Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

13th Lecture: 17 December 2008

Based on: information provided by ESO on their public website, incl. tutorial by A. Glindemann; Rep. Prog. Phys. 66 (2003) 789–857 by J.D. Monnier, astro-ph/9609092v1 by T. Bedding; and ARA&A 30, 457-98 (1992) by M. Shao & M.M. Colavita.

Content:

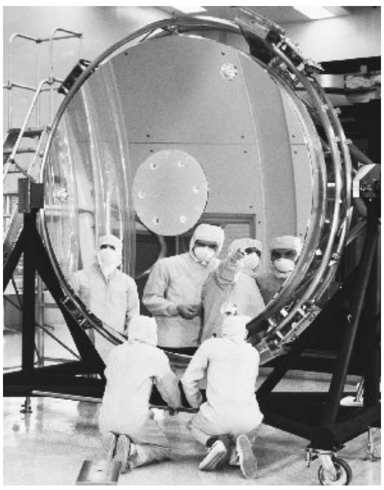
1. Basic Principle
2. Main Components of an Interferometer
3. Data from an Interferometer
4. Fundamental Limitations
5. Baselines and 2D Imaging
6. Interferometry (Radio) Projects

Basic Principle

The Basic Idea

Angular resolution $\theta = 1.22 \frac{\lambda}{D}$

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

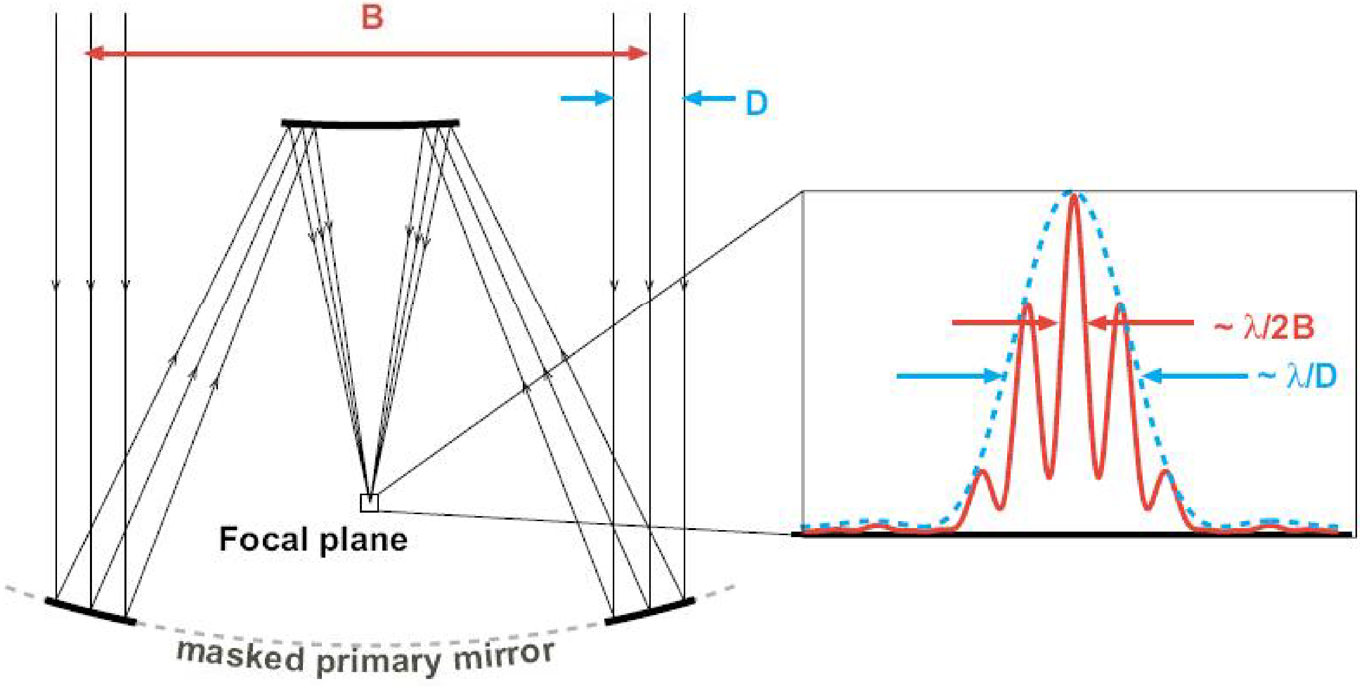


Angular resolution is determined by interference; interference does not need a continuous aperture (see Young's double slit experiment)!

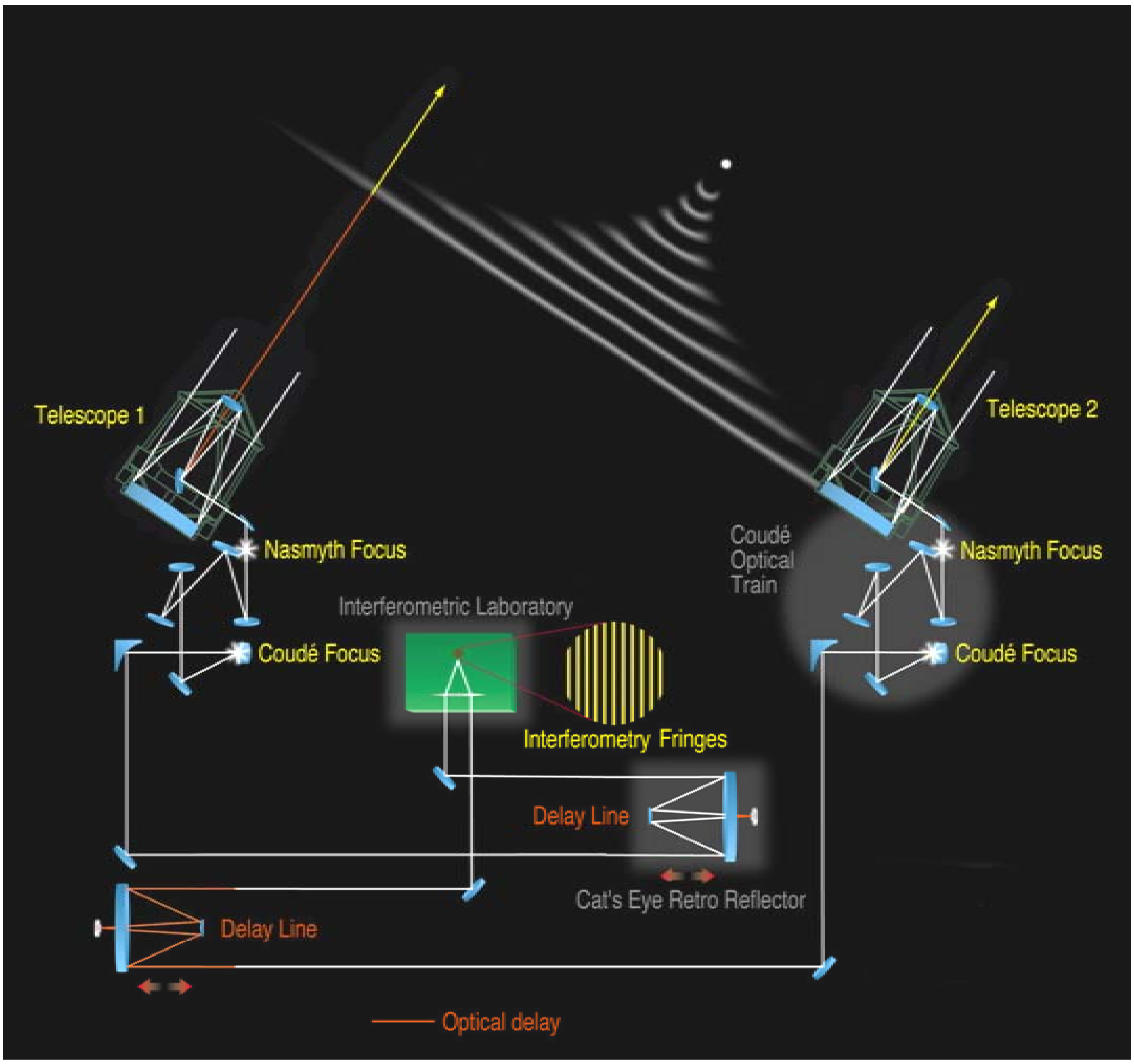
→ *Hippolyte Fizeau (1868): basic concept of stellar interferometry*

The Consequence

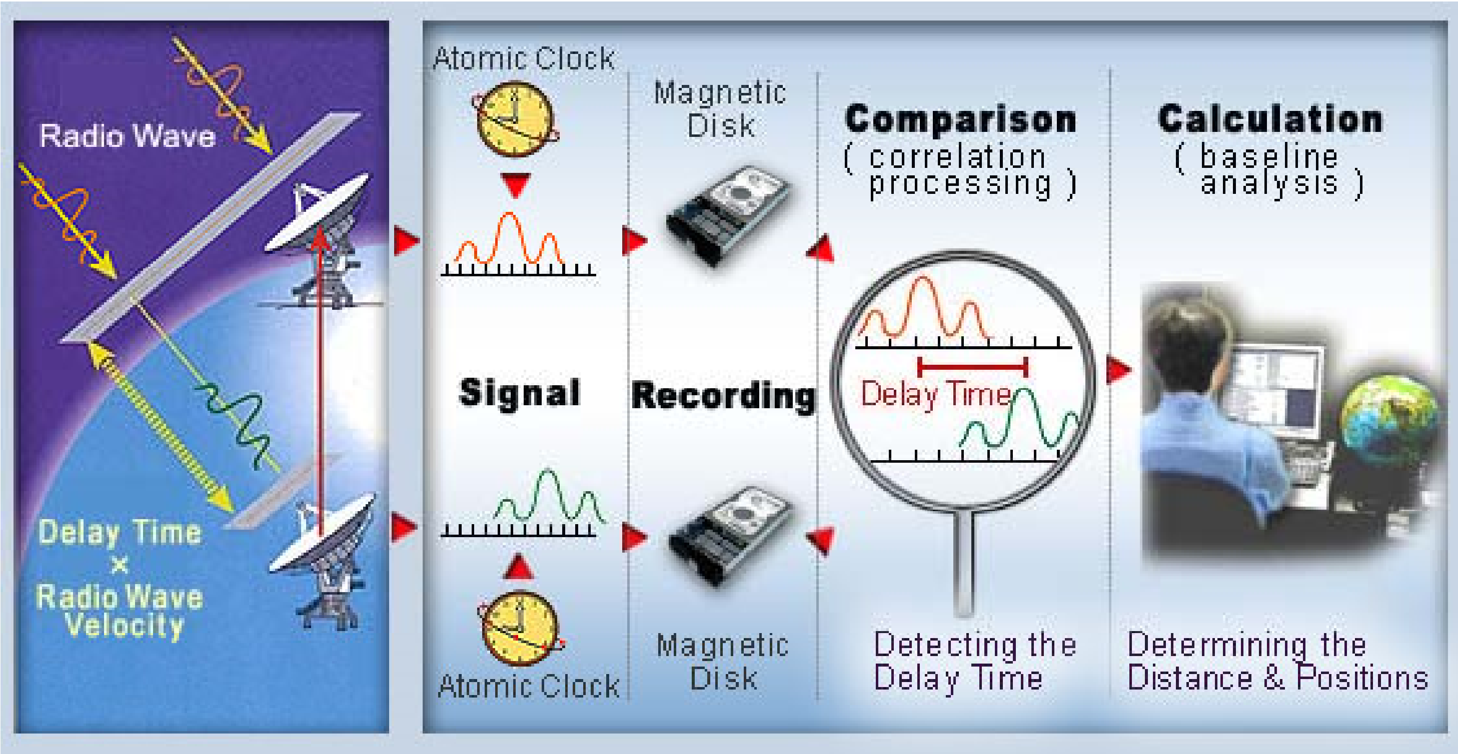
Interferometry is like masking a giant telescope:



The Basic Principle - Optical



The Basic Principle – VLBI



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

Types of Interferometers (from Wikipedia)

* Astronomical interferometer
* Classical interference microscopy
* Cyclic interferometer
* Diffraction-grating interferometer
* Double-slit interferometer
* Fabry-Perot interferometer
* Fizeau interferometer
* Fourier-transform interferometer
* Fresnel inteferometer
* Fringes of Equal Chromatic Order inteferometer
* Gabor hologram
* Gires-Tournois etalon
* Heterodyne interferometer (see heterodyning)
* Holographic interferometer
* Linnik interferometer (microscopy)
* Mach-Zehnder interferometer
* Martin-Puplett interferometer
* Michelson interferometer
* Mirau interferometer
* Moire interferometer
* Multi-beam interferometer
* Near-field interferometer
* Newton interferometer
* Nonlinear Michelson interferometer
* Phase-shifting interferometer
* Planar lightwave circuit (PLC) interferometer
* Polarization inteferometer
* Point diffraction interferometer
* Rayleigh Interferometer
* Sagnac interferometer
* Schlieren inteferometer
* Shearing interferometer
* Twyman-Green interferometer
* Talbot Lau interferometer
* Watson interferometer
* White-light interferometer
* White-light scatterplate interferometer
* Wedge interferometer
* Young's double-slit interferometer
* Zernike phase contrast microscope

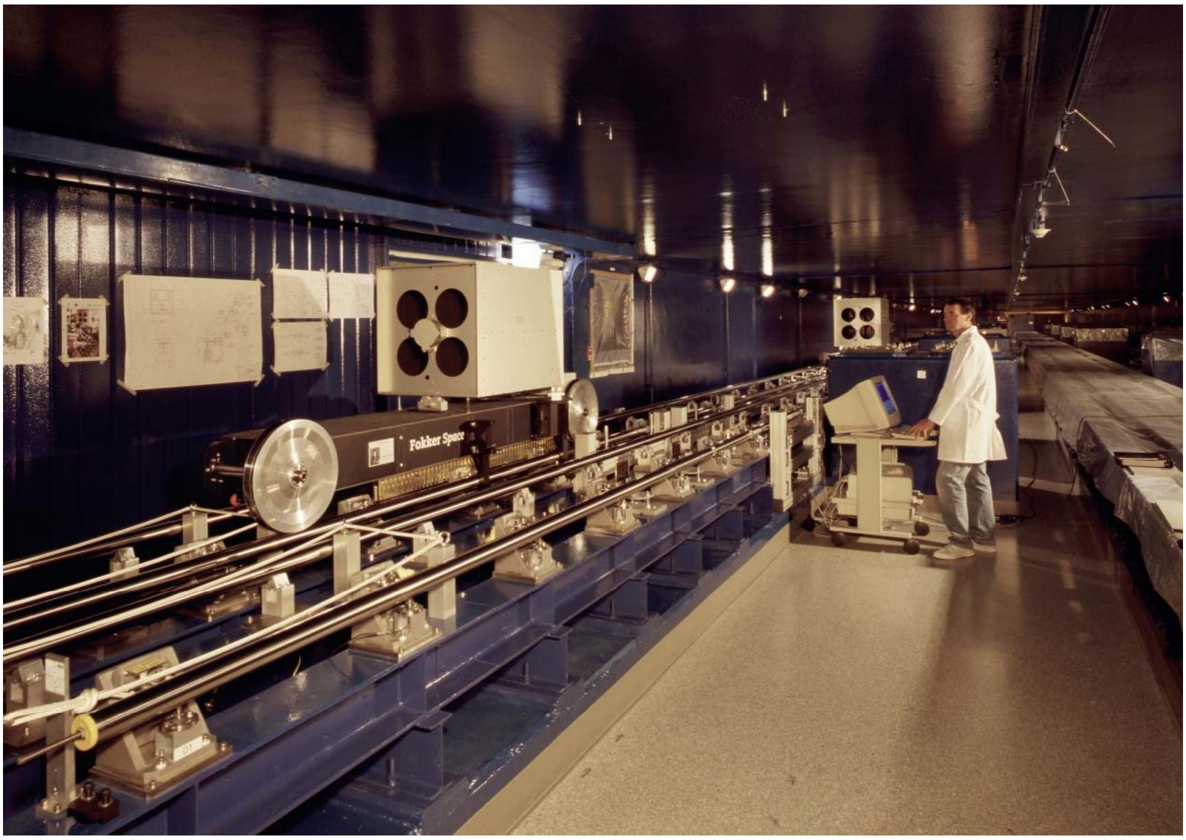
Main Components

Main Components: 1) Telescopes

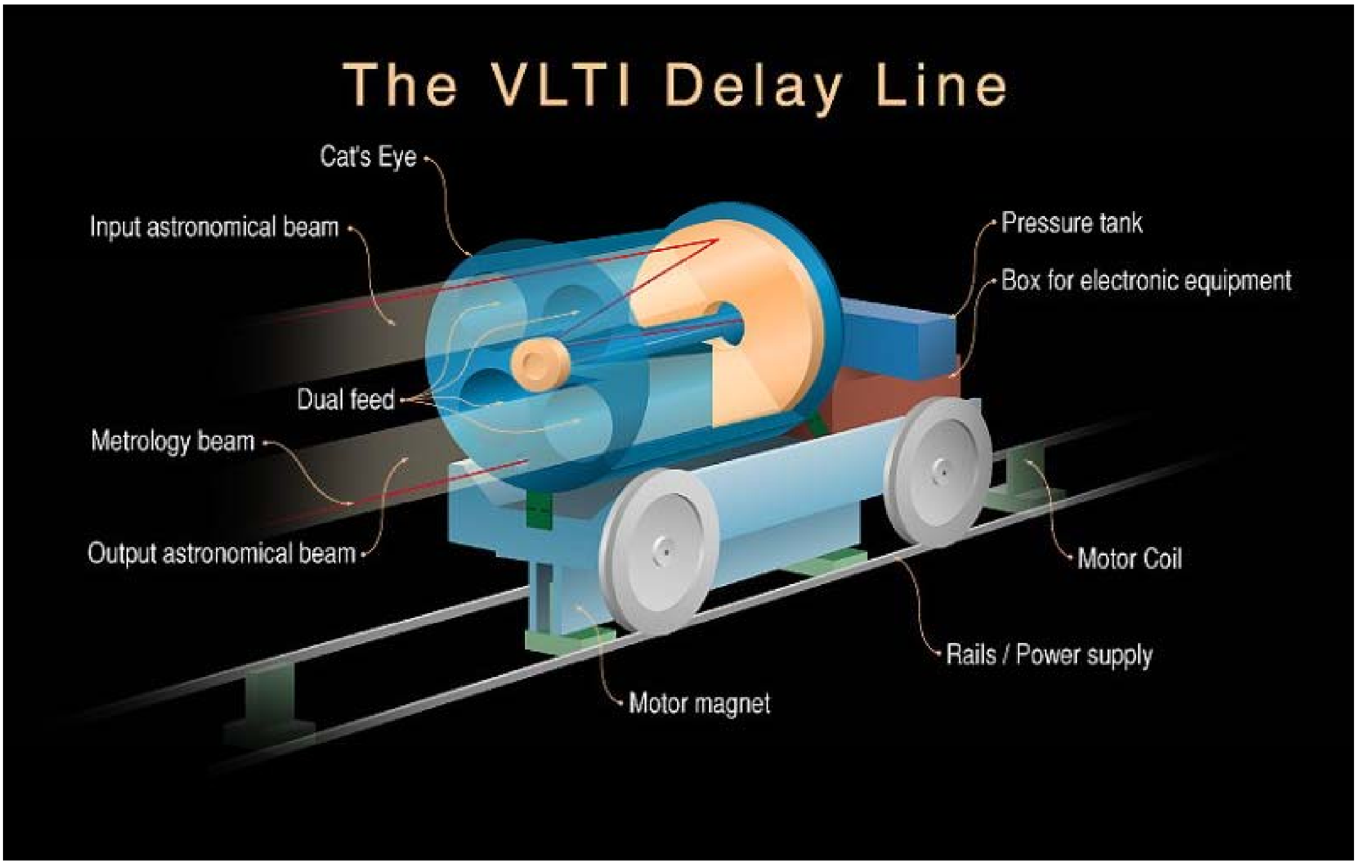
An optical interferometer typically consists of n telescopes of similar type and characteristics

Main Components: 2) Delay Lines

Delay lines are needed to compensate the optical path difference between the various telescopes (depends on object location on the sky)



Delay Lines cont'd



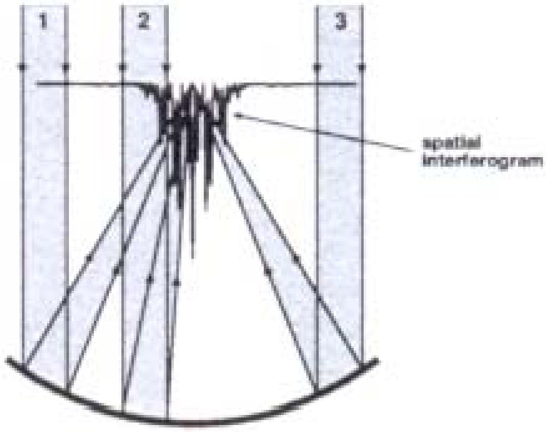
Challenge: travel over tens of meters, positioning to fractions of micrometers ➔ dynamic range of > 10^9 !

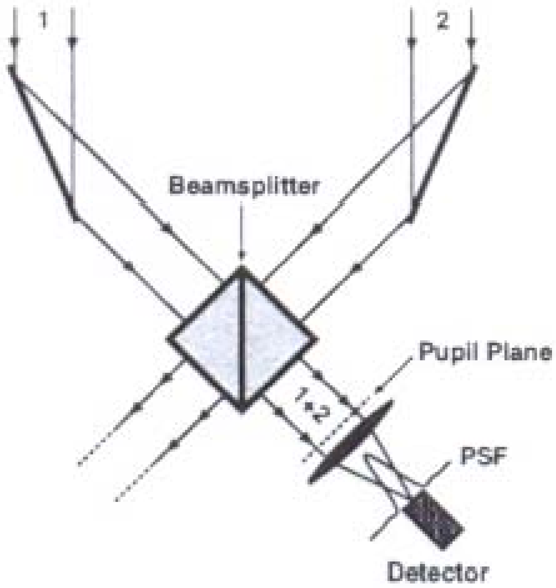
Main Components: 3) Beam Combiner

Two main types:

• multi-axial (image plane) (left): beams are place adjacent to each other and form a fringe pattern in space.

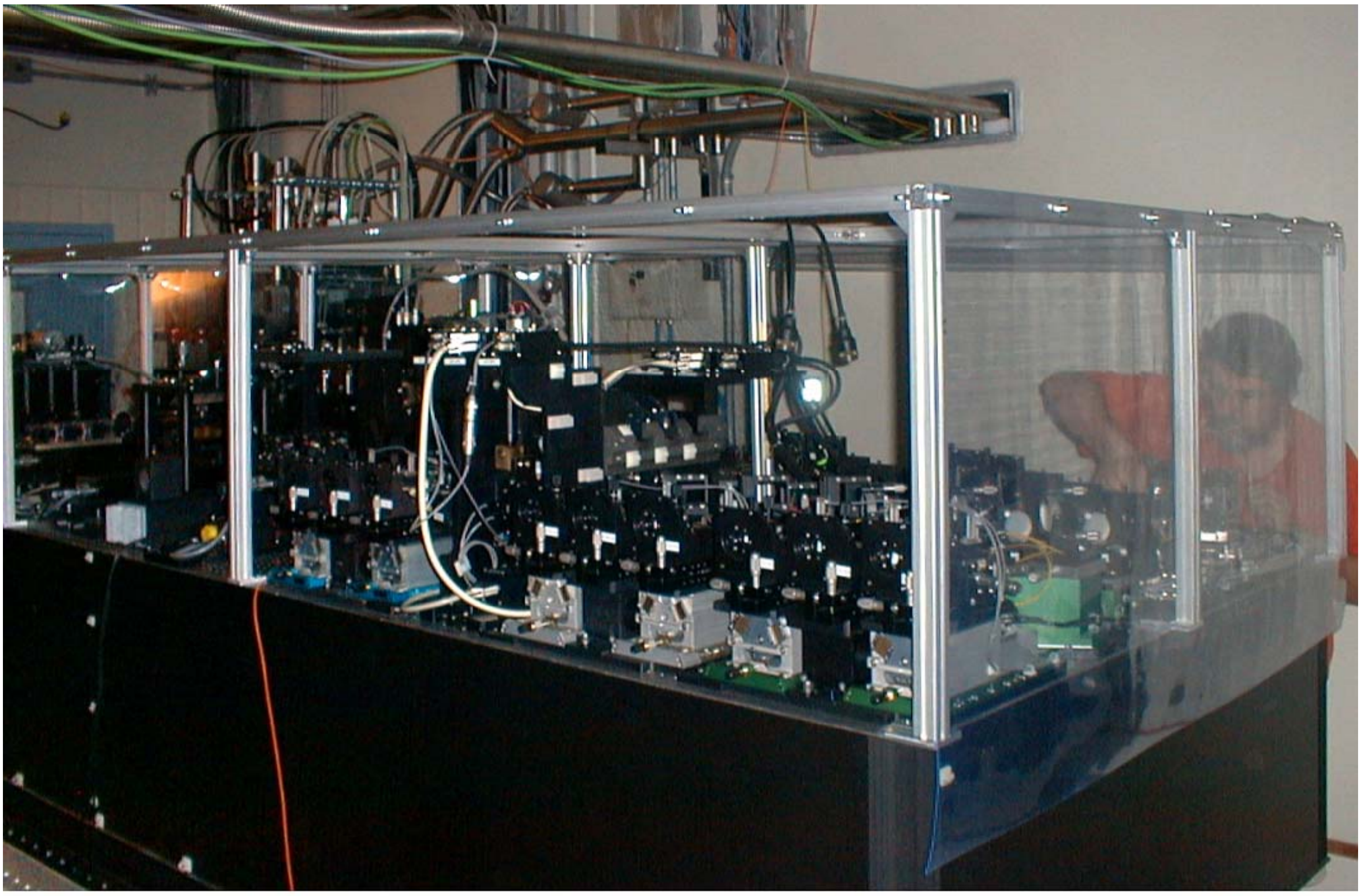
• co-axial (pupil plane) (right): beams are added on top of each other e.g. via a beam splitter.





• but also single-mode fibers and integrated optics.

Beam Combiner cont'd



The AMBER Instrument at the VLT Interferometer

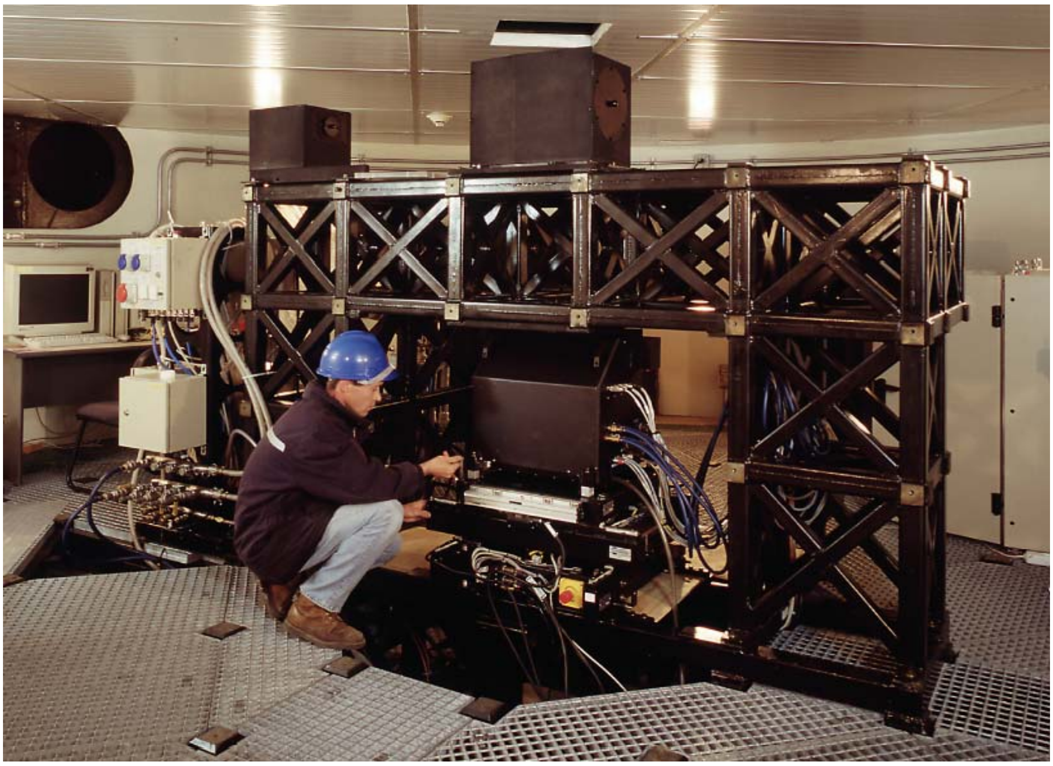
Main Components: 4) Adaptive Optics

Adaptive optics (or for telescopes with $D < r_0$ tip-tilt correction) is essential to correct wavefront aberrations for good interference.

The amplitude of the fluctuations is: $\sigma = \sqrt{6.88 \left(\frac{B}{r_0} \right)^{5/6}}$ rads RMS

Hence, for a baseline B = 100m and a seeing of 1″ this amounts to 70μm!

Adaptive Optics cont'd



The MACAO (Multi Application Curvature Adaptive Optics) system on a 8m VLT. Can be used with natural guide stars with $1 < V < 17$, seeing < 1.5", $\tau_0 > 1.5$ms and airmass < 2. The ATs are equipped with STRAP (System for Tip/tilt Removal with Avalanche Photodiodes) units, which provide tip-tilt correction for targets brighter than V=13.5.

Data from an Interferometer

Fringe Visibility – Defintion

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

It is the Fourier transform of the object's brightness distribution.

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

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

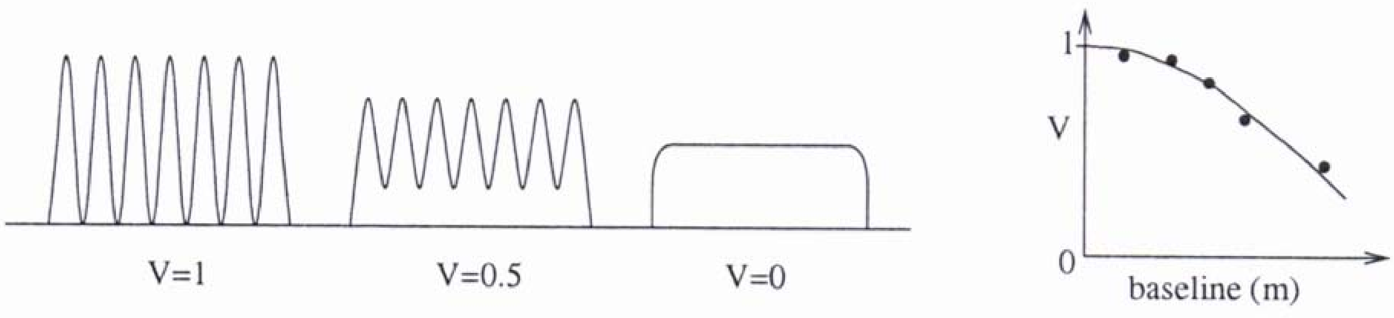
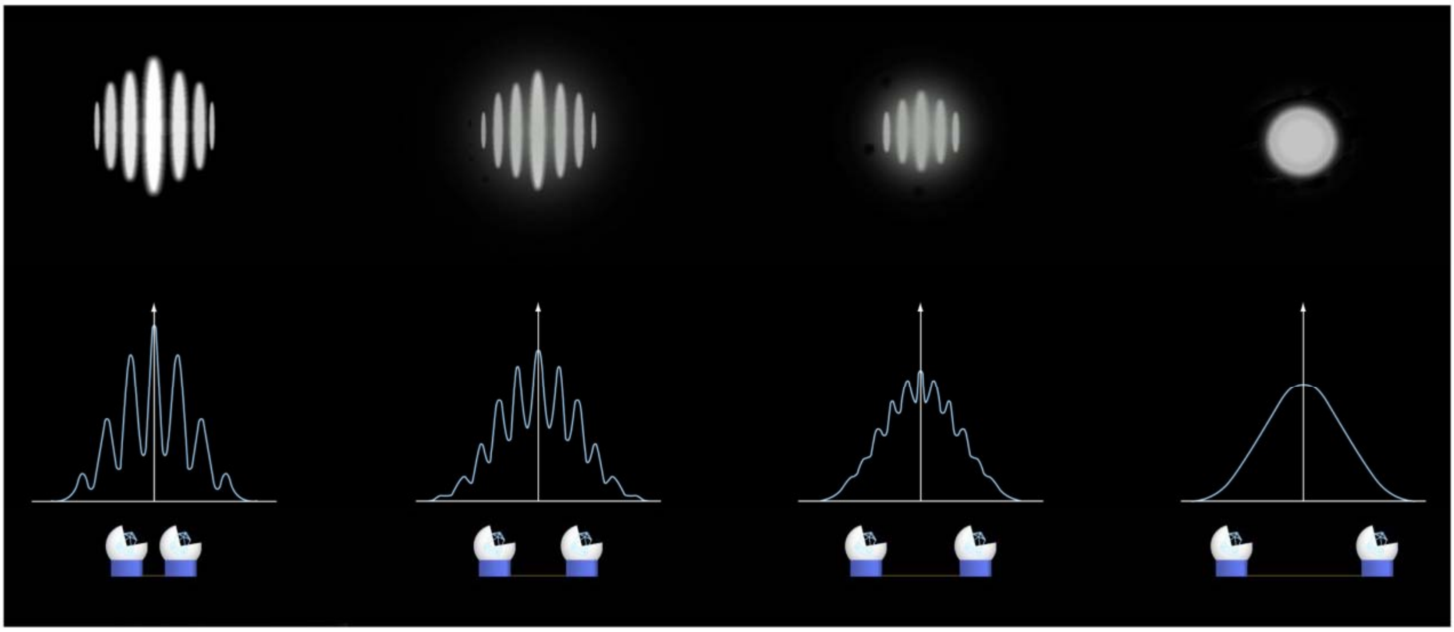


Fig. 2. Left: examples of fringes with visibilities of 1, 0.5 and 0. Right: visibility as a function of baseline for a resolved star.

Fringe Visibility – Baseline

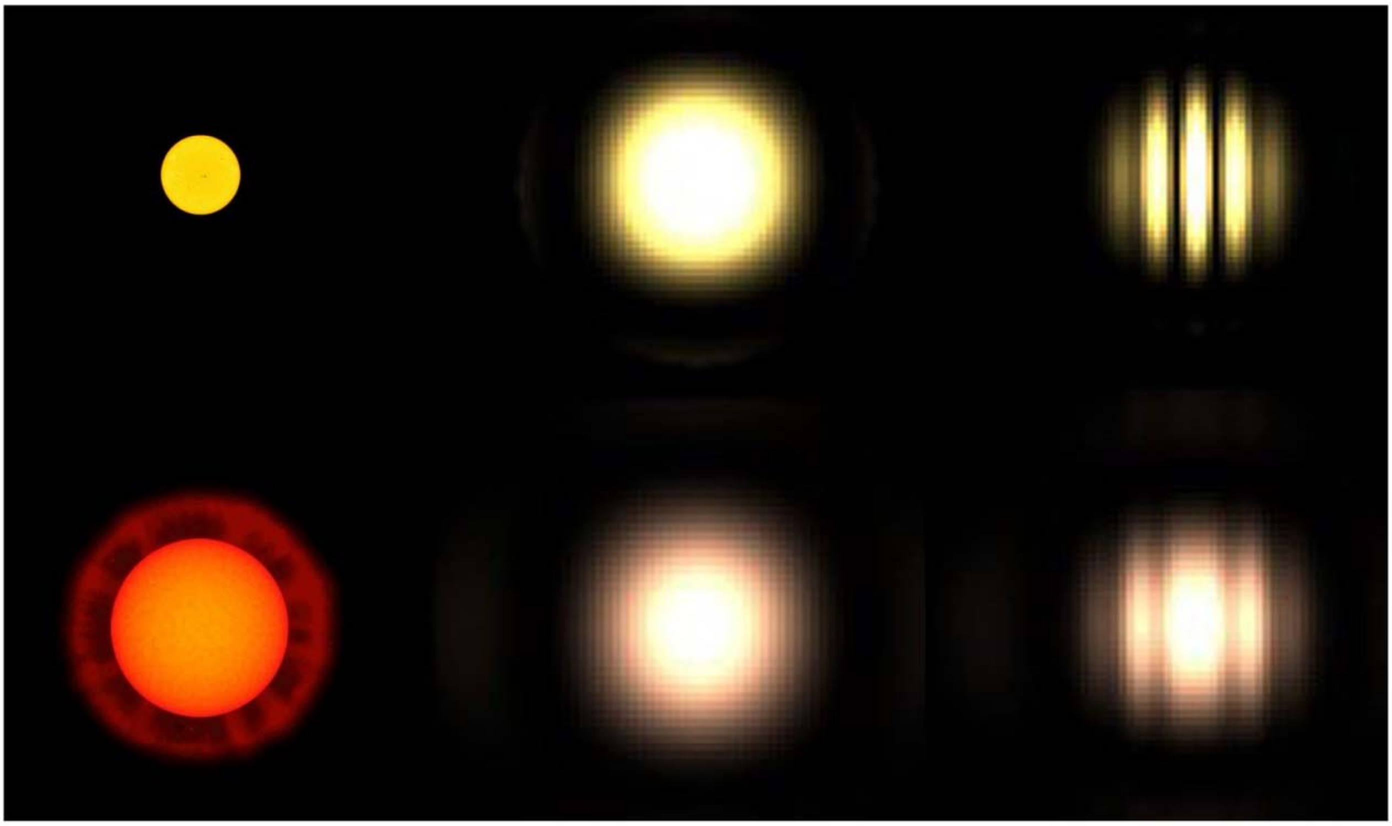


Interferometric Fringes at Different Telescope Baselines
(Simulation)

ESO PR Photo 10e/01 (18 March 2001) © European Southern Observatory

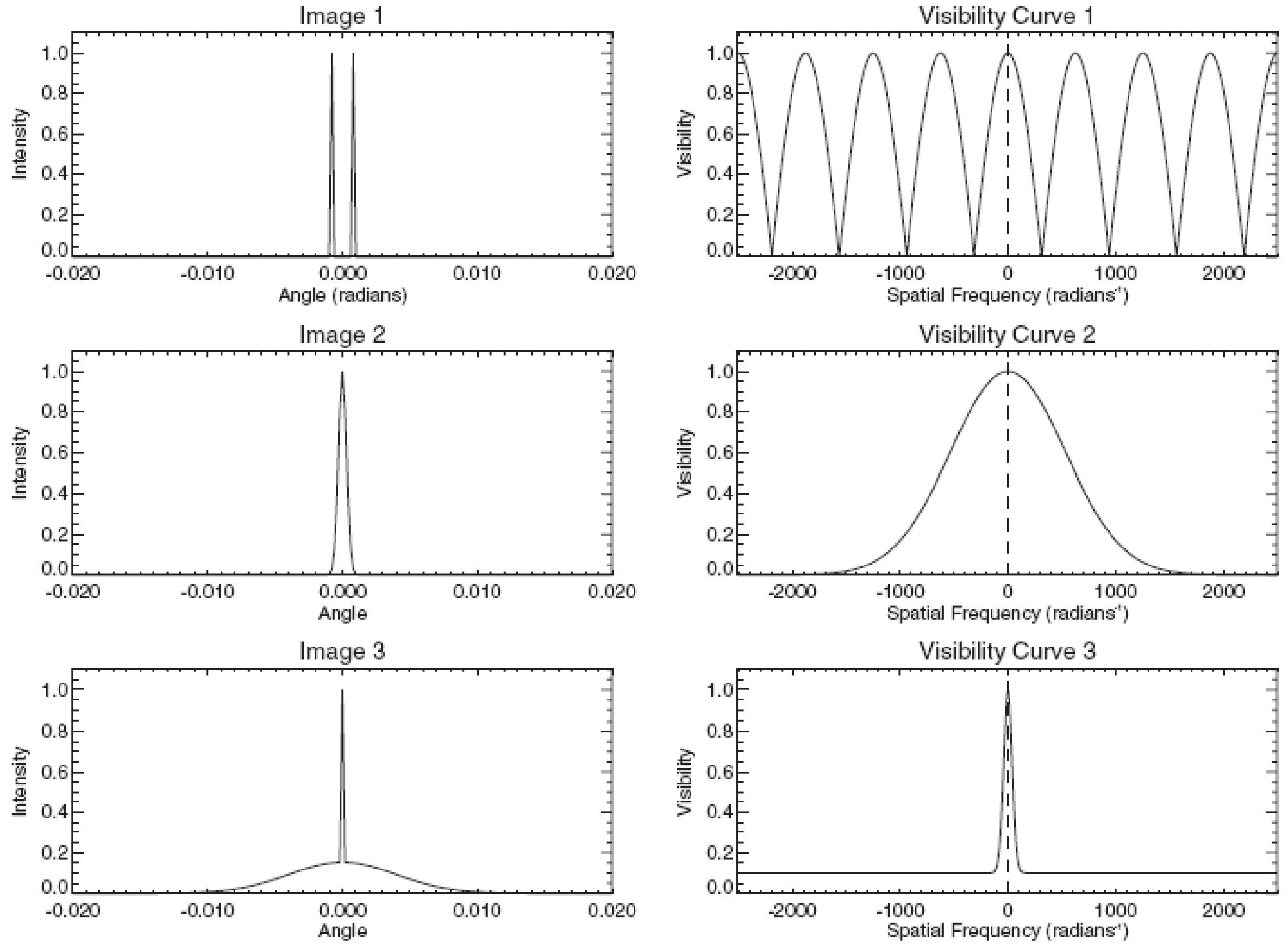
The observed pattern from a single star at the focal plane clearly changes as the distance between the two telescopes is gradually increased. The "fringes" disappear completely when the star is resolved.

Fringe Visibility – Resolution

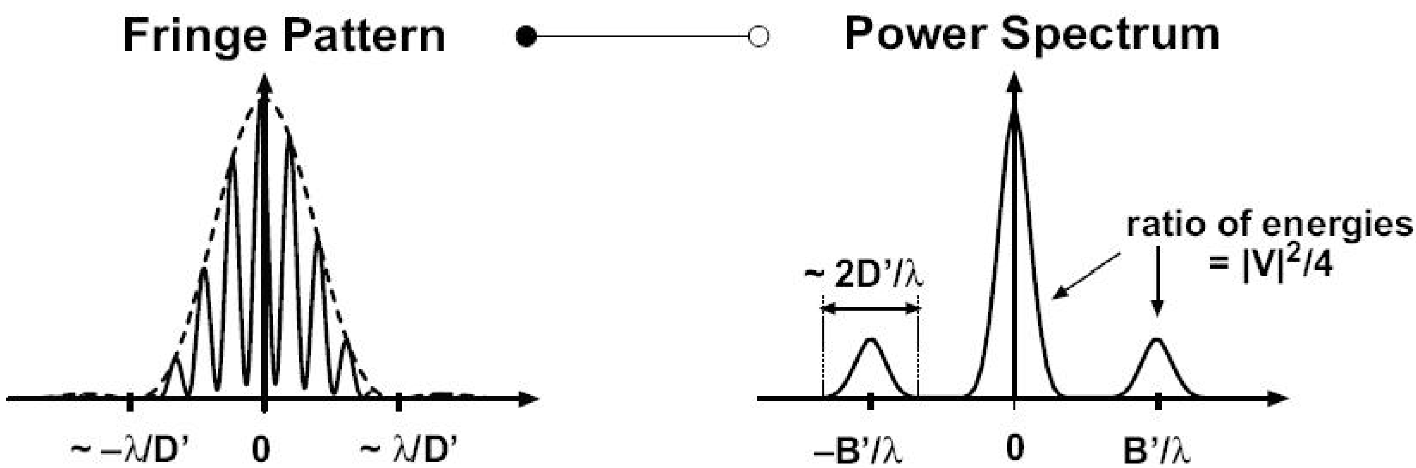


Left: two stars of different size; Middle: imaged with a single telescope; Right: observed with an interferometer → the appearance of the fringe pattern provides a measure of the star's angular diameter (credit: ESO).

Fringe Visibility – Object Structure



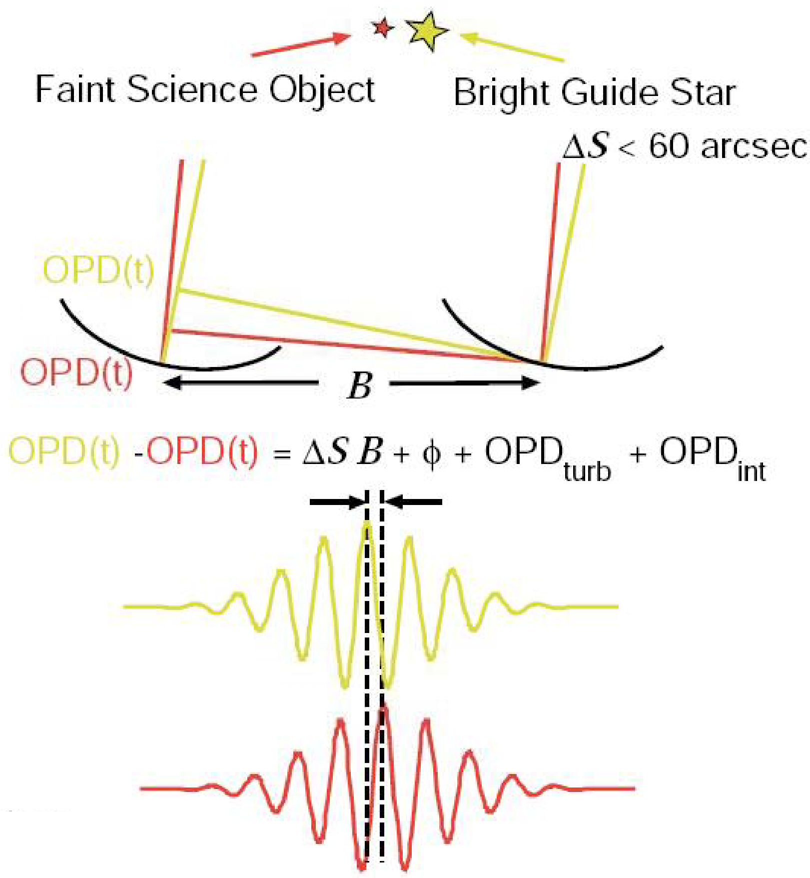
Fringe Visibility and Power Spectrum



Fringe Tracking (Co-Phasing)

The white-light fringe has to be actively tracked, which requires tracking fluctuations within a small fraction of wavelength in real-time.

Example: ESO's FINITO scans the center of the 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.



Closure Phase (1)

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

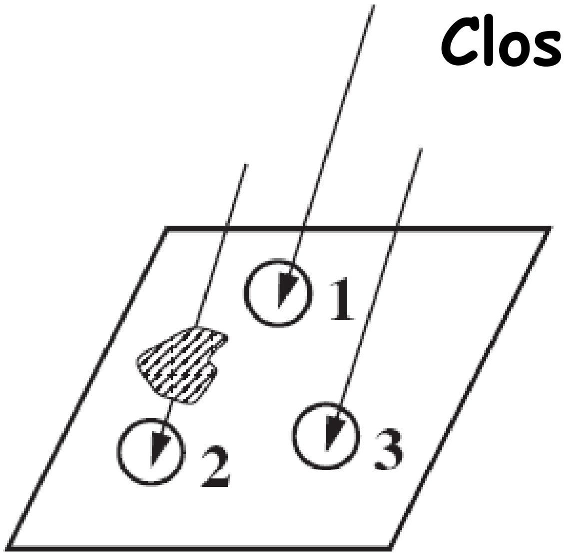
The phase is determined by the position of the fringes.

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

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

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

The 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

Fundamental Limitations

Fundamental Limitations

The field of view is typically limited to a few arcseconds only (except for Fizeau intererometers):

$$\theta_{\max} \leq \frac{\lambda}{D}\frac{\lambda}{\Delta\lambda}$$

• the size of the complex transfer optics. Larger field = larger optical elements

• spatial filters, which limit the FOV

The limiting magnitude is given by the atmospheric turbulence, which requires either:

• to use integration times shorter than τ_0 or

• to use an AO system (guide stars!)

Sensitivity of an Interferometer

The signal-to-noise for the measurement of visibility or phase with an interferometer is:

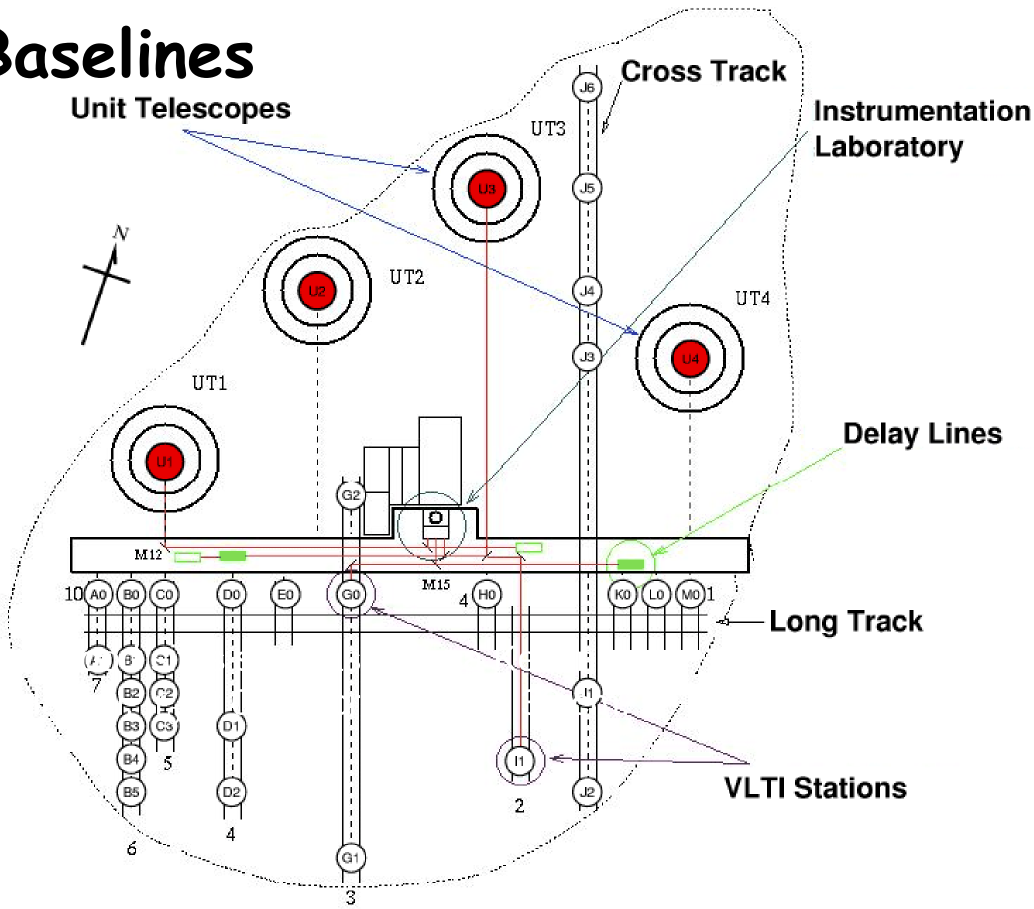
in the photon-limited regime (visible): $$SNR_{Poisson} = \sqrt{\frac{nV^2}{1+\frac{1}{nV^2}}} \propto \sqrt{n} \cdot V$$

in the background-limited regime (IR): $$SNR_{BLIP} = \sqrt{\frac{n^2V^2/b}{1+\frac{1}{n^2V^2/b}}} \propto n \cdot V$$

where n is the number of source photons per coherence volume $D^2 \cdot \tau_0$, b is the number of background photons per coherence volume, and V is the fringe visibility.

Baselines and 2D Imaging

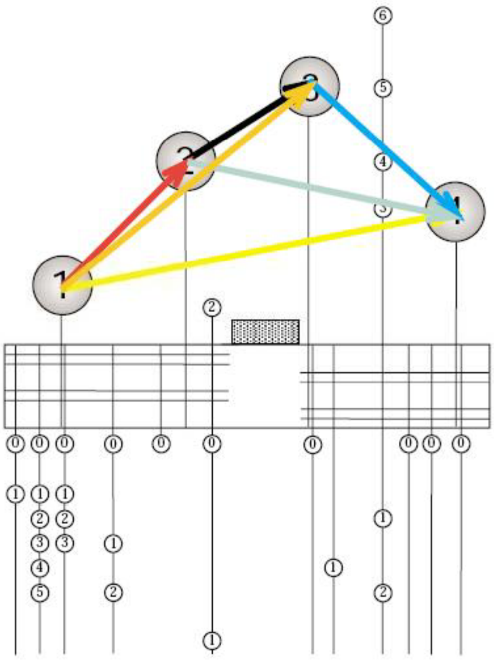
The VLTI Baselines

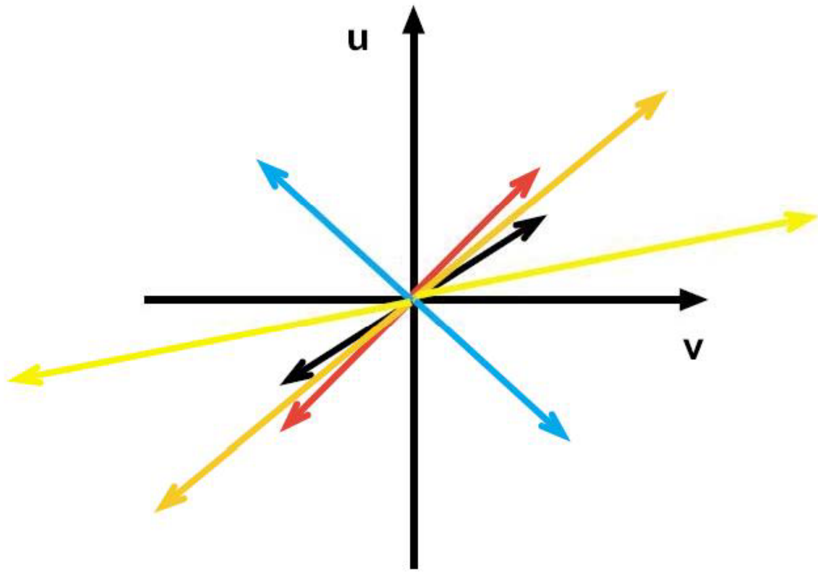


The three ATs move on rails between the thirty observing stations above the holes that provide access to the underlying tunnel system. The light beams from the individual telescopes are guided towards the centrally located, partly underground Interferometry Laboratory

Baseline Coverage (1)

A smooth reconstruction of the object's intensity distribution *I* requires a good coverage of the (u,v) plane.

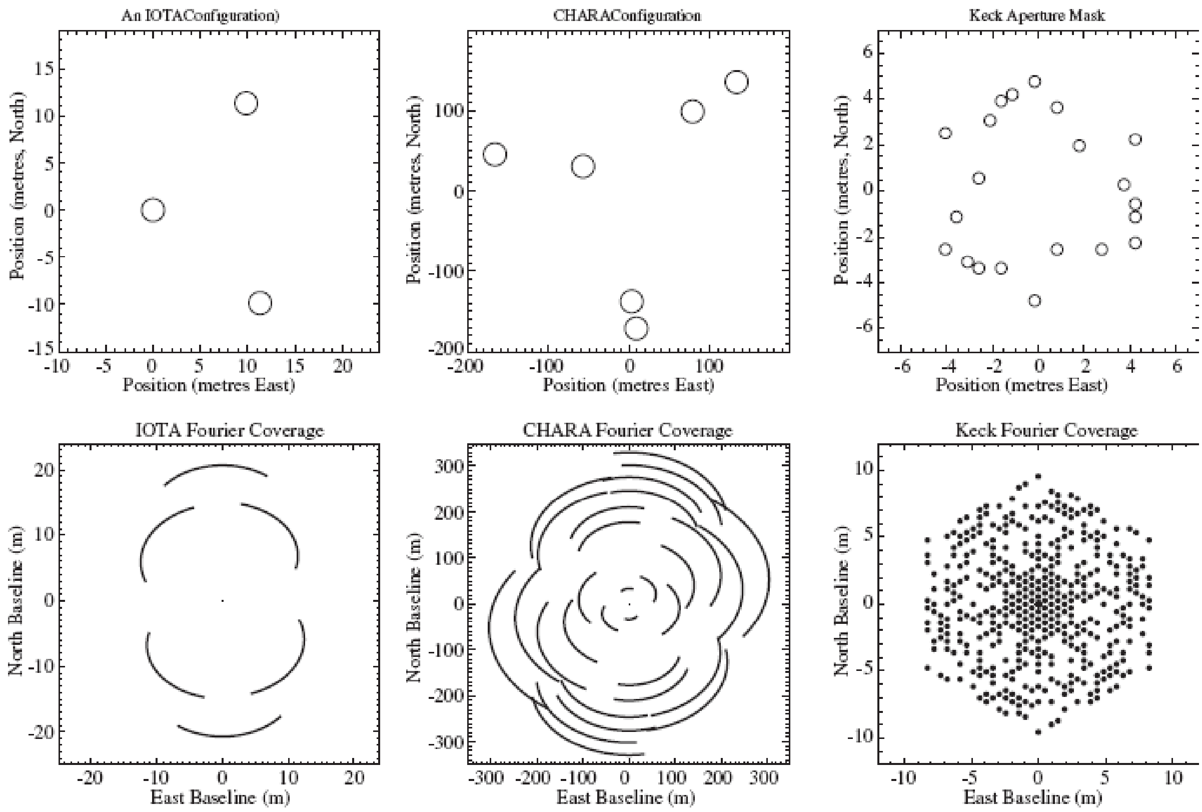




Note: This is the uv-plane for an object at zenith.
In general, the projected baselines have to be used.

Baseline Coverage (2)

The Earth's rotation helps to fill the (u,v) plane. Assumed is a source at 45° declination, observed for 3 hr both before and after transit.



Interferometry Projects

Some Optical Interferometry Projects

CHARA Interferometer http://joy.chara.gsu.edu/CHARA/

COAST Interferometer http://www.mrao.cam.ac.uk/telescopes/coast

GI2T: Grand Interféromètre à 2 télescopes http://wwwrc.obs-azur.fr/fresnel/gi2t/gi2t.htm

IOTA: Infrared Optical Telescope Array http://cfa-www.harvard.edu/cfa/oir/IOTA

ISI: Infrared Spatial Interferometer http://isi.ssl.berkeley.edu/isi.html

KECK Interferometer http://planetquest.jpl.nasa.gov/Keck/keck_index.html

LBT: Large Binocular Telescope http://medusa.as.arizona.edu/lbtwww/lbt.html

NPOI: Navy Prototype Optical Interferometer http://ftp.nofs.navy.mil/projects/npoi/

PTI: Palomar Testbed Interferometer http://huey.jpl.nasa.gov/palomar/index.html

SUSI Interferometer http://www.physics.usyd.edu.au/astron/astron.html

Westerbork

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

Australia Telescope Compact Array ATCA

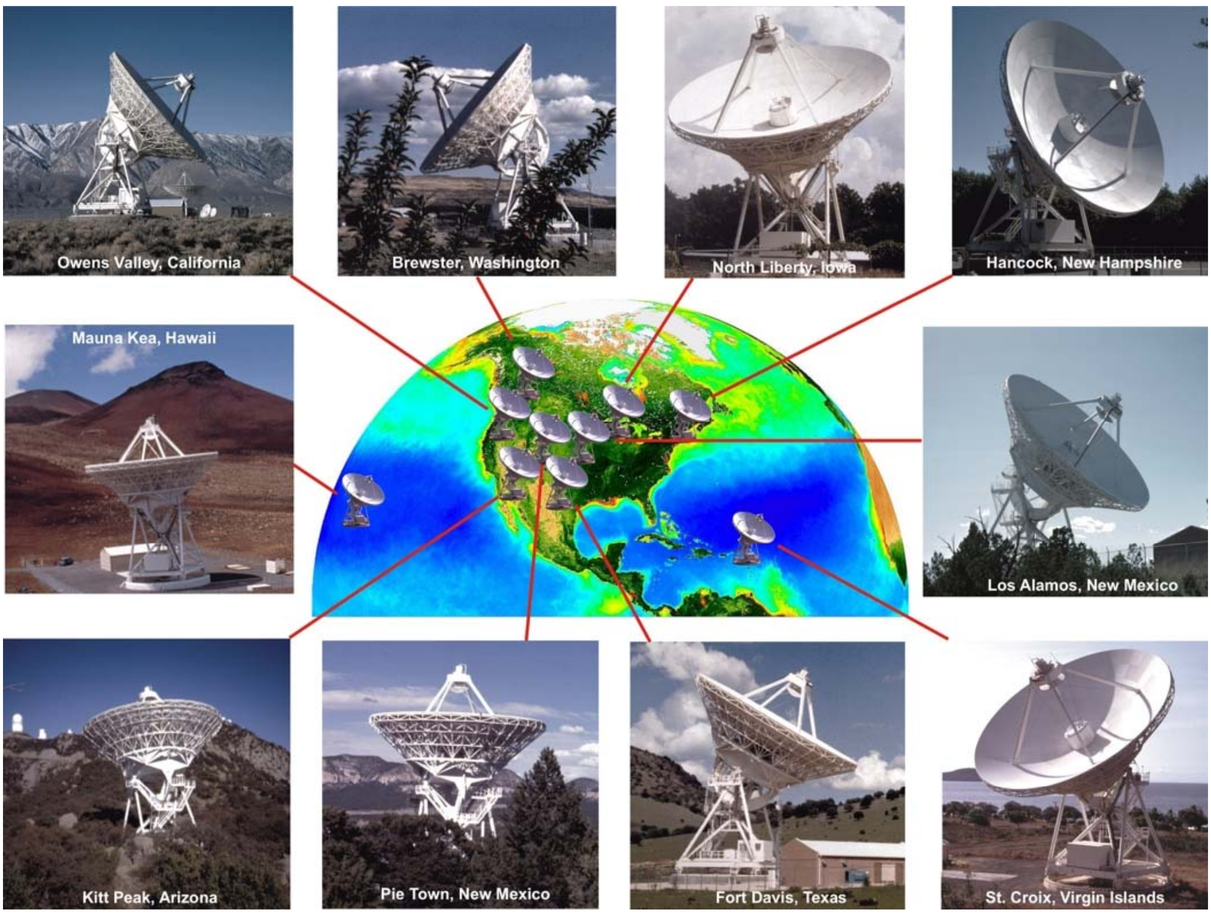
Six 22 m telescopes on an east-west baseline

Very Large Array VLA

- *Y-shaped array of 27 telescopes moved on railroad tracks*
- *telescope diameter 25-m each*
- *located: high Plains of San Augustin in New Mexico*
- *"D", "C", "B", and "A" configurations, spanning 1.0, 3.4, 11, and 36 km, respectively*

Very Long Baseline Array VLBA

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



European VLBI (Very Long Baseline Interferometry) Network

Plateau de Bure

Interferometer of six 15 m antennas

Combined Array for Research in Millimeter-wave Astronomy (CARMA)

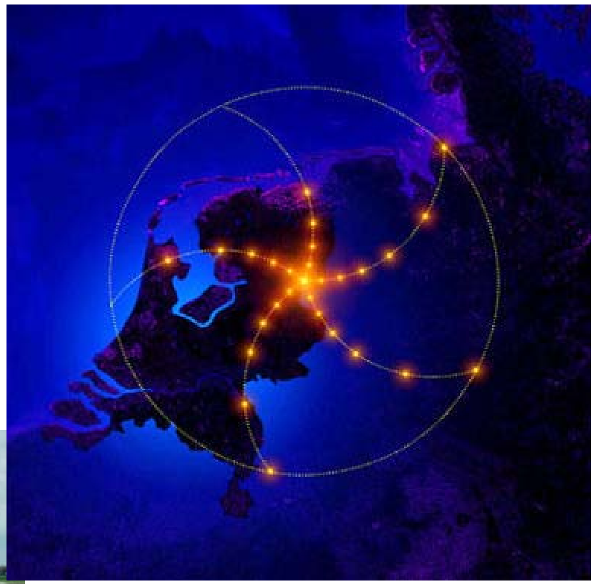
CARMA = six 10-meter telescopes from Caltech's Owens Valley Radio Observatory + nine 6-meter telescopes from the Berkeley-Illinois-Maryland Association → Cedar (CA)

Sub-Millimeter Array (SMA)

The SMA consists of eight 6 m antennas on Mauna Kea (HI)

LOFAR

25,000 antennas for radio frequencies below 250 MHz.



...and many future projects like ALMA, SKA, ...