Introduction to Interferometer and Coronagraph Imaging

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Michelson Summer School on Astrometry
Caltech, Pasadena
25-29 July 2005

Goals of this talk:

1. Learn to think in terms of wavelets.

2. Learn how to calculate the interference of wavefronts for any optical system.

3. Learn how to separate astrophysical from instrumental effects.

4. Hear about coronagraphs and speckles.

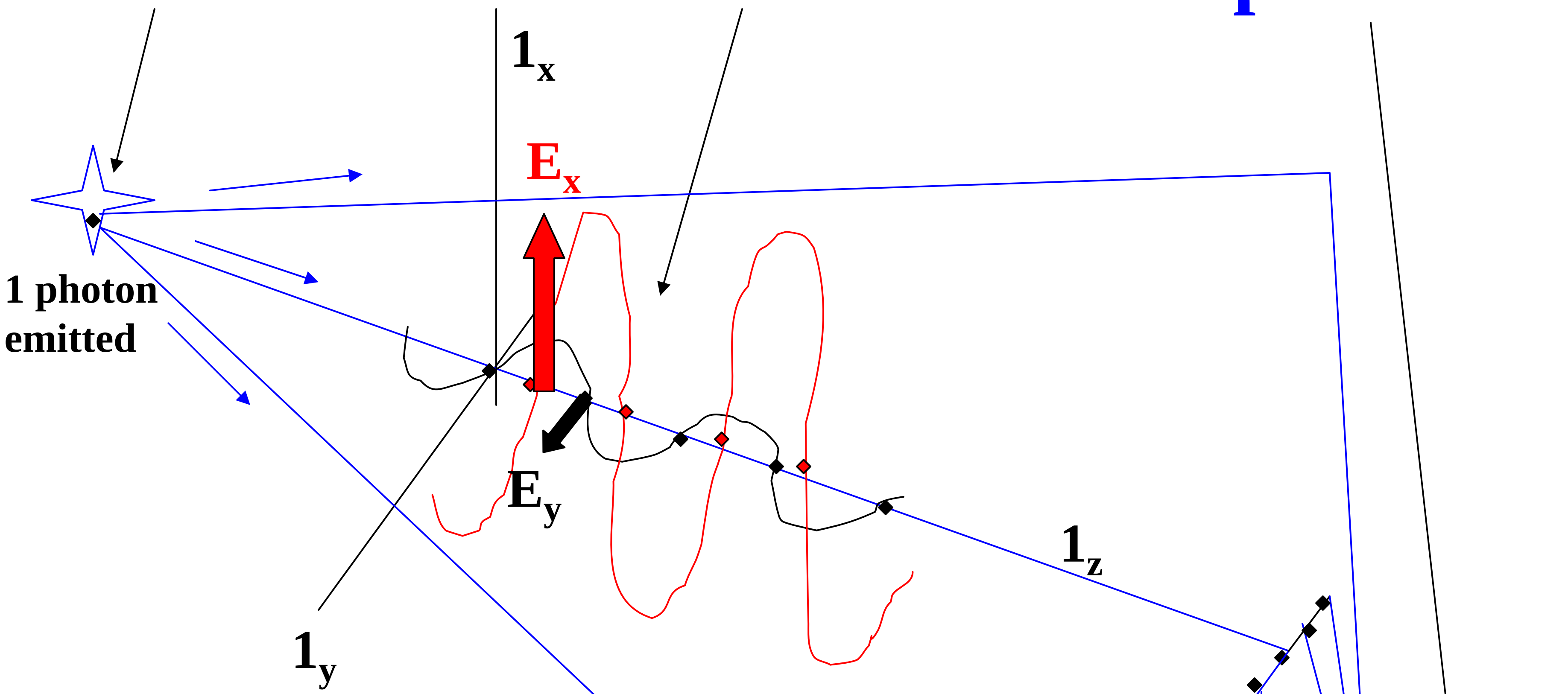
Note: We discuss optical methods (λ < 10 μm) of wavefront detection here (homodyne detection).
We do not discuss radio methods (heterodyne detection).

Photons and Waves

Basic photon-wave-photon process

We see **individual photons**. Here is the **life history** of each one:
Each photon is emitted by a **single atom** somewhere on the star.
After emission, the photon acts like a **wave**.
This wave expands as a **sphere**, over 4π steradians (Huygens).
A portion of the wavefront enters our telescope **pupil(s).**
The wave follows **all possible paths** through our telescope (Huygens again).
Enroute, its **polarization on each path** may be changed.
Enroute, its **amplitude on each path** may be changed,.
Enroute, its **phase on each path** may be changed.
At each possible detector, the wave "senses" that it has followed these **multiple** paths.
At each detector, the electric fields from all possible paths are **added**, with their polarizations, amplitudes, and phases.
Each detector has **probability =** amplitude^2 to detect the photon.

Photon..........wave.................photon



$\mathbf{E}(x,y,z) = \mathbf{1_x} E_x \mathit{sin}(kz\text{-}wt\text{-}p_x) + \mathbf{1_y} E_y \mathit{sin}(kz\text{-}wt\text{-}p_y)$

where the electric field amplitude in the x direction is

$\mathit{sin}(kz\text{-}wt\text{-}p_x) = \mathrm{Im}\{\ e^{i(kz\text{-}wt\text{-}px)}\ \}$

and likewise for the y-amplitude.

At detector, *add the waves* from *all possible paths*.

Fourier optics vs geometric optics

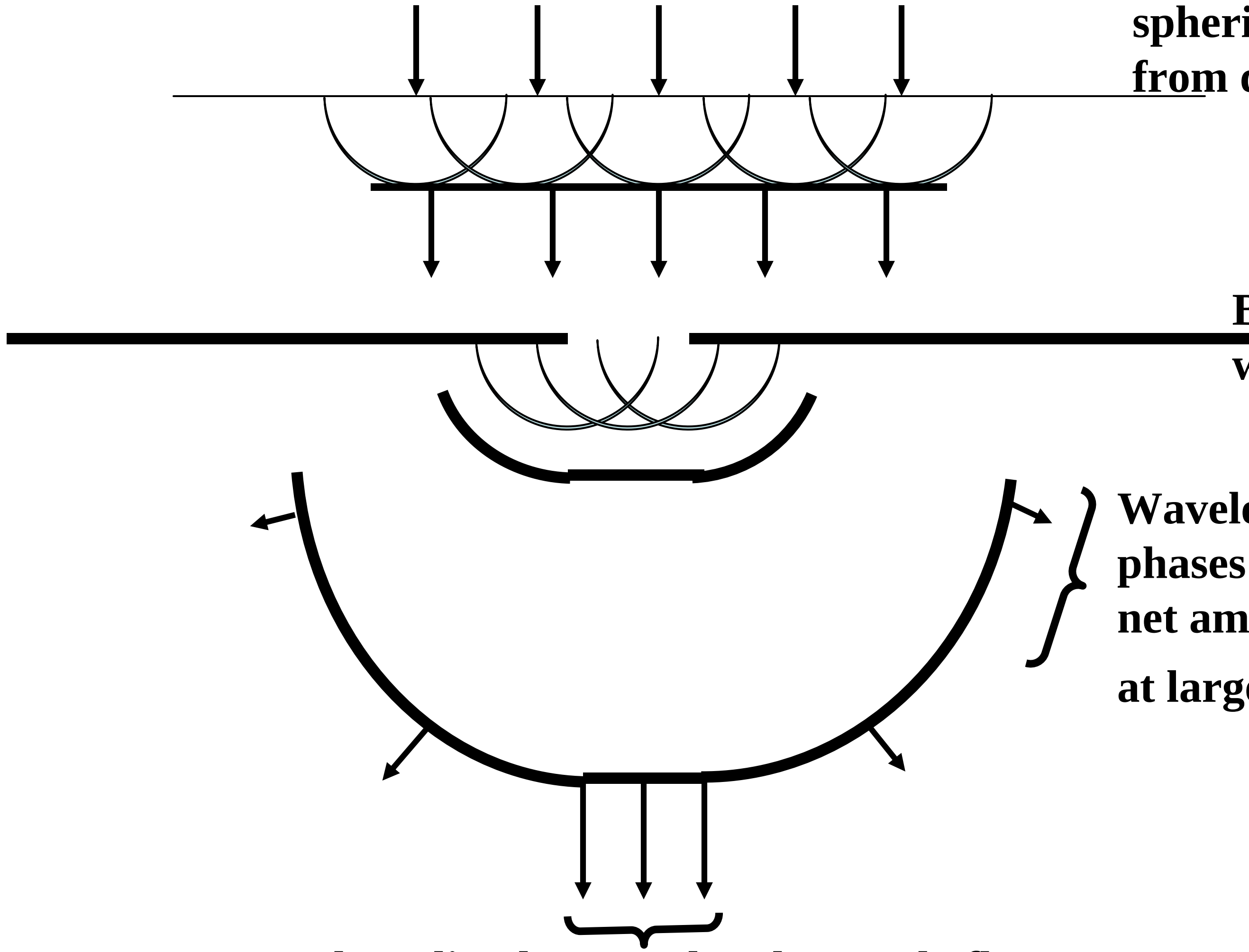
Fourier optics (or physical optics) describes ideal diffraction-limited optical situations (coronagraphs, interferometers, gratings, lenses, prisms, radio telescopes, eyes, etc.):

If the all photons start from the same atom, and follow the same many-fold path to the detectors, with the same amplitudes & phase shifts & polarizations, then we will see a diffraction-controlled interference pattern at the detectors.

In other words, **waves** are needed to describe what you see.

Geometric optics describes the same situations but in the limit of zero wavelength, so no diffraction phenomena are seen. In other words, **rays** are all you need to describe what you see.

Huygens wavelets



Portion of large, spherical wavefront from distant atom.

Blocking screen, with slit.

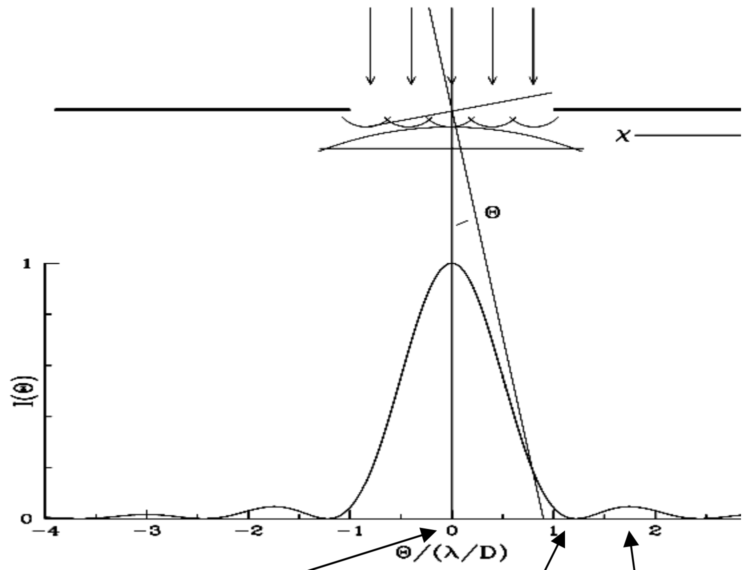
Wavelets add with various phases here, reducing the net amplitude, especially at large angles.

Wavelets align here, and make nearly flat wavefront, as expected from geometric optics.

Huygens' wavelets --> Fraunhofer --> Fourier transform

The phase of each wavelet on a surface
Tilted by theta = x/f and focused by the
Lens at position x in the focal plane is

$$\begin{aligned}\phi(z) &= 2\pi x \sin(\theta)/\lambda \\ &\simeq 2\pi x\theta/\lambda\end{aligned}$$



The sum of the wavelets across the potential wavefront at angle theta is

$$\begin{aligned}A_{tel}(\theta) &= \sum(\text{wavelets}) \\ &= \int_{pupil} e^{i\phi(x)}dx \\ &= \int_{-D/2}^{+D/2} e^{i(2\pi x\theta/\lambda)}dx \\ &= \frac{\lambda}{2\pi i\theta}\left[e^{+i\pi\theta D/\lambda} - e^{-i\pi\theta D/\lambda}\right] \\ &= \frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda}D\end{aligned}$$

All waves add in phase here

The net amplitude is zero here

The net amplitude mostly cancels, but not exactly, here

Fourier relations: pupil and image

We see that an ideal lens (or focussing mirror) acts on the amplitude in the **pupil plane**, with a **Fourier-transform** operation, to generate the amplitude in the **image plane**.

A second lens, after the image plane, would convert the **image-plane** amplitude, with a second **Fourier-transform**, to the plane where the initial **pupil is re-imaged**.

A third lens after the **re-imaged pupil** would create a **re-imaged image** plane, via a third **FT**.

At each stage we can **modify the amplitude** with masks, stops, polarization shifts, and phase changes. These all go into the **net transmitted** amplitude, before the next FT operation.

Summation of wavelets

Born and Wolf (7th edition, p. 428) define the wavelet summation integral as the Fourier-transform relation between amplitude in the pupil $A_{in}(x,y)$ and amplitude in the focal plane $A_{out}(u,v)$.

Image amplitude = Sum of wavelet amplitudes

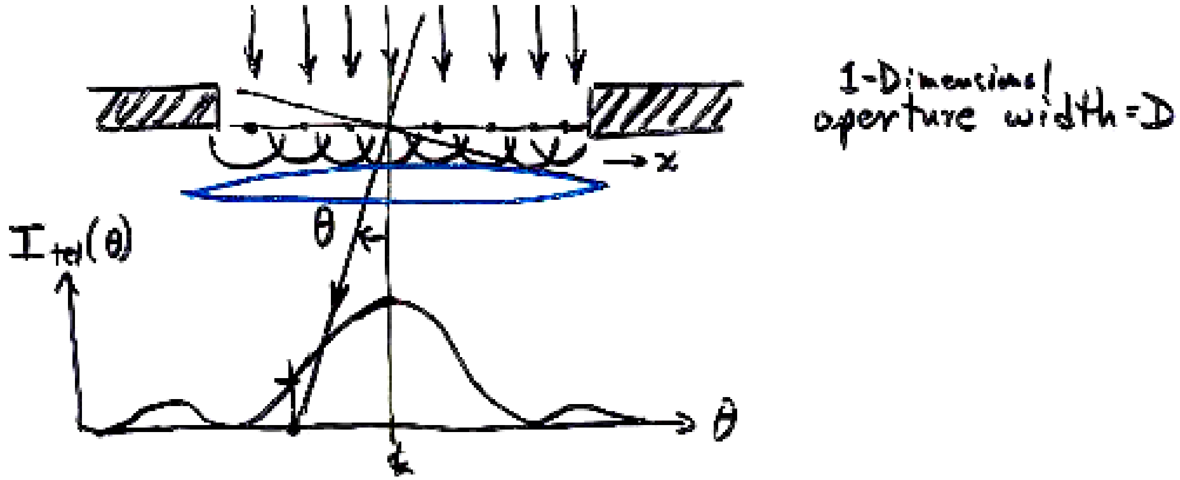
$$A_{out}(u,v) = \frac{1}{\lambda f} \int A_{in}(x,y) e^{-ik(xu+yv)/f} \, dxdy$$

where

$$\left|A(x,y)\right|^2 = energy / area = Intensity$$

Simplify: (1) 2D→1D; (2) coef.= 1; (3) u/f = θ = angle in focal plane.

Derive single-telescope response to point source



amplitude. $$A_{tel}(\theta) = \sum_{wavelets} = \int_D e^{i(\text{phase at } x)}\,dx$$

$$= \int_{-D/2}^{+D/2} e^{i\left(2\pi \frac{x\theta}{\lambda}\right)}\,dx \Big/ \int dx$$

$$= \frac{\lambda}{2\pi i\theta}\left[e^{+i\pi\theta D/\lambda} - e^{-i\pi\theta D/\lambda}\right] / D$$

$$= \frac{\sin(\pi\theta D/\lambda)}{(\pi\theta D/\lambda)}$$

intensity. $$I_{tel}(\theta) = |A_{tel}|^2 = \left[\frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda}\right]^2$$

1st zero. $I_{tel}(\theta_{tel}) = 0$ when $\theta_{tel} = \lambda/D$

circular aperture. $$\int_{circle} \cdots \Rightarrow I_{tel}(\theta) = \left[\frac{2J_1(\pi\theta D/\lambda)}{\pi\theta D/\lambda}\right]^2$$

$$\theta_{tel} = 1.22\,\lambda/D$$

Single telescope again

add constant phase ϕ:

$$A_{tel}(\theta) = \int_{-D/2}^{+D/2} e^{i\left(2\pi \frac{x\theta}{\lambda} + \phi\right)} dx \Big/ \int dx = \frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda} \cdot e^{i}$$

I_{tel} is unchanged.

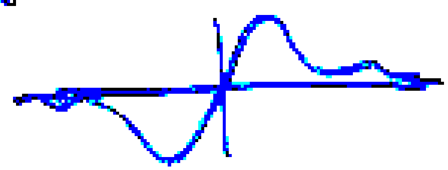
add off-axis angle θ_0:

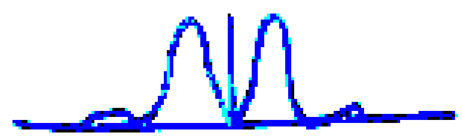
$$A_{tel}(\theta) = \int_{-D/2}^{+D/2} e^{i\left(2\pi x(\theta + \theta_0)/\lambda\right)} dx \Big/ \int dx = \frac{\sin(\pi(\theta-\theta_0)D/}{\pi(\theta-\theta_0)D/\lambda}$$

I_{tel} is shifted to center at θ_0.

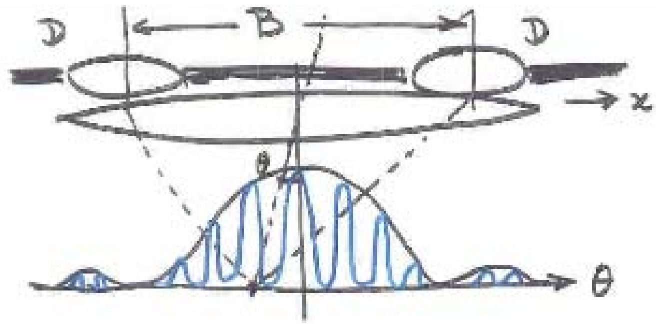
add phase step (across 1/2 aperture) of π:

$$A_{tel}(\theta) = \left[\int_{0}^{+D/2} e^{i\left(2\pi x\theta/\lambda + \pi/2\right)} dx + \int_{-D/2}^{0} e^{i\left(2\pi x\theta/\lambda - \pi/2\right)} dx\right] \Big/ \int$$

$=$ 

$I_{tel}(\theta) =$  i.e. 2 speckles.

Derive interferometer (2-tel.) response



amplitude. $$A_{int}(\theta) = \sum_{wavelets} = \int e^{i\,(\text{phase at } x)}\,dx$$

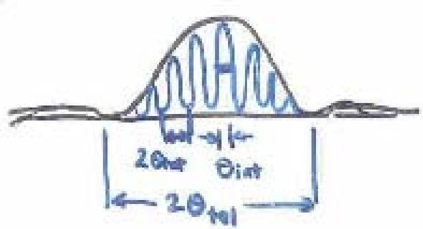
$$= \left[\int_{+\frac{1}{2}B-\frac{1}{2}D}^{+\frac{1}{2}B+\frac{1}{2}D} \sim + \int_{-\frac{1}{2}B-\frac{1}{2}D}^{-\frac{1}{2}B+\frac{1}{2}D} \sim \right] / 2D$$

$$= \frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda} \cdot \cos(\pi\theta B/\lambda)$$

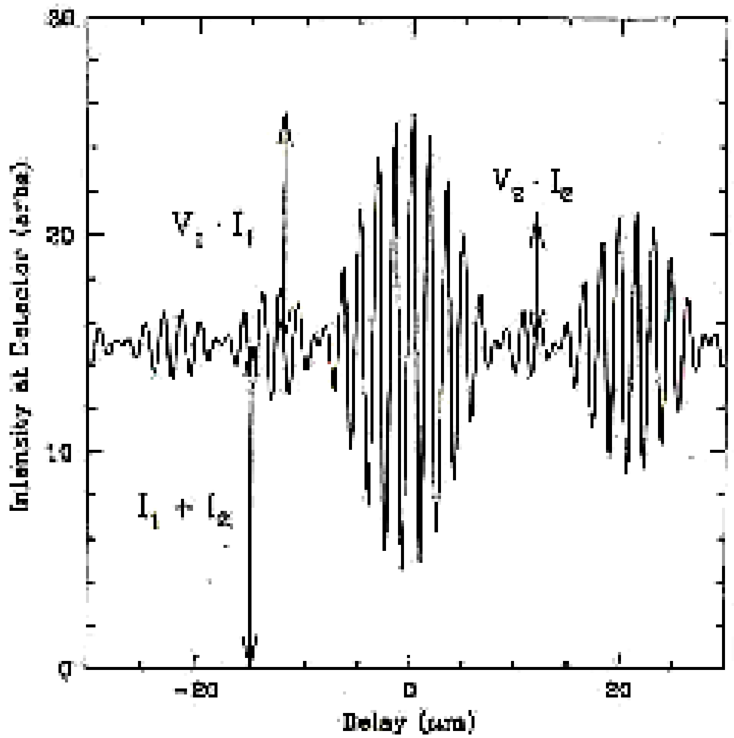
intensity. $$I_{int}(\theta) = I_{tel}(\theta) \cdot \tfrac{1}{2}\left[1 + \cos(2\pi\theta B/\lambda)\right]$$

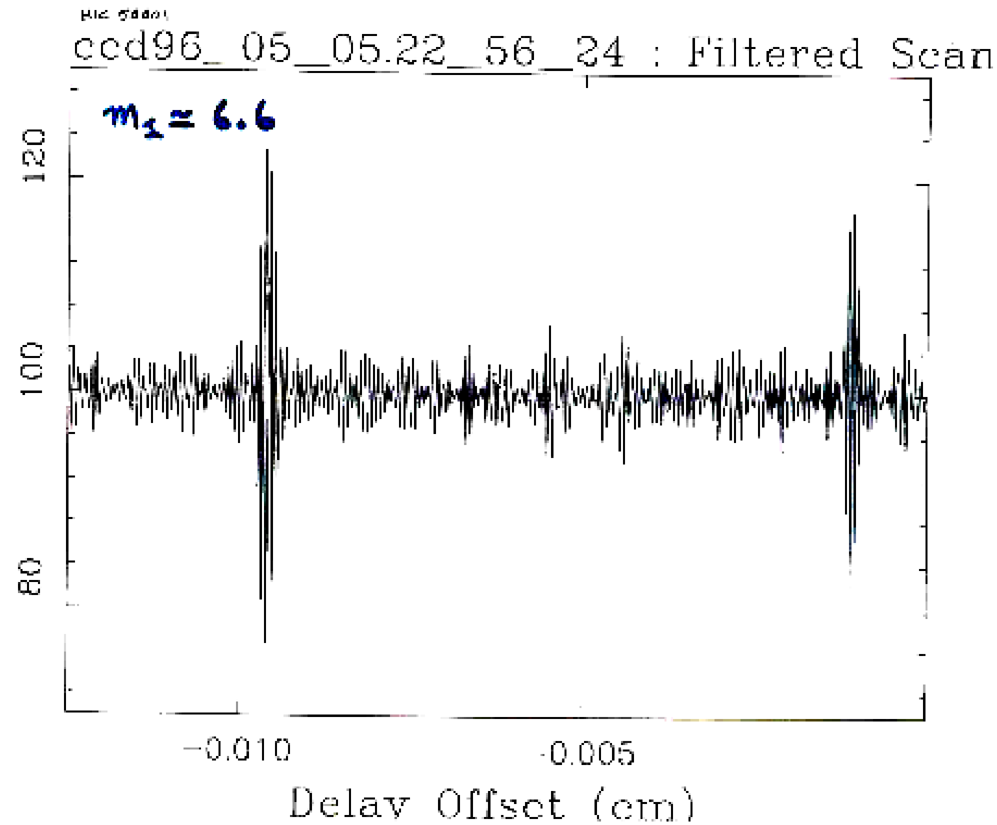
1st zero. $I_{int}(\theta_{int}) = 0$ when $\theta_{int} = \frac{\lambda}{2B}$ = width of fringe.

number of fringes in packet. $$(\text{no. fringes}) = \frac{2\,\theta_{tel}}{2\,\theta_{int}} = \frac{1.22\,\lambda/D}{0.50\,\lambda/B} = 2.44\,\frac{B}{D}$$



Binary star interferograms





Model interferogram for a binary star, with well-separated fringe packets.

Observed interferogram of a very wide-spaced binary. CCD detector, no filter, IOTA interferometer, 1996 data.

Derive uniform disk response

Add up (incoherent) fringe patterns from square disk :

intensity. $I_{USD}(\theta) = \sum_{\text{sq. disk}} (\text{intensities}) = \int_{\text{sq. disk}} I_{int}(\theta - \theta_x) \cdot d\theta_x \, d\theta_y \Big/ \int d\theta$

$$= \int_{-\theta_{disk}/2}^{+\theta_{disk}/2} I_{tel}(\theta) \cdot \tfrac{1}{2}\left[1 + \cos 2\pi(\theta - \theta_x) B/\lambda\right] \cdot \theta_{disk} \cdot d\theta_x \Big/ \theta_{disk}^2$$

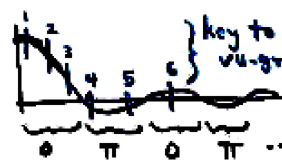
$$\approx I_{tel}(\theta) \cdot \tfrac{1}{2}\left[1 + \underbrace{\left(\frac{\sin \pi B \theta_{disk}/\lambda}{\pi B \theta_{disk}/\lambda}\right)}_{V_{USD}} \cdot \cos \frac{2\pi\theta B}{\lambda}\right]$$

visibility. $V_{USD} = \dfrac{\sin(\pi B \theta_{disk}/\lambda)}{\pi B \theta_{disk}/\lambda}$, square disk.

$V_{UD} = \dfrac{2 J_1(\pi B \theta_{disk}/\lambda)}{\pi B \theta_{disk}/\lambda}$, round disk.

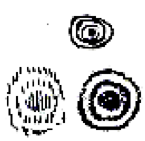
1st zero. $V_{UD} = 0$ when $\theta_{disk} = 1.22\ \lambda/B$, $B = 1.22\ \lambda/\theta_{disk}$

phase. phase $= \begin{cases} 0 & \text{inside odd lobes} \\ \pi & \text{inside even lobes} \end{cases}$



example 1. see next vu-graph from Born & Wolf.

example 2.



SIM pocket demonstration card.

$D \simeq 0.07$ mm so $\theta_{tel} = 1.22\ \lambda/D \simeq 2000.''$ $\simeq$ sun, moon.

$B \simeq 0.25$ mm so $\theta_{int} = \frac{\lambda}{2B} \simeq 200.''$ $\simeq$ Mag-light at 6-18 inches.

(# fringes in packet) $= 2.44\ B/D \simeq 8$.

Uniform disk: interferograms

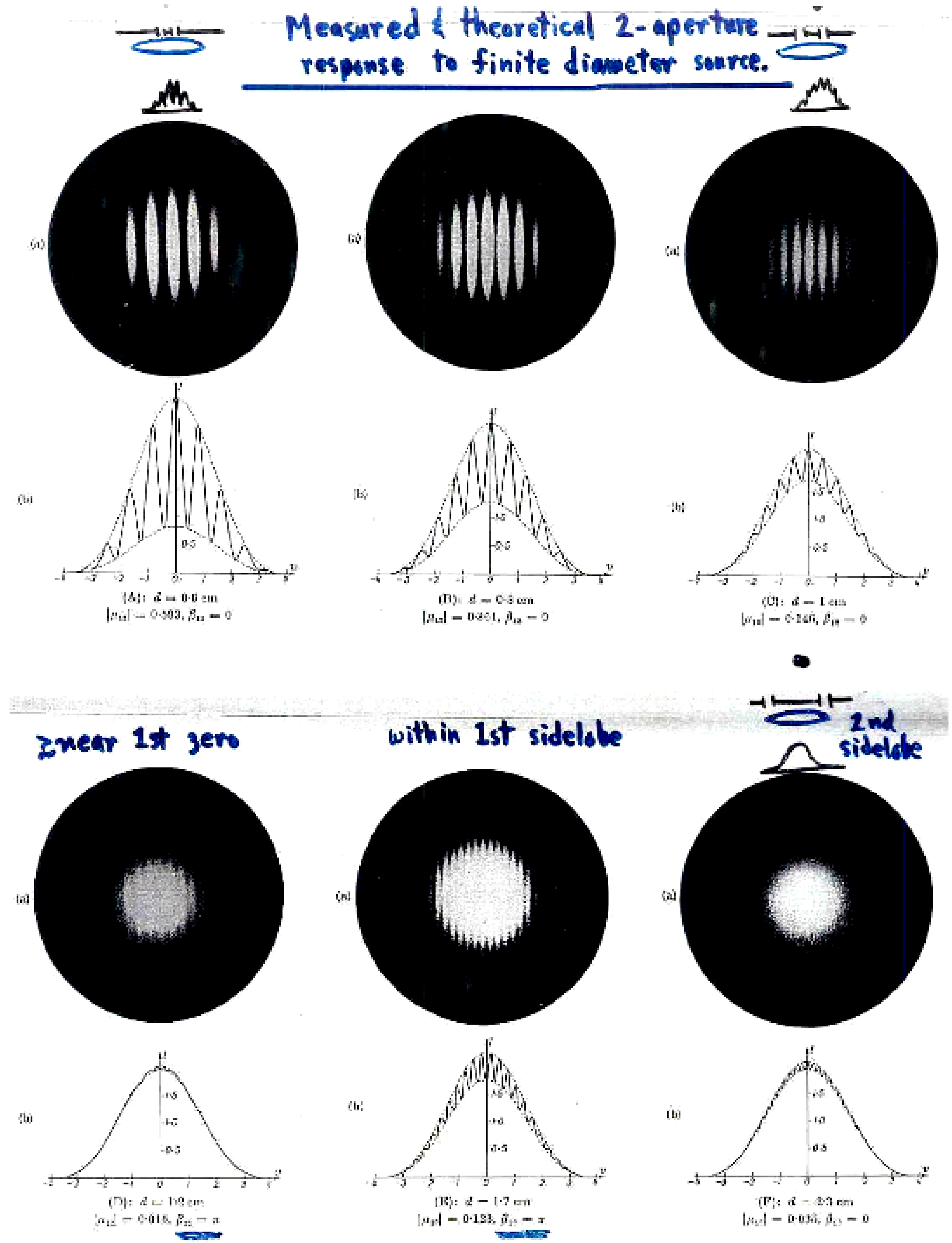


Fig. 10.6. Two-beam interference with partially coherent light.

Van Cittert-Zernike theorem

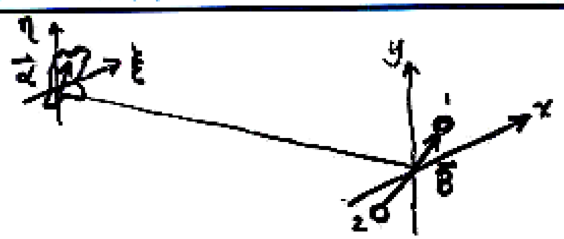
Beam pattern on sky.

Think like a radio astronomer.

The antenna pattern is considered to be projected out from the receiver horn & antenna & array onto the sky. As you move the antenna, or change the phase at an array element, the pattern sweeps across the sky. The received signal is the convolution of the moving pattern and the sources in the sky.

A sinusoidal pattern picks out the Fourier component at that spacing of fringes.

van Cittert – Zernike theorem (1934, 1938).



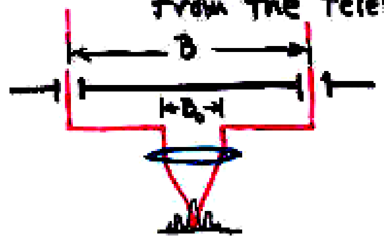
Complex degree of coherence. $$\mu_{12}(\vec{B}) = \int_{FOV} I(\vec{\alpha})\cdot e^{-ik\vec{B}\cdot\vec{\alpha}}\cdot d\vec{\alpha} \Big/ \int_{FOV} I(\vec{\alpha})\cdot d\vec{\alpha}$$

degree of coherence. $|\mu| \equiv V$ = visibility ; phase = $\arg(\mu)$.

inverse relation. $$I(\vec{\alpha}) \Big/ \int_{FOV} I(\vec{\alpha})\, d\vec{\alpha} = \int_{\text{all } \vec{B}} \mu(\vec{B})\cdot e^{+ik\vec{B}\cdot\vec{\alpha}}\cdot d\vec{B}$$

Michelson's stellar interferometer

Suppose we decouple the collecting apertures at B from the telescope feed apertures at B_o.



The coherence is measured by B.

The display pattern is set by B_o.

$$I_{int}(\theta) = I_{tel}(\theta)\cdot\frac{1}{2}\left[1 + \left(\frac{\sin \pi B\theta_{disk}/\lambda}{\pi B\theta_{disk}/\lambda}\right)\cos\left(2\pi\theta B_{tel}/\lambda\right)\right]$$

- $I_{tel}(\theta)$: envelope vs θ
- $\left(\frac{\sin \pi B\theta_{disk}/\lambda}{\pi B\theta_{disk}/\lambda}\right)$: degree of modulation indep. of θ
- $\cos\left(2\pi\theta B_{tel}/\lambda\right)$: modulation vs θ with period indep. of B and θ_{disk}.

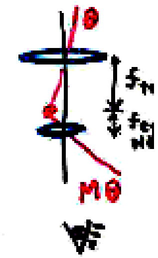
magnification. So can make B_o any convenient value. Michelson used $B_o = 1.14$

so the fringe width is $\theta_{int} = \frac{\lambda}{2B_o} = 0.045$ arcsec.

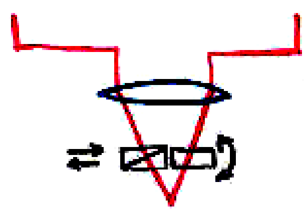
Assume his eye had $\theta_{eye} \simeq 1.22\,\frac{\lambda}{5\,mm} \simeq 25.$ arcsec.

Magnify θ_{int} to match θ_{eye} with eyepiece M,

$$M = \theta_{eye}/\theta_{int} \simeq \frac{25}{.045} \approx 600.$$



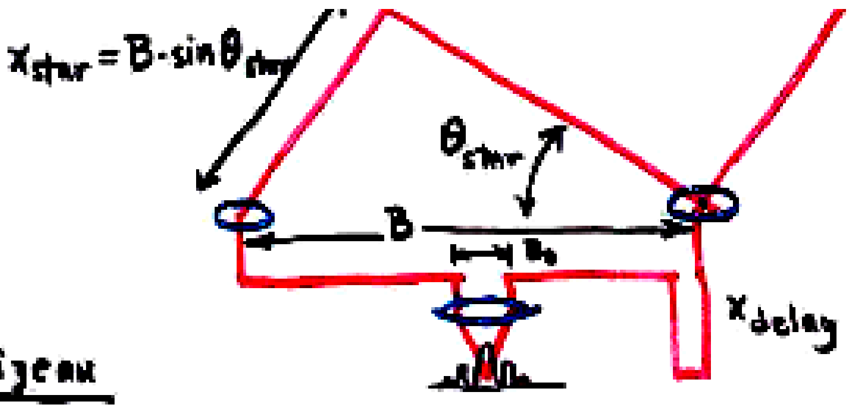
details.



Tilt plate gives angle motion,
+ superposes images,
ie., makes wavefronts parallel at entrance pupil.

Wedge plates give variable thickness,
to compensate for tilt plate's thickness,
is., makes all color wavefronts arrive at same time
as in other beam.

Image-plane interferometer



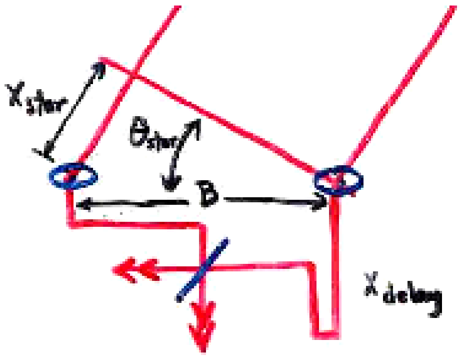
Phase difference between beams

$$\phi = \frac{2\pi}{\lambda}\left(x_{delay} - x_{star}\right)$$

Fizeau type.

$$I_{int}(\theta) = \underbrace{I_{tel}(\theta)}_{\text{envelope vs } \theta} \cdot \frac{1}{2}\left[1 + \underbrace{V}_{\text{visib. of star}} \cdot \cos\frac{2\pi}{\lambda}\left(\underbrace{\theta B_0}_{\text{fringe modulation}} + \underbrace{x_{delay} - x_{star}}_{\text{fringe phase or position.}}\right)\right]$$

Pupil-plane interferometer



Phase difference between beams

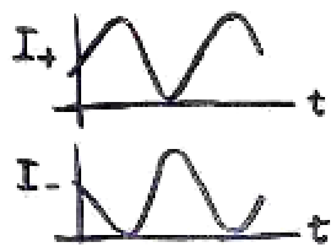
$$\phi = \frac{2\pi}{\lambda}\left(X_{delay} - X_{star}\right) + \frac{\pi}{2}$$

conservation of energy at lossless beamsplitter

Michelson type.

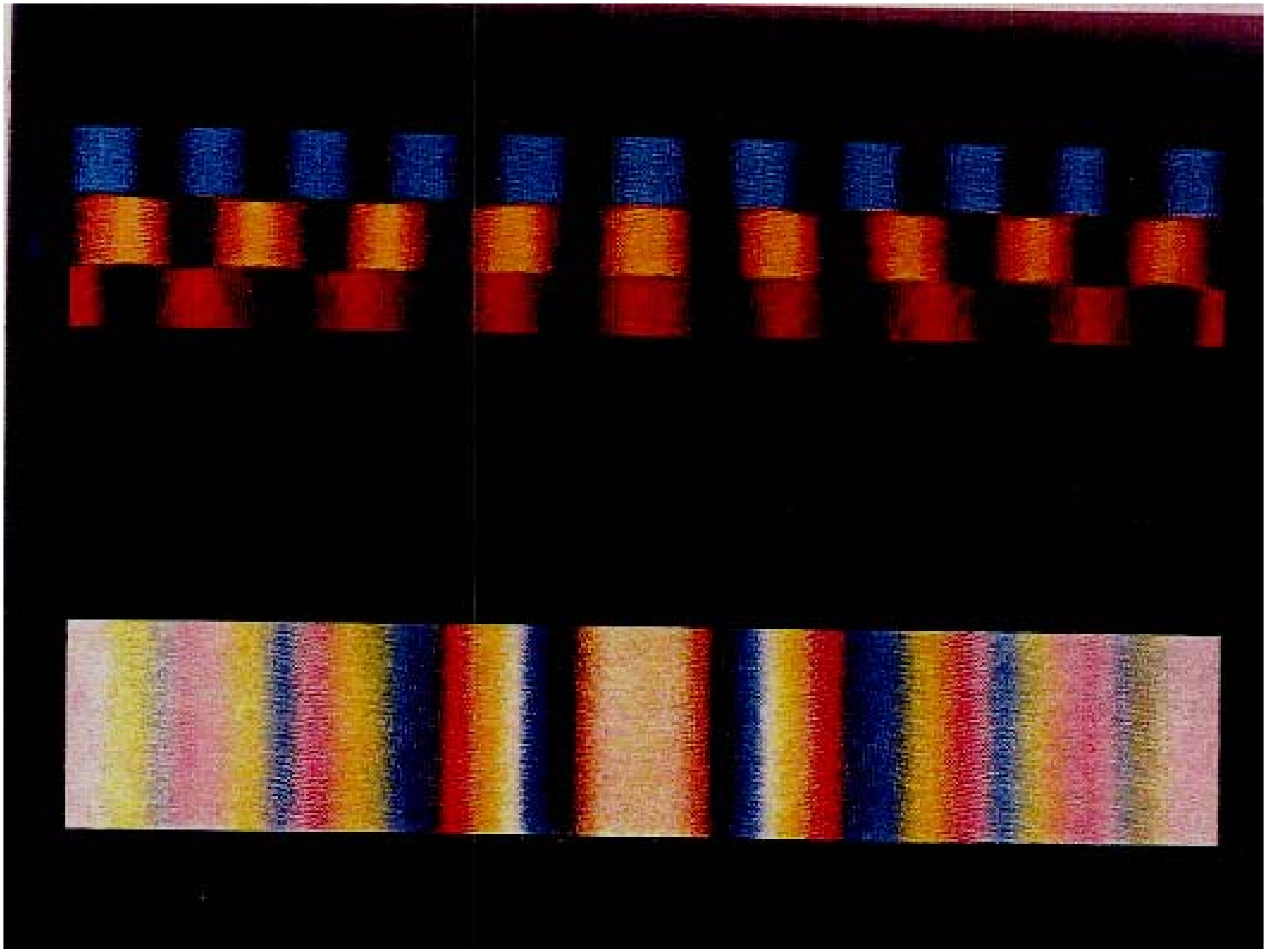
$$I_{int}(t) = I_{tel}(\theta)\cdot\frac{1}{2}\left[1 \pm V\cdot\sin\frac{2\pi}{\lambda}\left(X_{delay} - X_{star}\right)\right]$$

Note: B_0 here is zero; use time modulation $X_{delay}(t) - X_{star}(t) = vt$ and 1 pixel each for $I_\pm$.



Channel spectrum. Spatially display each wavelength segment of I_{int}, with delay $\approx$ few λ.

Colors in interferogram

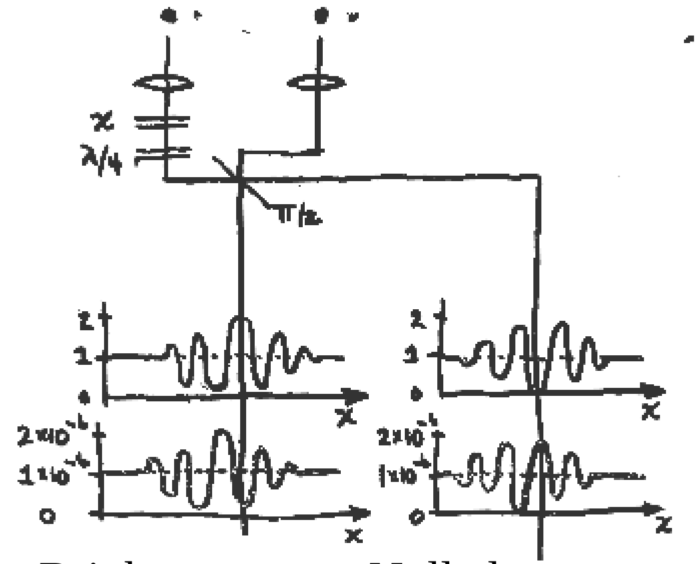


Nulling

Nulling interferometer
(Bracewell)

Star:

Planet:

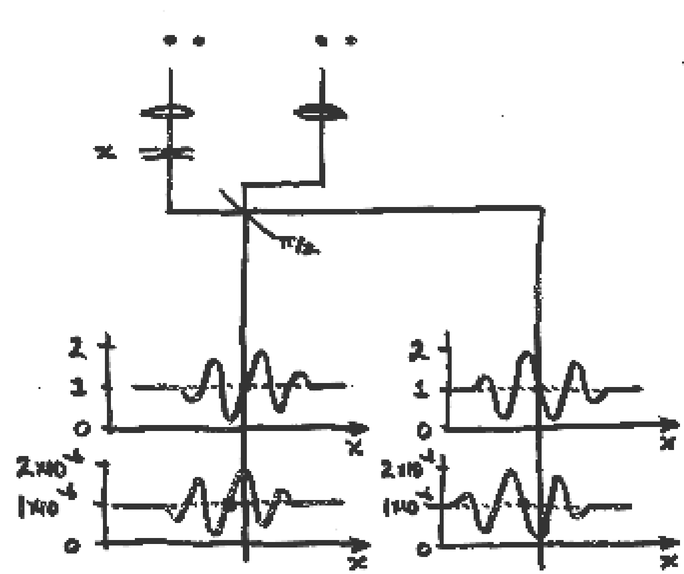


Bright output Nulled output

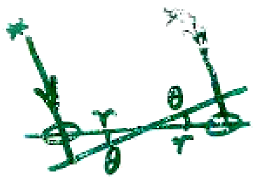
Stellar interferometer
(Michelson)

Star:

Planet:



mixed outputs



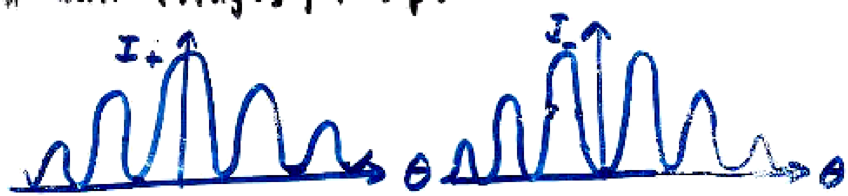
Standard Nulling

Theta² nulling

Assume that an ideal achromatic null can be arranged. Then the intensity is

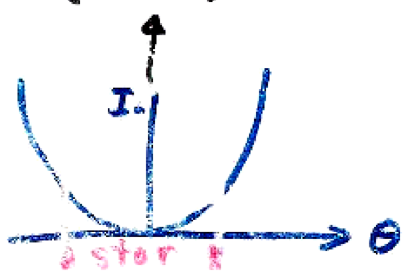
$$I_\pm = \left| e^{ik\theta r} \pm e^{-ik\theta r} \right|^2$$
$$= 2 \cdot \left[1 \pm \cos 2k\theta r \right]$$

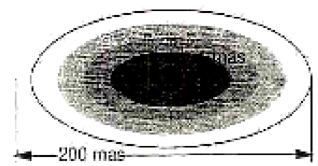
The complementary outputs are the bright & null fringes, resp.

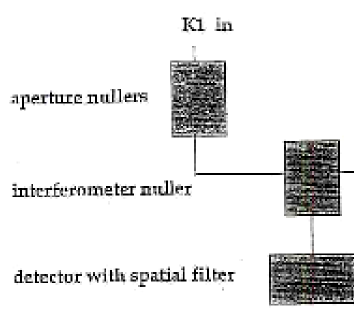


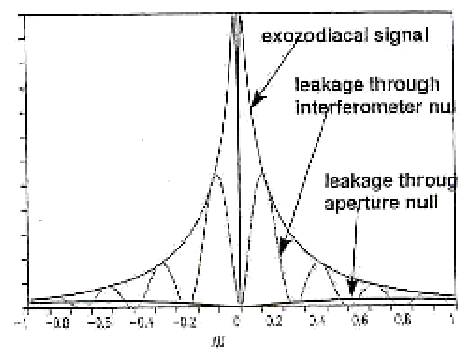
Near the null, the intensity is quadratic

$$I_-(\theta) \approx 2 \cdot \left[1 - \left(1 - \frac{(2k\theta r)^2}{2!} + \cdots \right) \right]$$
$$\approx (2k\theta r)^2 - \cdots$$





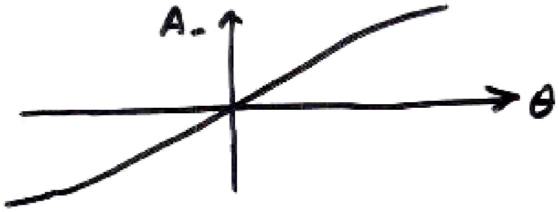




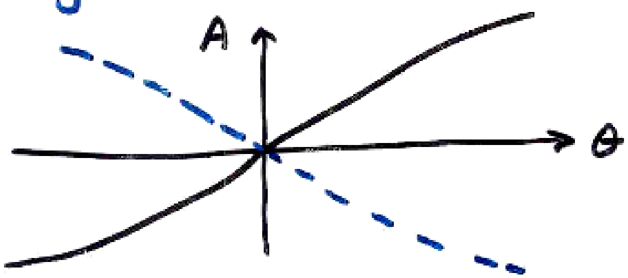
Theta[4] nulling

The amplitude (electric vector) in a standard null is

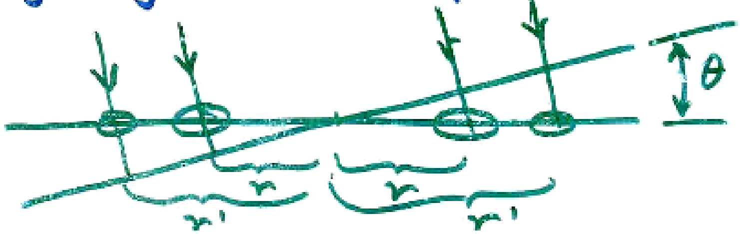
$$A_- = e^{+ik\theta r} - e^{-ik\theta r}$$
$$= 2i \cdot \sin(k\theta r).$$



If we could cancel this amplitude with one of opposite sign, we could make a very wide null.



Try using 2 more apertures:



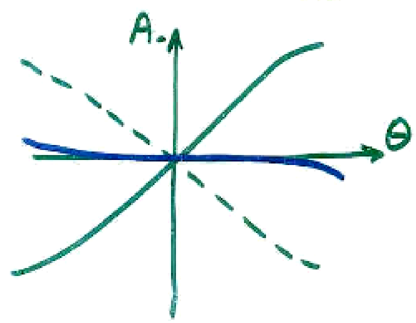
The amplitude from all 4 apertures is, assuming the outer ones have relative weight ε :

$$A_- = -\varepsilon e^{+ik\theta r'} + e^{+ik\theta r} - e^{-ik\theta r} - (-\varepsilon e^{-ik\theta r'})$$
$$= 2i \cdot \{ \sin(k\theta r) - \varepsilon \sin(k\theta r') \}$$

where we have added exactly π retardation to flip the sign.

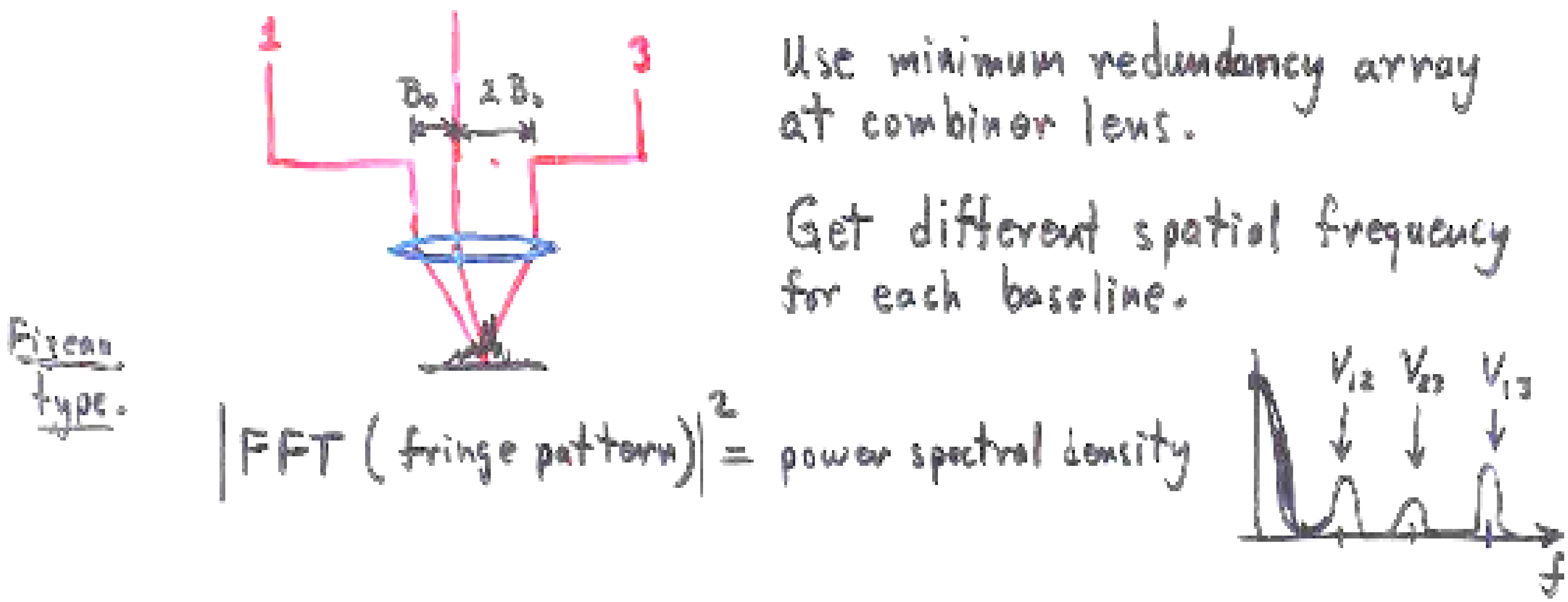
$$A_- \simeq \underbrace{k\theta(r - \varepsilon r')}_{=0 \text{ if } \varepsilon = r/r'} - \frac{(k\theta)^3}{3!}(r^3 - \varepsilon r'^3) + \cdots$$

Then $A_- \simeq -\frac{(k\theta r)^3}{3!} \cdot (1 - 1/\varepsilon^2) + \cdots$

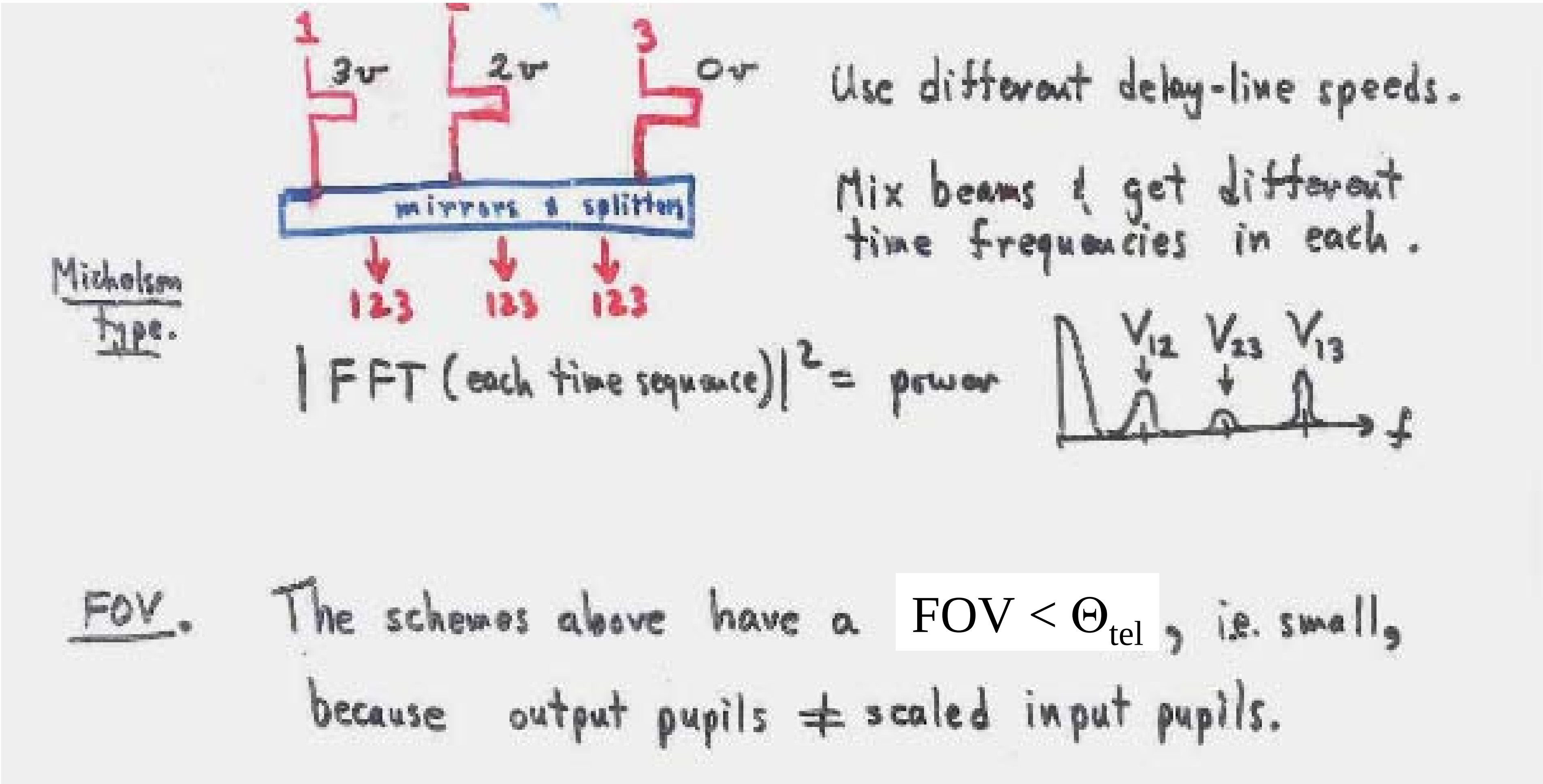


So 2 extra mirrors, or petals, will work, provided that phase control exists.

Multiplexing in the image plane



Multiplexing in the pupil plane



Golden rule

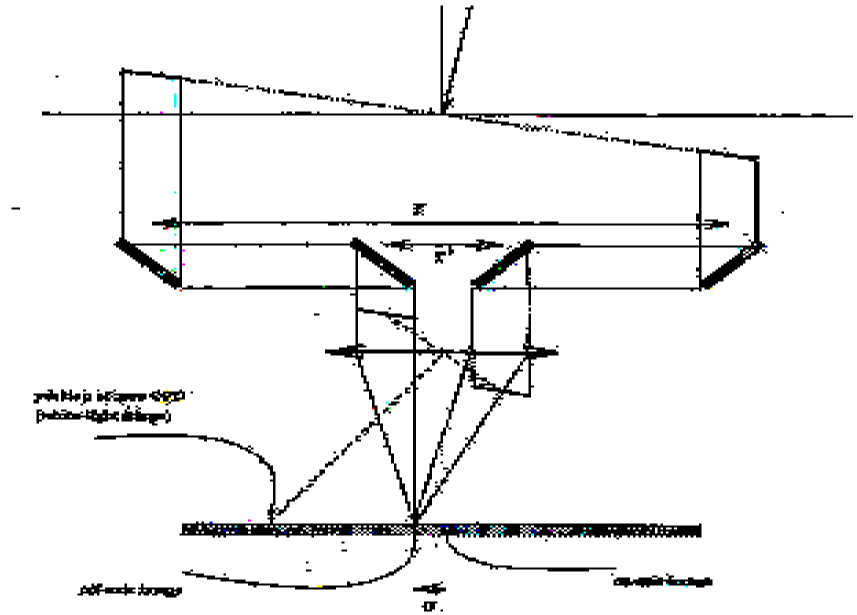
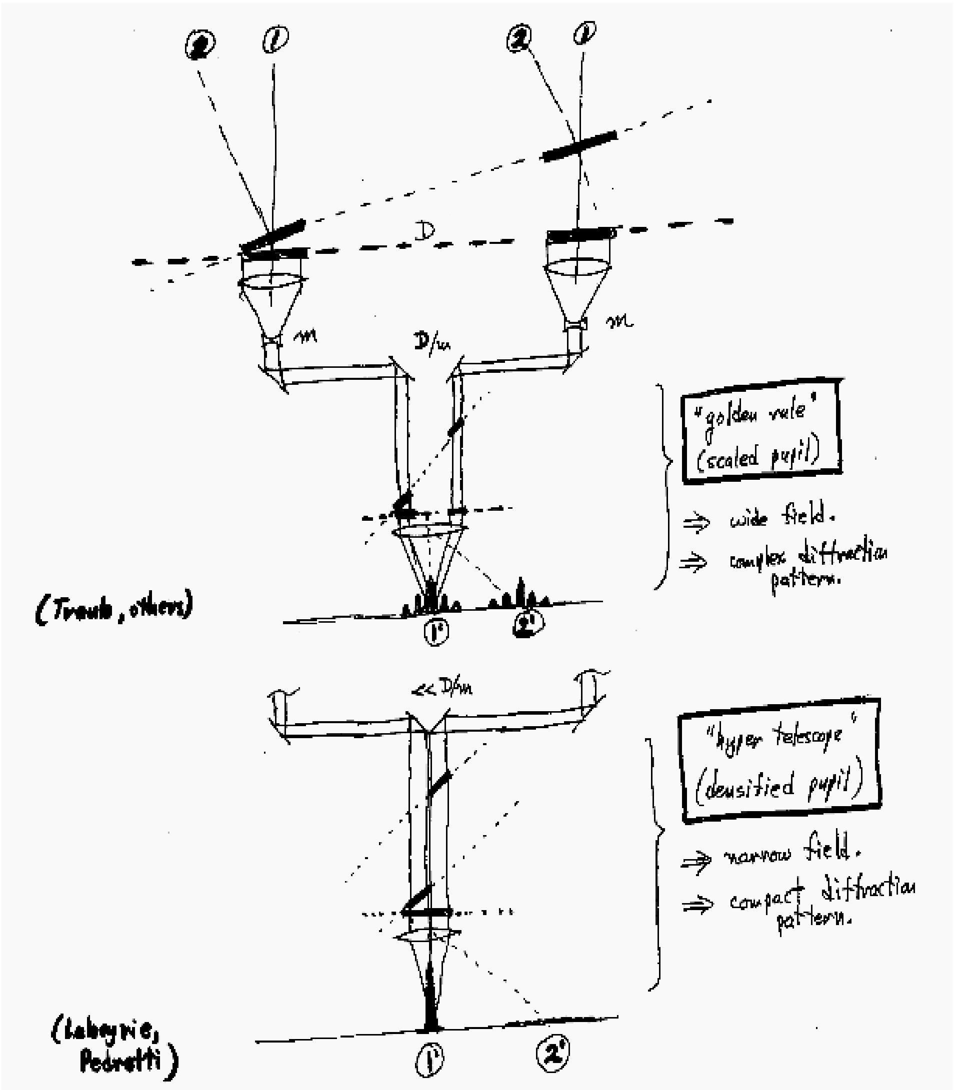


Figure 4.9: Geometry for 2 element Michelson interferometer.



Output pupil must be a scaled version of input pupil in order to obtain a wide field of view.

Pupil densification

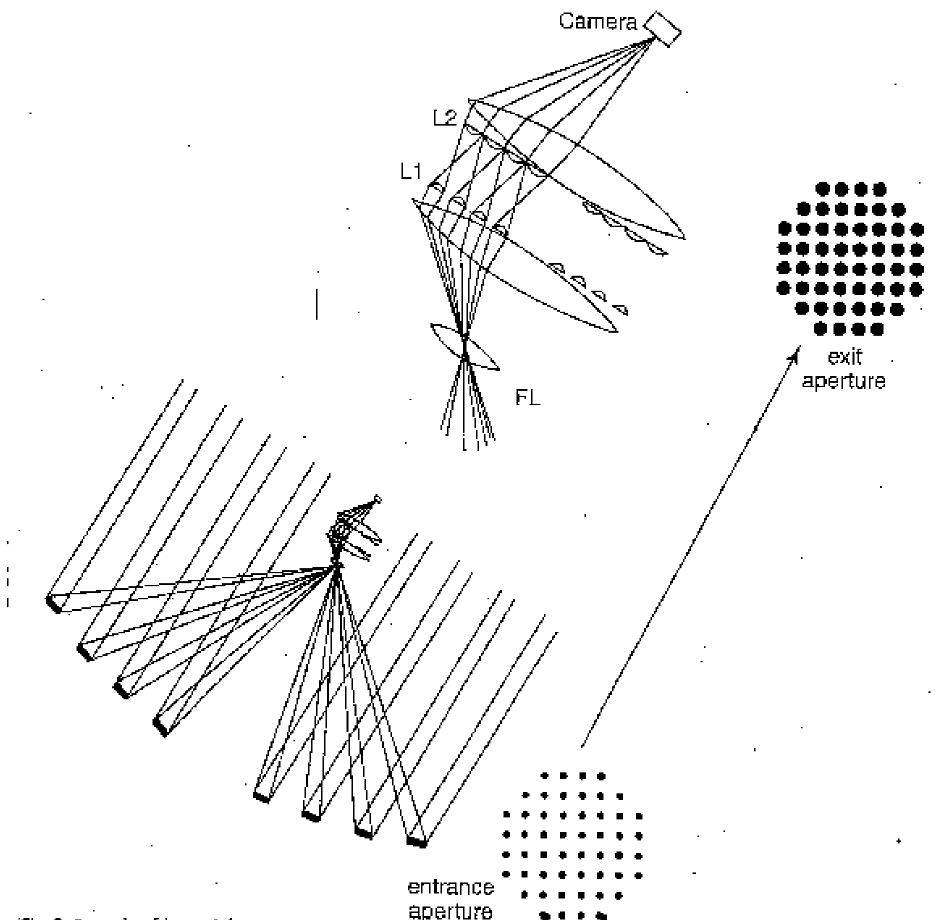


Fig. 2. Example of hyper-telescope optics. Multiple mirrors form a sparse paraboloidal giant mirror, and a lens (FL) in the focal plane forms a pupil image on a pair of lens arrays L1 and L2, having short and long focal lengths, respectively. This setup enlarges the subpupils in the exit aperture compared to those in the entrance aperture, producing a usable image on the camera.

A. Labeyrie, Science, 1999 or 2000

Instrumental effects: 1

Bandpass. If rectangular bandpass of width $\Delta\sigma$ (where $\sigma = \frac{1}{\lambda}$),

then $V_{bandpass} = \frac{\sin \pi \cdot x \cdot \Delta\sigma}{\pi \cdot x \cdot \Delta\sigma}$ where $x \equiv X_{delay} - X_{star}$.

Wavefront tilt. If wavefronts are tilted by angle α, then

$V_{tilt} = \frac{\sin \pi \cdot D \cdot \alpha / \lambda}{\pi \cdot D \cdot \alpha / \lambda}$ (square) or $\frac{2 J_1(\pi D \alpha / \lambda)}{\pi D \alpha / \lambda}$ (circular)

For $V_{tilt} > 0.90$ need $\alpha < 0.3 \lambda / D$.

Relative intensity. If the relay optics and/or beam combiner have intensity ratio ρ, then

$V_{rel\text{-}int.} = \frac{2}{\rho^{1/2} + \rho^{-1/2}}$.

Instrumental effects: 2

<u>Non-flatness of surfaces.</u> If the wavefronts have rms perturbations δ, then

$$V_{surfaces} \approx e^{-(2\pi\delta/\lambda)^2} .$$

If there are N surfaces of δ_0 each, then

$$\delta \approx N^{1/2} \cdot \delta_0 .$$

If $\delta = \lambda/20$ is rms of each beam, then

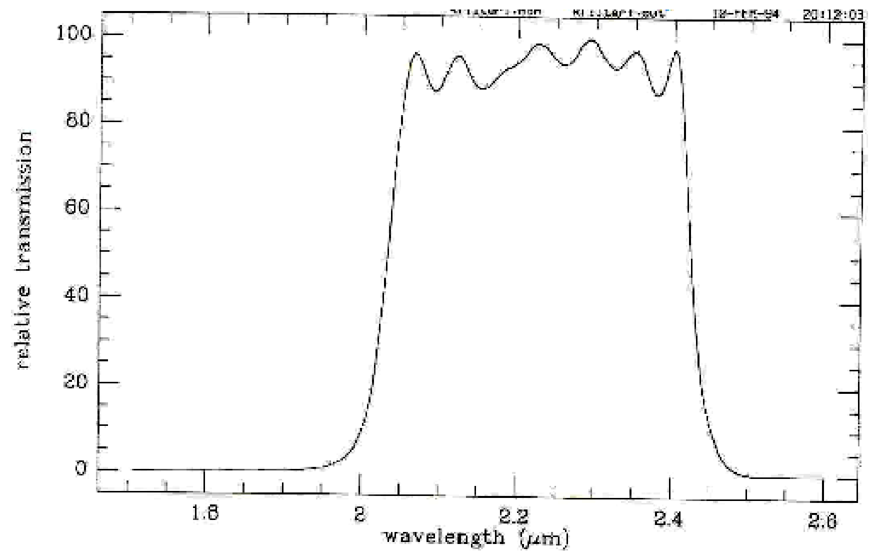
$$V(\lambda/20) \approx e^{-(\pi/10)^2} \approx 0.90 .$$

<u>Shear.</u> No effect, unless beams no longer overlap.

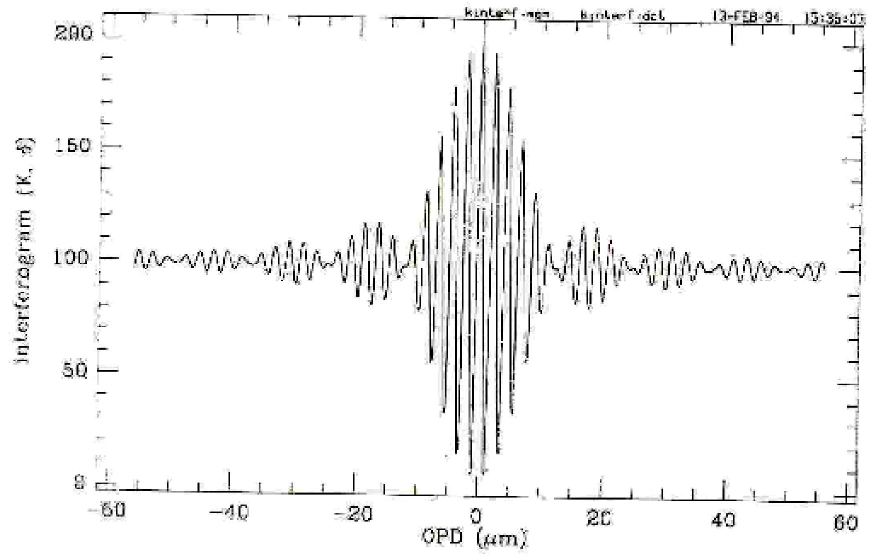
<u>Different telescope diameters.</u> See rel. int. calc.

Filter and interferogram shapes

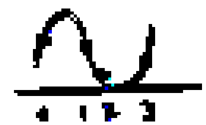
K-band filter transmission



K-band interferogram



Measuring visibility

$\lambda/4$ steps. Change x by $(\lambda/4)\cdot(0,1,2,3)$, measure $I(x)$, calculate $V \sim \dfrac{0-2+1-3}{0+1+2+3}$  .

many λ sweep. Change $x = vt$ and repeat in triangle wave.

- fit theoretical wave packet to time data;
- calculate $|FFT|^2$ & ratio high freq. to low;
- wavelet analysis.

dispersed (channel) spectrum. Allow atmosphere to give few λ path variation of x calculate peak-to-valley variations at each λ.

Strehl: 1

Strehl ratio is approximately

$$S = e^{-\varphi^2} = \exp(-\varphi^2)$$

where φ is the rms phase error across a wavefront.

Observed visibility is the product of 3 terms:

$$V_{observed} = S_{atmos} S_{instrum} V_{object}$$

Instrumental Strehl ratio is the product of many terms:

$$S_{instrum} = S_{servo} S_{flat} S_{align} S_{diffraction} S_{flux} S_{overlap} S_{vibration} S_{window} S_{polarization}$$

Strehl: 2

Atmospheric variance, with tip-tilt removed
by a servo system with bandwidth $v/\pi D$, is

$$\varphi^2 = (0.134 + 0.096)(D/r_0)^{5/3}(\lambda_0/\lambda)^2$$

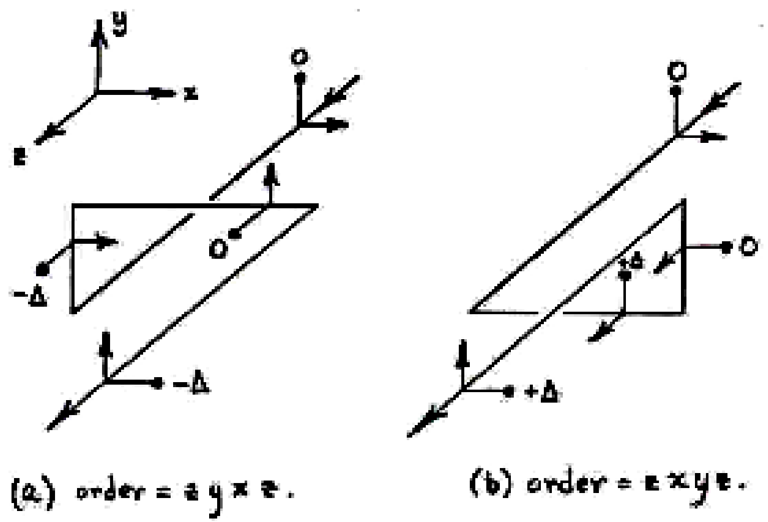
Wavefront flatness variance from mirror surfaces is

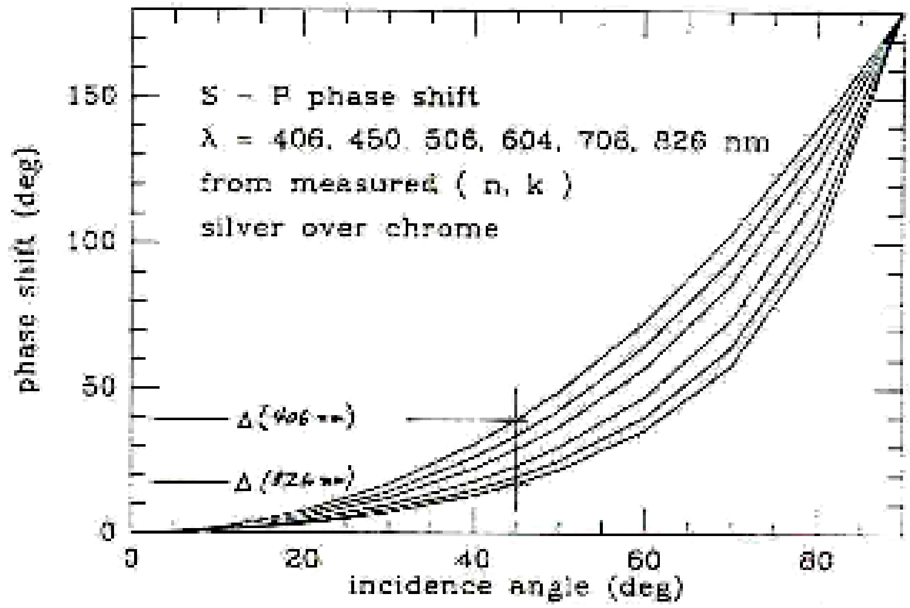
$$\varphi^2 = \varphi_1^2 + \ldots + \varphi_n^2$$

Mirrors are often specified in terms of surface peak-to-valley
where an empirical relation is

PV = 5.5 RMS

Polarization and visibility





S and P refer to the electric vector components perpendicular and parallel to the plane of incidence. For a curved mirror, these axes vary from point to point.

Visibility reduction factor

Beam 1: $\vec{A}_1 = (A_x, A_y)_1 = a_1 e^{ikz}(1, e^{i\phi_1})$

Beam 2: $\vec{A}_2 = (A_x, A_y)_2 = a_2 e^{ik(z+l)}(1, e^{i\phi_2})$

Combined: $I = |\vec{A}_1 + \vec{A}_2|^2$

$$I = \bar{I} \cdot \left[1 + \underbrace{\left(\frac{2a_1 a_2}{a_1^2 + a_2^2}\right)}_{\text{visibility term}} \cdot \underbrace{\cos\left(kl + \frac{\phi}{2}\right)}_{\text{modulation term}} \cdot \underbrace{\left|\cos\frac{\phi}{2}\right|}_{\text{polarization term} \equiv \text{constant}} \right]$$

where $\phi \equiv \phi_2 - \phi_1$ = relative phase shift between 2 beams.

∴ In unpolarized light, the measured visibility can be permanently degraded by purely instrumental polarization effects, in the amount

$$\left|\cos\frac{\phi}{2}\right|$$

which is a function of wavelength only.

Single-mode fiber optics

Core.
- Core index n_1, radius a $(n_1 \sim 1.48,\ a \sim 2\mu m)$.
- Cladding index n_2, radius b $(n_2 \sim 1.46,\ b \sim 60\mu m)$.
- Incident / exit cone $\sin i = (n_1^2 - n_2^2)^{1/2} \equiv NA$ $(i \sim 14°$ $f/2.0$

Dispersion.
- intermodal $= 0$ for SM fiber.
- material
- waveguide

} balance these to get zero.

Waveguide parameter. $V = \frac{2\pi}{\lambda_0} a\, (n_1^2 - n_2^2)^{1/2}$ $> 10 \Rightarrow$ geometric optics; $< 10 \Rightarrow$ wave optics.

Coupling.

z = coupling length $\approx$ 3 mm typically.

Mfg. couplings.
- twist & melt (fused)
- polish & mate (polished).

Cutoff λ_c. For $\lambda > \lambda_c$ the fiber is single-mode.

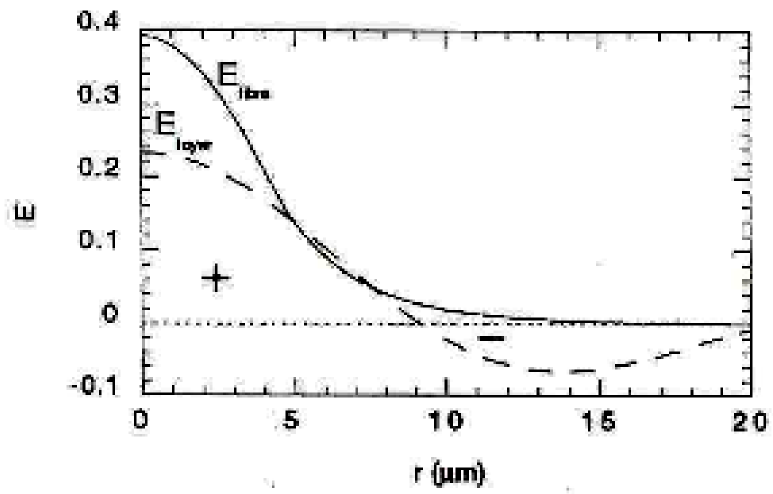
$$\lambda_c = \frac{2\pi a}{2.4048}(n_1^2 - n_2^2)^{1/2}.$$ If $NA \sim .24$, $\lambda_c \sim 0.6a$.

Etendue. $A\Omega = \pi a^2 \pi i^2 = \pi a^2 \pi (NA)^2 \approx (1.202\lambda_c)^2 \approx \lambda^2$.

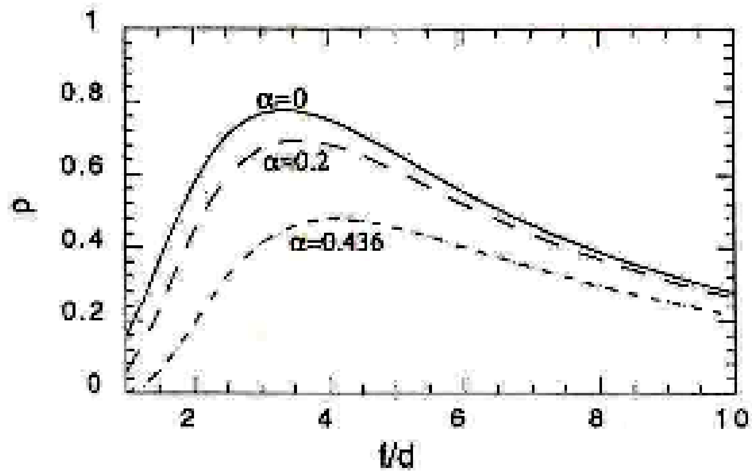
Transmission. loss < 1 dB/km for silica & fluoride.

Integrated optics. Fibers on a chip.

Injecting starlight into a fiber



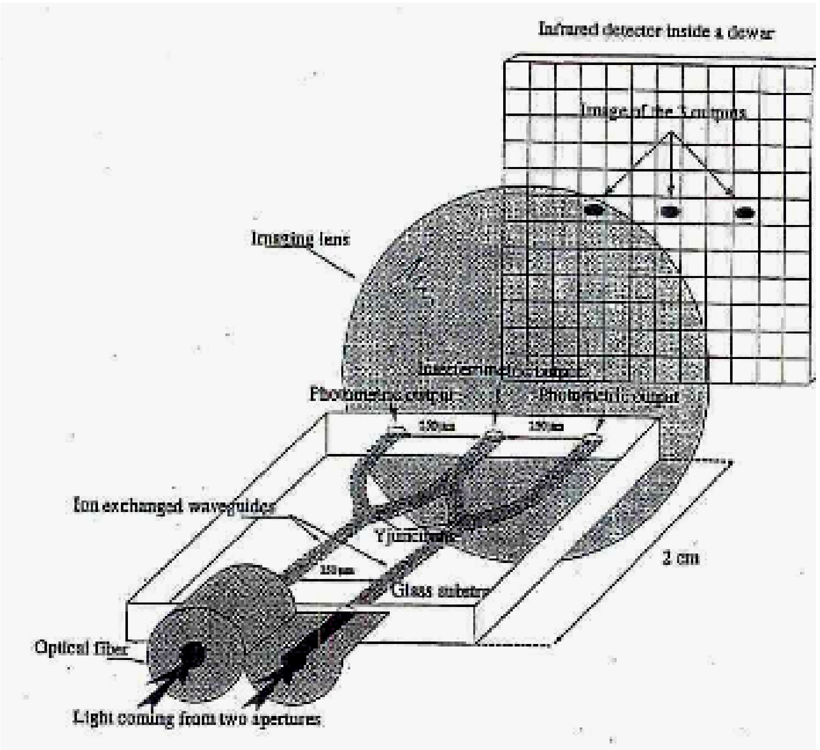
- The optimal f/d is the one that maximizes the overlap integral
- Maximum possible efficiency: $\rho_{max} = 78\%$ (but less if the pupil has a central obstruction α)



- Efficiency set by the overlap integral: in the focal plane: $\rho = \left| \iint E_{tel} \, E^*_{fibre} \right|^2$

=> the field *amplitudes* must match

Integrated optics: 1



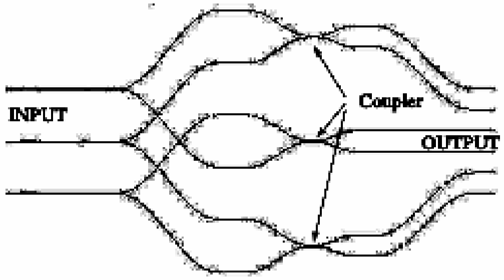


Figure 1. Description of the IONIC-IOTA three-way beam combiner. Three inputs are split with three "Y" junctions to provide a pairwise beam combination with another set of three couplers

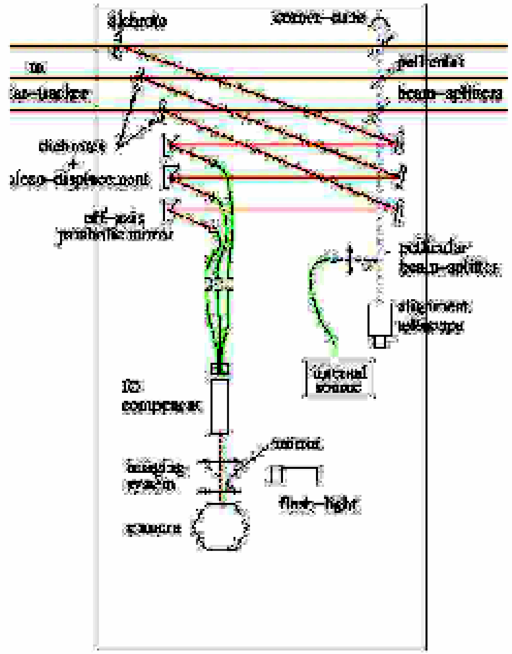
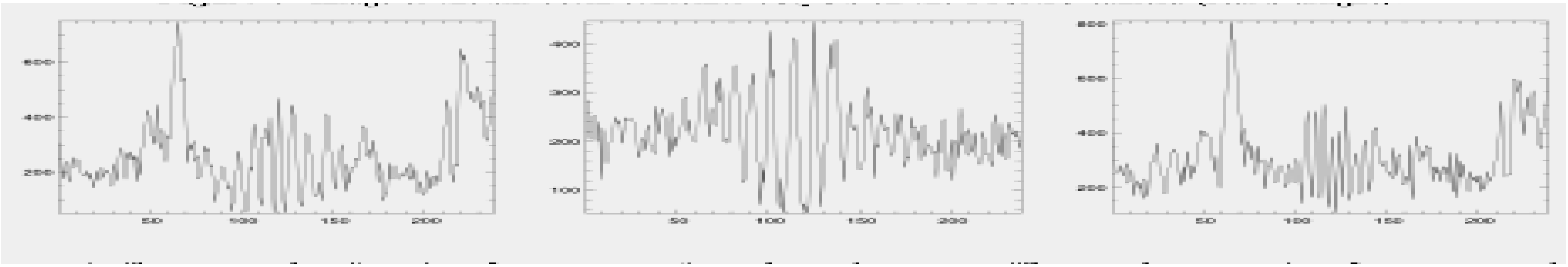
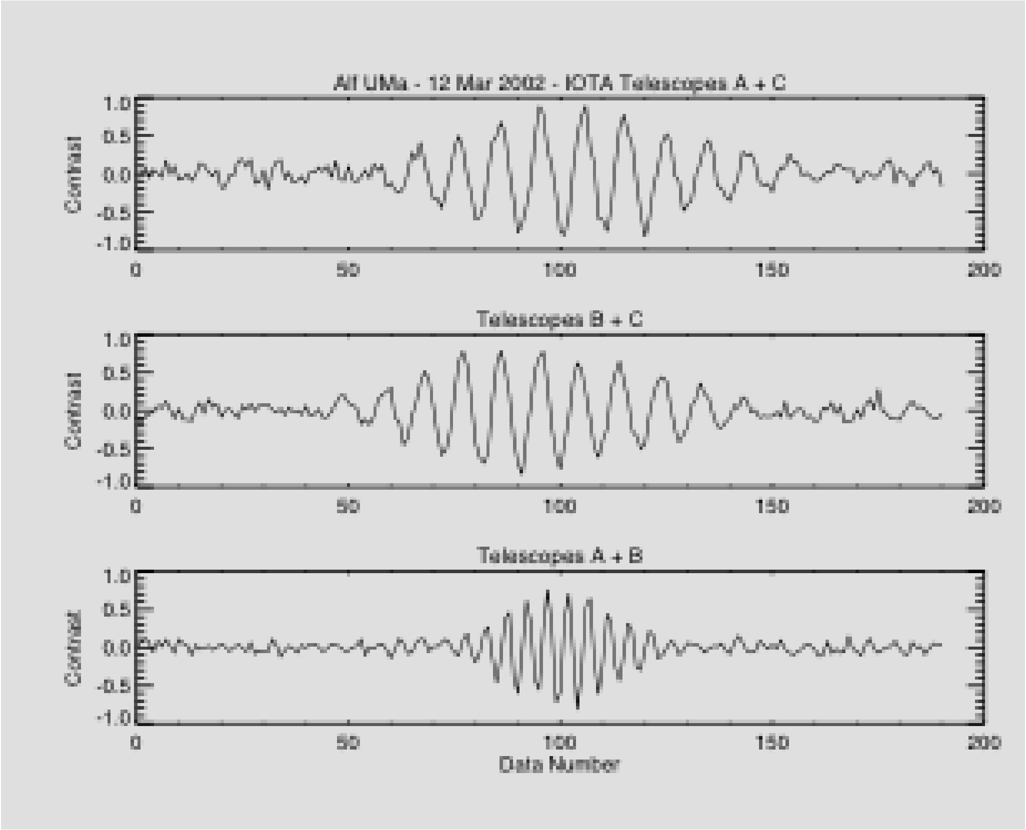


Figure 2. Schematic description of the IONIC bench (see text for details)

Integrated optics: 2





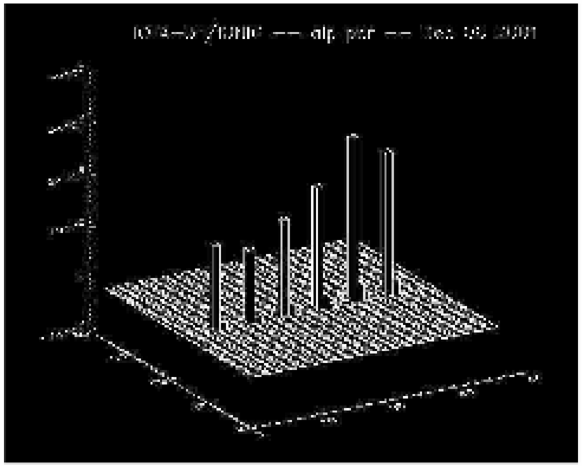
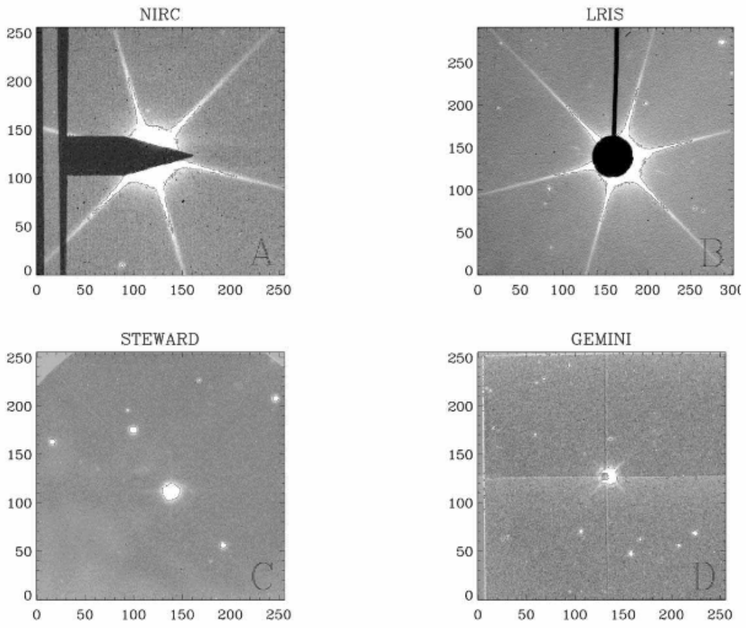
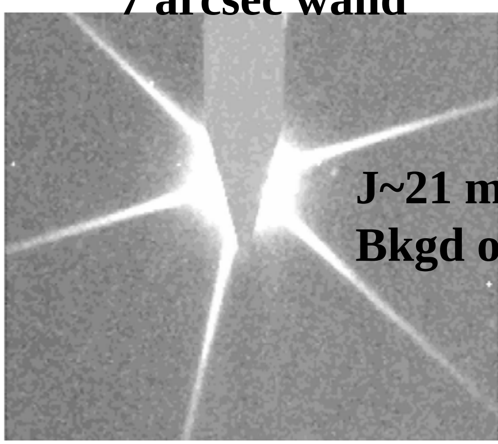
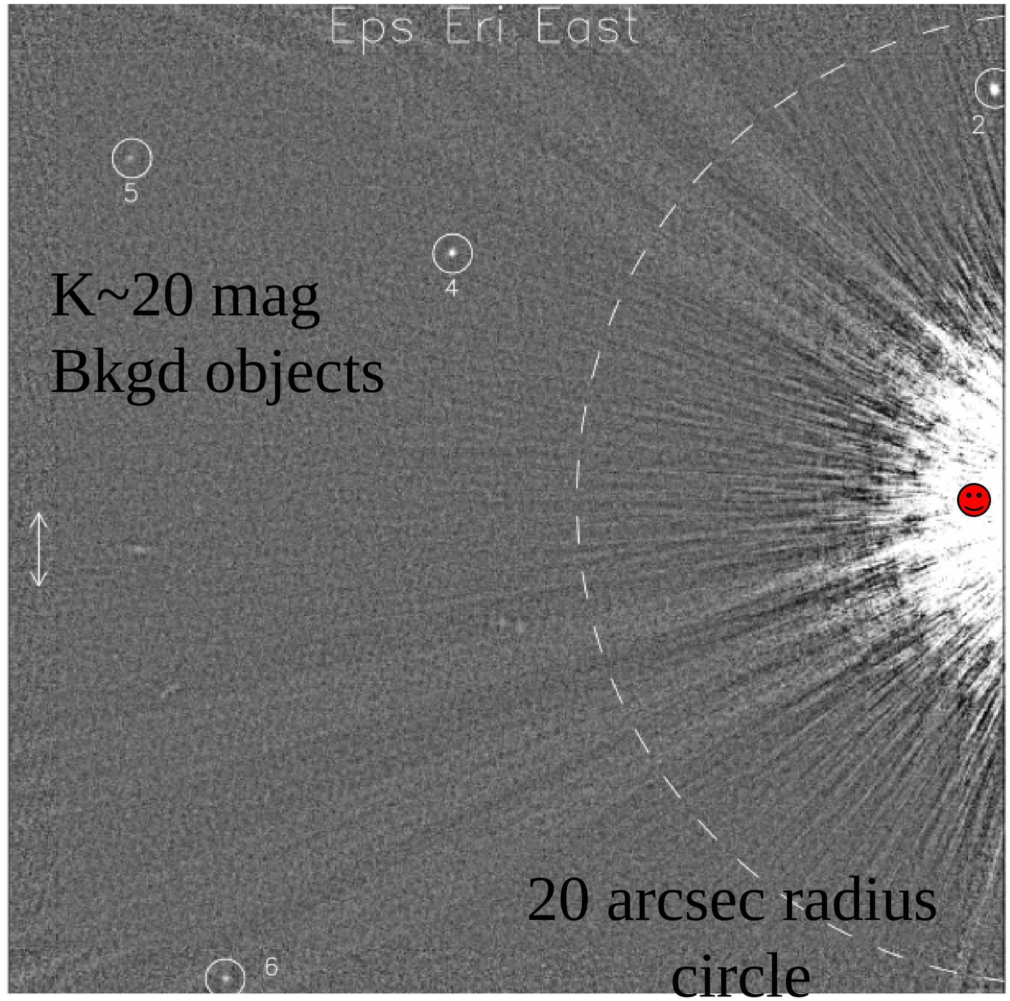


Image-plane Coronagraphs: a Very Quick Introduction

Current ground-based coronagraph examples

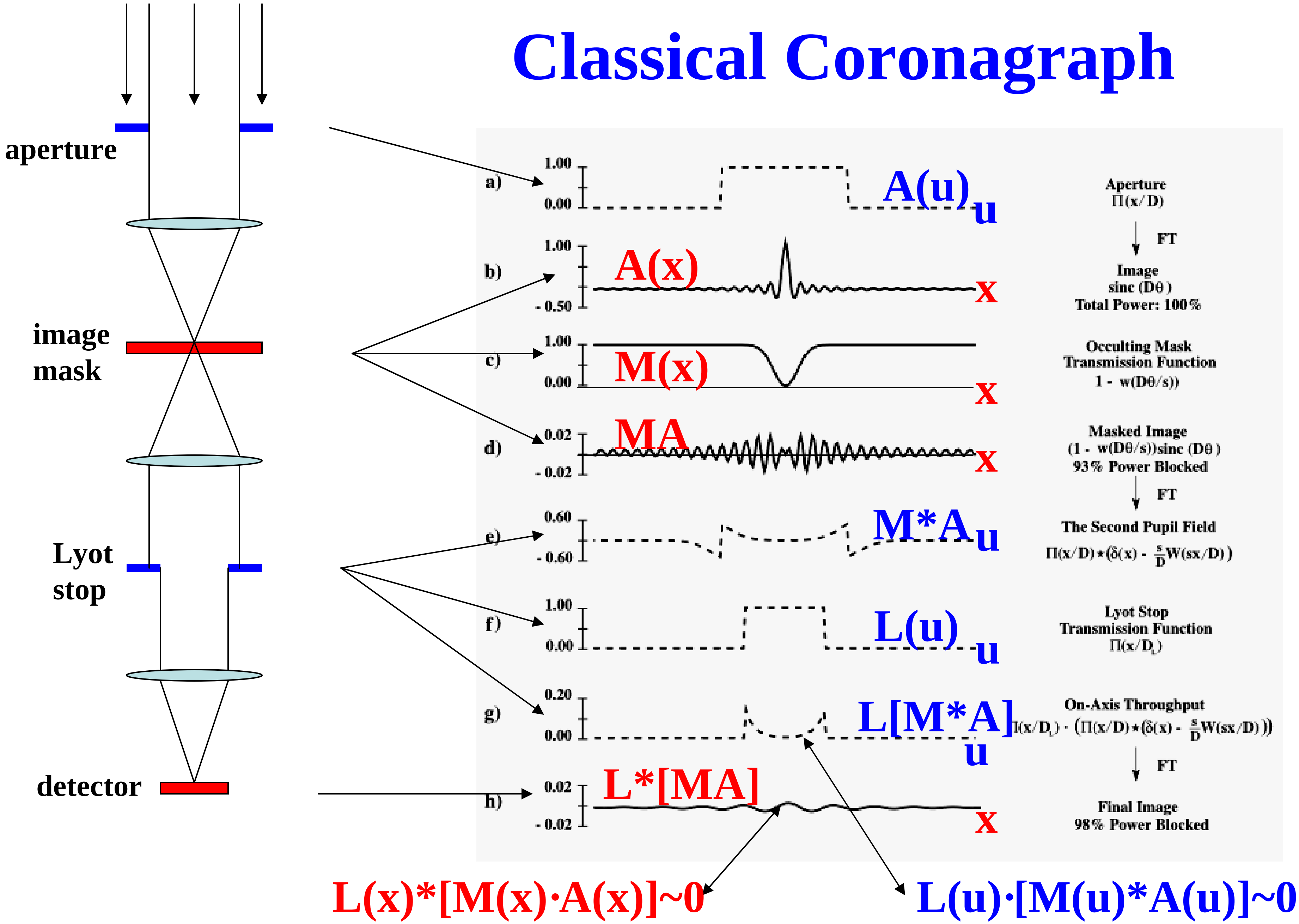






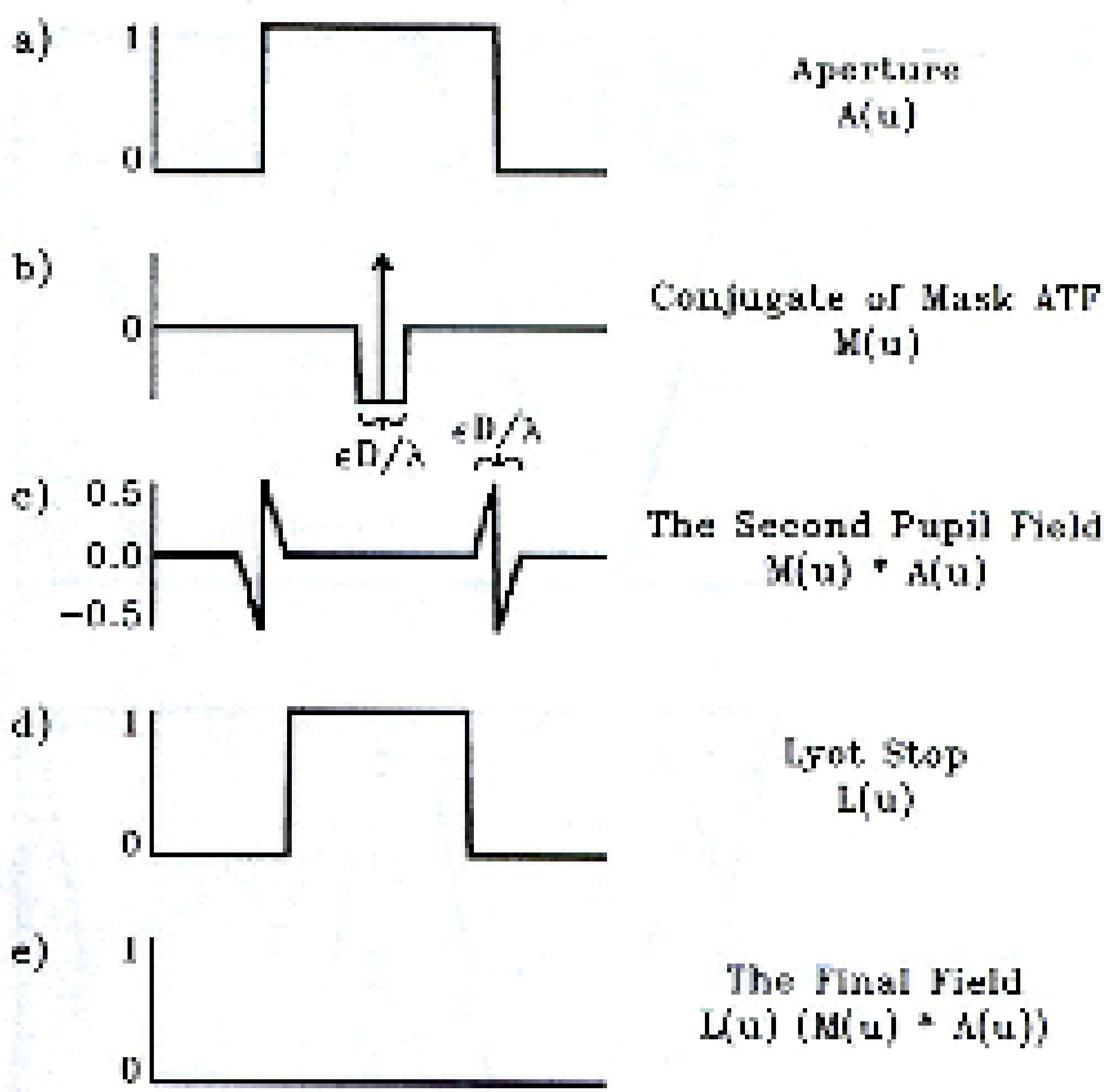
Ref: McCarthy & Zuckerman (2004); Macintosh et al (2003)

Classical Coronagraph



Ref.: Sivaramakrishnan et al., ApJ, 552, p.397, 2001; Kuchner 2004.

Band-limited (*1 - sin x/x*) mask



Amplitude of on-axis star = $1\ e^{i0}$

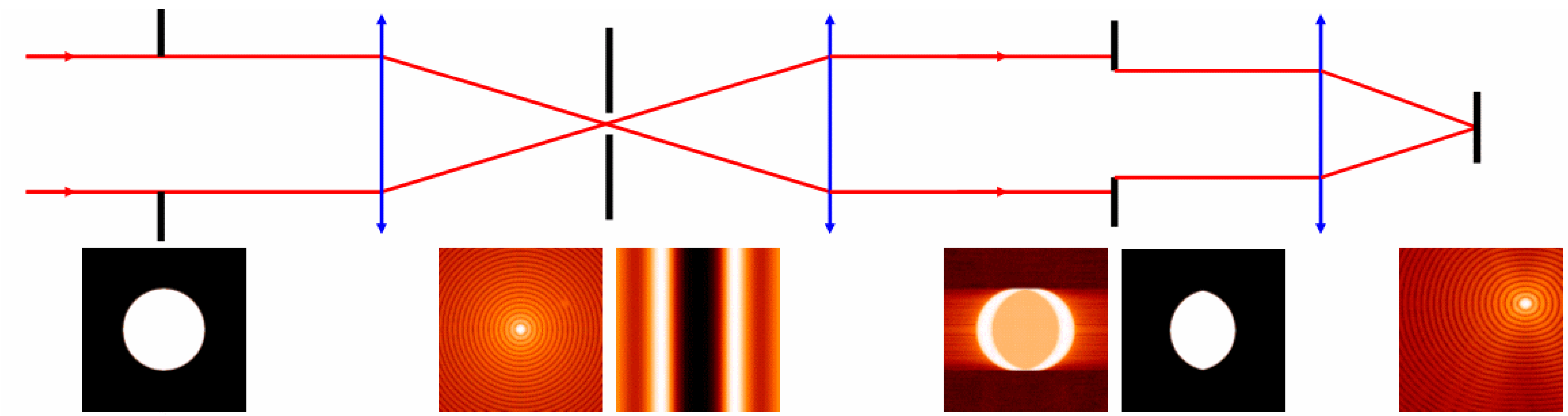
FT(*1 - sin x/x*) = delta(u) + rect(u)

Convolution

Lyot stop blocks bright edges

Zero transmission of on-axis star

Image-plane coronagraph simulation



1st pupil

1st image with Airy rings

mask, centered on star image

2nd pupil

Lyot stop, blocks bright edges

2nd image, no star, bright planet

Ref.: Pascal Borde 2004

Perturbation #1: ripples and speckles

Phase ripple and speckles

Suppose there is height error h(u) across the pupil, where

$$h(u) = \Sigma_n\, a_n \mathit{cos}(2\pi nu/D) + b_n \mathit{sin}(2\pi nu/D) = \text{ripple}$$

The amplitude across the pupil is then

$$A(u) = e^{ikh(u)} \approx 1 + ik[\Sigma_n\, a_n \mathit{cos}(2\pi nu/D) + b_n \mathit{sin}(2\pi nu/D)]$$

In the image plane at angle α the amplitude will be

$$\mathbf{A(\alpha) = \int A(u)\, e^{ik\alpha u}\, du}$$

$$\mathbf{= \delta(0) + (i/2)\, \Sigma_n\, [(a_n\text{-}ib_n)\delta(k\alpha\text{-}Kn) + [(a_n\text{+}ib_n)\delta(k\alpha\text{+}Kn)]}$$

where we use $K = 2\pi/D$. The image intensity is then

$$\mathbf{I(\alpha) = \delta(0) + (1/4)\, \Sigma_n\, (a_n^2\text{+}b_n^2)\, [\delta(k\alpha\text{-}Kn) + \delta(k\alpha\text{+}Kn)] = speckles}$$

at $\alpha = \pm n\lambda/D$

If we add a deformable mirror (DM), then $a_n \rightarrow a_n + A_n$ and $b_n \rightarrow b_n + B_n$
Commanding $A_n = -a_n$ and $B_n = -b_n$ forces all speckles to zero.

Phase + amplitude ripple and speckles

Suppose the height error h(u) across the pupil is **complex**, where

$$h(u) = \Sigma_n (a_n + i a_n')\,\mathit{cos}(Knu) + (b_n + i b_n')\,\mathit{sin}(Knu) \;= \text{ripple}$$

i.e., we have both **phase and amplitude** ripples (= errors).

The image intensity is then

$$I(\alpha) = \delta(0) + (1/4)\,\Sigma_n\, [(a_n+b_n')^2 + (b_n-a_n')^2]\,\delta(k\alpha+Kn) + [(a_n-b_n')^2 + (b_n+a_n')^2]\,\delta(k\alpha-Kn)] = \text{speckles}$$

If we add a deformable mirror (DM), and command

$A_n = -(a_n-b_n')$ and $B_n = -(b_n+a_n')$

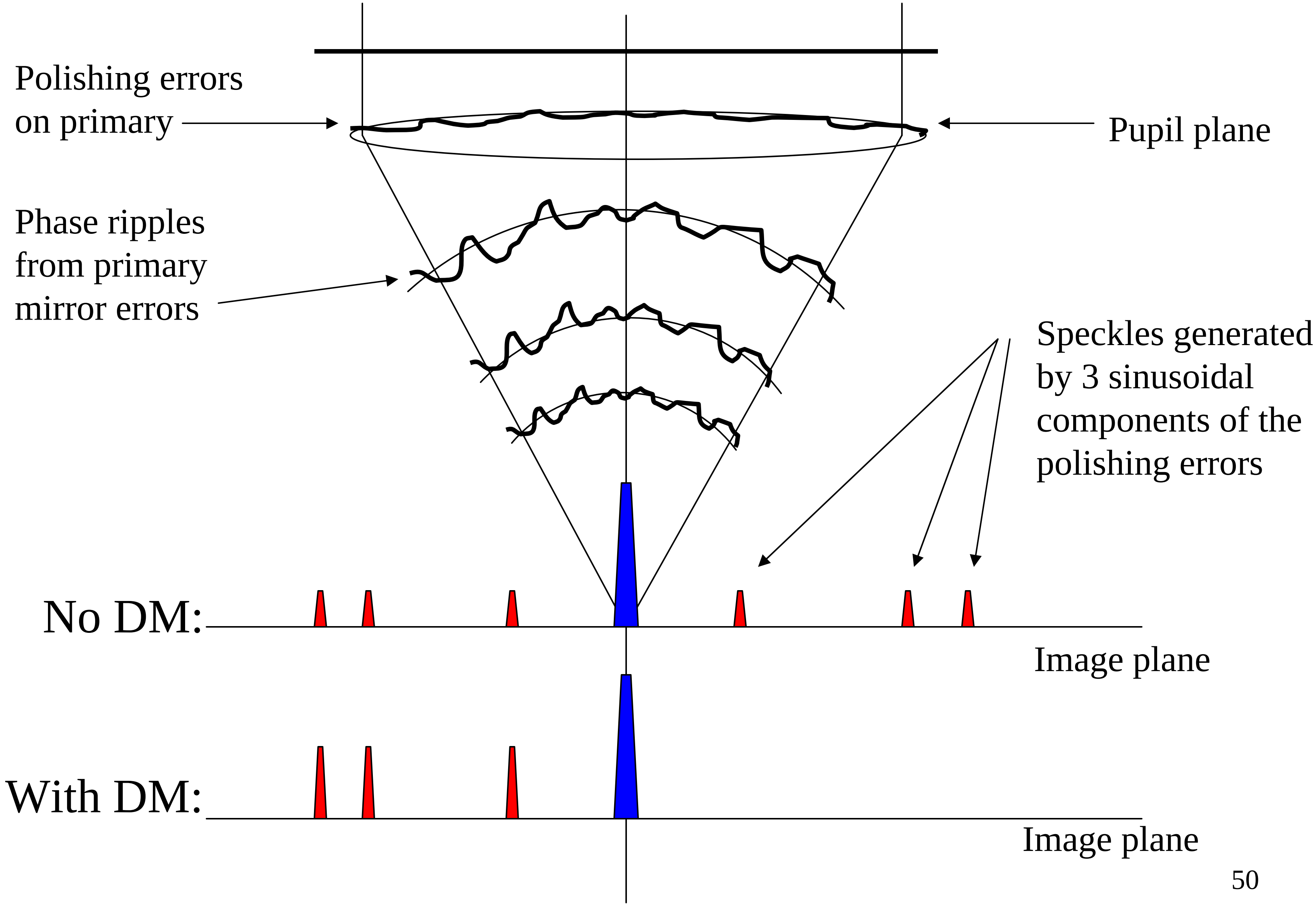
Then we get

$$I(\alpha) = \delta(0) + \Sigma_n\, [(b_n')^2 + (a_n')^2]\,\delta(k\alpha+Kn) \leftarrow \text{bigger speckles}$$

$$+ [\,\mathbf{0} + \mathbf{0}\,]\,\delta(k\alpha-Kn)] \leftarrow \text{smaller } (\textbf{zero}) \text{ speckles}$$

So in **half the field of view** we get **no speckles**,
but in the other half we get stronger speckles.

Phase ripple and speckles



So, we discussed these topics:

1. Thinking in terms of wavelets.

2. Calculating the interference of wavefronts for any optical system.

3. Learning about astrophysical vs instrumental effects.

4. A teaser about coronagraphs and speckles.