Fundamentals of astronomical optical Interferometry

OUTLINE:

Why interferometry ?
Angular resolution

Connecting object brightness to observables
-- Van Cittert-Zernike theorem

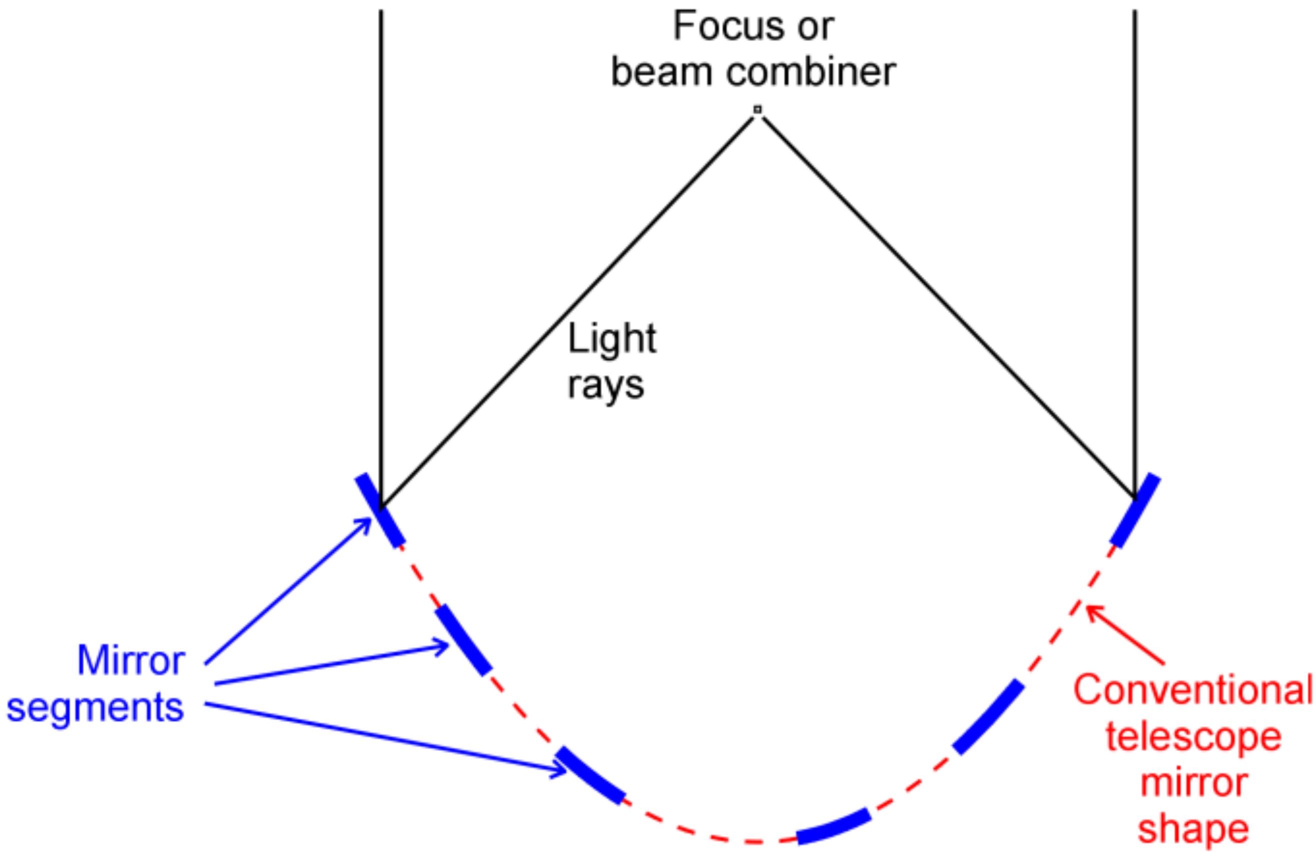
Scientific motivations:
- stellar interferometry: measuring stellar diameters
- Exoplanets in near-IR and thermal IR

Interferometric measurement
- 2-telescope interferometer

Interferometry and angular resolution

Diffraction limit of a telescope : λ/D (D: telescope diameter)
Diffraction limit of an interferometer: λ/B (B: baseline)

Baseline B can be much larger than telescope diameter D:
largest telescopes : D ~ 10m
largest baselines (optical/near-IR interferometers): B ~ 100m - 500m



Telescope vs. interferometer diffraction limit

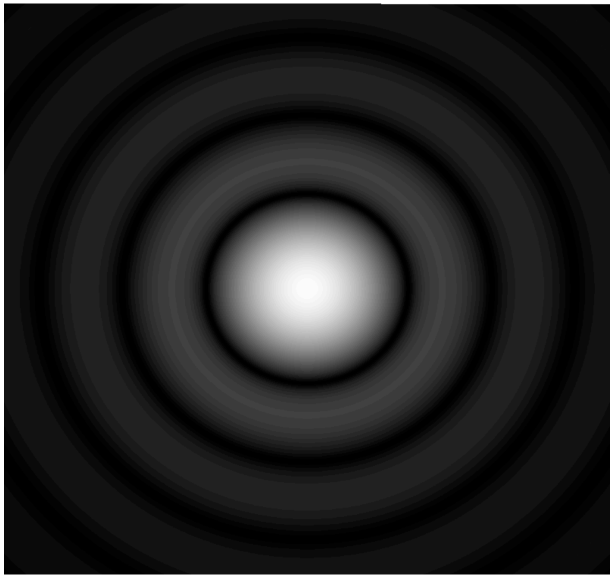
For circular aperture without obstruction : Airy pattern
First dark ring is at ~1.22 λ/D
Full width at half maximum ~ 1 λ/D
The “Diffraction limit” term = 1 λ/D

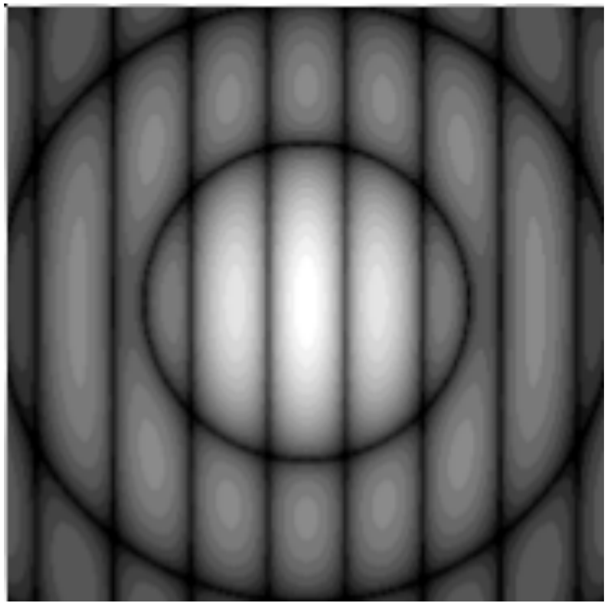
D=10m, λ=2 μm → λ/D = 0.040 arcsec

This is the size of largest star

With interferometer, D~400m
→ λ/B = 0.001 arcsec = 1 mas

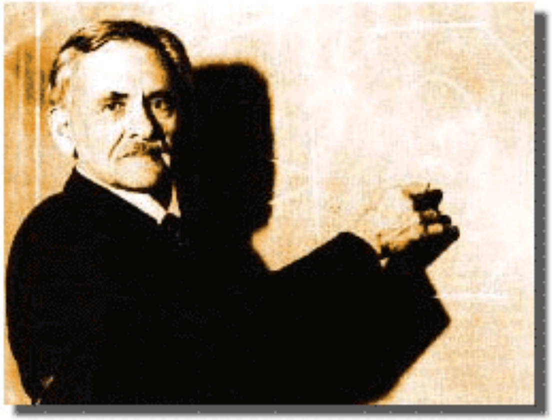
This is diameter of Sun at 10pc
Many stars larger than 1mas



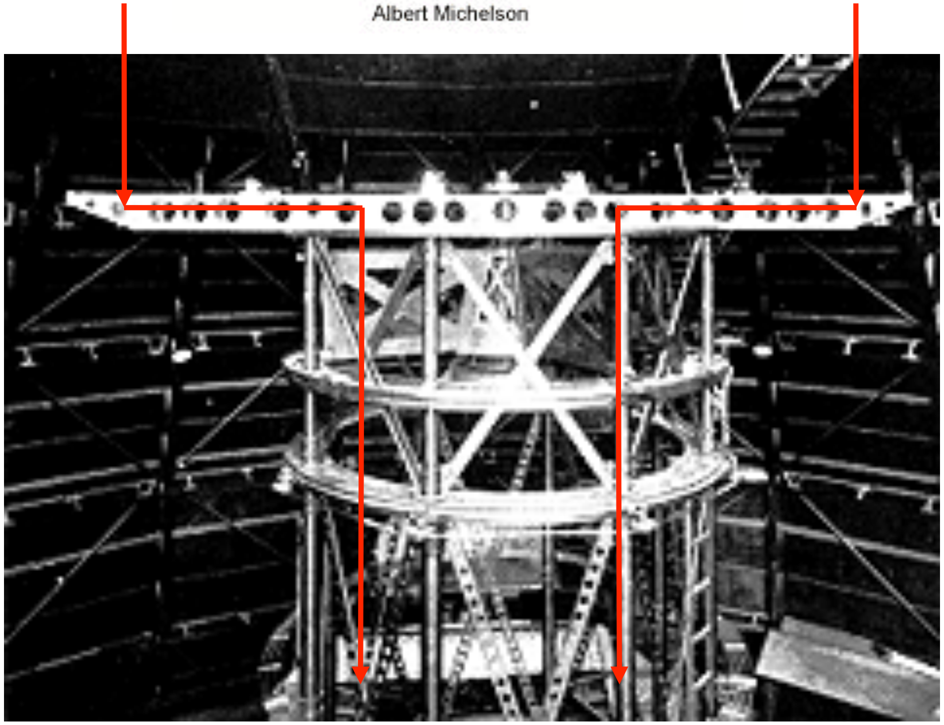


History of Astronomical Interferometry

- 1868 Fizeau first suggested stellar diameters could be measured interferometrically.
- Michelson independently develops stellar interferometry. He uses it to measure the satellites of Jupiter (1891) and Betelgeuse (1921).
- Further development not significant until the 1970s. Separated interferometers were developed as well as common-mount systems.
- Currently there are approximately 7 small-aperture optical interferometers, and three large aperture interferometers (Keck, VLTI and LBT)

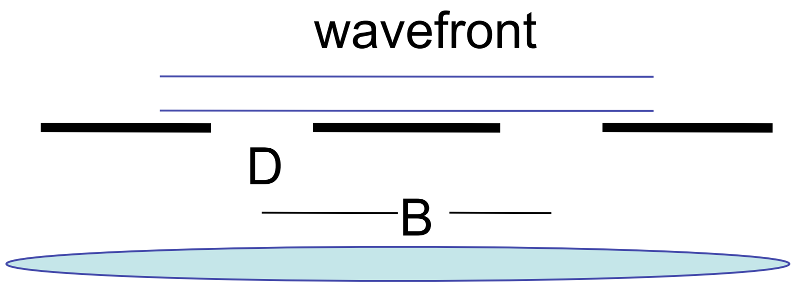


Albert Michelson



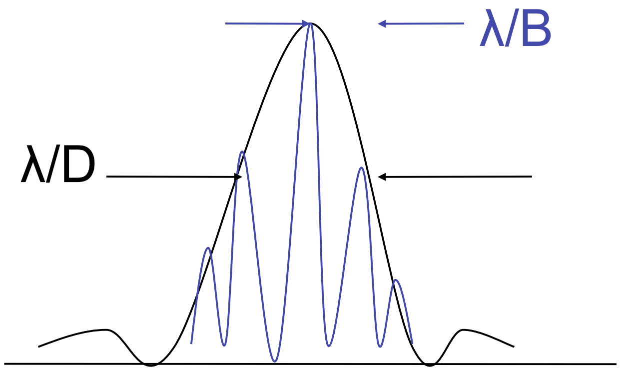
Interferometry Measurements

Interferometers can be thought of in terms of the Young's two slit setup. Light impinging on two apertures and subsequently imaged form an Airy disk of angular width λ /D modulated by interference fringes of angular frequency λ/B. The contrast of these fringes is the key parameter for characterizing the brightness distribution (or "size") of the light source. The fringe contrast is also called the visibility, given by



Visibility is also measured in practice by changing path-length and detecting the maximum and minimum value recorded.

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$



Optical vs. Radio Interferometry

Radio interferometry functions in a fundamentally different way from optical interferometry.

Radio Telescope arrays are *heterodyne*, meaning incoming radiation is interfered with a local oscillator signal before detection. The signal can then be amplified and correlated with signals from other telescopes to extract visibility measurements.

Optical interferometers are *homodyne*, meaning incoming radiation is interfered only with light from other telescope. This requires transport of the light to a central station, without the benefit of being able to amplify the signal. However, homodyne interferometry allows large bandwidths to be used since the interfered light is detected directly.

(One heterodyne optical interferometer (ISI) has been built to operate at 10 microns. The technique is feasible, but limited to bright sources.)

Observations with Interferometers

So what is actually measured?
How is it used?

Visibility	→	Size of objects
Astrometry	→	Position of objects
Imaging	→	Structure of objects
Nulling	→	Detection of faint objects

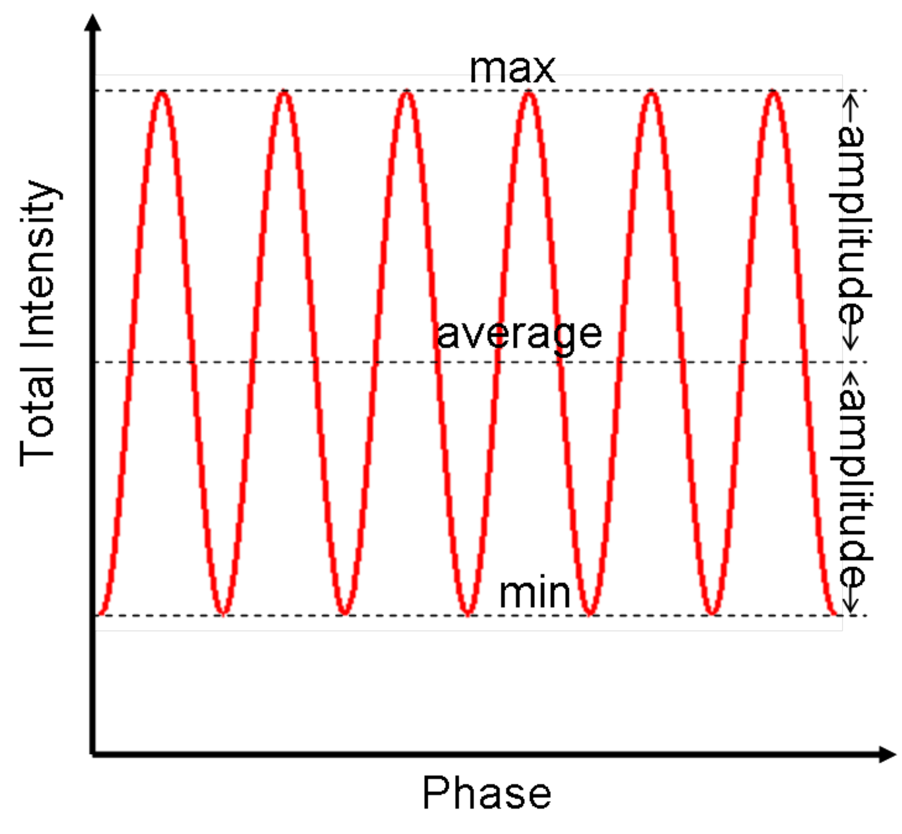
2-telescope interferometer: Fringe visibility and phase

With a single baseline interferometer, the only information measured are:

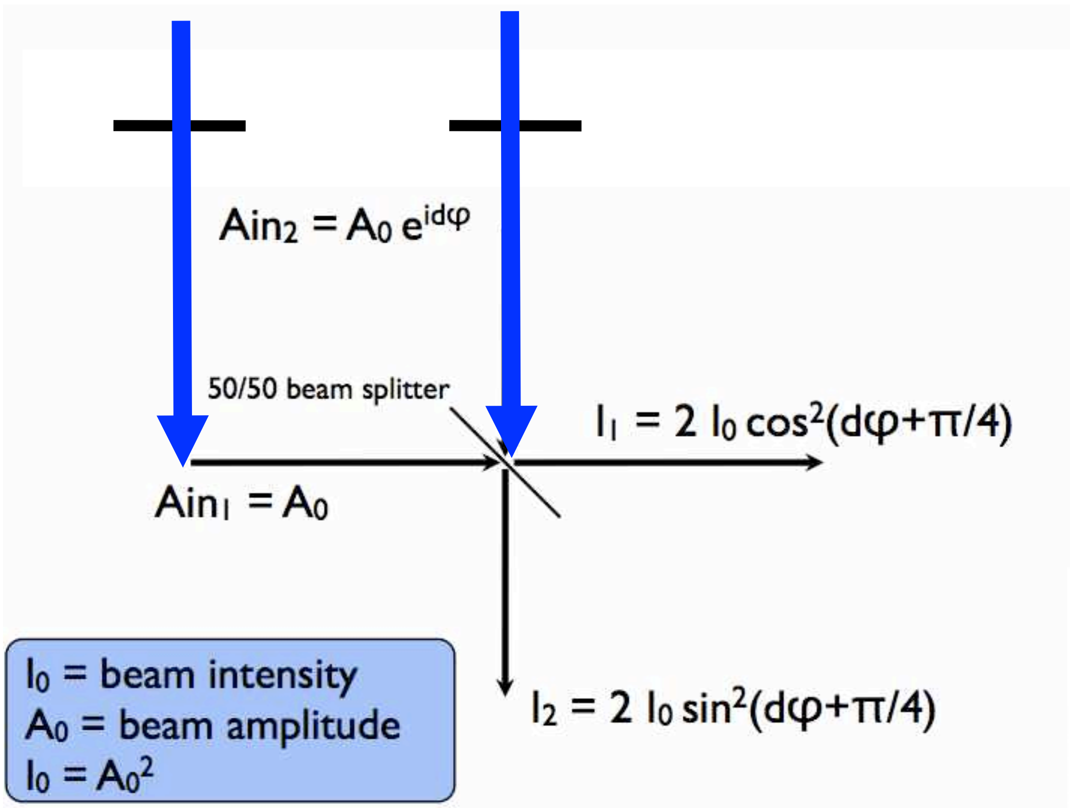
- fringe average intensity → source brightness
- fringe visibility = amplitude / average → single constraint on spatial distribution of light, visibility = 1 if source is unresolved (BUT visibility =1 does not imply that the source is unresolved)
- fringe phase → single constraint on spatial distribution of light (BUT needs to be referenced)

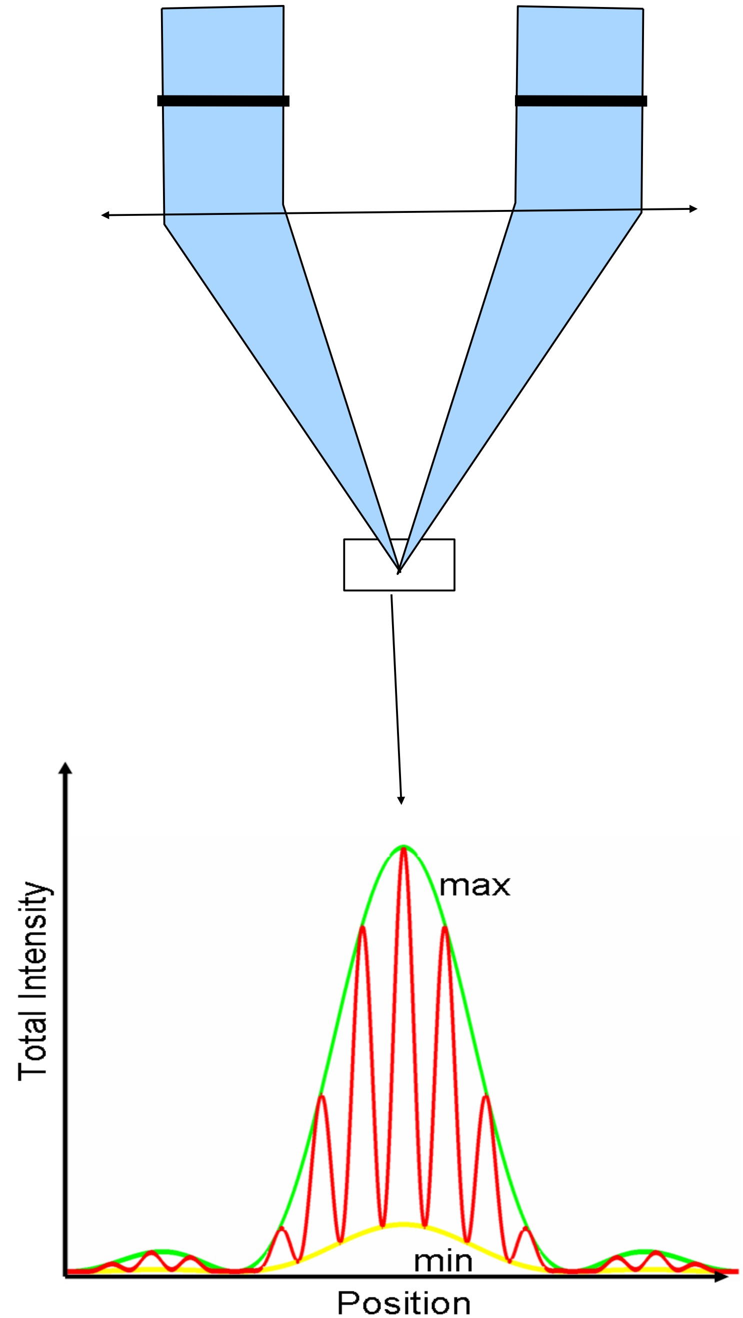
Fringe frequency DOES NOT contain information about object, as it is only a function of the baseline

Interferometers measure at most these 3 quantities for a single baseline
This can be done by imaging fringes, or by measuring intensity after combination with a known phase offset



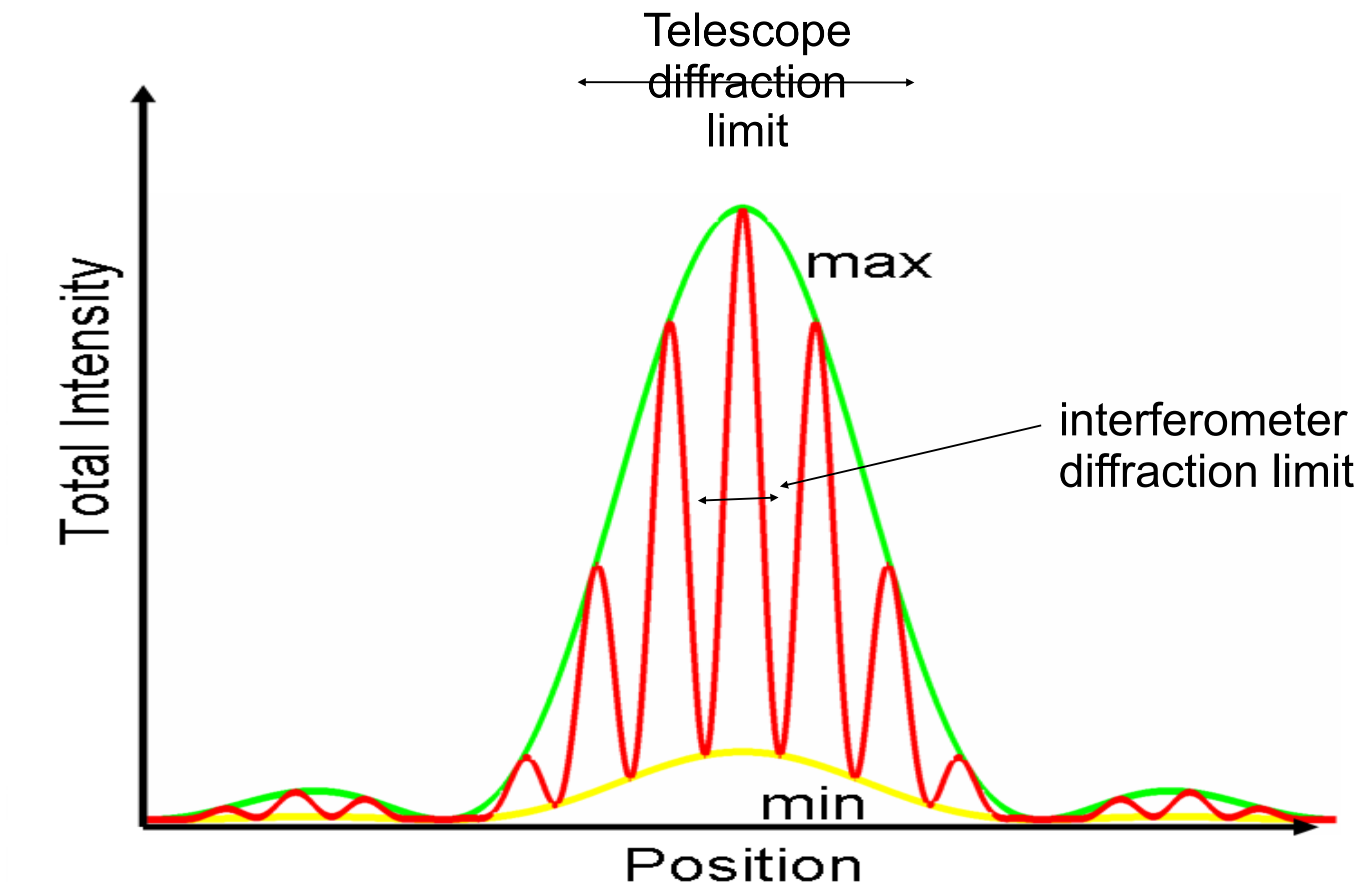
2-telescope interferometer:
Fringe visibility and phase can be measured either by discrete flux measurements (beam splitter(s)) or direct imaging of fringes





Note:
- at least 3 measurements required to constrain fringe visibility (1), phase (1) and intensity (1)
- fringe scanning can be used to temporally sample fringes

Interferometer field of view



If two sources are separated by more than the diffraction limit of the individual telescopes, they will not interfere in the interferometer:

interferometric field of view ~ diffraction limit of a single aperture

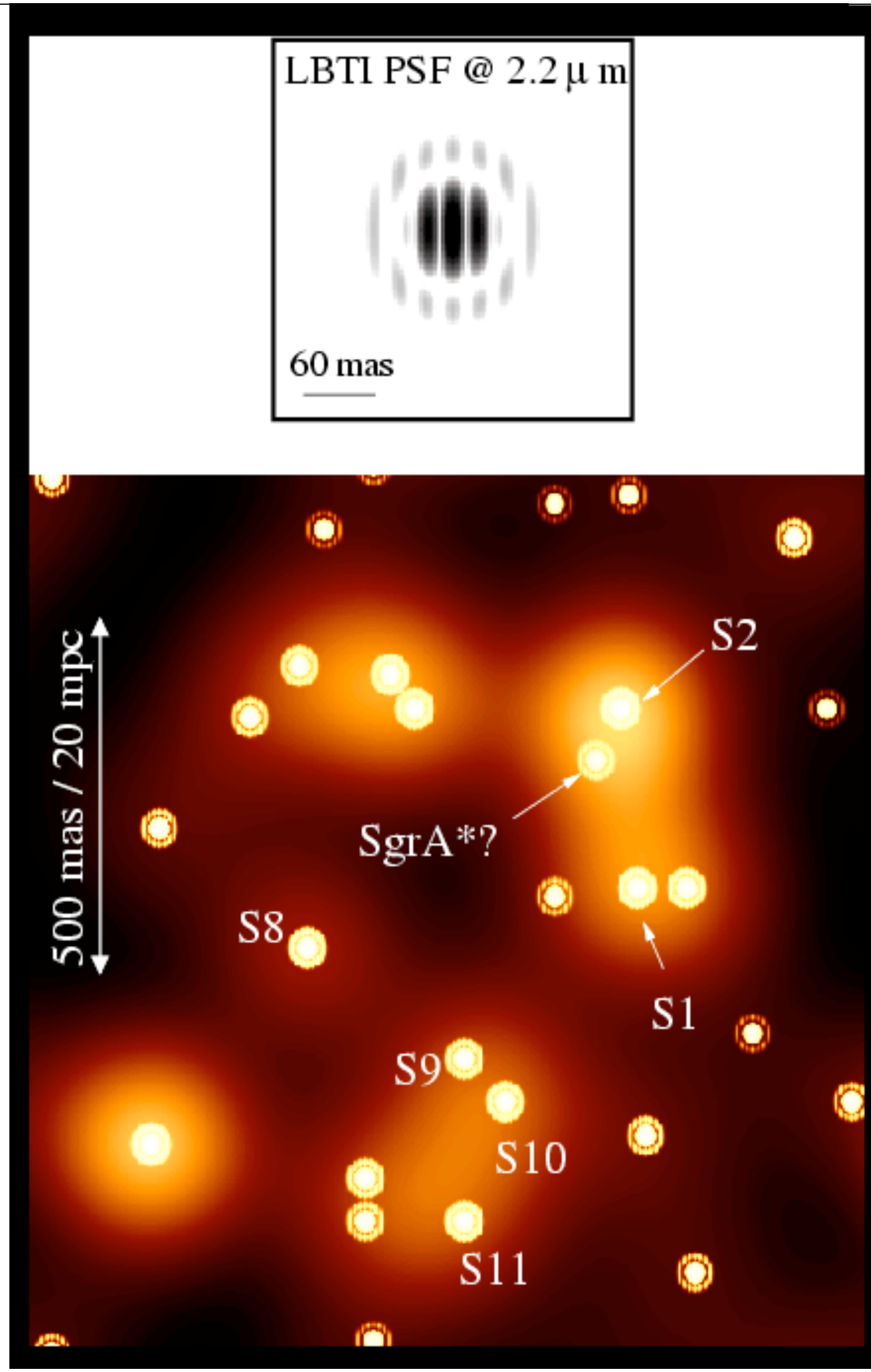
Interferometer field of view

BUT: each telescope can have large field of view, and interferometer can create multiple fringe packets (1 per source)

Spatial information at the scale < telescope diffraction limit comes from interferometer

Spatial information at the scale > telescope diffraction limit comes from telescopes

Rubilar & Eckart, 2000



Van Cittert-Zernike theorem

Assumes object of intensity I(l,m), spatially incoherent

- l,m : angular coordinates on sky
- spatially incoherent: light different points of the objects cannot interfere (this is almost always true in astronomical observations)

Theorem expresses mutual coherence (= fringe visibility and phase) between 2 points on a plane perp to line of sight, separated by (u,v)

- u,v : interferometer baseline

$$\Gamma_{12}(u,v,0) = \iint I(l,m) e^{-2\pi i(ul+vm)} dl\, dm$$

→ theorem shows that a single baseline of the interferometer measures a single point in the Fourier transform of the object

Intuitively, this makes sense:
Point source (l,m) observed by a single baseline (u,v):
- Modulo of Fourier transform is = 1 everywhere in (u,v) plane : fringe visibility is always = 1
- Phase is (ul+vm), proportional to both source position and baseline

→ the equation makes sense for a single point source
Spatial incoherence leads to additivity of fringes

Van Cittert-Zernike theorem

$$\Gamma_{12}(u,v,0) = \iint I(l,m)e^{-2\pi i(ul+vm)}dl\,dm$$

Physical interpretation:
Each point on the object creates a fringe with visibility = 1, average level = point brightness, and phase = position of the point along line perp. to baseline

Measured fringe is incoherent sum of all individual fringes (double integral in theorem)

Small source, small baseline, large lambda = high visibility
Large source, large baseline, small lambda = low visibility

With a single baseline, single lambda, only one constraint is measured on the object. Stellar interferometry is very successful because object is simple, and can be parametrized in a few parameters

    single measurement can constrain stellar diameter with simple model (perfect disk)

Complicated objects which cannot be described with a few parameters require many baselines

    multiple telescopes (>2)
    use of Earth's rotation to change baseline

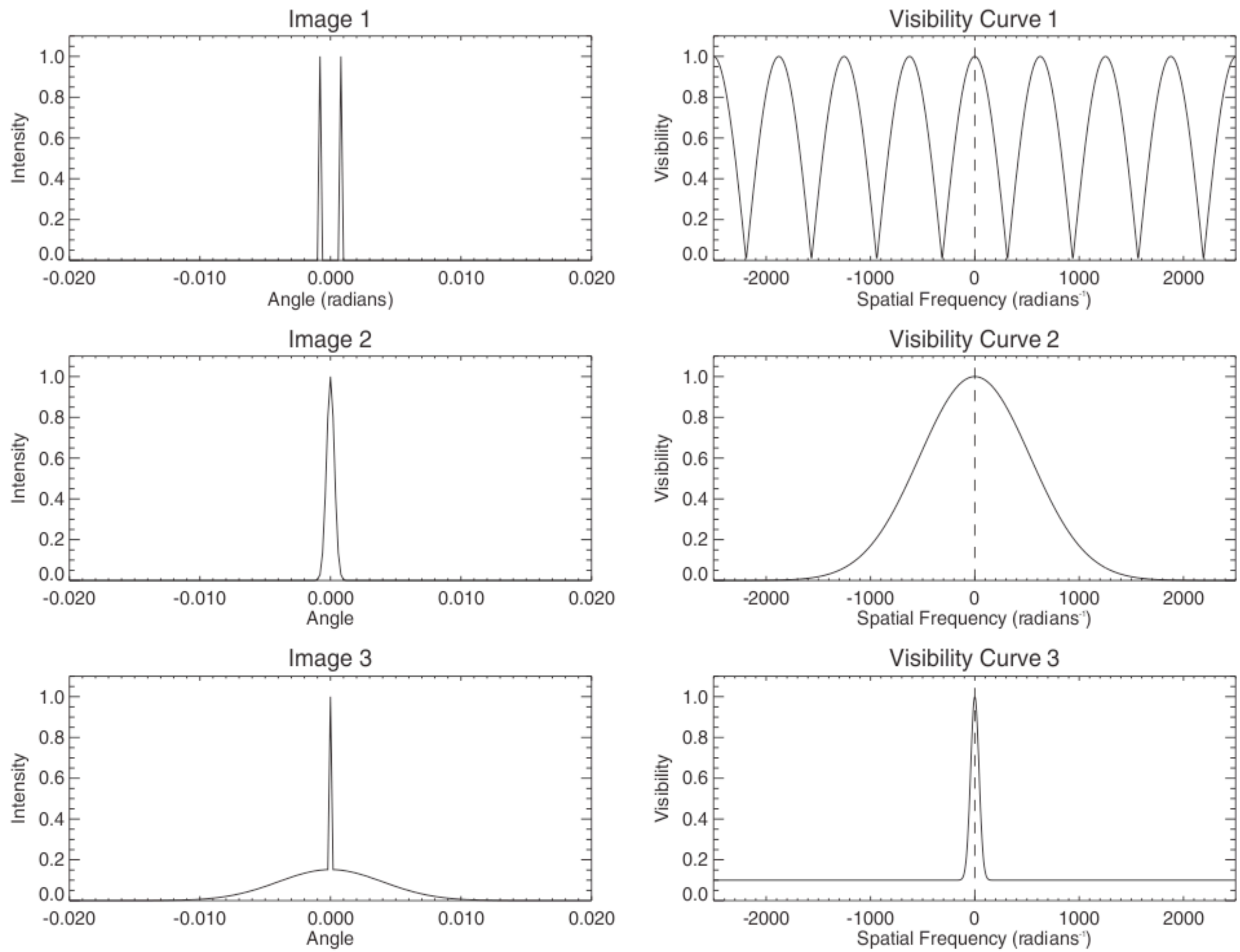


Figure 2. This figure shows simple one-dimensional images and their corresponding visibility curves. The left panels are the images while the right panels correspond to the Fourier amplitudes, i.e. the visibility amplitudes. Note that 'large' structure in image-space result in 'small' structure in visibility-space.

J. Monnier, Optical Interferometry in Astronomy

Stellar Interferometry

Van Cittert-Zernike gives the fringe Visibility as a function of baseline, λ, and stellar apparent size.

$$\Gamma_{12}(u,v,0) = \iint I(l,m) e^{-2\pi i(ul+vm)} dl\, dm \longrightarrow V^2(B\theta/\lambda) = \left(2\frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2$$

(J1 = Bessel function of 1st kind)

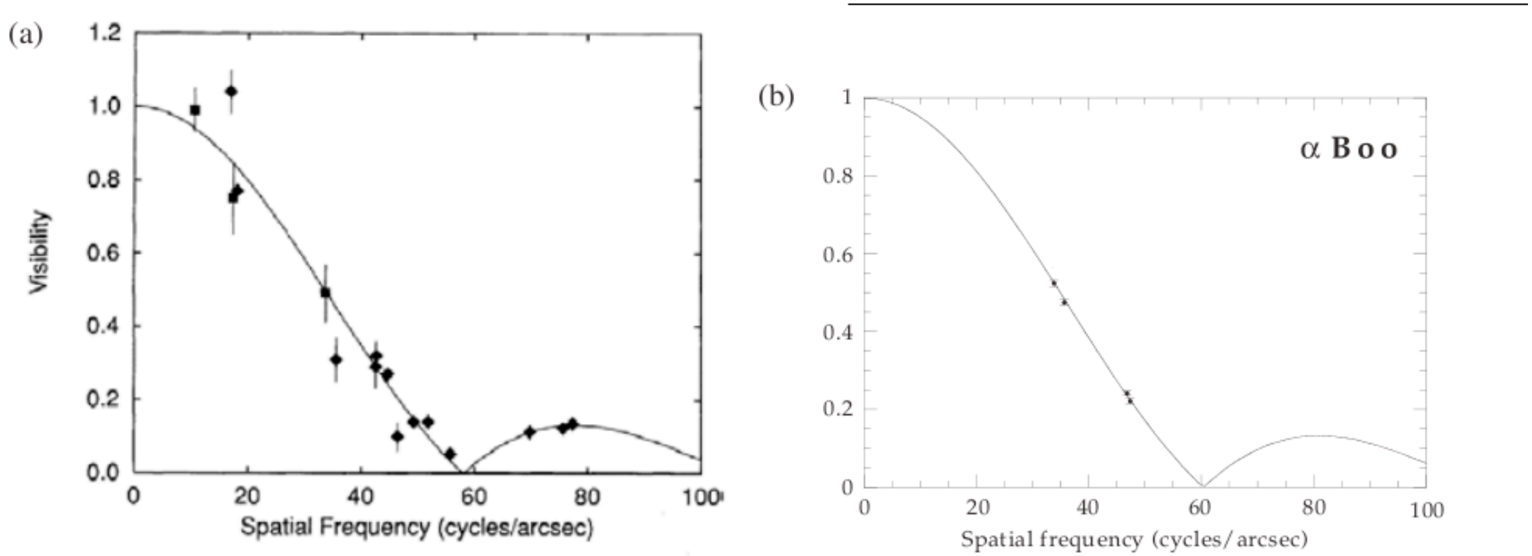


Figure 15. (*a*) This figure shows visibility data for α Boo by the CERGA interferometer (♦) and the IRMA interferometer (■), and originally appeared in the Publications of the Astronomical Society of the Pacific (Copyright 1993, Astronomical Society of the Pacific; Dyck *et al* (1993), reproduced with permission of the editors). (*b*) The incredible gain in calibration using spatial filtering and photometric monitoring is evident in this figure reproduced from Perrin *et al* (1998, figure 2(*a*)) with permission from ESO.

Stellar Interferometry
Measuring distance to Cepheids

$$V^2(B\theta/\lambda) = \left(2\frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2$$

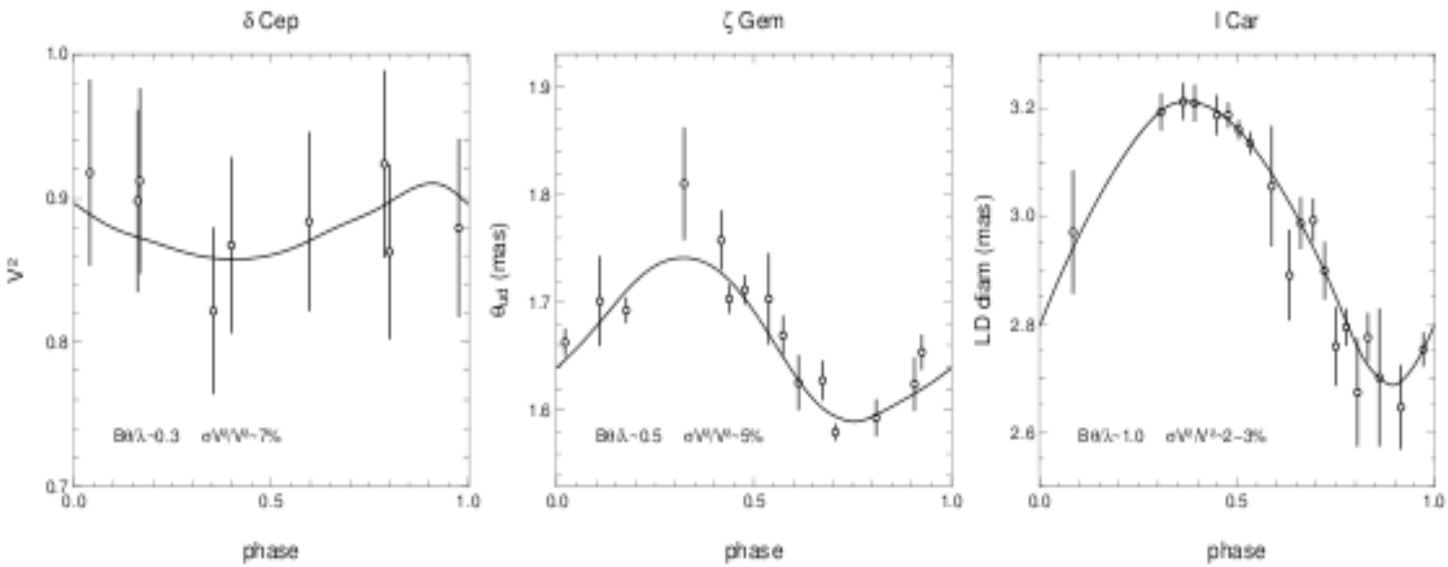
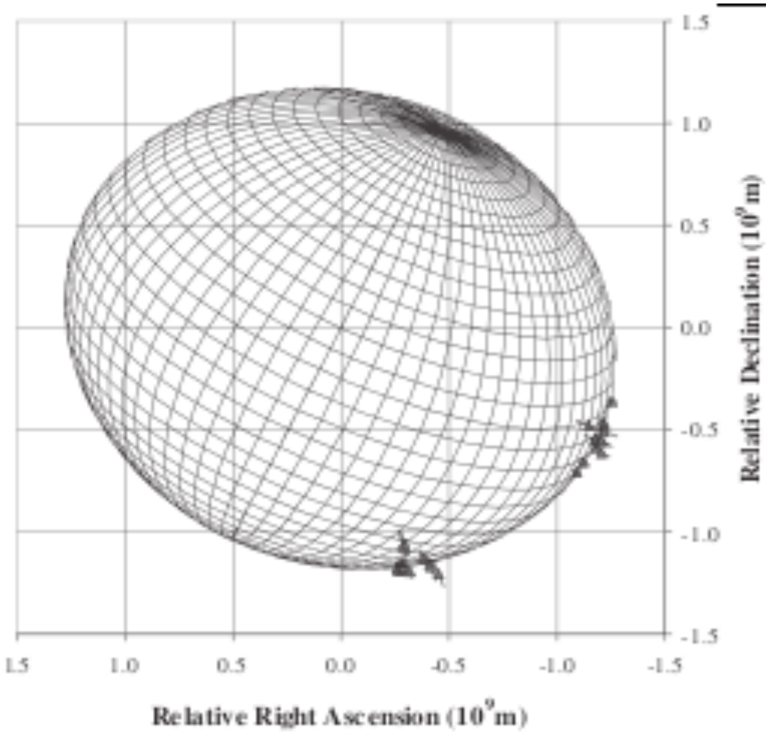


Figure 1. Different interferometric attempts to measure Cepheid angular diameter variations. From left to right: Mourard et al. (1997[6]), Lane et al. (2000[7]) and Kervella et al. (2004[8]). The left panel is V^2 as a function of phase, while the panels to the right are angular diameters with respect to phase. The thin, continuous line is the integration of the pulsation velocity (distance has been adjusted). From left to right, one can see the effect of increasing resolution ($B\theta/\lambda$) and improving precision ($\sigma V^2/V^2$). In the left panel, the pulsation was not claimed to be detected; the middle panel was the first detection, with a 10% precision on the distance; the right panel displays one of the best: 4% in the distance.

A. Merand, Cepheids at high angular resolution

Stellar Interferometry
Measuring oblateness of Altair

$$V^2(B\theta/\lambda) = \left(2\frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2$$



Also possible:

Measure limb darkening (deviation from Bessel function above)

Measure diameter as a function of λ: envelopes around evolved stars

Palomar Testbed Interferometer
Van Belle et al. 2001

Imaging exoplanets with interferometers – Example concept

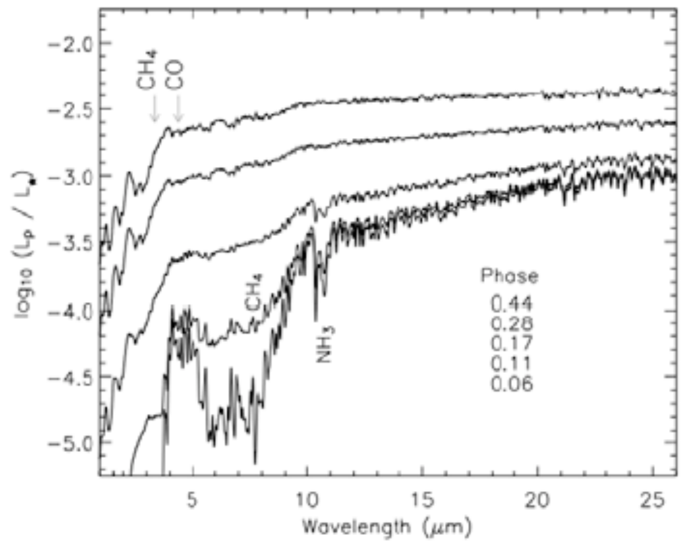


Figure 1. Planet-star flux density ratios for HD209458b at different orbital phase (from Barman *et al.* 2005).

Hot Jupiters (of the 51 Peg type) offer moderate planet/star contrast but very challenging angular separation
→ interferometer is well-suited to observe them

PEGASE mission concept (CNES)

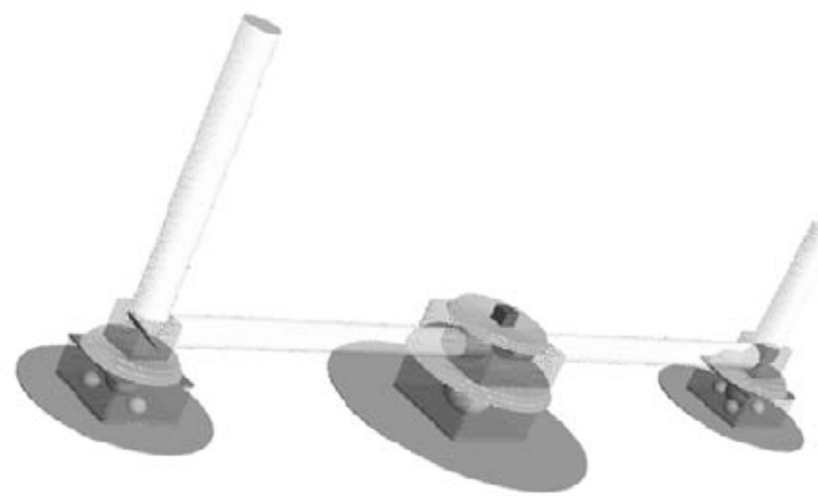
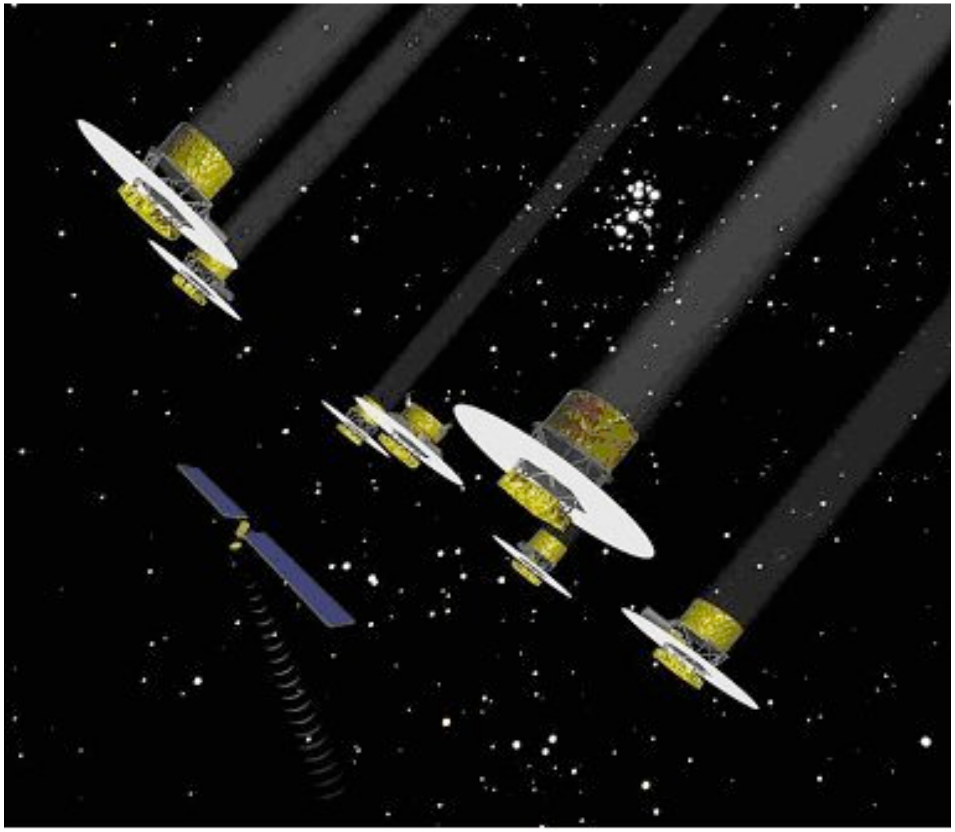


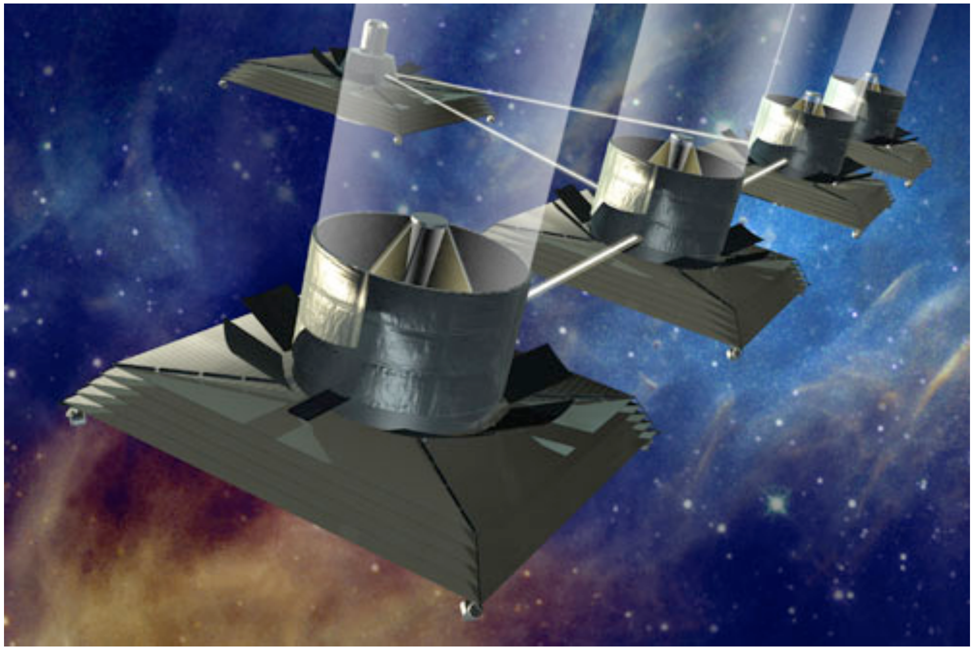
Figure 3. Artist view of the PEGASE observatory (courtesy CNES).

Imaging exoplanets with interferometers – Earth-like planets



DARWIN mission concept (ESA)

Earh is relatively bright at 10um (peak of thermal emission, ~1e7 contrast instead of ~1e10 in visible light), but diffraction limit of a single telescope at 10um is insufficient
→ interferometer well-suited



Terrestrial Planet Finder Interferometer (NASA)

Beam combination in astronomical interferometers

OUTLINE:

2 telescopes interferometer
- what does it take to combine light from 2 telescopes ?
- phase and amplitude measurement

Multi (N<2) telescopes interferometry
- why >2 telescopes ?
- examples: VLT, CHARA

Technology:
- beam transport (delay lines discussed in next lecture)
- beam splitters
- fiber combiners
- image plane beam combination (also called Fizeau combination, or multi-axial combination)

From telescopes to interferometric signals: transporting and combining light beams from individual apertures

Telescopes collect the light, which needs to be **transported** and **combined** between telescopes.

Challenges:

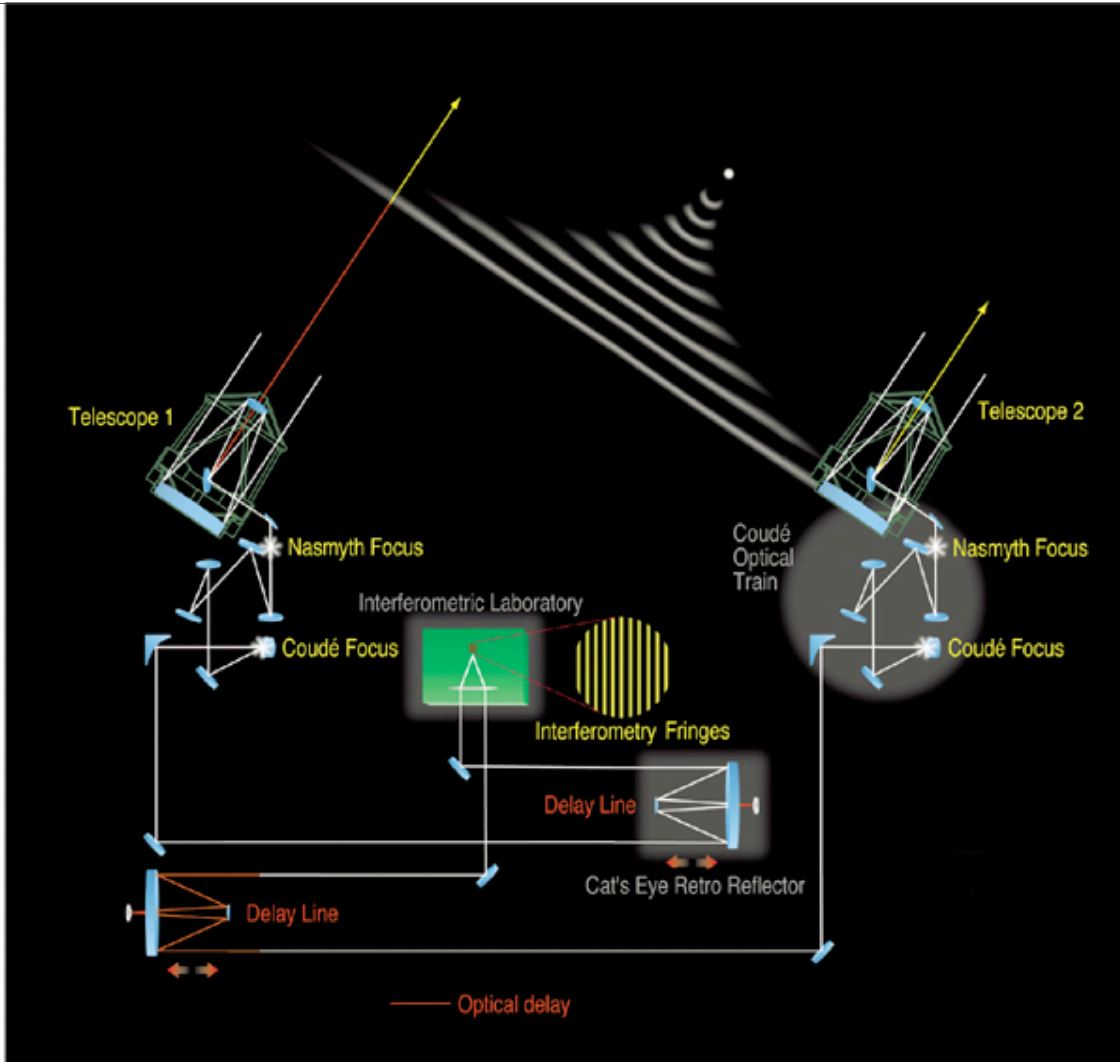
- Telescopes are moving structures, and light needs to be <u>efficiently</u> extracted from telescopes and injected into (usually) fixed optical train
- Optical Pathlength Difference (OPD) between arms of the interferometer needs to be a few waves at most. For a 100m baseline interferometer in optical, OPD is ~1e-8 of baseline. On the ground, telescopes are fixed (usually) relative to Earth, and object is continuously moving in the apparent sky : OPD is continuously changing
- OPD needs to be stable to << a wave during a single exposure

All above requirements must be satisfied over a finite wavelength range

An interferometer includes:

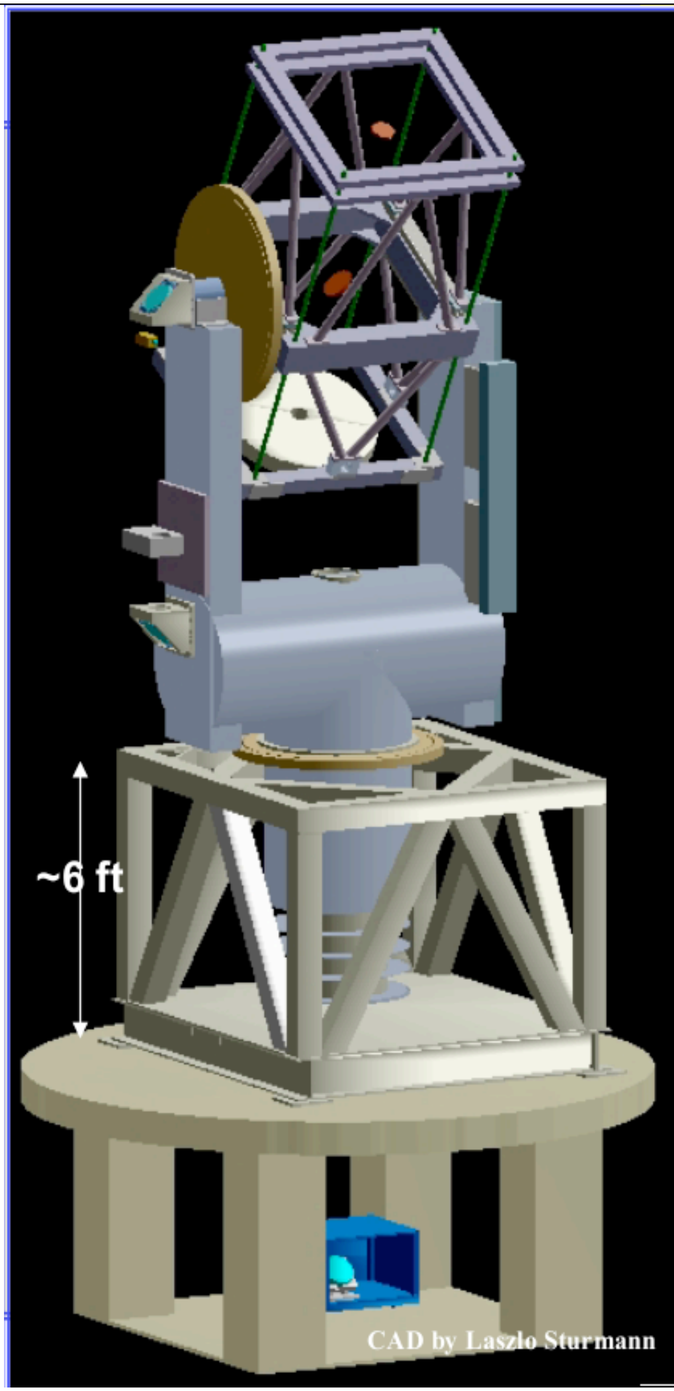
TELESCOPES : extract light from object
BEAM TRANSPORT OPTICS : transport light from telescopes to beam combiner
DELAY LINES : maintain near-zero OPD
BEAM COMBINER OPTICS : coherently mix light between telescopes
DETECTOR : measure interferometric signal

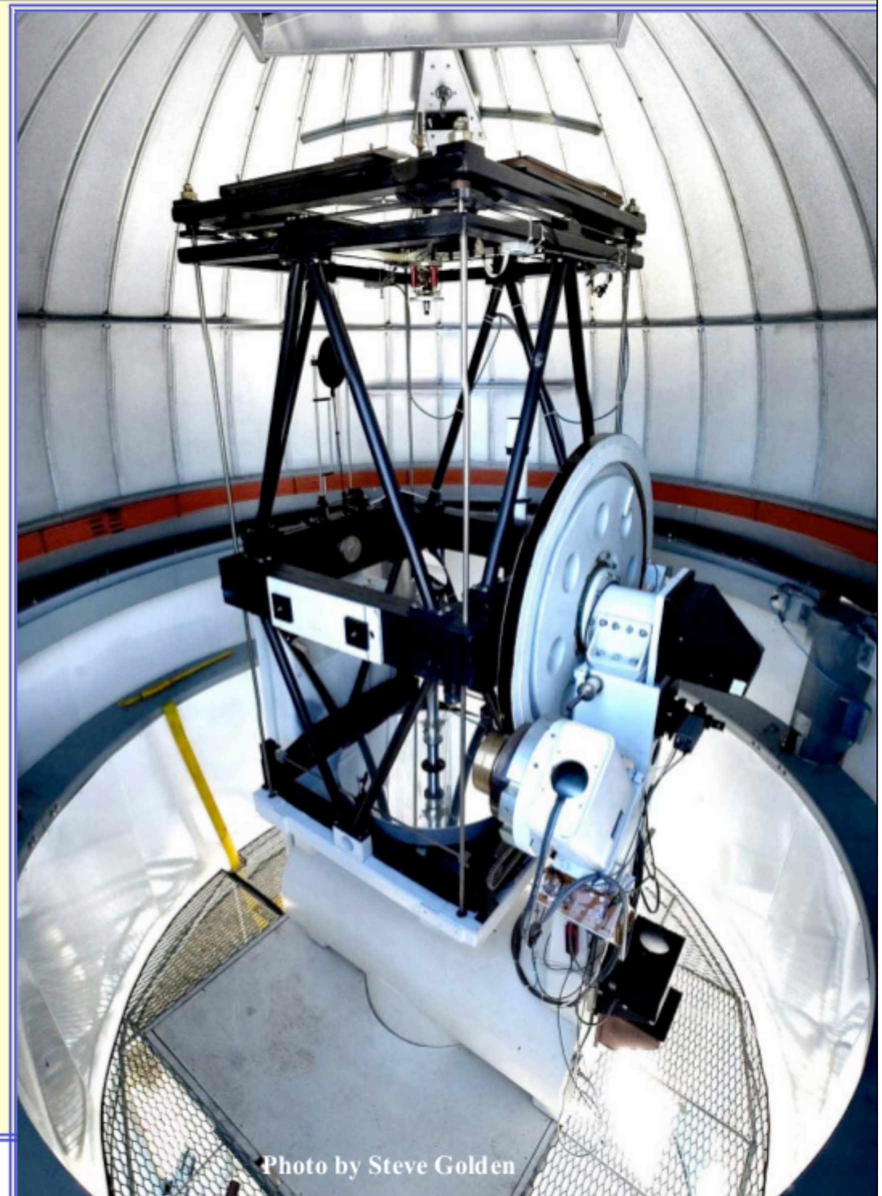
Next slide shows these steps (VLT, ESO)


Telescope 1
Telescope 2
Nasmyth Focus
Nasmyth Focus
Coudé Optical Train
Interferometric Laboratory
Coudé Focus
Coudé Focus
Interferometry Fringes
Delay Line
Cat's Eye Retro Reflector
Delay Line
Optical delay

Telescopes I.

Telescope designs for interferometry





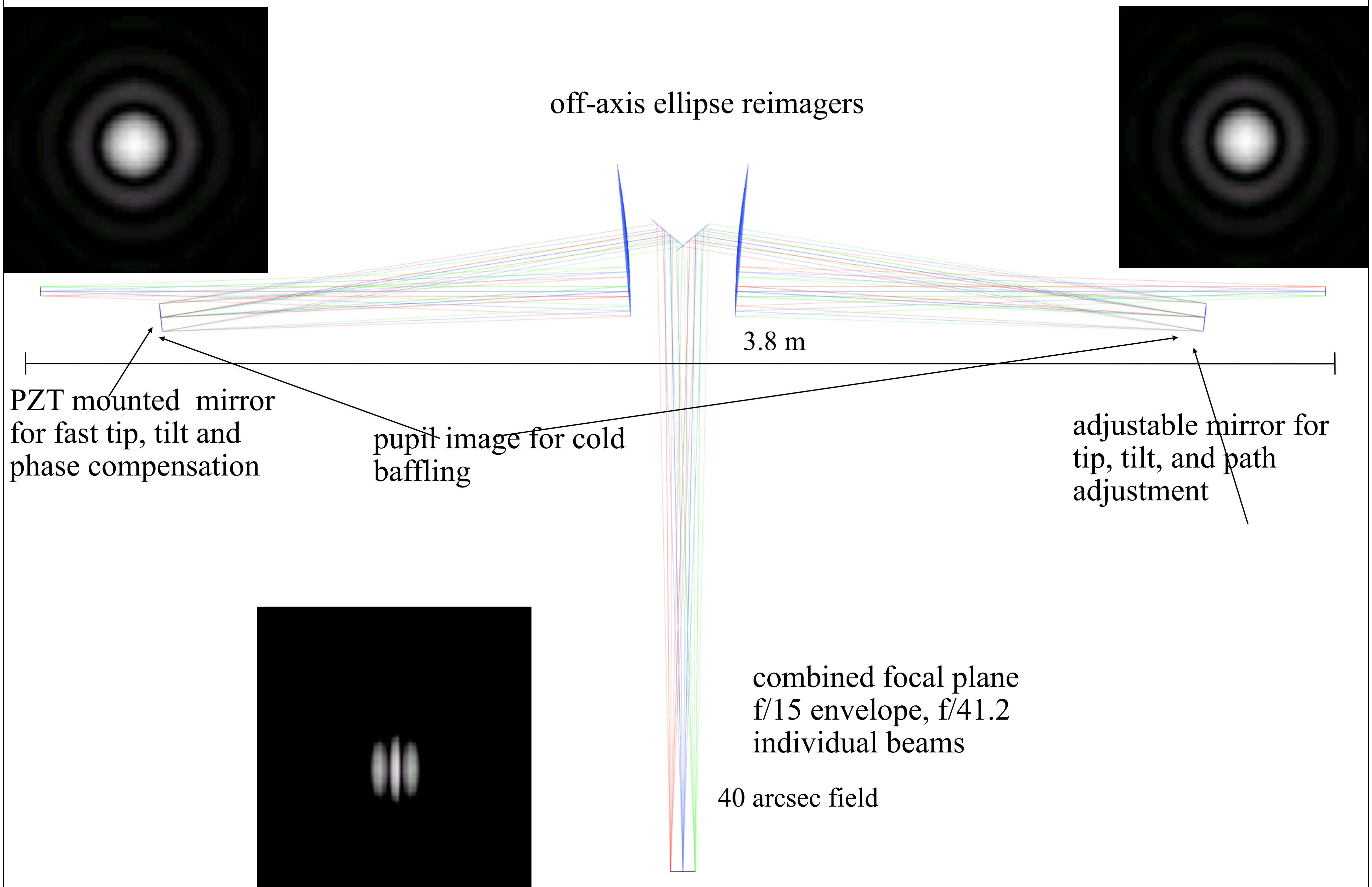
CHARA interferometer telescopes designed for easy beam extraction:
beam travels through alt and az rotation axis of the telescope

Telescope designs for interferometry

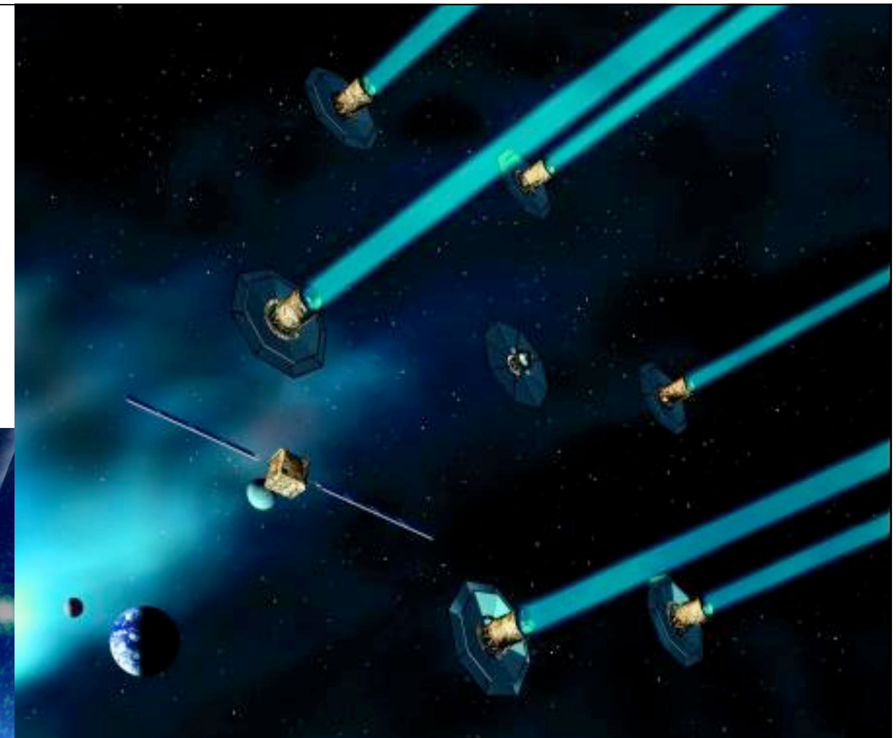
Large Binocular Telescope (LBT) interferometer. Two telescopes share a common mount, and the interferometer moves with the telescopes, greatly simplifying beam transport:
No need for long delay lines, or complex beam steering optics to carry light into inteferometer.

Advantage: higher throughput and lower emissivity in IR (fewer optics)
Common mount interferometer limited to short baselines on ground, but can be large in space.

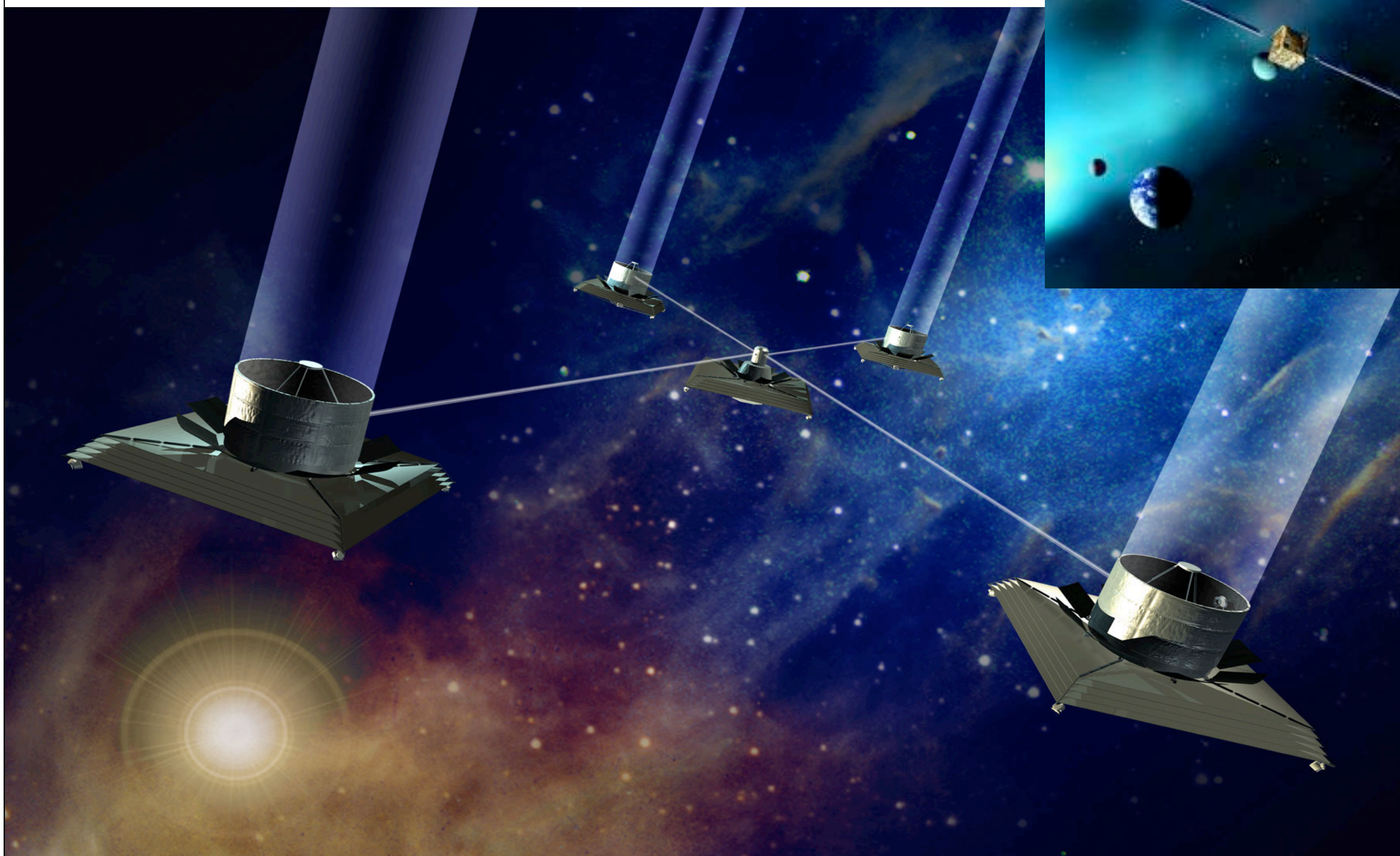
Beam Combination



Telescope designs for interferometry (Space)



Darwin mission concept (ESA)
Note: mission did not go beyond concept



Terrestrial Planet Finder mission concept (NASA)
Note: mission did not go beyond concept

Space interferometry is possible without delay lines.
All telescopes at equal distance from central recombination hub.