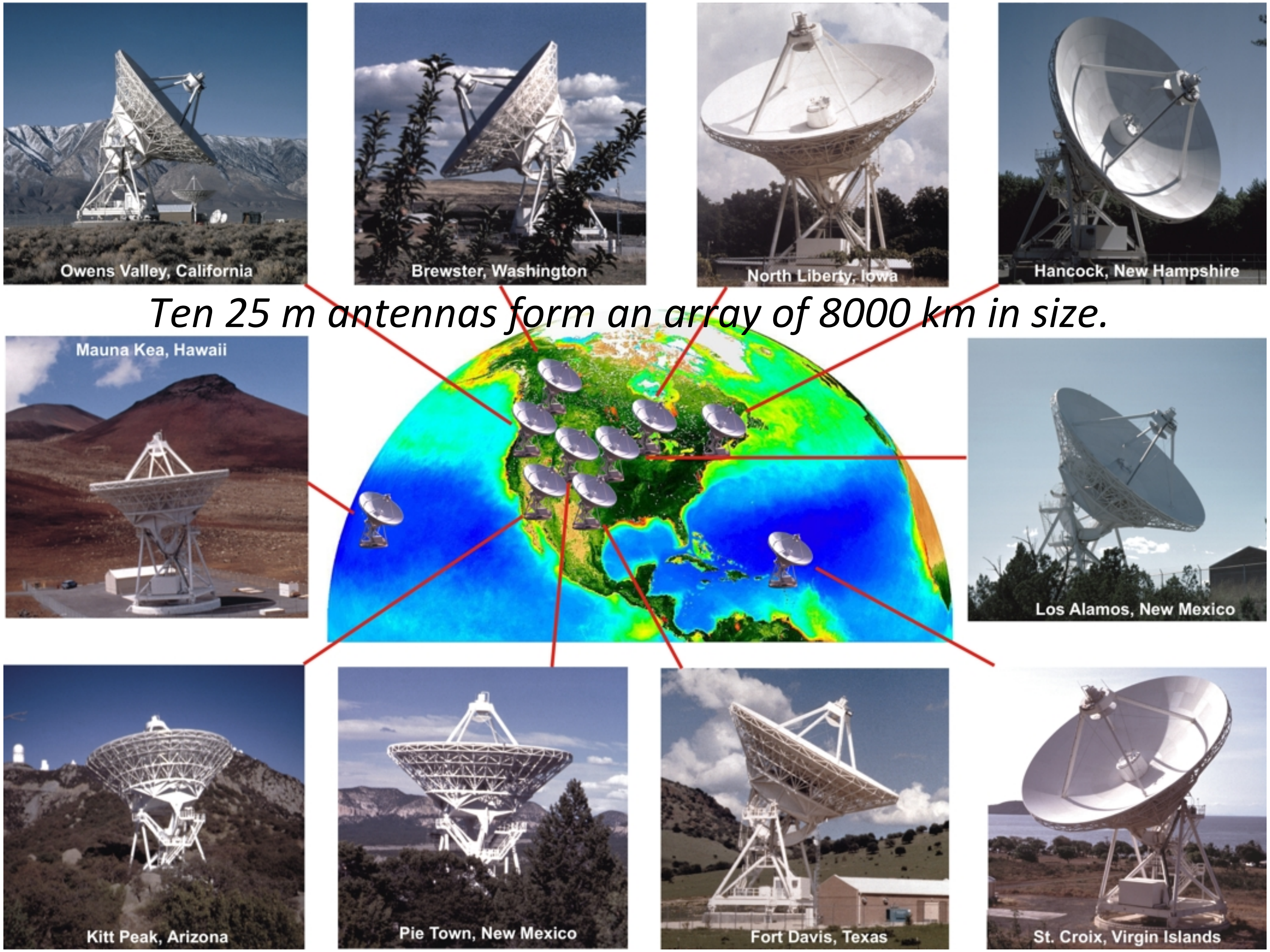
Baselines: 100m – 1500km

The Very Long Baseline Interferometer (VLBI) Technique



vldb.gsi.go.jp/sokuchi/vlbi/en/whatisvlbi/principle.html

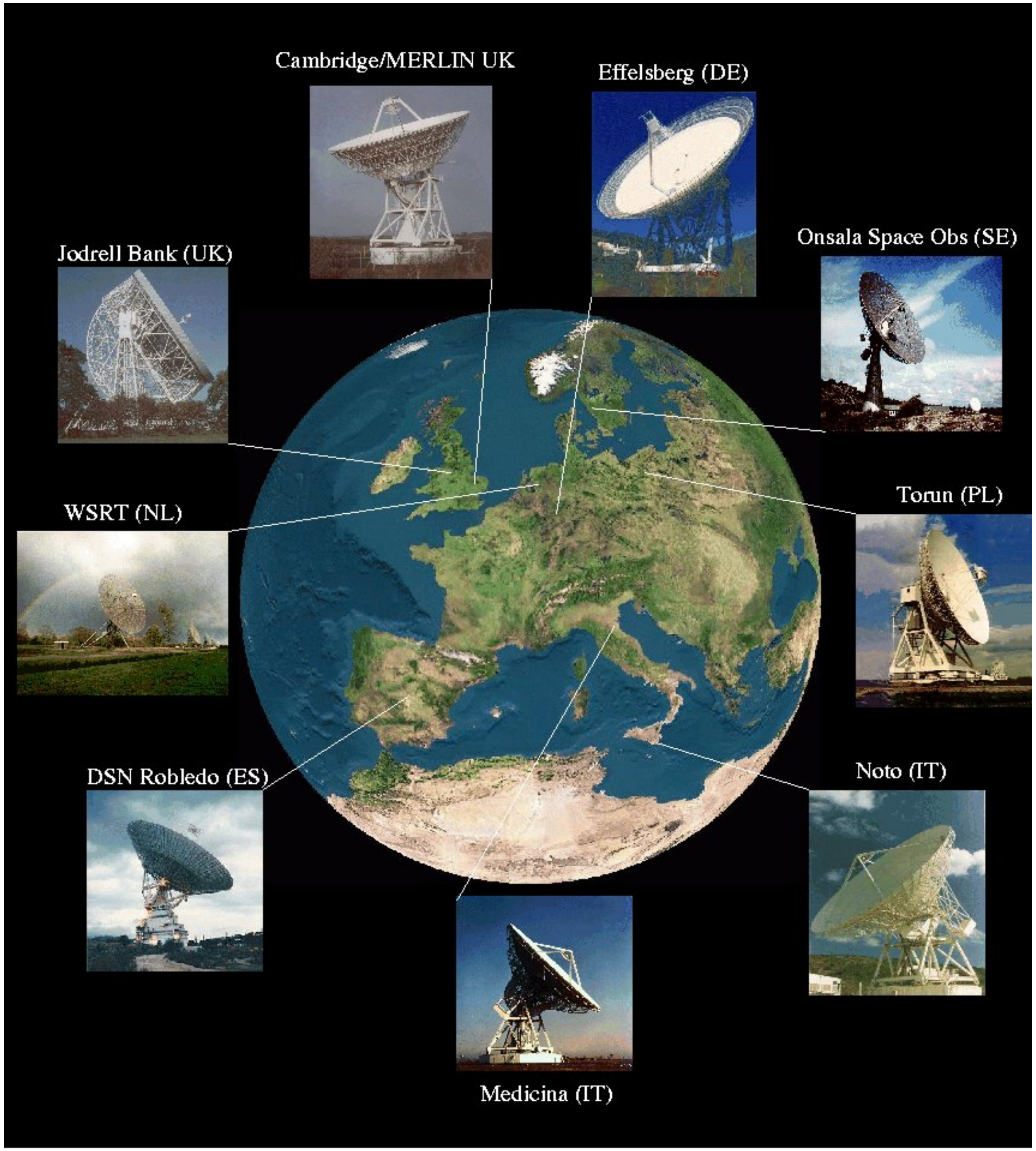
Very Long Baseline Array VLBA (USA)



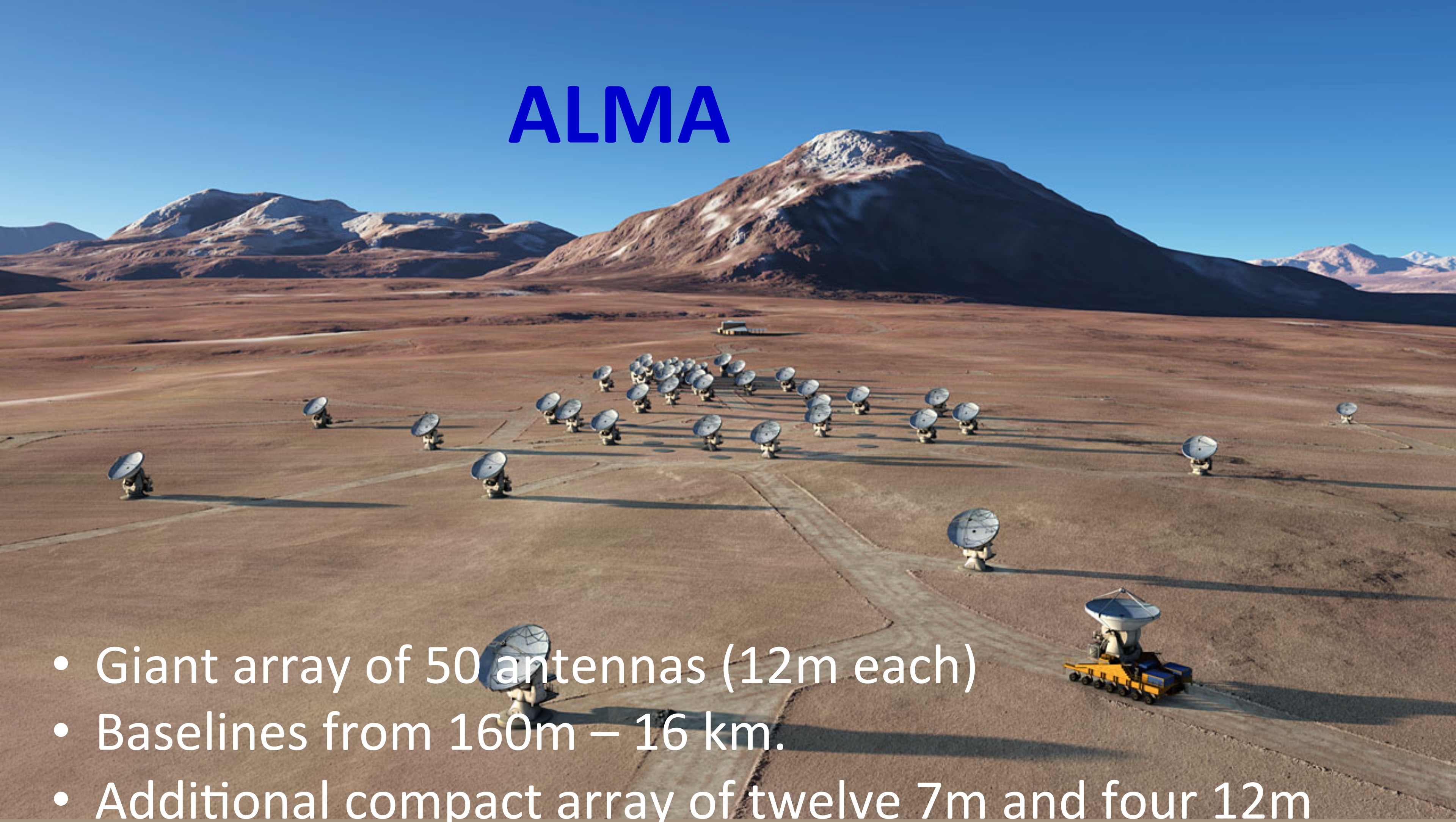
Ten 25 m antennas form an array of 8000 km in size.

VLBI in Europe: European VLBI Network (EVN)

- now possible to connect VLBI radio telescopes in real-time → e-VLBI
- In Europe, six radio telescopes of the EVN are now connected with Gbit/s-links
- Data processing in real time at the European Data Processing centre at JIVE (Astron/ Dwingeloo)



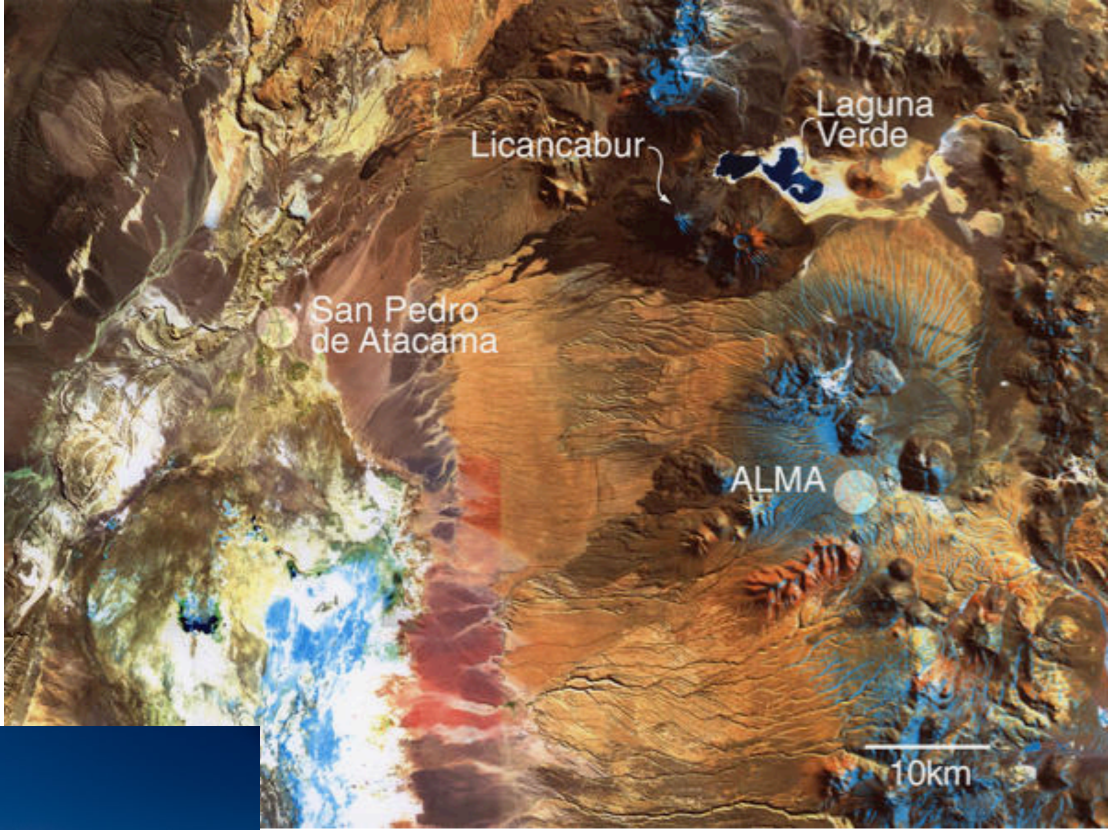
ALMA



- Giant array of 50 antennas (12m each)
- Baselines from 160m – 16 km.
- Additional compact array of twelve 7m and four 12m antennas
- Located on the Chajnantor plain at 5000m altitude
- Wavelength range 3 mm – 400 µm (84 to 720 GHz)

ALMA

- Frequencies: Band 3 (>84 GHz) to band 9 (<720 GHz).
- Field of view depends on antenna diameter and frequency
  - independent of array configuration!
  - FWHM of beam: 21" at 300 GHz
  - *uniform sensitivity over larger field requires mosaicking*
- Spatial resolution depends on frequency & maximum baseline
  - Most extended configuration (~16 km): 6 mas at 675 GHz
  - *Structures > $0.6»\lambda/b_{min}$ (b_{min}=shortest baseline) are not well reproduced in reconstructed images → measure with the ALMA Compact Array (ACA) using the 7-m antennae (come closer)*
- Spectral resolution: up to 8192 frequency channels (spectral resolution elements). At 110 GHz, R=30,000,000 or 10m/s velocity resolution.


Laguna Verde
Licancabur
San Pedro de Atacama
ALMA
10km