Fundamentals of astronomical optical Interferometry

OUTLINE:

Why interferometry ?
Angular resolution

Van Cittert-Zernike theorem

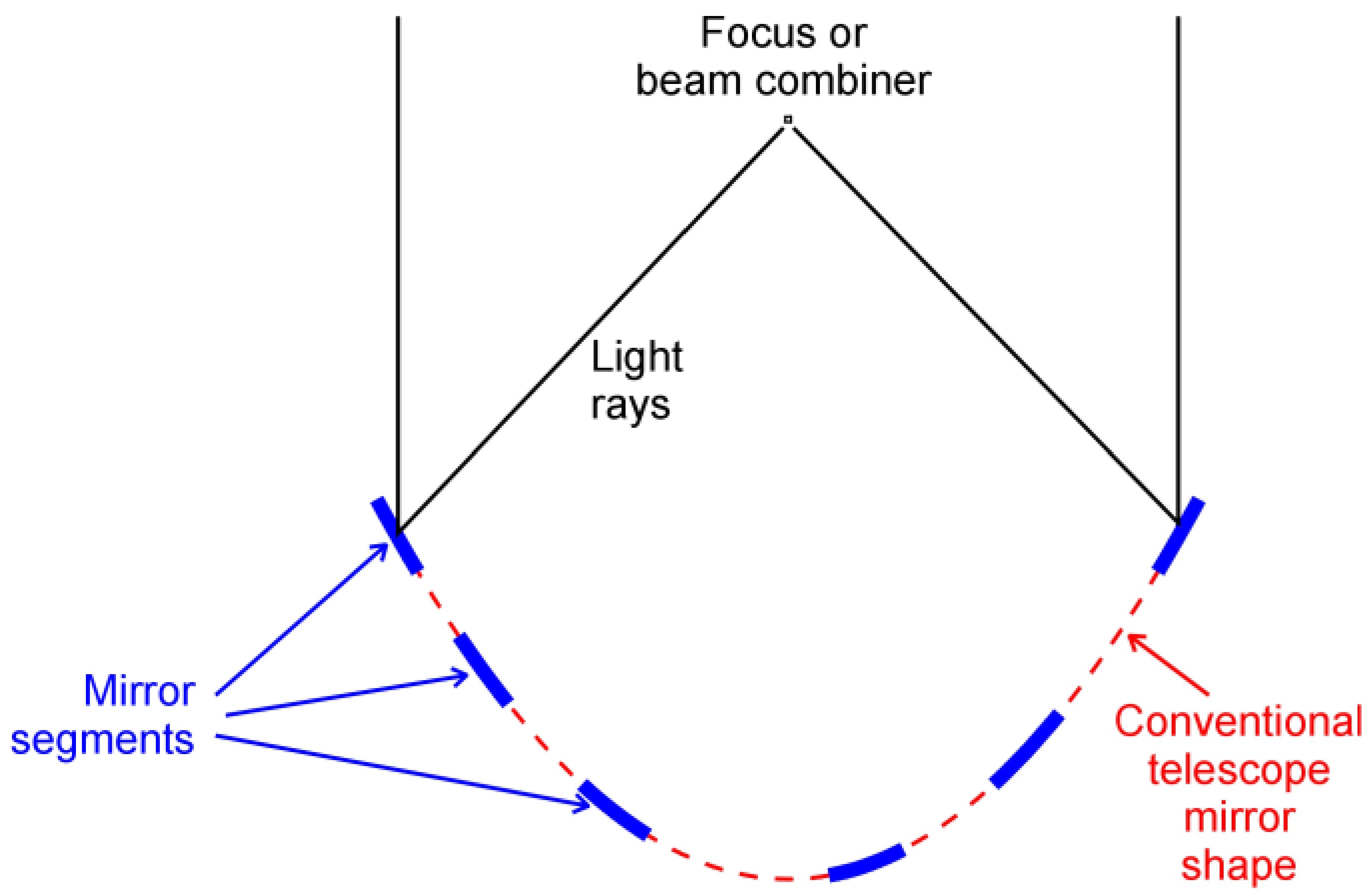
Scientific motivations:
- stellar interferometry: measuring stellar diameters
- Exoplanets in near-IR and thermal IR

Interferometric measurement
- 2-telescope interferometer

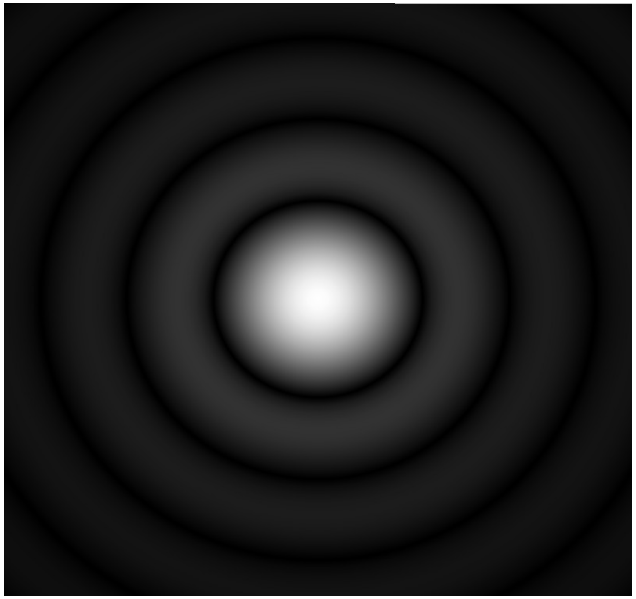
Interferometry and angular resolution

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 : $D \sim 10$m
largest baselines (optical/near-IR interferometers): $B \sim 100$m - 500m



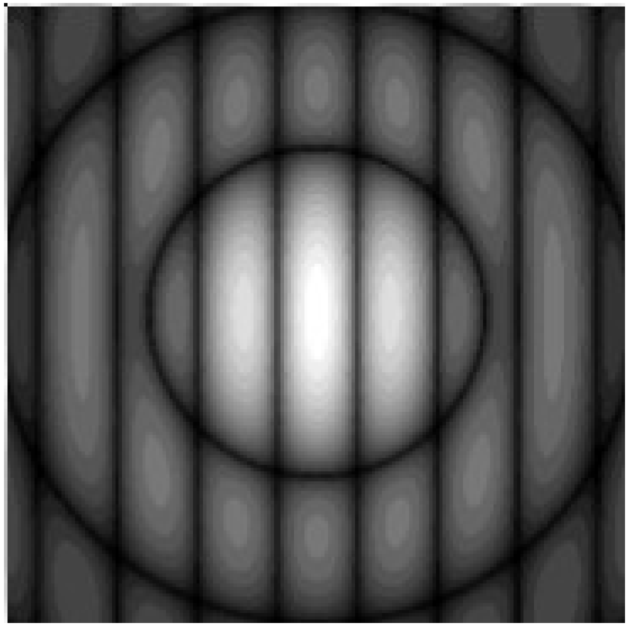
Telescope vs. interferometer diffraction limit



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

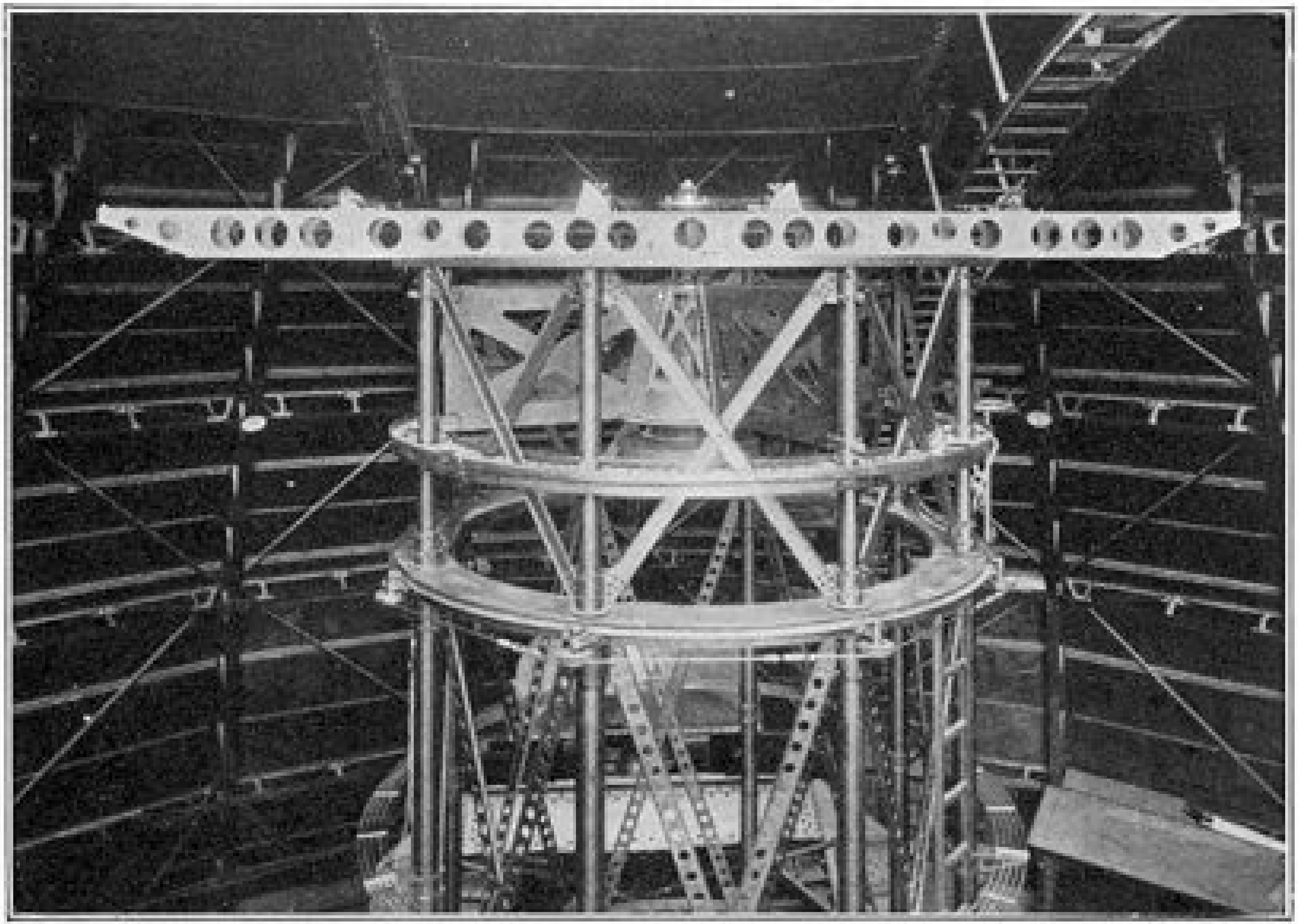


With interferometer, D~400m
→ λ/B = 0.001 arcsec = 1 mas

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

Michelson interferometer (1920)

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



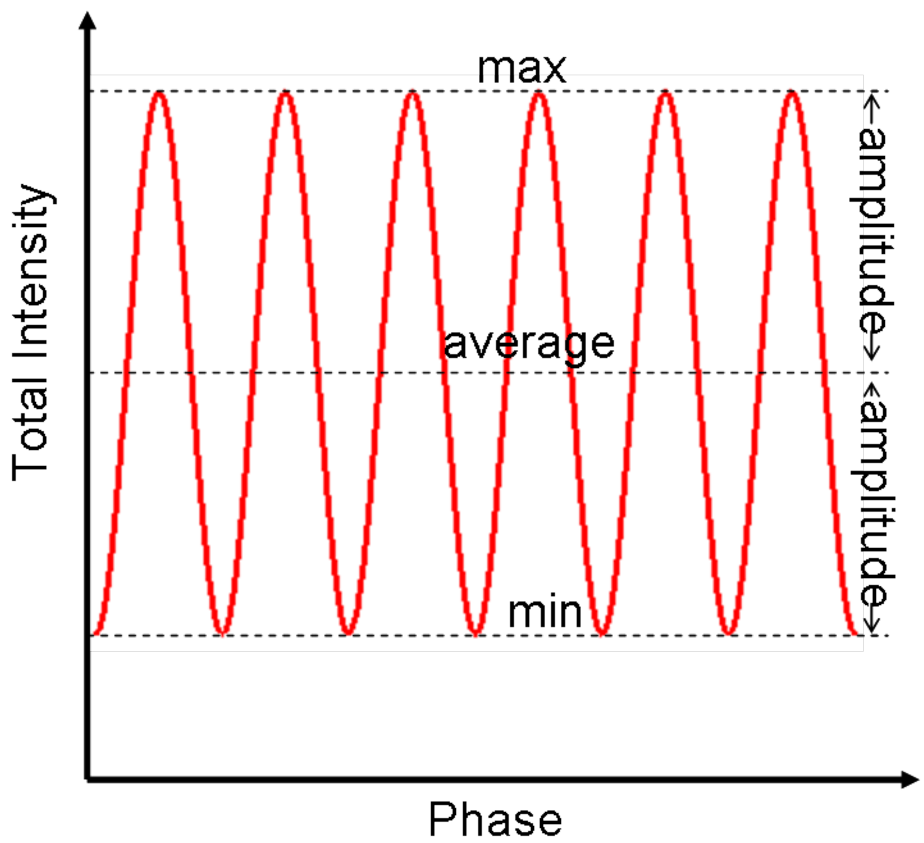
2-telescope interferometer: Fringe visibility and phase

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

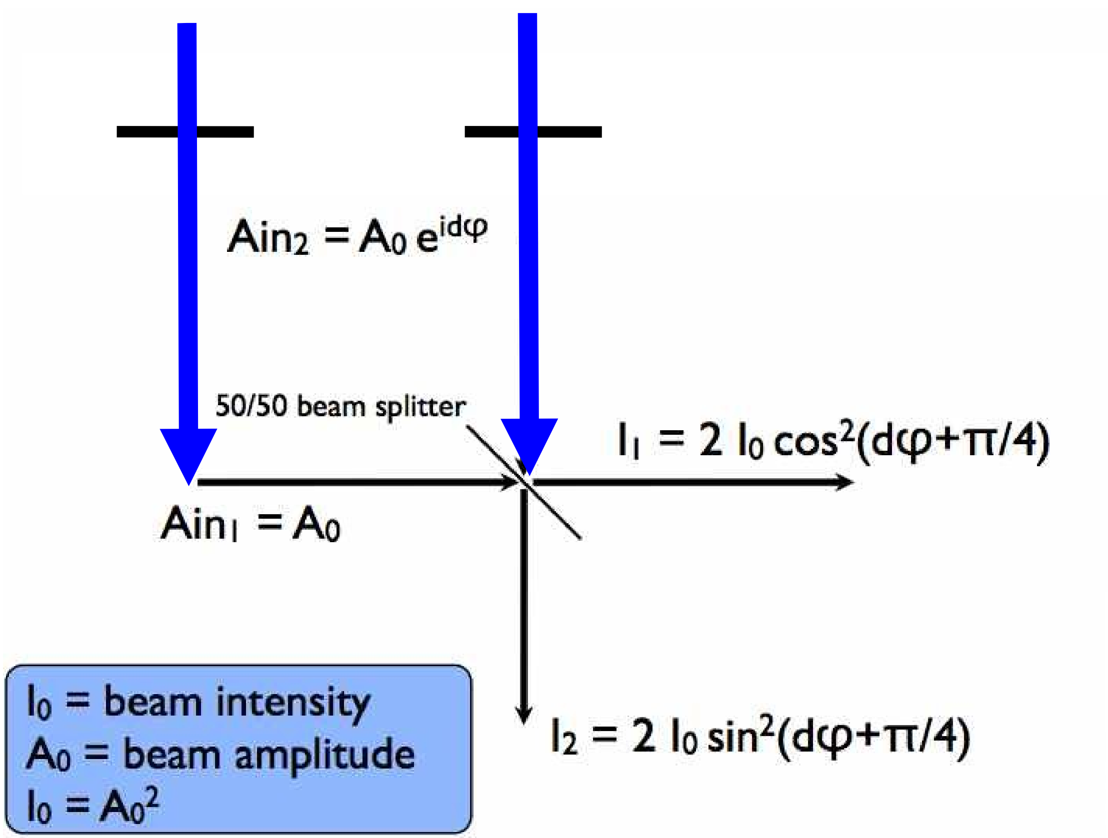
- fringe average intensity → source brightness
- fringe visibility = amplitude / average → single constraint on spatial distribution of light, visibility = 1 if source is unresolved (BUT visibility =1 does not imply that the source is unresolved)
- fringe phase → single contraint on spatial distribution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

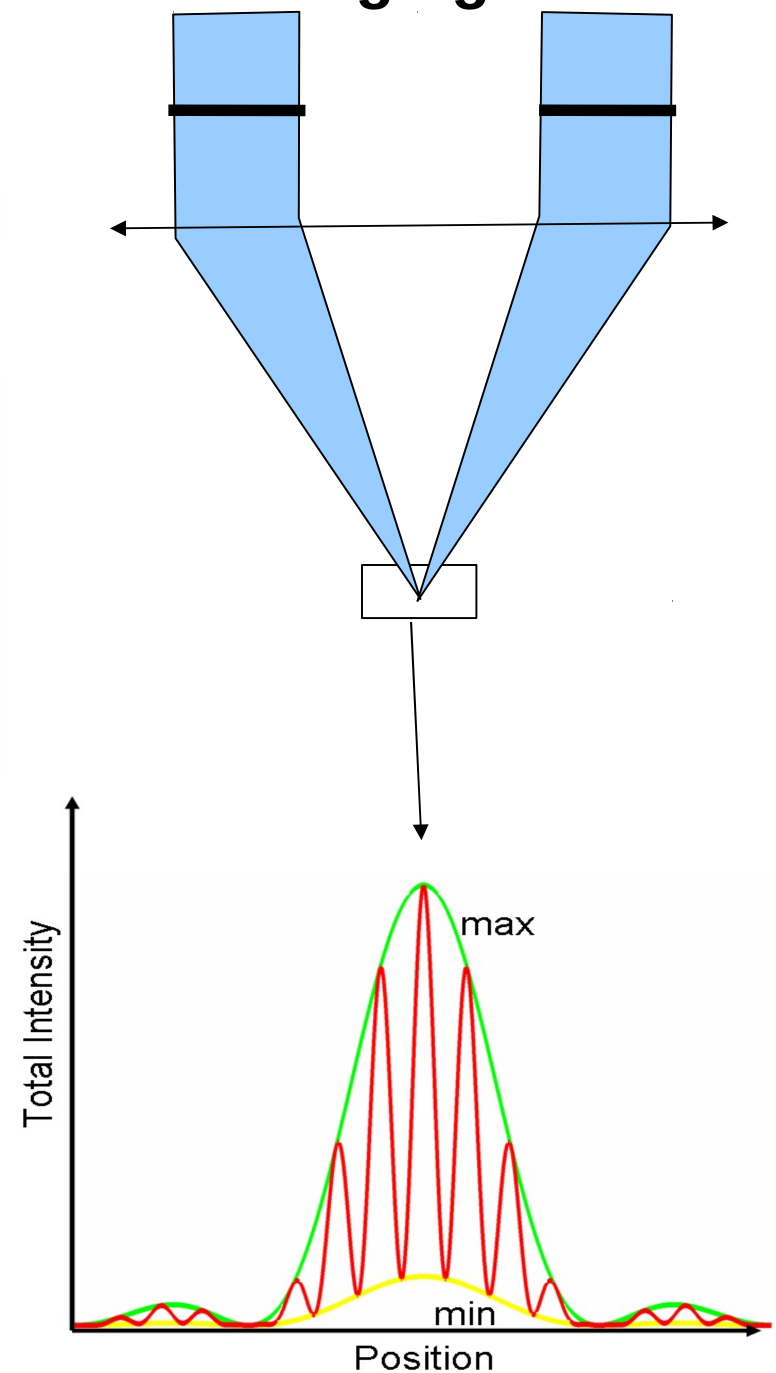
Fringe frequency DOES NOT contain information about object, as it is only a function of the baseline

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



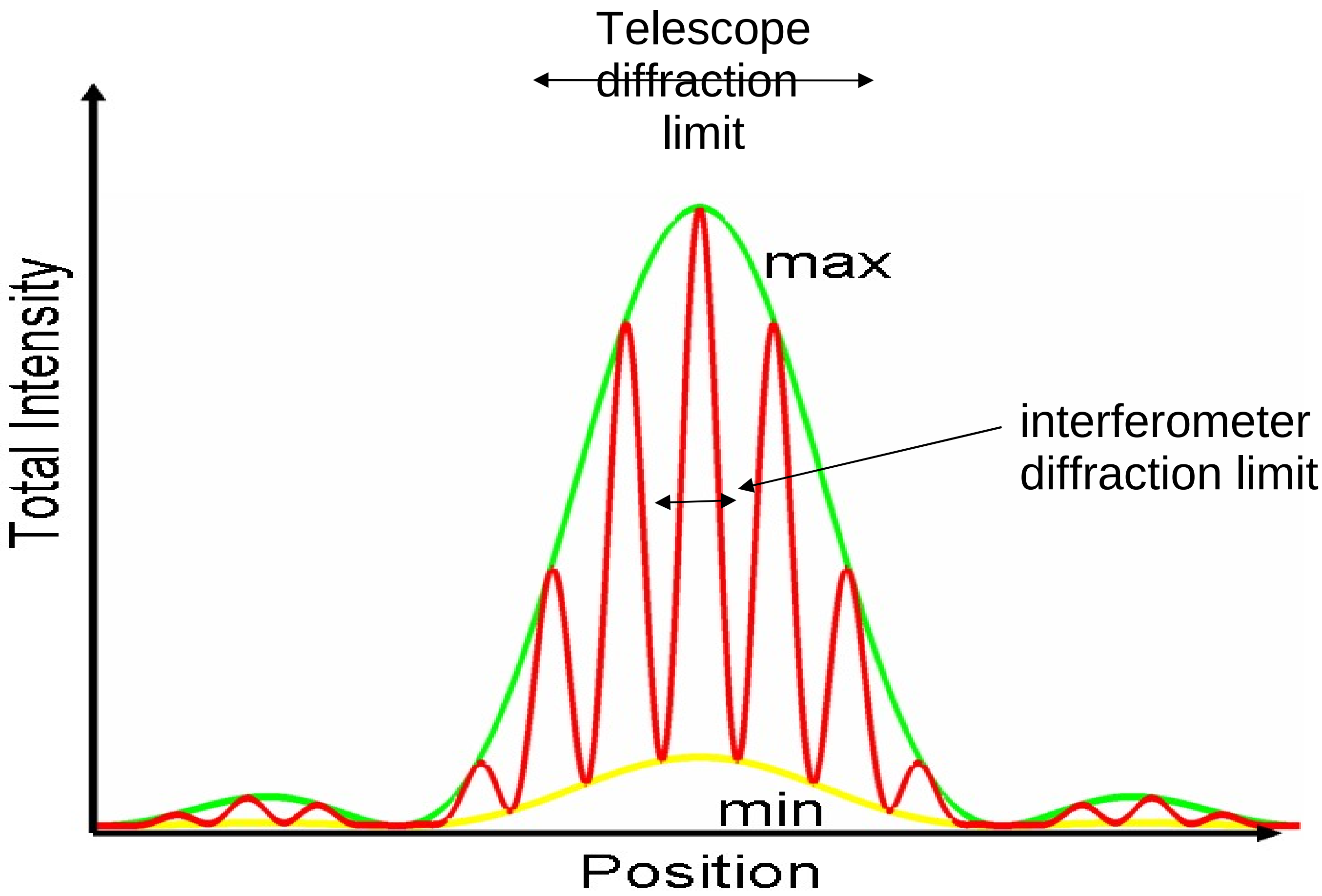
2-telescope interferometer:
Fringe visibility and phase can be measured either by discrete flux measurements (beam splitter(s)) or direct imaging of fringes





Note:
- at least 3 measurements required to contrain 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

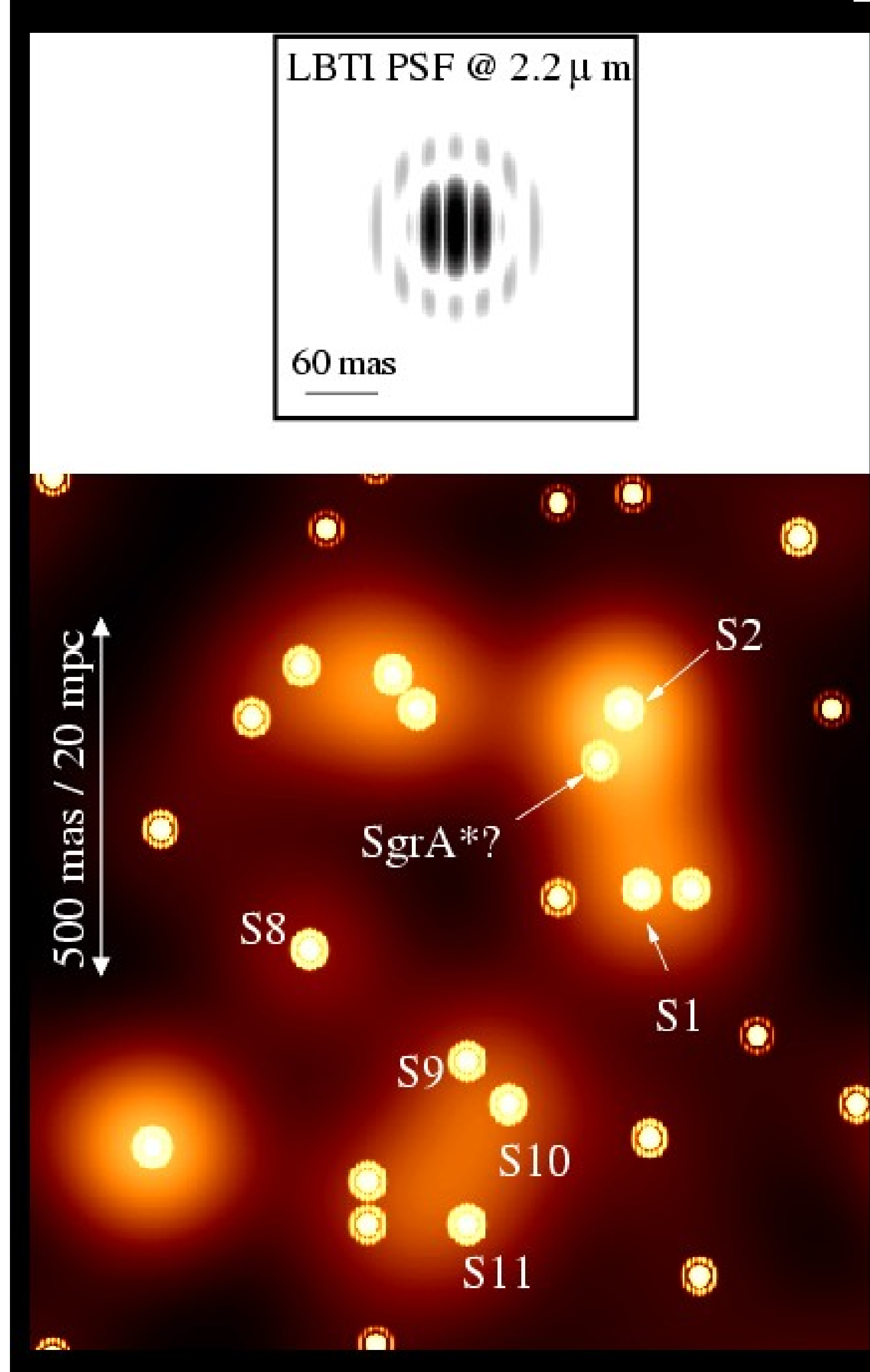
Interferometer field of view

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

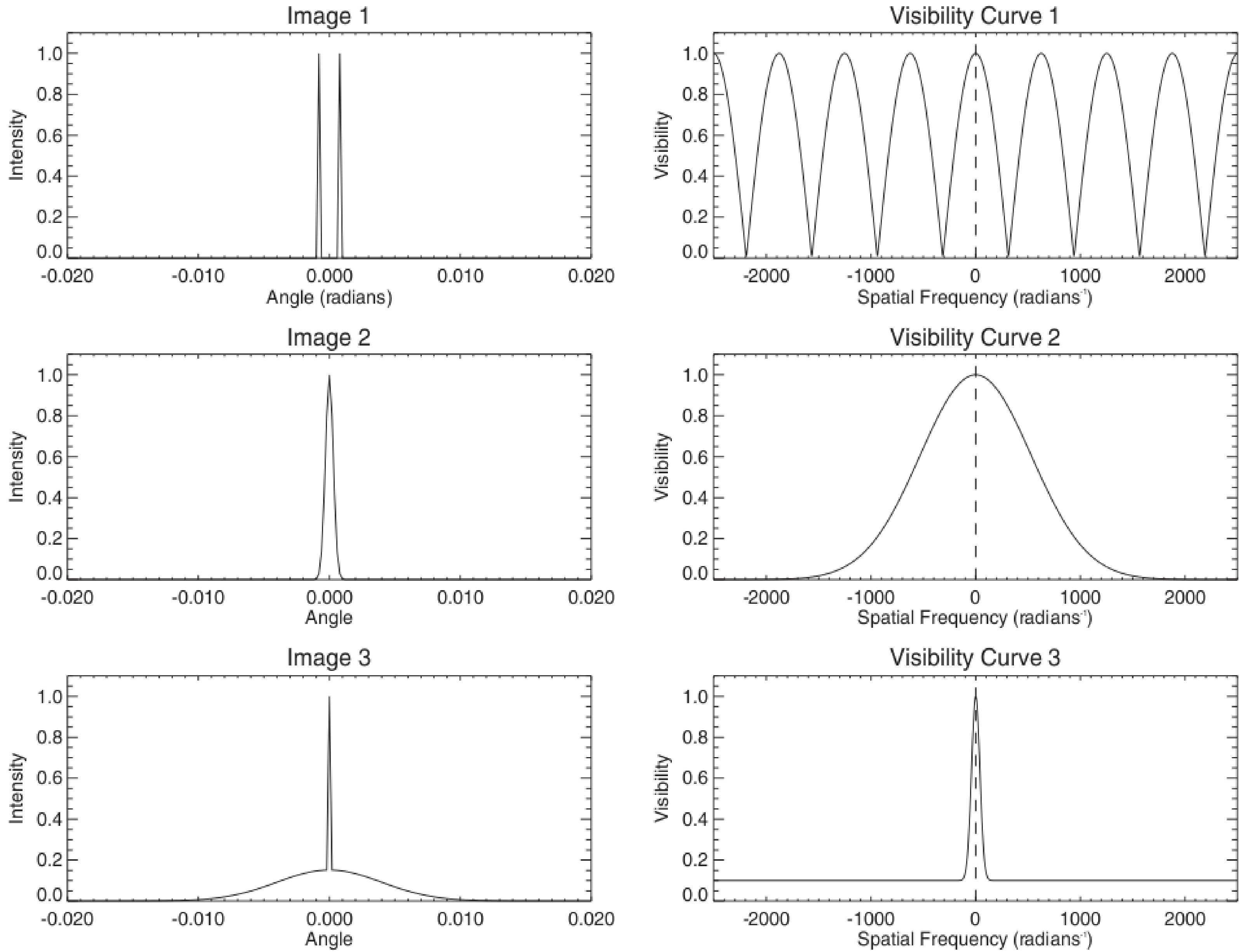


Figure 2. This figure shows simple one-dimensional images and their corresponding visibility curves. The left panels are the images while the right panels correspond to the Fourier amplitudes, i.e. the visibility amplitudes. Note that 'large' structure in image-space result in 'small' structure in visibility-space.

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)

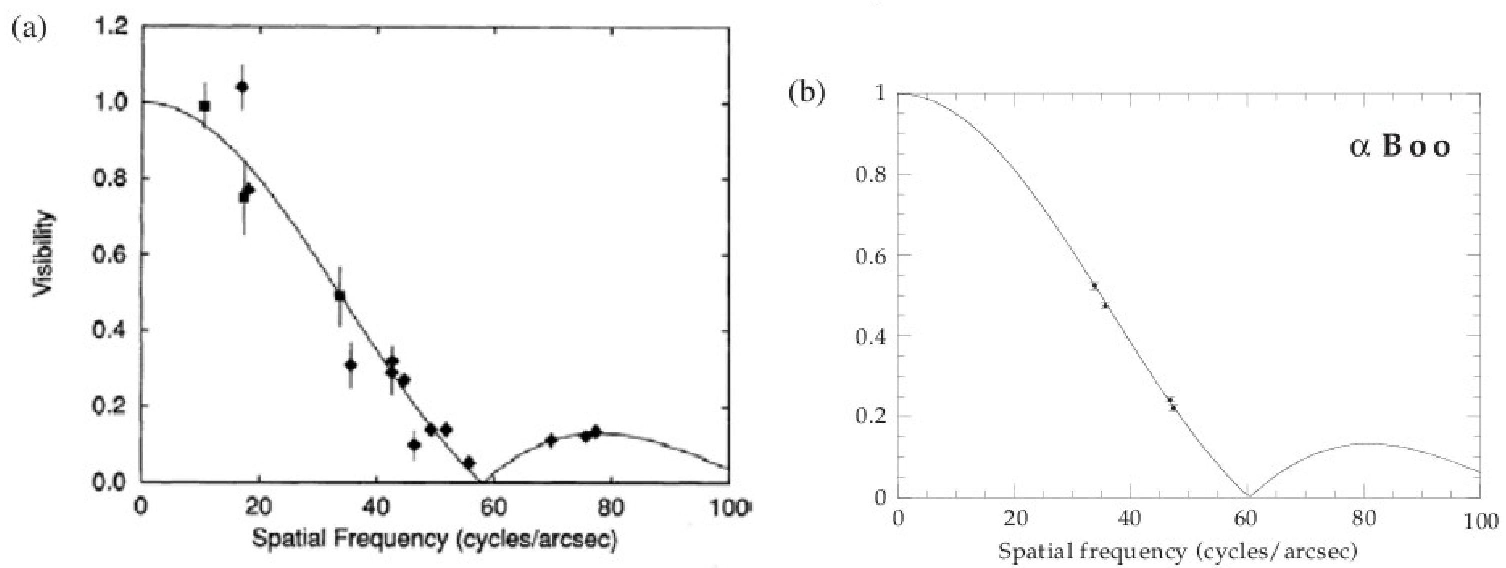


Figure 15. (*a*) This figure shows visibility data for α Boo by the CERGA interferometer (♦) and the IRMA interferometer (■), and originally appeared in the Publications of the Astronomical Society of the Pacific (Copyright 1993, Astronomical Society of the Pacific; Dyck *et al* (1993), reproduced with 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

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

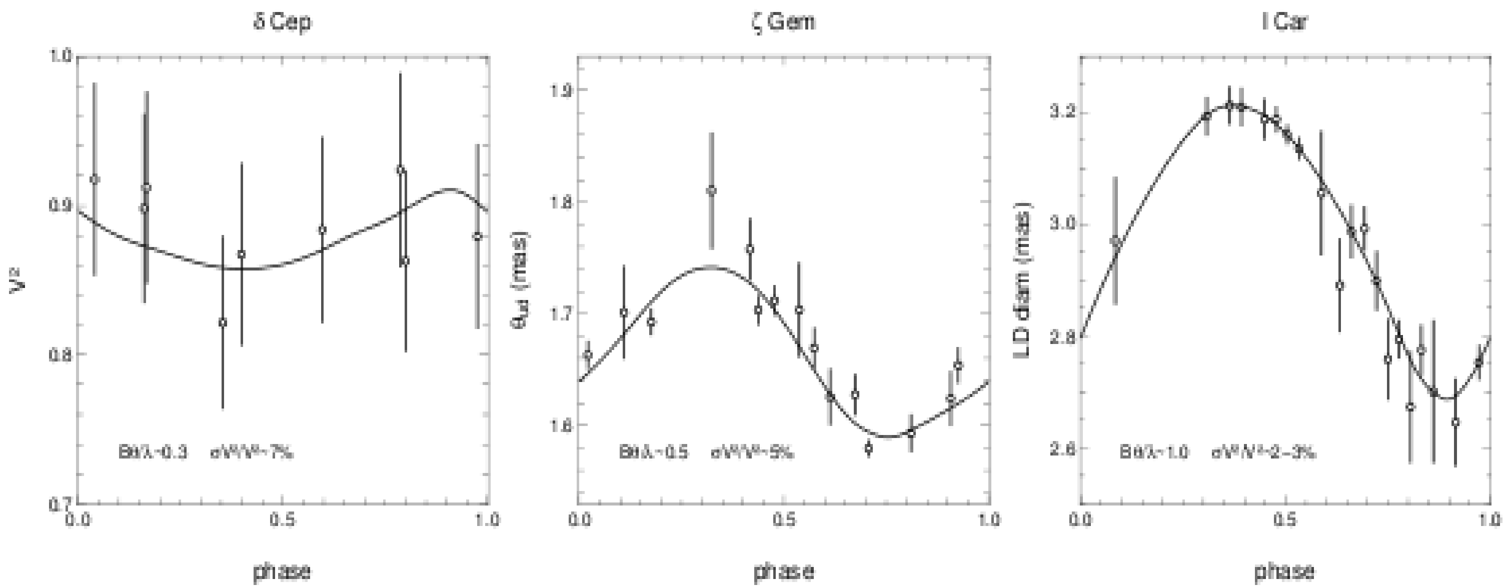
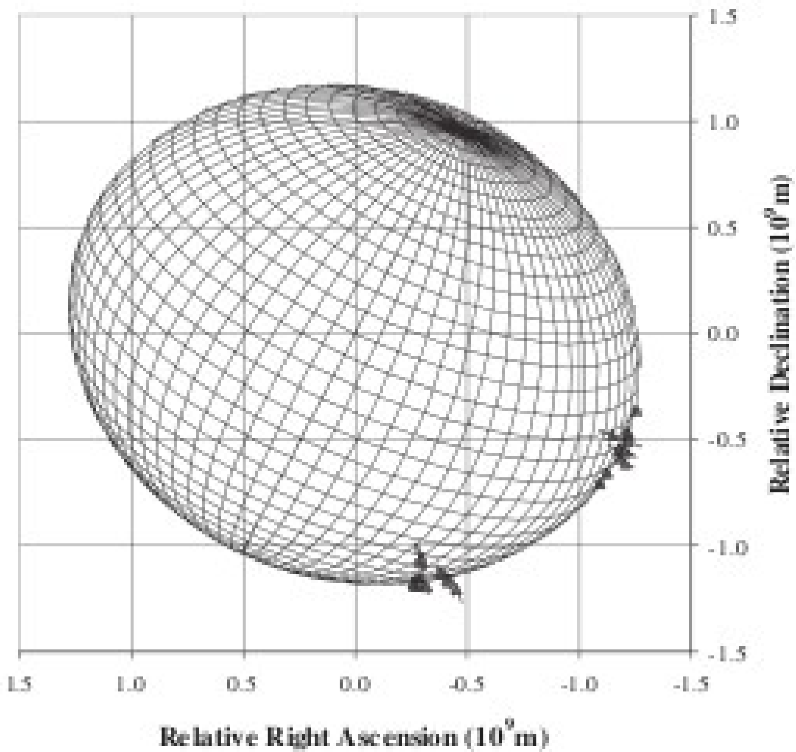


Figure 1. Different interferometric attempts to measure Cepheid angular diameter variations. From left to right: Mourard et al. (1997[6]), Lane et al. (2000[7]) and Kervella et al. (2004[8]). The left panel is V^2 as a function of phase, while the panels to the right are angular diameters with respect 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

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



Palomar Testbed Interferometer
Van Belle et al. 2001

Also possible:

Measure limb darkening (deviation from Bessel function above)

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

Imaging exoplanets with interferometers – Example concept

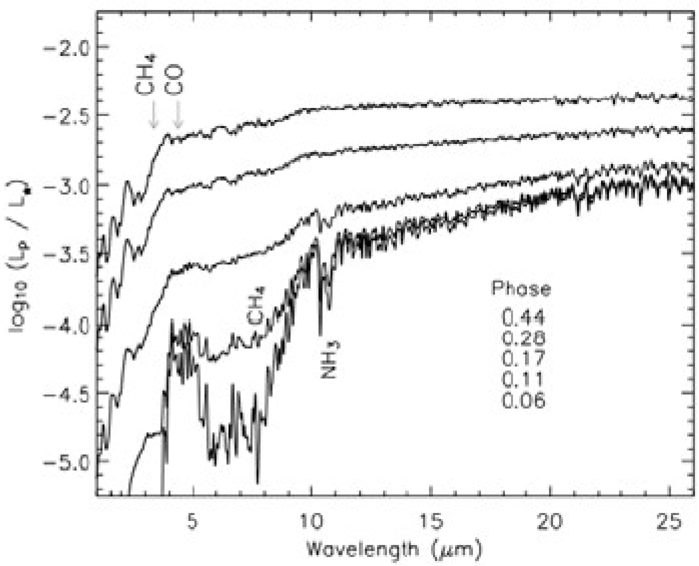


Figure 1. Planet-star flux density ratios for HD209458b at different orbital phase (from Barman *et al.* 2005).

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)

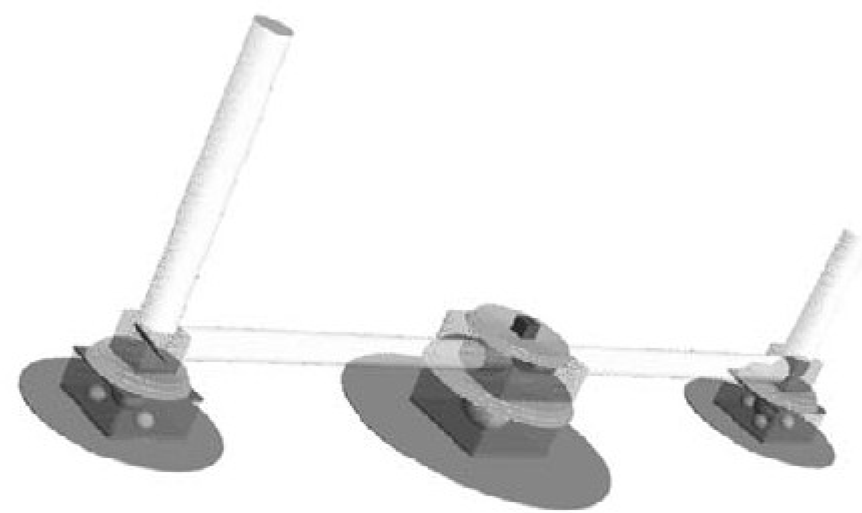
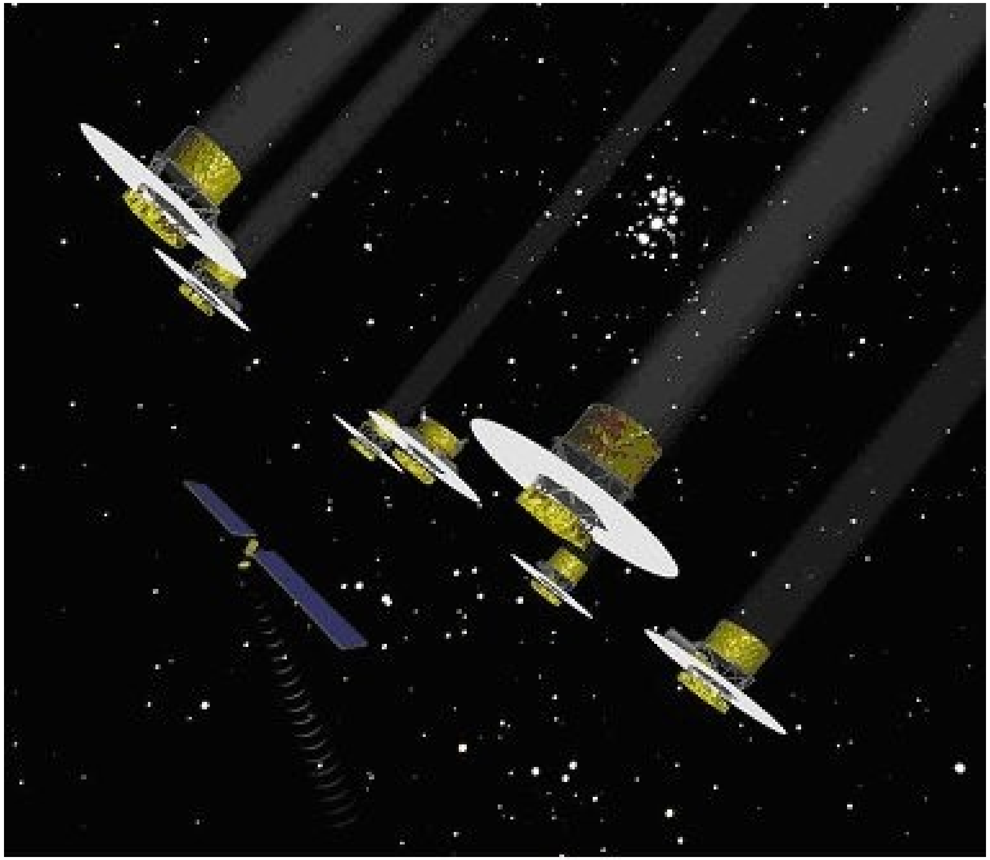


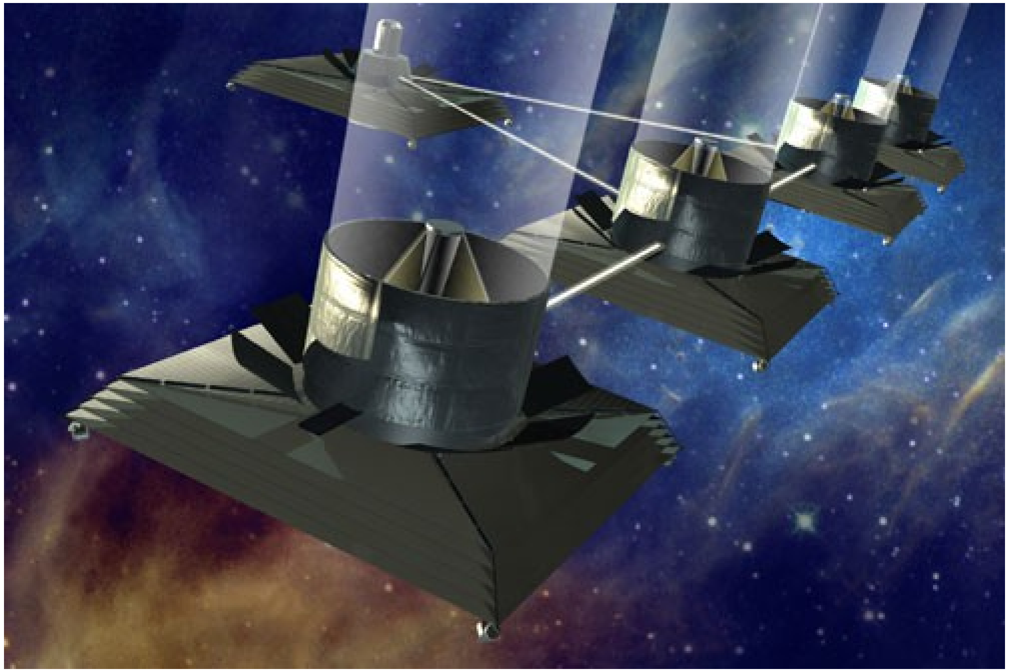
Figure 3. Artist view of the PEGASE observatory (courtesy CNES).

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)