Topic 5: Measurement of Optical Properties

Aim: Covers the measurement of the basic optical properties of lenses and optical systems.

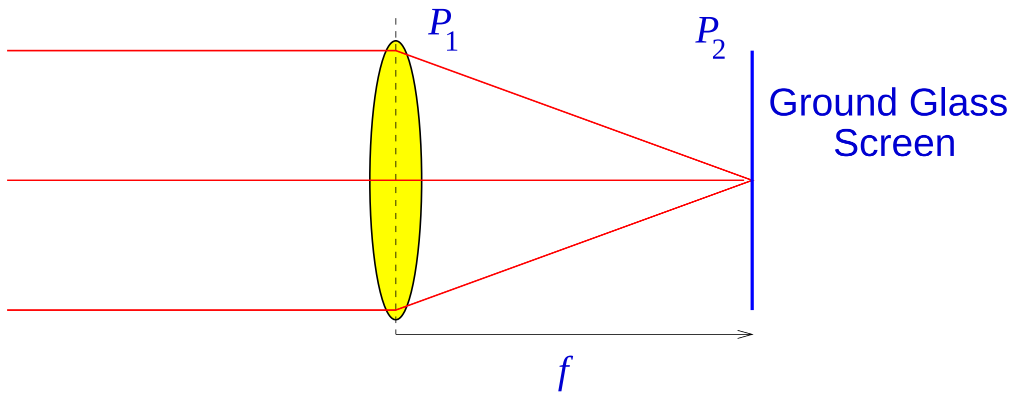
Contents:

- Physical Characteristics
- Point Spread Function
- Optical Transfer Function
- Wavefront Aberration

Physical Characteristics

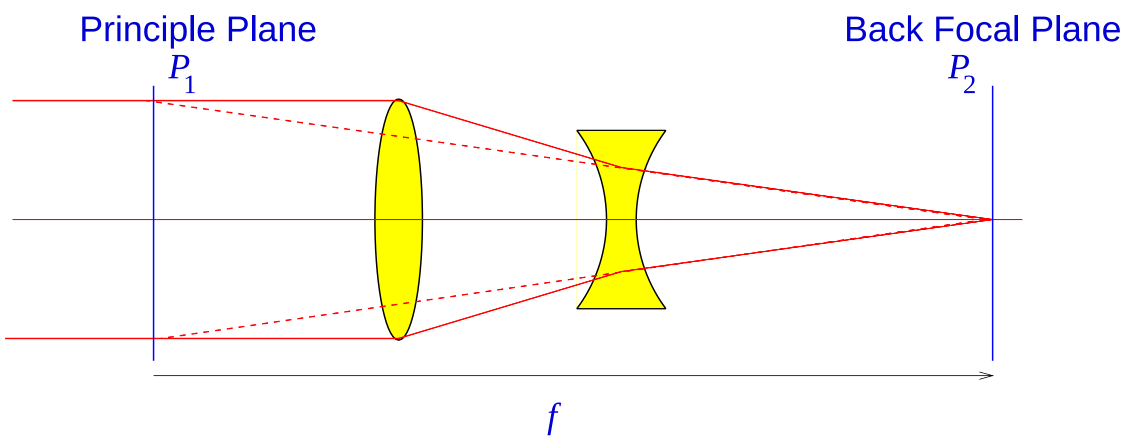
Focal Length:

Easy for single lens,



Focus on to Ground Glass Screen. Maximum scatter when screen exactly in back focal plane.

More difficult with compound lens, for example telephoto



where the focal length is defined wrt to Principle Plane, which may be "outside" the physical lens.

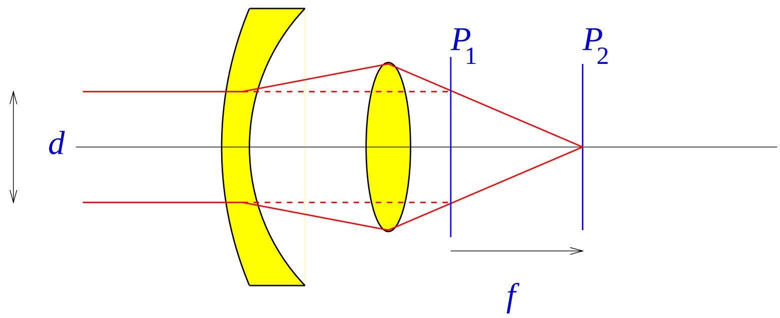
Similar problem with mirror systems and inverse telephoto (wide angle) systems.

Diameter:

Diameter usually quoted as

$$F_{No} = \frac{f}{d}$$

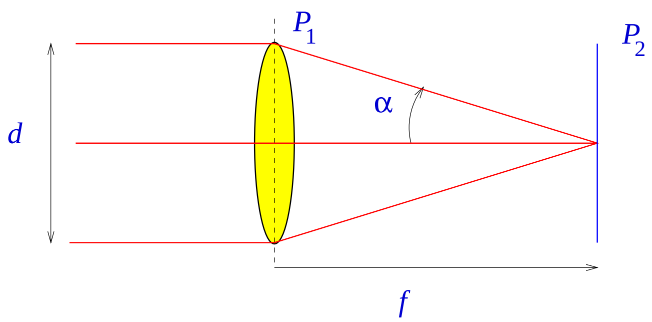
Usually obvious, but care must be taken with ultra-wide angle lenses.



Large front element to allow use over wide field of view.

Numerical Aperture:

Alternative measure of "diameter".

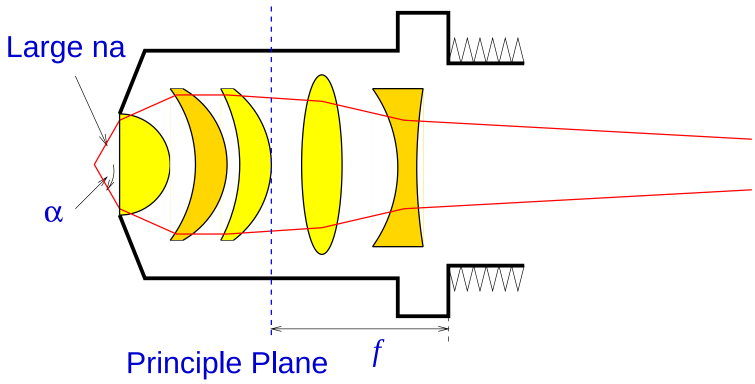


$$\mathrm{na} = \sin\alpha$$

if α is small, then

$$\mathrm{na} \approx \frac{d}{2f} = \frac{1}{2F_{No}}$$

but numerical aperture is usually used when α is **NOT** small. For example is microscope objectives.



Numerical Aperture of 0.95 common $(\pm 72^\circ)$.

See Tutorial 1.3 for relation between focal length and magnification.

Aside:

Strictly speaking,

$$\mathrm{na} = n \sin \alpha$$

where n is refractive index of imaging material. Common to use oil between microscope objective and object, lenses of

$$\times 100 \quad \mathrm{na} = 1.25$$

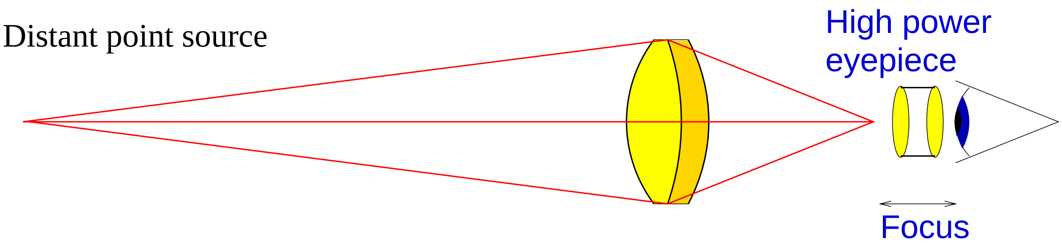
are common.

Point Spread Function

PSF determines the property of lenses in incoherent light.

Difficult to measure PSF directly, but it is possible:

Star Test



Useful for **Very Good** and **Very Poor** systems

Very Good Systems (about Strehl Limit).
PSF should have correct shape, also we are able to measure position of zeros. (do they agree with theory).

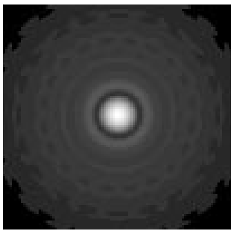
Ideal Coma Astigmatism Mixed

Aberrations at about **twice** Strehl limit.

Particularly useful for microscope objectives. Use tiny hole is silvered slide. Standard test when you buy a new microscope.

Very Poor Systems

PSF will be round "blob". PSF characterised by its physical size. Measure with traveling microscope.



4× Strehl Limit.

Useful for:

- Low quality photographic objectives.
- Low quality telescopes

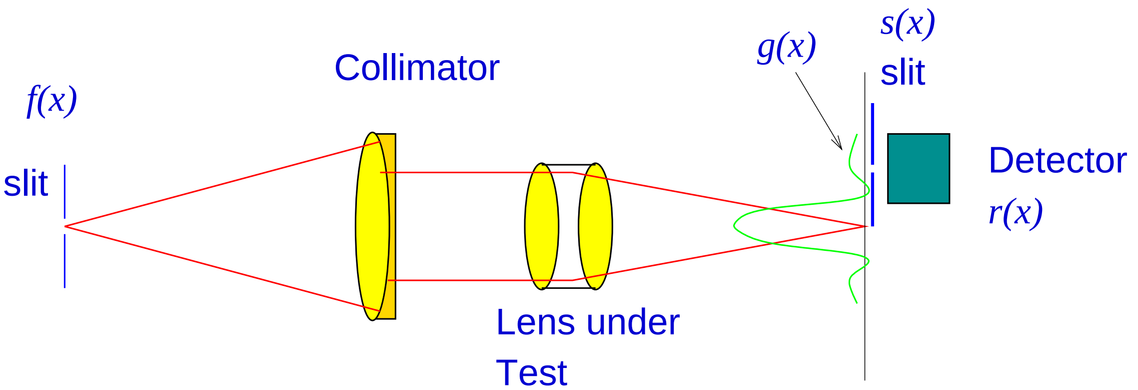
In any optical systems where the PSF is NOT limited by diffraction.

Not able to get much quantative information about aberrations.

See Malacara, "Optical Shop Testing" for deatils.

PSF by Slit Measurement

Measure the "line-spread" function. Easier due to more light.

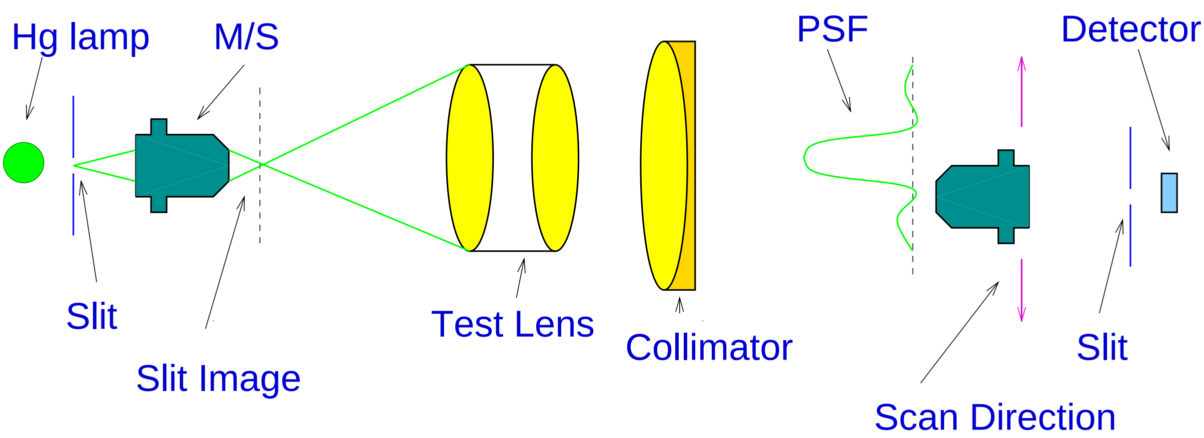


Scan slit to get "Line Spread".

"It-can-be-shown" that if **both** slits below resolution limit of lens, then

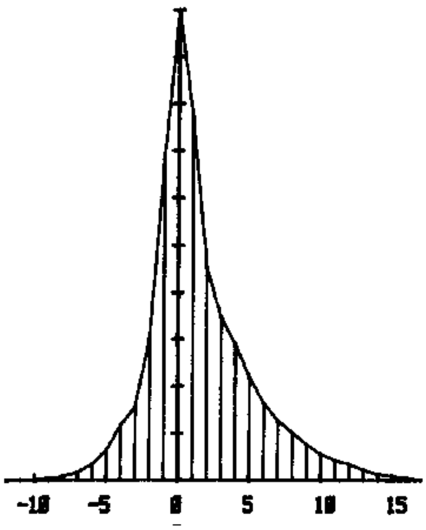
$$H(u) = \text{1-D FT of Line Scan}$$

Practical system:

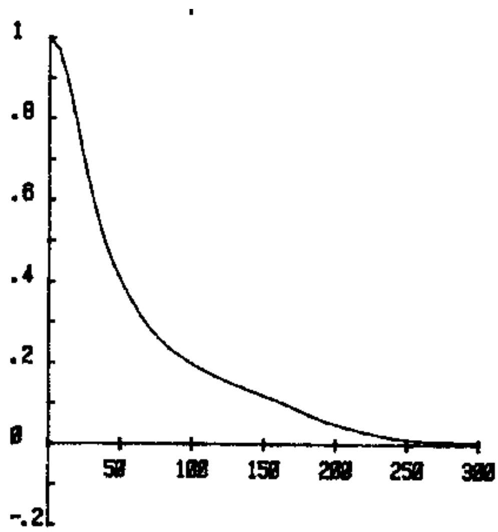


Test Lens at Focus

Results for a 5 inch (127 mm) focal length $F_{No} = 5.6$ large format camera lens.



Line scan of focal plane in μm

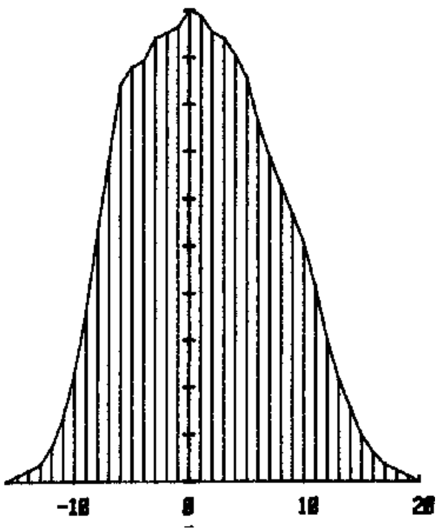


OTF in mm^{-1}

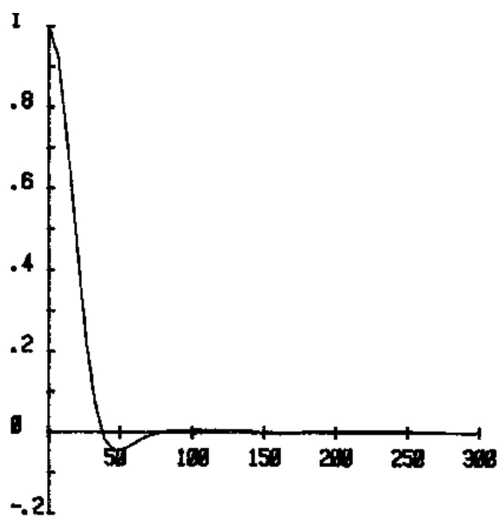
Close to expected OTF. Diffraction limited $\nu_0 = 323\,\mathrm{mm}^{-1}$

Test Lens at 0.5 mm Defocus

Results for above lens with 0.5 mm of defocus,



Line scan of focal plane in μm



OTF in mm^{-1}

Linescan *much* wided and expected drastic reduction in OTF.

Note: Negative section of OTF which corresponds to constrast reversal at about $50\,\mathrm{mm}^{-1}$.

Direct OTF Measure

OTF is the contrast with which grating a certain spatial frequency is passed.

$$f(x,y) = 1 + \cos(2\pi bx)$$

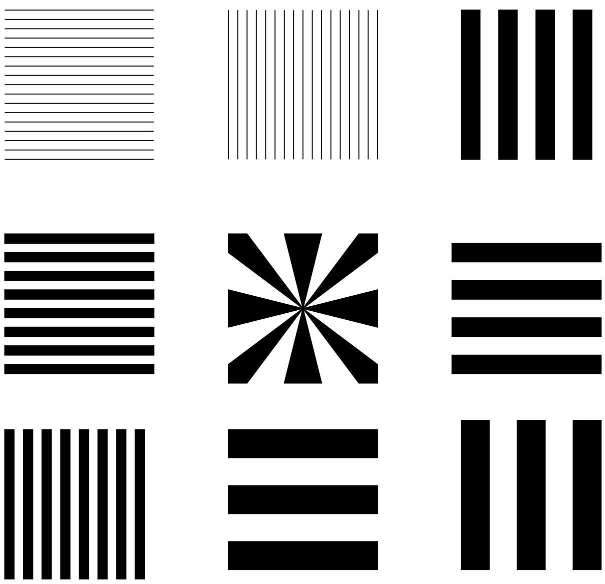
then image is

$$g(x,y) = 1 + H(b)\cos(2\pi bx)$$

where $H(b)$ is the OTF at spatial frequency b.

Range of gratings of varying spatial frequency, measure OTF by measuring the contrast gratings.

Fixed Gratings: Usually a "test-chart" of square wave gratings. (same mathematics). Most common test-chart is US airforce resolution chart.



Measure the contrast of each spatial frequency. Usually photograph with calibrated film and measure contrast.

Moire Gratings: Rotate two fine gratings to produce variable Moire fringes, (fringes rather rough).

Interferometrically produced fringes: (Michelson or Shearing interferometer). Good even cosine fringes, but optics expensive.

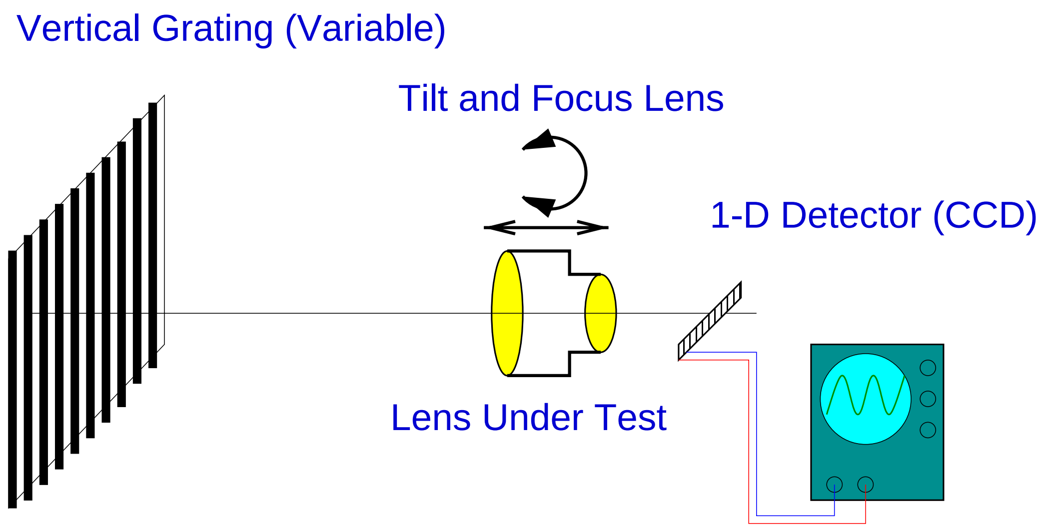


Image a series of gratings of unit (or known) contrast. The OTF is then found from the contrast of the imaged grating.

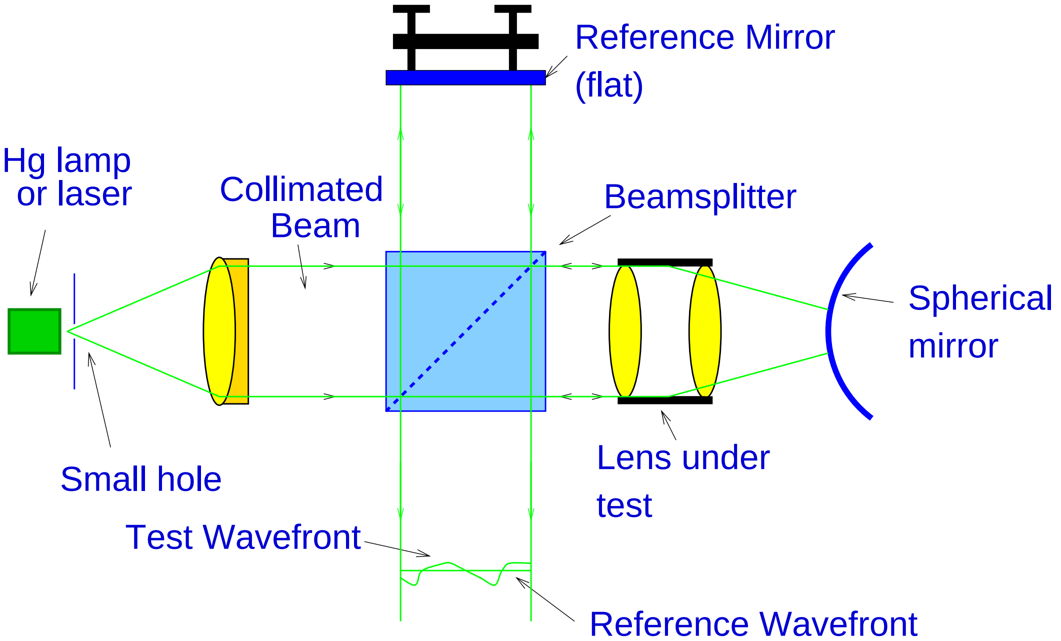
If use known direction we only need a 1-Dimensional sensor, (CCD or Photo-diode array.) Best contast at focus so allows simple fully automated system.

Basis of camera and video "auto-focus" system.

Wavefront Aberration

To get quantative results from system, need to measure the Wavefront Aberration.

Range of interferometers, best known is Twyman-Green



Note the Double Pass through the lens under test.

Interference between reference (flat) wavefront and double pass through test lens.

$$\text{Bright Fringe} \quad \rightarrow \quad \text{OPD} = \pm n\lambda$$
$$\text{Dark Fringe} \quad \rightarrow \quad \text{OPD} = \pm(n+1/2)\lambda$$

We get Contour Map of OPD. So Contour Map of

$$2W(u,v)$$

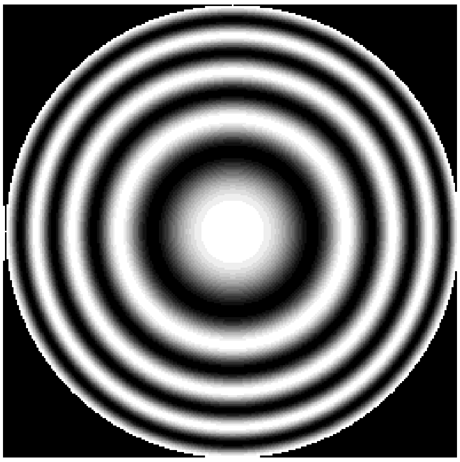
the wavefront aberration function.

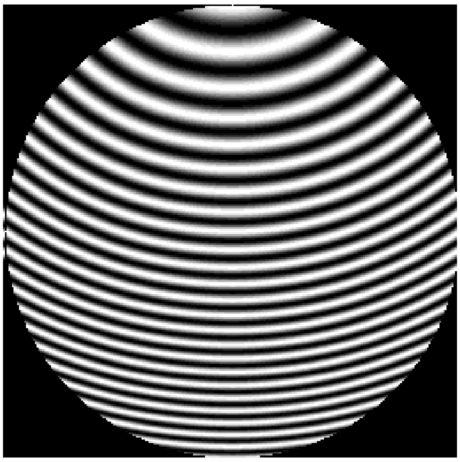
Shape of Interferograms

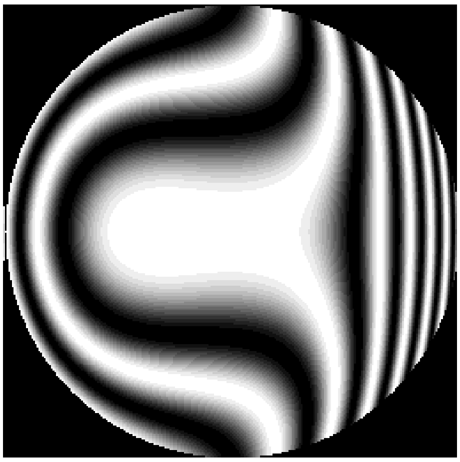
Simple aberrations give simple patterns, eg:

Defocus $\rightarrow$ Newton's Rings

but complex aberrations give complex fringe patterns.







Wavefronts with, 2λ of defocus, 2λ of defocus plus 3λ of tilt, and mixed aberrations.

Get "Contour Map" but not absolute value of aberration function.

Fringe Analysis:
If wavefont aberration "smooth", able to number fringes and unwrap phase to get wavefront.

Phase Ambiguity: Still have "Hill/Valley" ambiguity. By tilting reference mirror in known direction we can form dirivative, so resolve ambiguity.

Fully automatic system (Zygo), reference mirror moved by piezzo stacks and wavefront aberration calculated by curve fitting to interferogram.

Other Interferometers

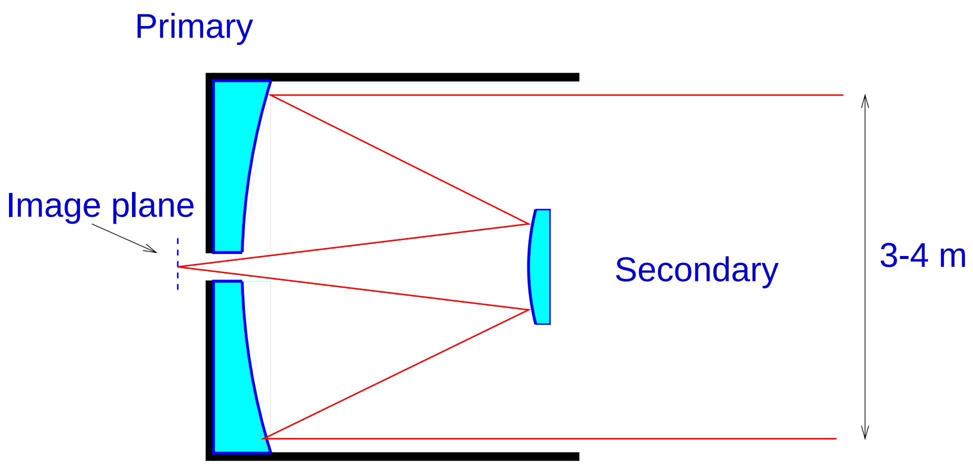
Vast range, see Steel, *Interferometry*. Two basic types

- Reference Beam: Aberrated wavefront compared to ideal reference. Contour of aberration obtained directly.
- Shearing Systems: Aberrated wavefront split, sheared and recombined. This gives differential of aberrated wavefront.

All interferometers are difficult to align, prone to vibration and need expensive optics (very high quility mirrors and beamsplitters).

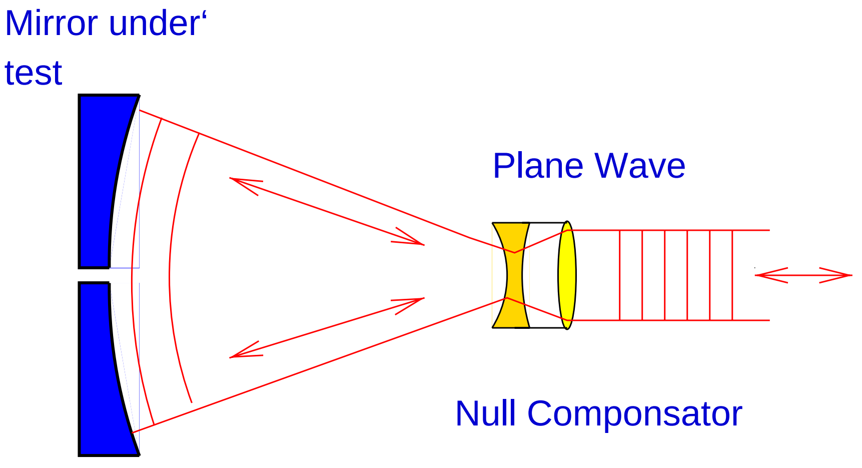
Null Test Components

Consider a big telescope.



Components are big, also surfaces are not spherical or parabolic. Difficult to test.

Trick is to use a "Null Componsator" so make system produce plane waves



Then when whole systems tested we should get straight fringes.

This technique depends on skillful fabrication of the Null Componsator. (most likely fault in manufacture of Hubble Space Telescope).