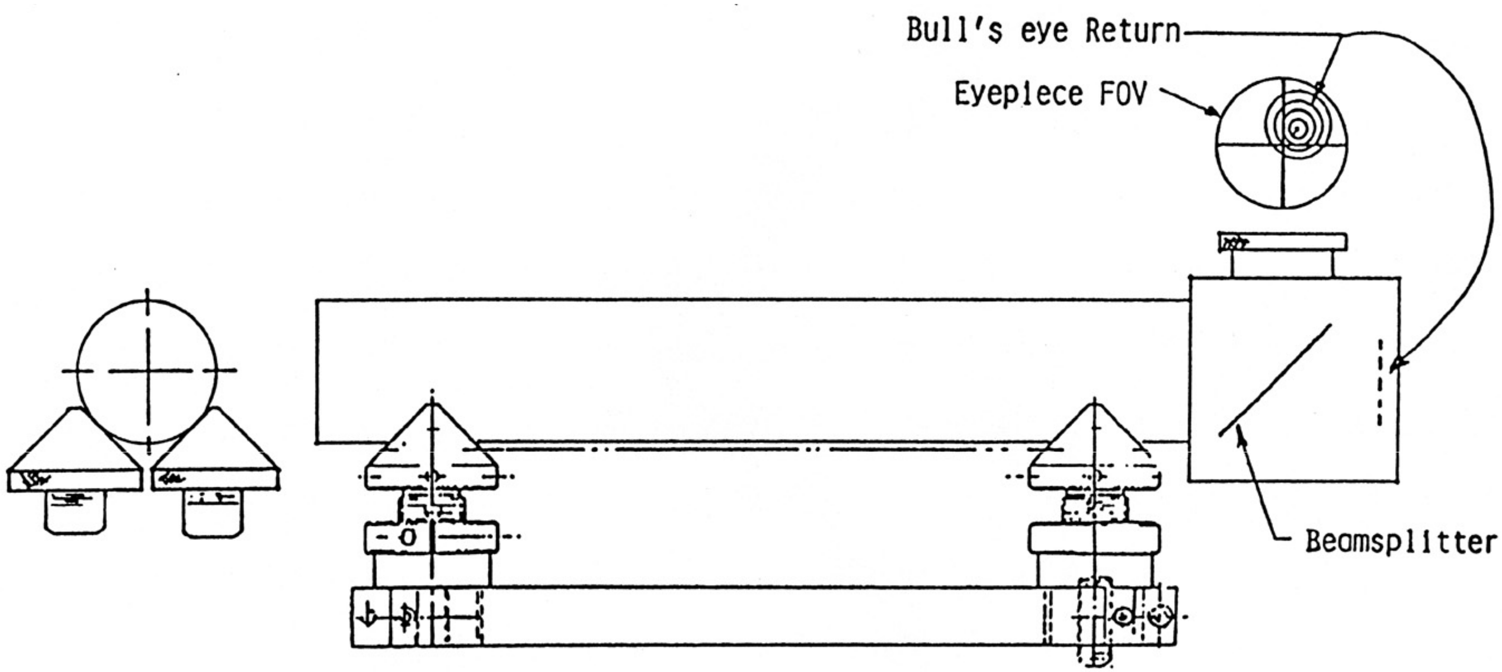
3.0 Alignment Equipment and Diagnostic Tools:

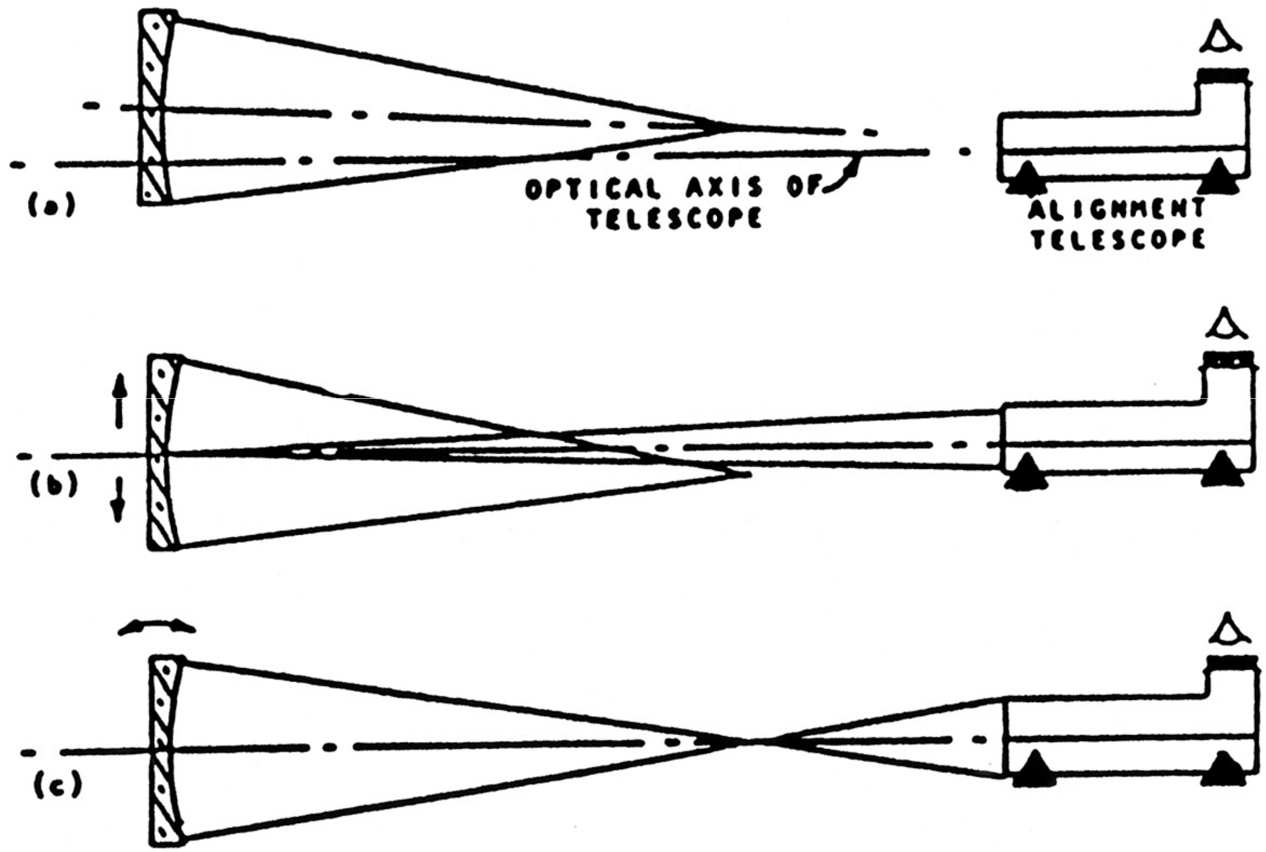
- Alignment equipment
  - The alignment telescope and its use
  - The laser autostigmatic cube (LACI) interferometer
  - A pin -- and how to find the center of curvature
  - The beamsplitting microscope
  - The lateral shear interferometer
- Alignment diagnostic tools
  - The star test
  - The knife-edge test
  - Interferometry
  - Inspecting for vignetting
  - Crossed polarizers

The Alignment Telescope (and Mount)



- Versatile alignment tool
- Reasonable accuracy (few arc-secs, few mils)
- Several manufacturers with a variety of features
- Uses principles of auto-reflection and retro-reflection (see text)

Alignment Procedure for Rotationally Symmetric Surfaces



(a) Misaligned (b) Decenter removed (c) Tilt removed

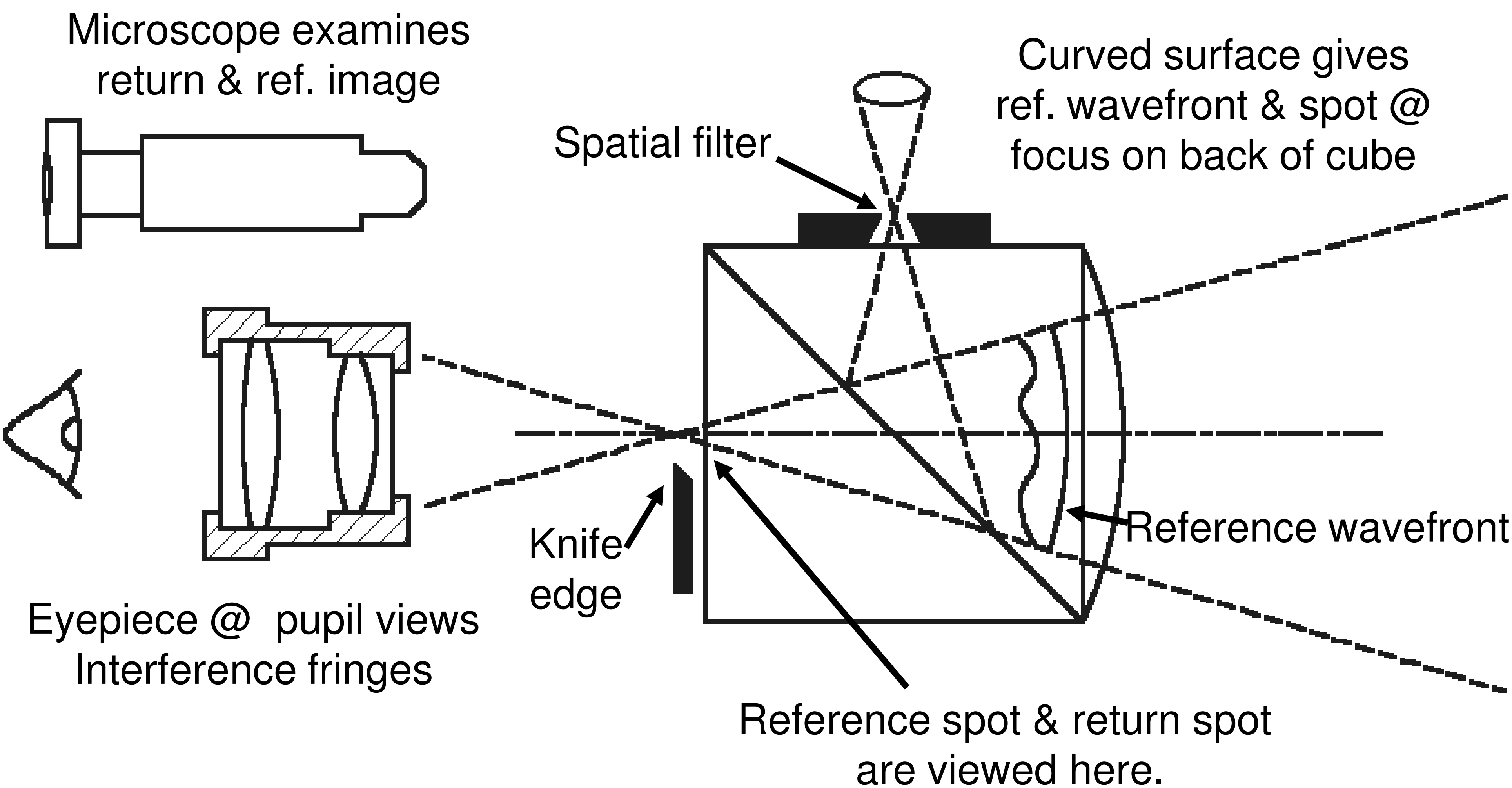
The Laser Autostigmatic Cube (LACI) Interferometer

- The LACI has the ability to quantitatively monitor the dynamic boresight stability of the optical system. The reference reflection will interfere with the return wavefront from the optical system, producing the interference fringes which can be directly observed with an eyepiece. By knowing the pupil diameter (D) and wavelength (λ) and number of fringes (N) across the pupil the boresight error (e) will be

$$E= n(\lambda)/2D$$

- Furthermore, if the number of fringes change over a short period of time due, for example, to vibration, the variation in the number of fringes can be put into the above formula in order to determine the magnitude of the vibration. Changes in fringe orientation will also indicate changes in the direction of the boresight error. Long term variations are probably an indication of thermal instabilities.

The LACI cube



Importance of the LACI cube

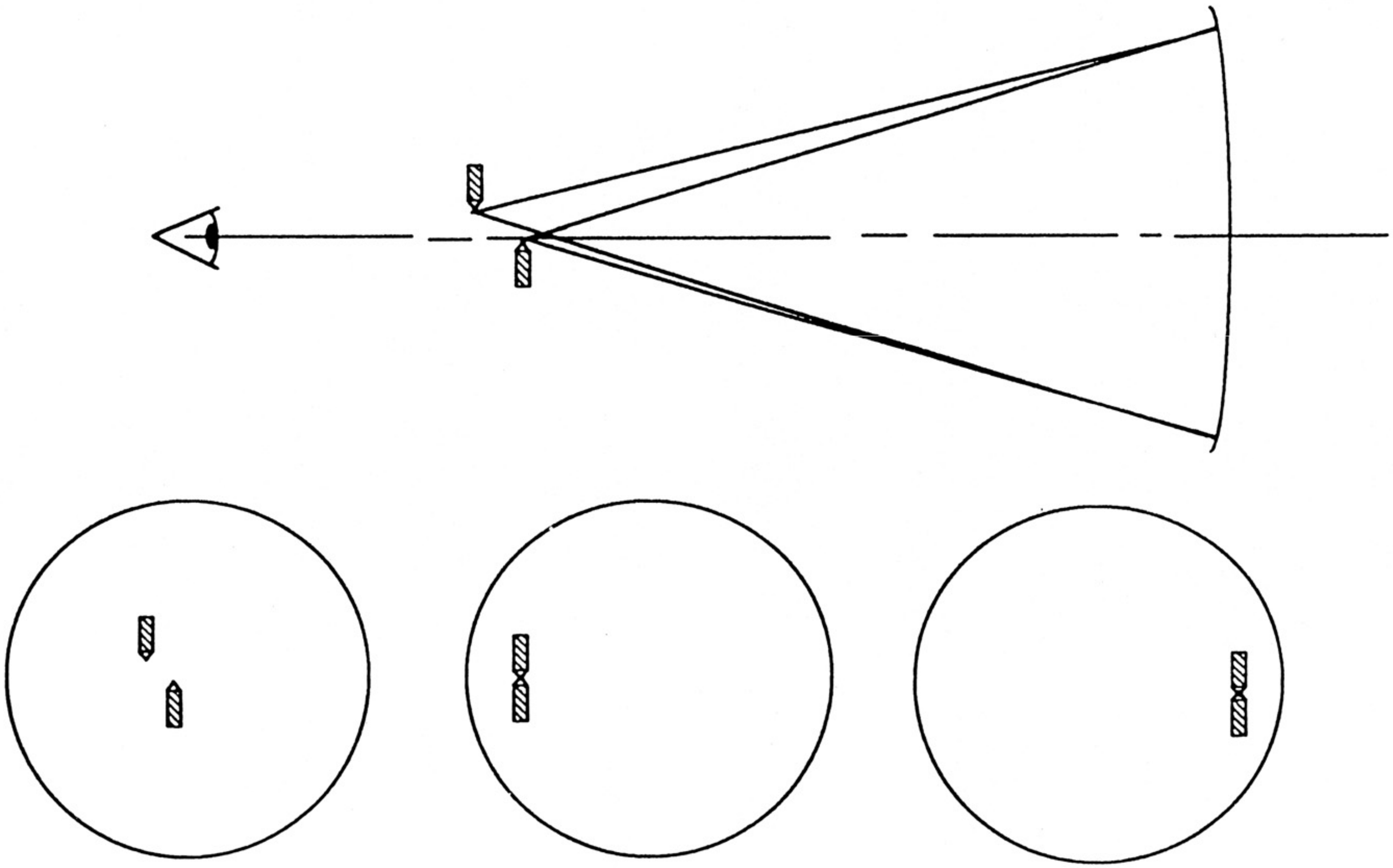
- The LACI cube allows us to:
- 1) “place” the reference point source on the optical axis
- 2) observe the reference point source from behind propagation direction (unencumbered by the source hardware, e.g. pinhole, fiber, etc.)
- 3) observe it and the return image simultaneously

→ this is all a big deal!

Finding Focus or Center of Curvature with a Pin

- Simple
- Accurate - We can calculate how accurate
- Helpful if surface is reflective
- How can accuracy be improved?
- What happens if the mirror is not a sphere, but is an aspheric?

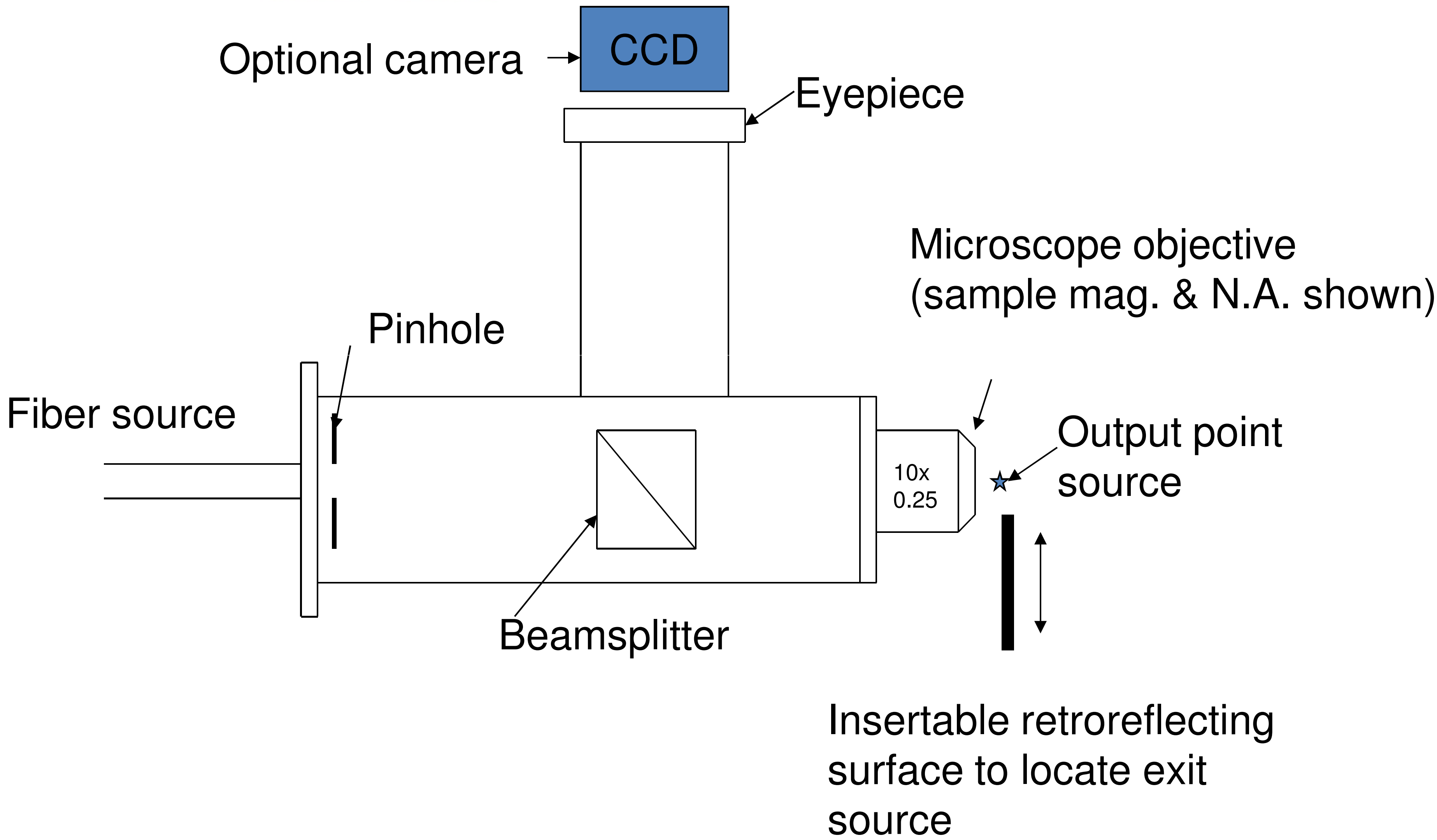
Finding Focus or Center of Curvature with a Pin



The beamsplitting microscope is used to create a point source

- The beamsplitting microscope (BSM) has a cube beamsplitter inserted in the 160mm path to the eyepiece – allows 2 observation paths
- Originally designed for 2 observers (or observer + camera)
- To use as a star-test alignment device, an illuminated pinhole is placed in one path as shown in the next chart

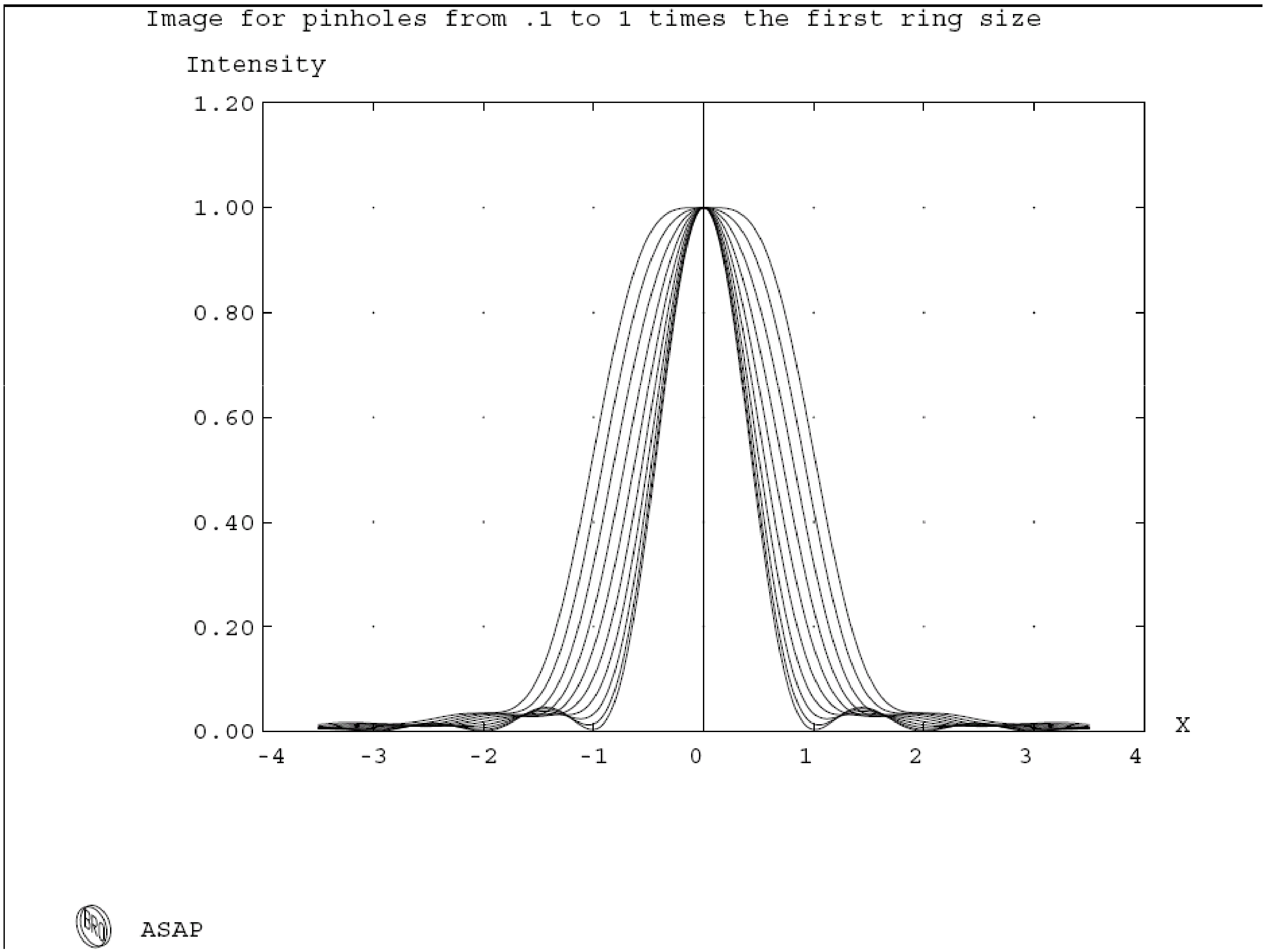
The Beamsplitting Microscope



The effect of pinhole size on Airy disk diameter

- The following parametric plot shows the resulting "star" image for pinholes varying in 10% increments up to the diameter of the Airy disk.
- Clearly, for pinholes < 20% of the Airy disk diameter, the resultant "star" image is very close to that of a perfect Airy disk
- The true Airy disk (i.e. 0% pinhole) is hard to distinguish from that formed by the 10% pinhole and is not shown
- How do we use this information?

Airy disk convolved with pinholes from 0.1 to 1.0 Airy disk diameters



How to choose the pinhole

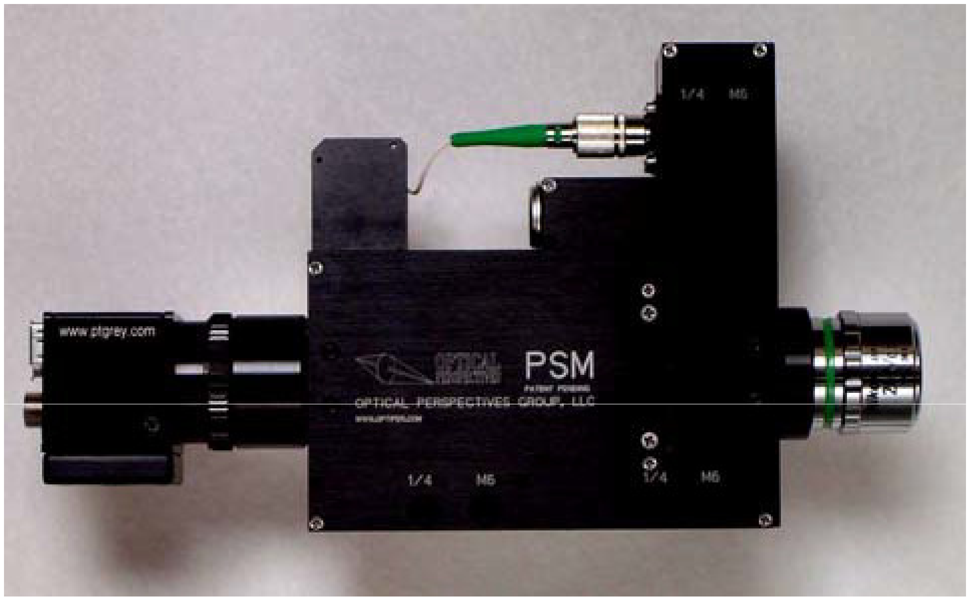
- Example: We want to perform the star test on an optical system of *any arbitrary F/#.*
- We will test this system with an F/10 collimator. The Airy disk diameter for this collimator in the visible is ~12.5µ
- 20% of 12.5µ = 2.5µ
- So, use a 50µ pinhole and a 20x microscope objective (50/20 = 2.5)!

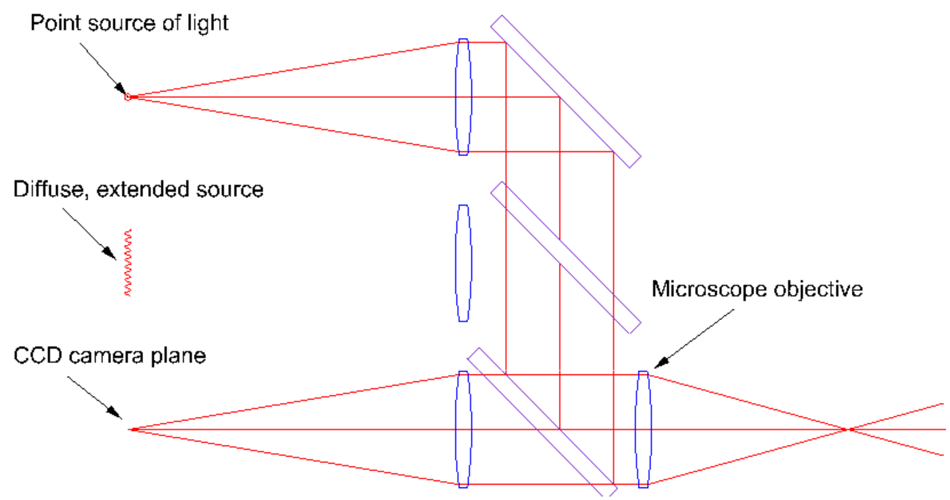
PSM – Point Source Microscope

- Traditional use for over 100 years to precisely measurement the radius of curvature of optical surfaces
- Use on coordinate measuring machine to precisely locate optical elements via centers of curvature
- Use with a precision rotary table to center optics in a lens barrel
- Use as a Star test device to find the optical axis of symmetric and off-axis parabolas in autocollimation
- Use to reverse engineer lenses by measuring radii and optical thickness and back focus
    - Can determine all 4 paraxial lens parameters, R1, R2, ct and index n
- Use as an autocollimator to determine wedge in windows, and parallelism of prism faces
- Use Cat's eye reflection to find focus on flawless (non-scattering) transparent surfaces
- Use Cat's eye reflection to find spacings between lenses in lens assemblies

Courtesy of Bob Parks

Commercial PSM Device
PSM in autostigmatic microscope mode



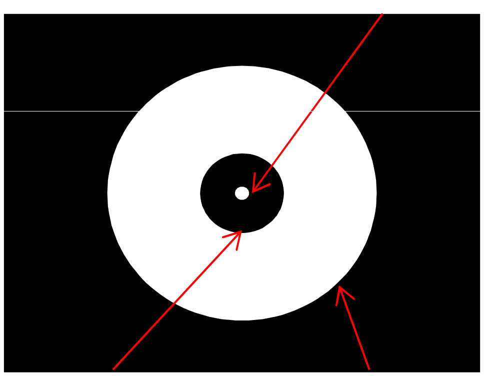


Courtesy of Bob Parks

W2-AM – Reticle based alignment tool

An LED based, Köhler illumination system back illuminates a chrome-on-glass reticle. The reticle acts as a field-stop for the imaging system and is conjugate to the camera. The reticle provides a large, easy to find "blob" to guide initial alignment to facilitate rapid location of the target. The obscuration provides further guidance to the operator to find the PSF or point image.

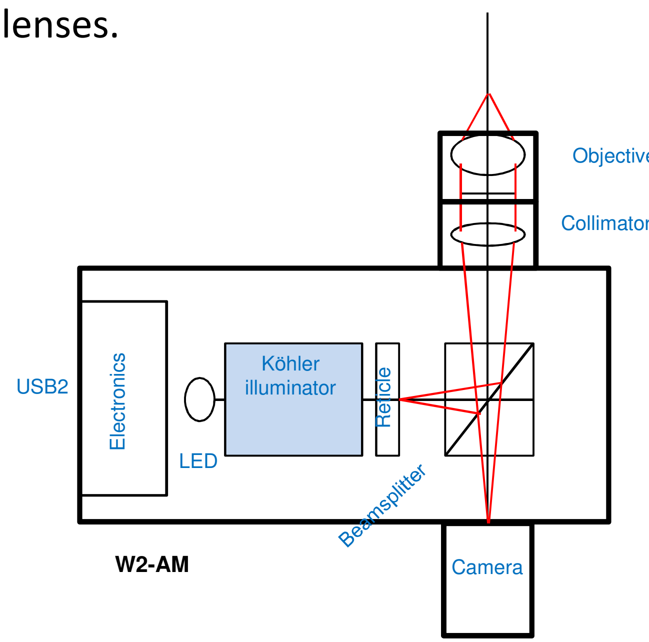
Not to scale.



The collimating lens is external to the housing making it possible for the operator to adjust focus as well as to install alternative collimating lenses, even custom lenses.

Built-in electronics with a USB2 interface provide power and control of the 4-channel digital current sources.

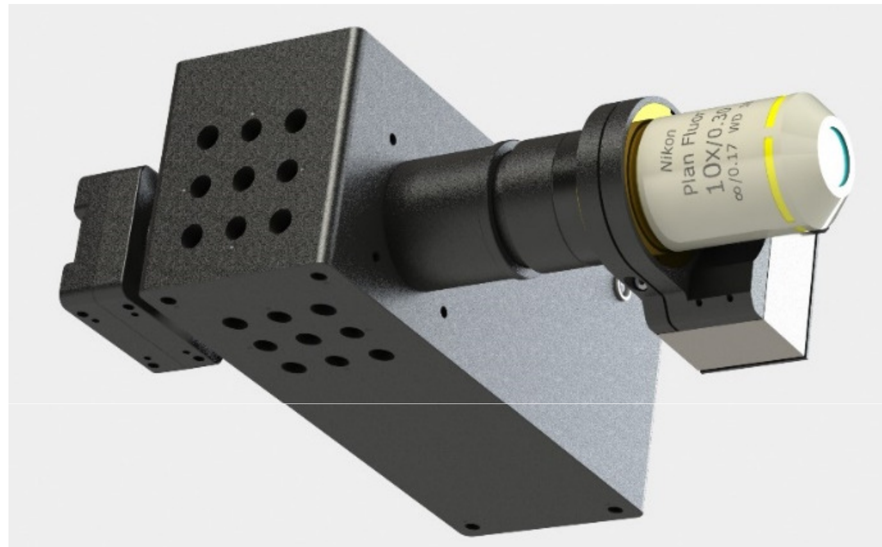
W2-AM can be built with sources from the UV through SWIR wavelengths.



W2-AM-PR – *Phase Retrieval*

- Once system is aligned the PR option allows one to measure the system wavefront with the same device.
- The measurement provides low-order Zernike coefficients that control focus, decenter, tilt, spacing and mounting errors.

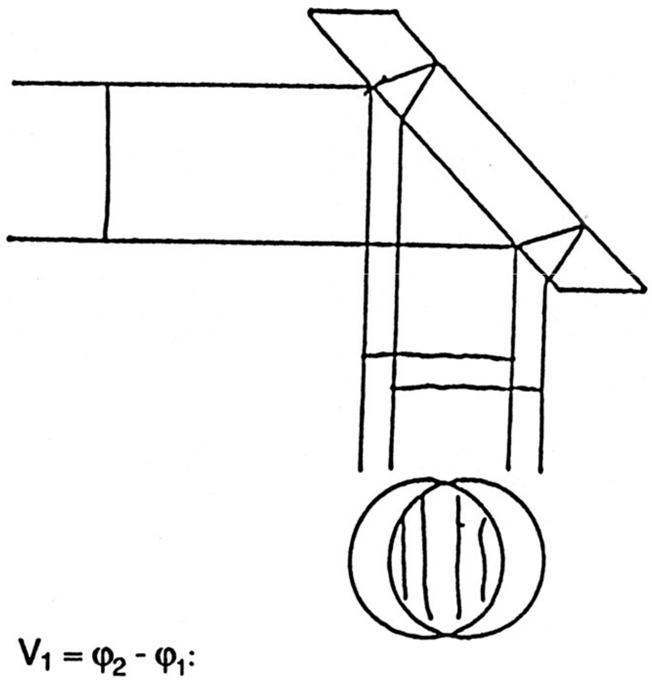
→ *You don't always need an interferometer*

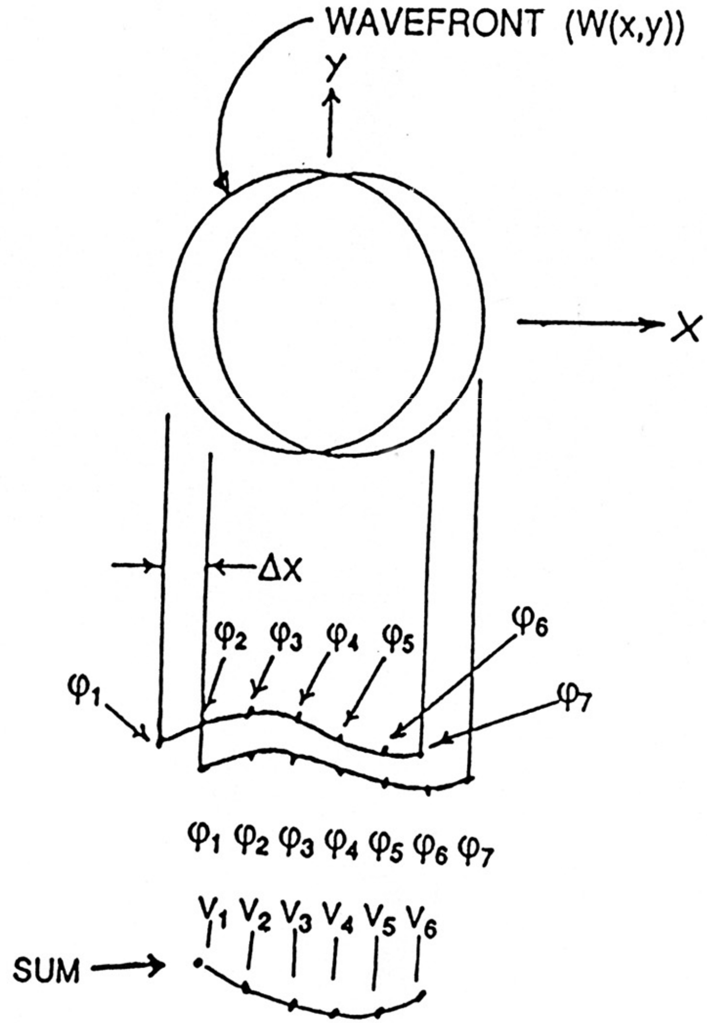


Courtesy of Bill Kuhn

PR system adds a closed-loop piezo stage to shift the objective along the optical axis. The amount of defocus in the wavefront is doubled due to the shift of the source location and the image plane in opposite directions. The piezo stage is appropriate for fast optical systems. Slower systems can use a stage to drive the entire instrument.

Lateral Shear Interferometer





Lateral Shear Interferometer

From the previous page we see:

$\phi_1 = \phi\ (x_1,y_1)$ and $\phi_2 = \phi(x_2,y_2)$

But Y = constant (looking at a slice in the x-direction)

Therefore, $y_1 = y_2$ and $x_2 = x_1 + \Delta x$

Therefore

$$\phi_2 = \phi_1\ (x + \Delta x,y)$$

At point v1 we observe the phase difference of all the sheared wavefront:

$v_1 = \phi_2 - \phi_1 = \phi_1\ (x+\Delta x,y) - \phi_1\ (x,y)$

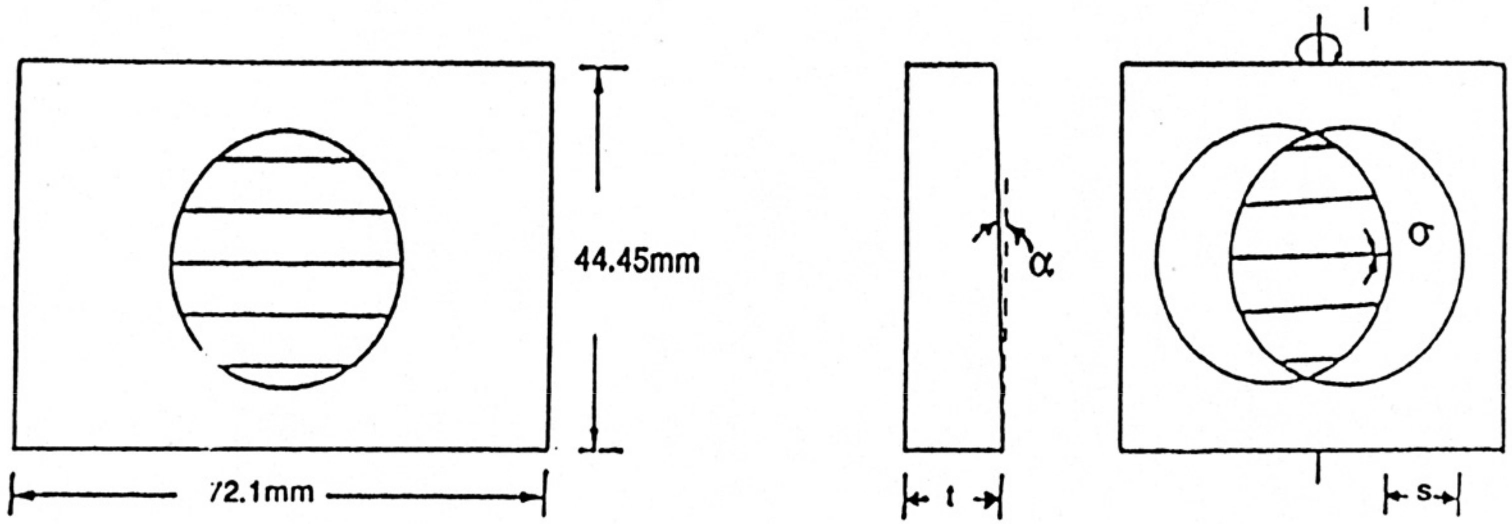
Let $\Delta x \varnothing 0$ and let s be the actual shear distance

Then the condition for seeing a fringe is:

$$\left[\frac{\Phi_1(x+\Delta x,y)-\Phi_1(x,y)}{\Delta x}\right]\Delta S = N\lambda$$

But the fraction is the definition of a derivative! Thus, the output wavefront from a shearing interferometer is the derivative of the input wavefront

Shear Plate Example



Material	= BK-7
Plate Thickness (t)	= 13.4 mm
Wedge Angle (α)	= 50 μrad
Angle of Incidence (i)	= 45 degrees
Lateral Shear (s)	= 10 mm
Fringe Tilt (σ)	= 2.8º at λ/10 defocus
Wedge in X Direction	= 0 ± 2 μrad

Interferometry

Estimating Wavefront Error

Rule #1 A fringe is a wave of wavefront error - always

+ 2 for surface information

+ 2 for double pass

in transmission: OPD = (n-1)T!!!

Rule #2 Something must move to determine proper orientation

a. Focus and note change OR

b. Move reference arm - note direction of motion OR

c. "Squeeze" to determine wedge direction

Rule #3 Always use fiducials when diagnosing non-rotationally symmetric errors

Rule #4 Piston, tilt, focus and (usually) coma are always removable

Rule #5 Always look at bullseye fringes

Rule #6 Always, at least once, come in from the edge of the surface or pupil with a finger, ruler, etc. to insure that no clipping (vignetting) occurs

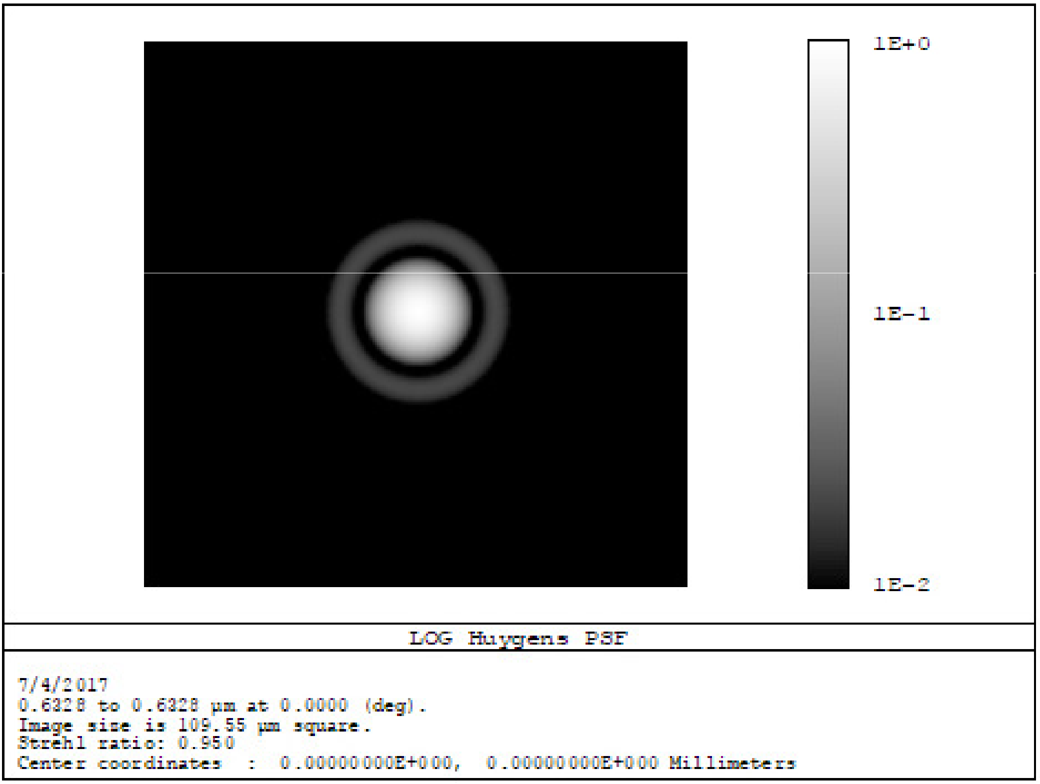
The Star Test

Features

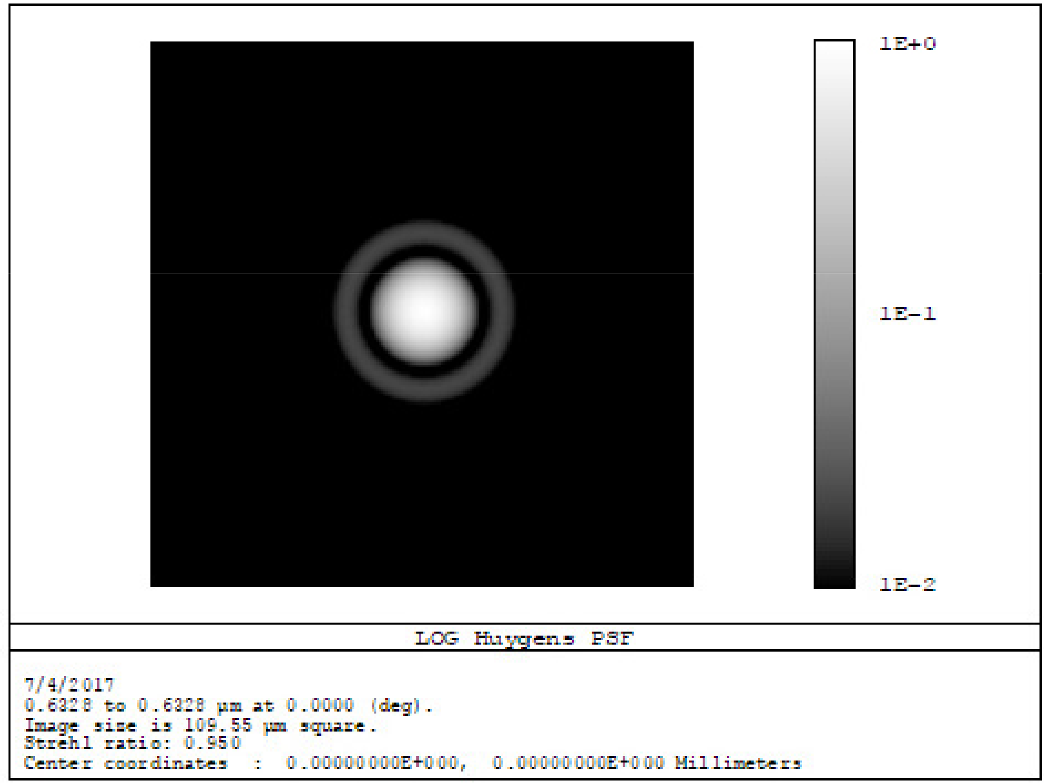
- Sensitive - Can detect $\lambda/10$ or better (see Hartmann photos)
- Good for qualitative verification - instant visual recognition
- Quick and inexpensive - laser or white light
- Above features apply to both diffraction limited systems and geometric blur limited systems

No Aberration, λ/8 focus changes

Inside Focus

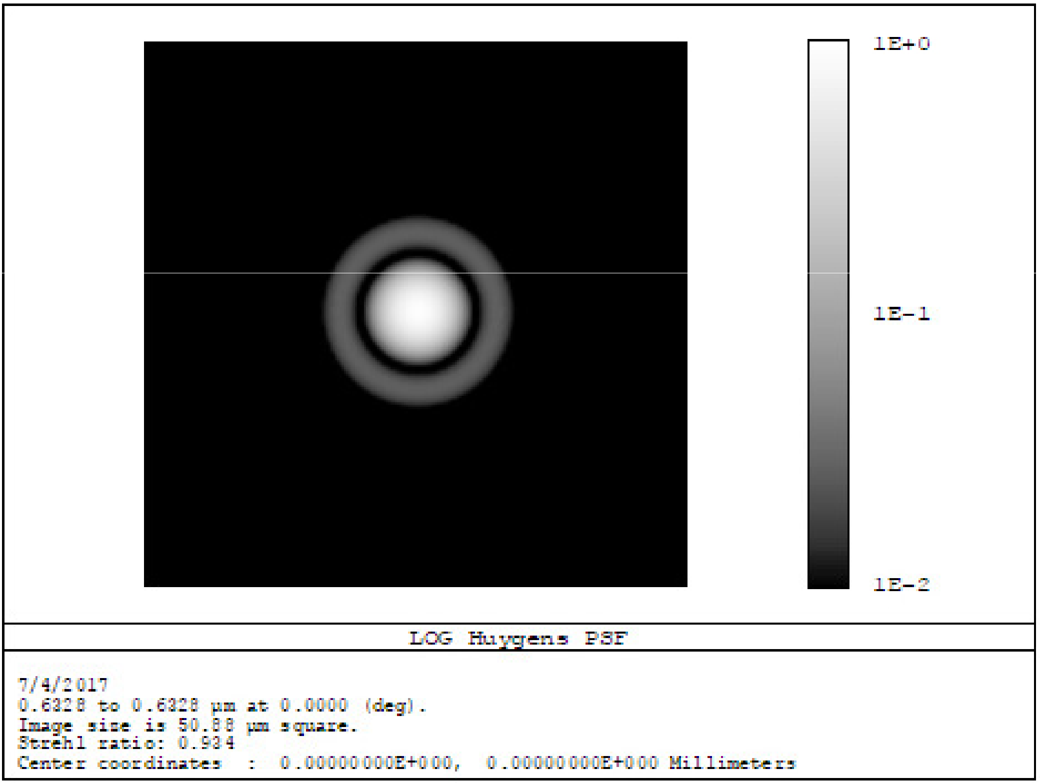


Outside Focus

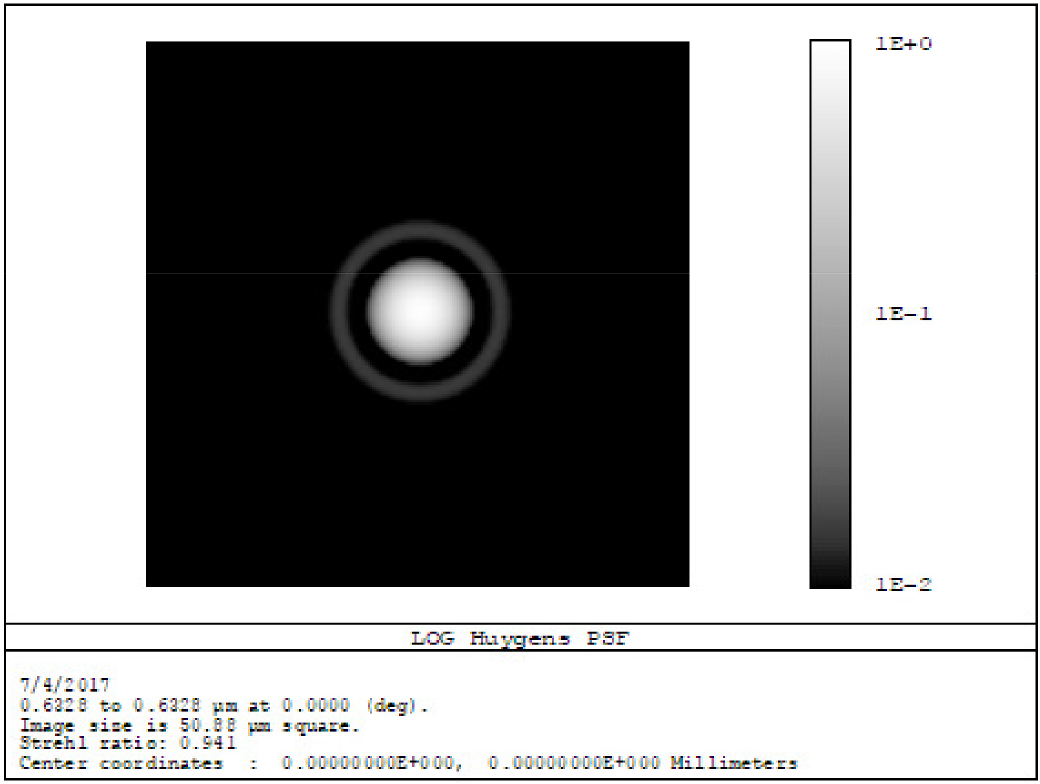


λ/10 Spherical Aberration Sensitivity

Inside focus 25 microns

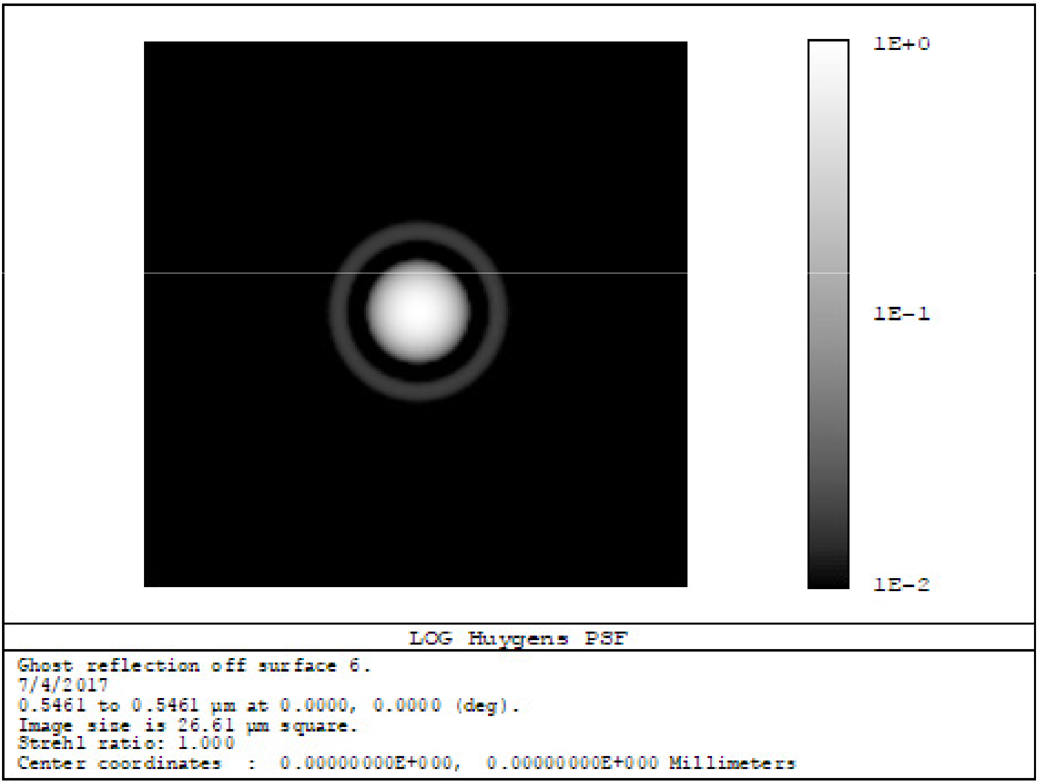


Outside focus 25 microns

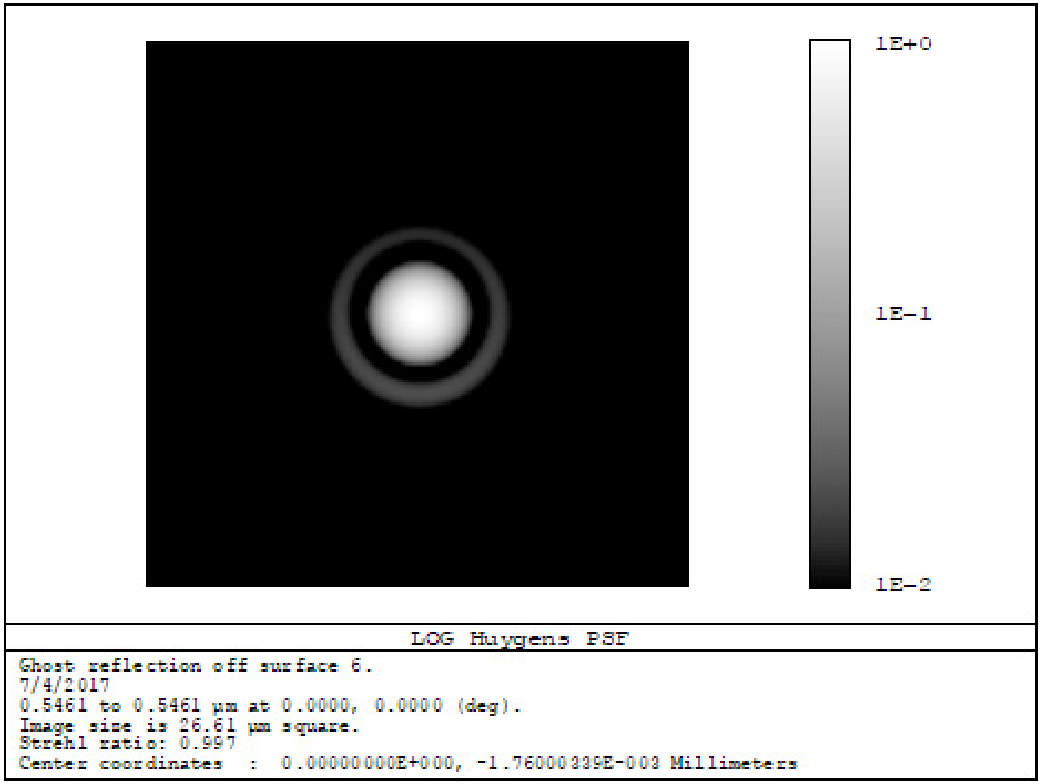


Coma Sensitivity

Coma Free

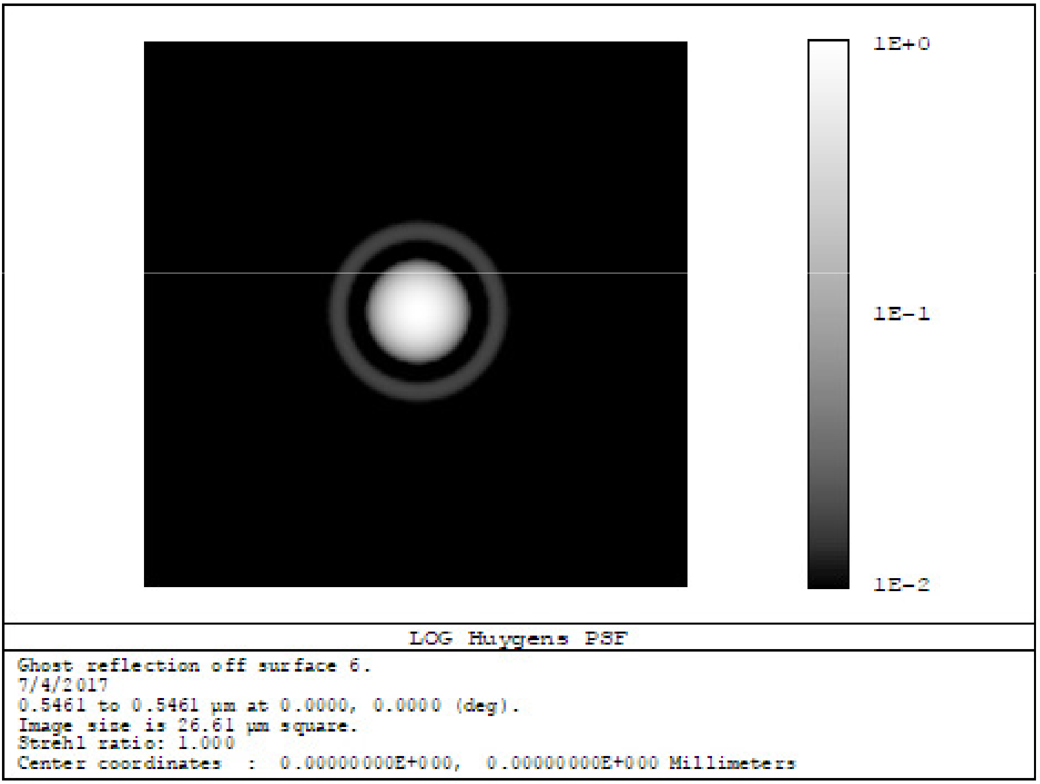


λ/10 Coma

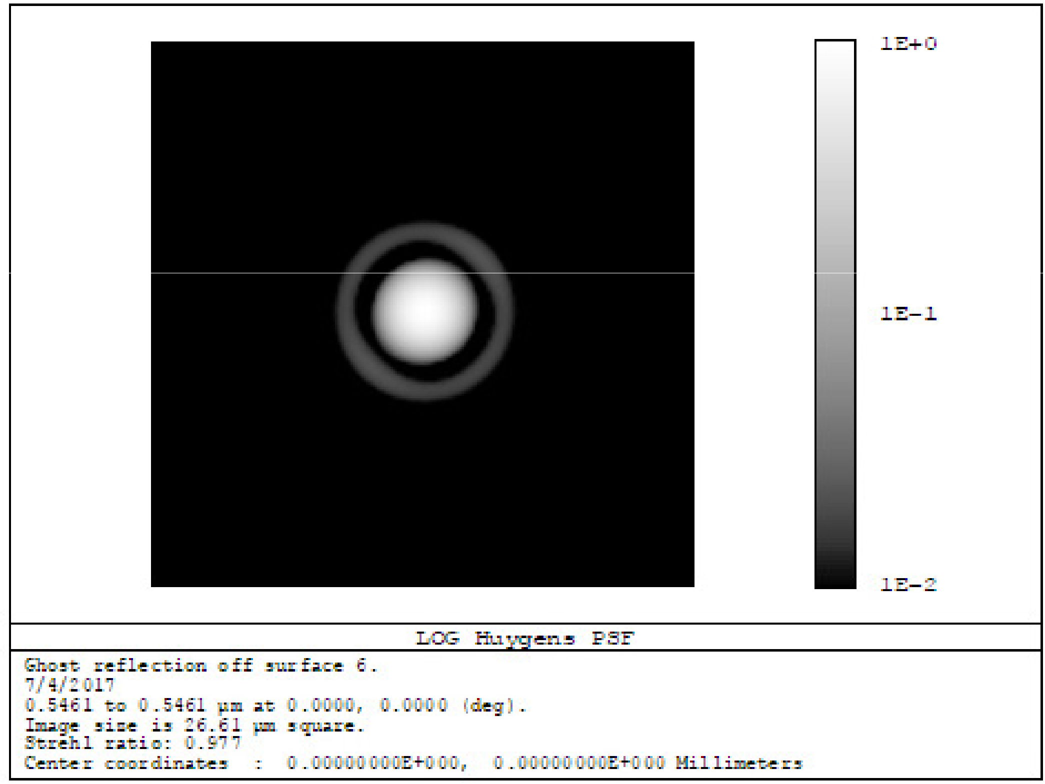


Astigmatism Sensitivity

Astigmatism Free



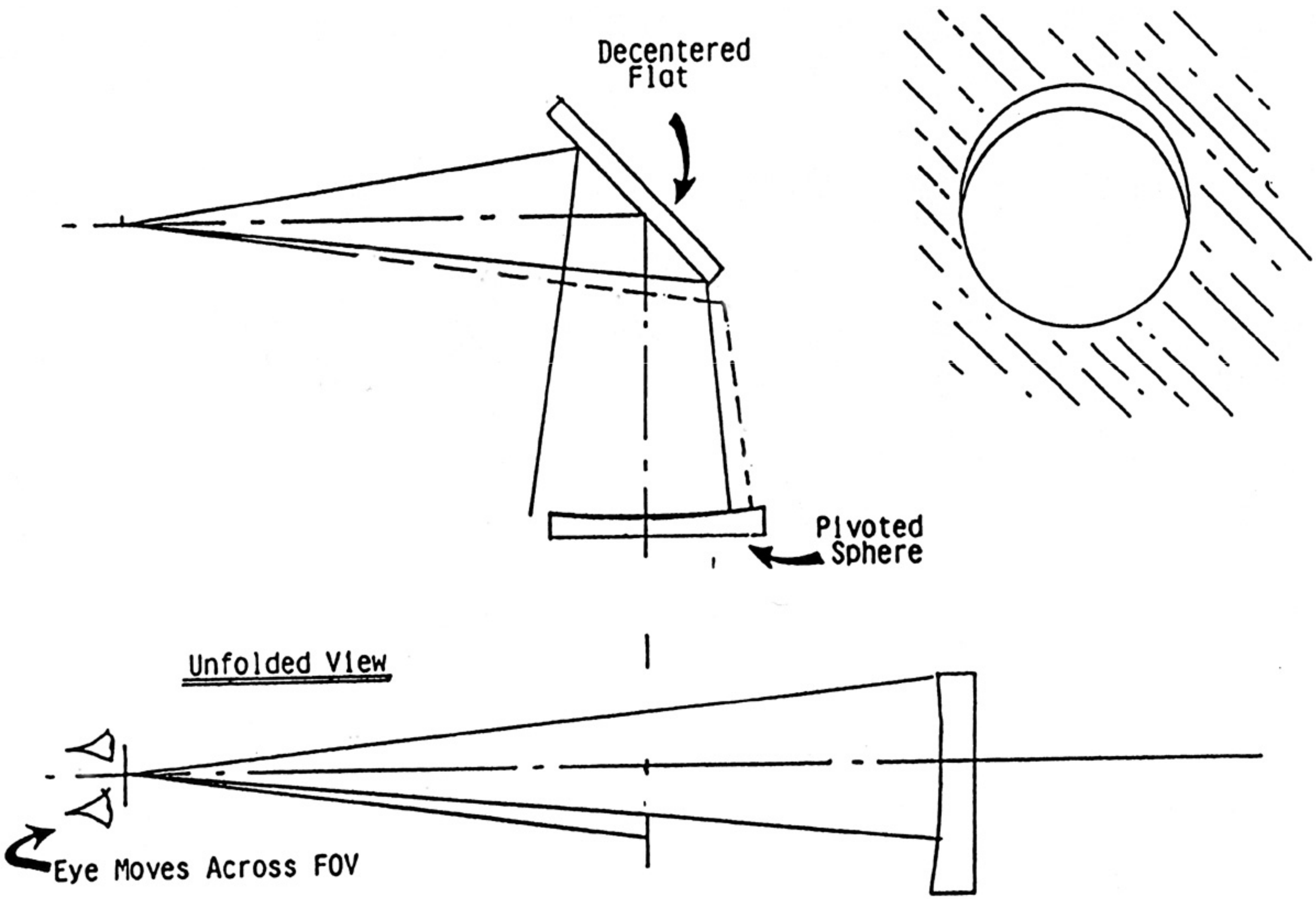
λ/10 Astigmatism



Checking for Vignetting

- Why we usually think of misalignment as an introduction of aberration
- It is possible to be misaligned and have a good image
- A good example is a fold mirror that is decentered, or a spherical mirror rotated about its center of curvature
- By placing the observer's eye at the focus, it is often easy to diagnose a vignetting problem
- In order to fully determine vignetting problems, the eye should be moved around the periphery of FOV
- Vignetting causes a loss of light through the optical system
- Even small amounts of vignetting in I.R. systems can be a disaster because the detector might see warm hardware
- Sometimes vignetting is deliberately introduced to reduce aberrations

Observing Vignetting



RUDA CARDINAL

Visual Inspection of Vignetting

Examples: Visual inspection of a collimated beam with fold mirror