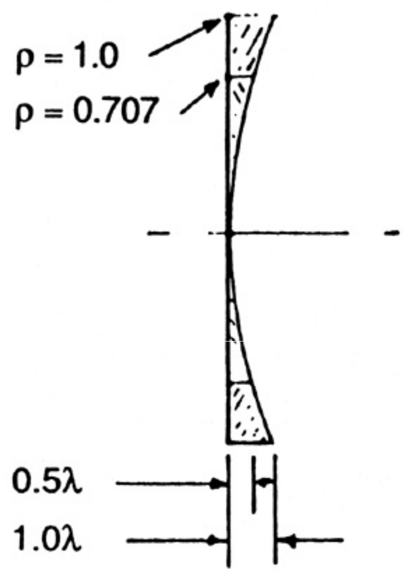
Why is There a Black Dot when Defocus = 1λ?



$W = W_{020} = a_{020}\rho^2$

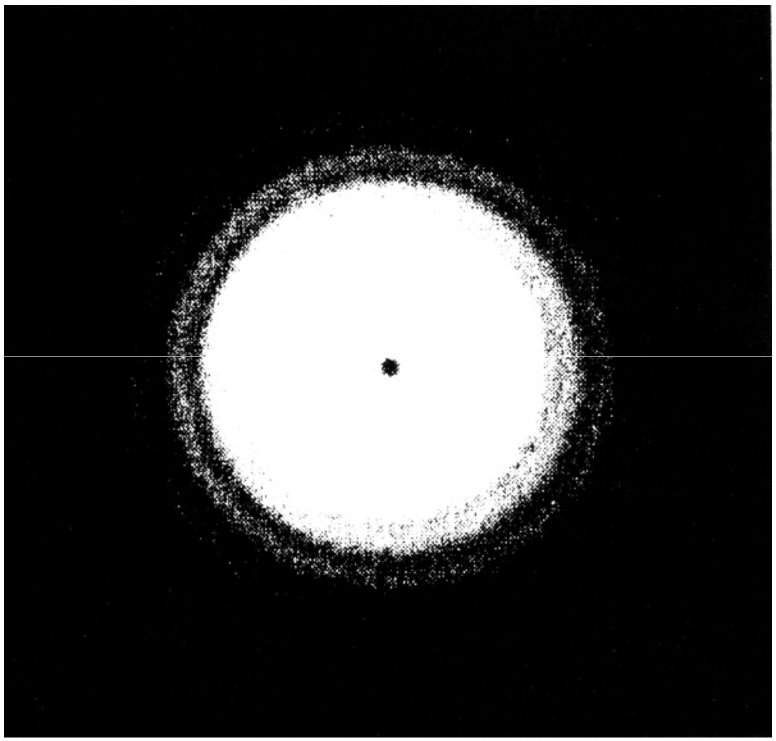
When $a_{020} = 1\lambda$

- Sag of the wavefront at full aperture ($\rho = 1$) = 1λ
- Sag of the wavefront at $\rho = 0.707 = 0.5\lambda$
- Area of the pupil from $\rho = 0$ to $\rho = 0.707$ equals area of annular pupil from $\rho = 0.707$ to $\rho = 1.0$

Therefore, for every point within r = 0.707, there is a point in annulus that is $\lambda/2$ out of phase

Consequently, on-axis everything cancels! No light! Black Dot!

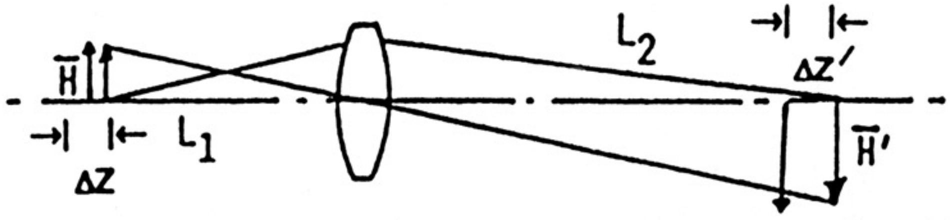
The Black Dot



- When a perfect circular wavefront is defocused exactly 1λ, a black dot appears at the center of the spot
- Find the $\pm 1\lambda$ planes, then split the difference for sharp focusing

Longitudinal Magnification

- First what is transverse magnification?



$M = L_2/L_1$

- Longitudinal Magnification is simple. If we move the object along the axis by an amount, DZ, the image will move DZ'
- Longitudinal Magnification is defined as:

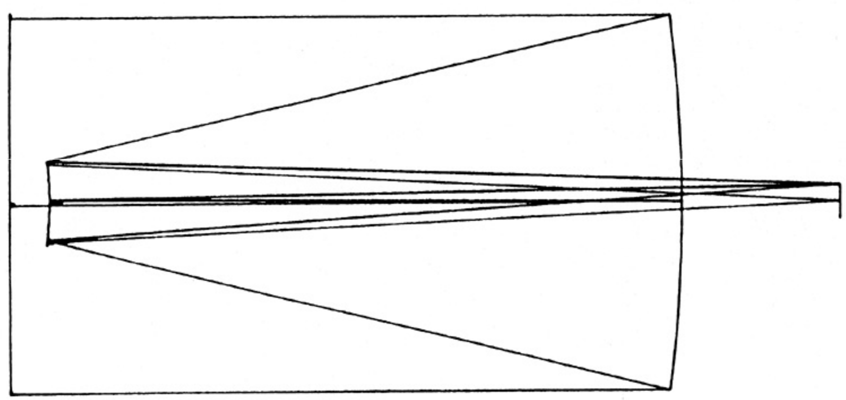
$$M_L = \frac{\Delta Z'}{\Delta Z}$$

- It can be shown that
  - $M_L = M^2$

- So what?
  It is useful for measuring despacing sensitivities of optical components.
  It is also why your nose looks so big on a doorknob!

The Usefulness of Depth of Focus and Longitudinal Magnification Formulas (example)

Problem: Find the spacing tolerance between the primary and secondary mirror of a diffraction limited, F/10 Cassegrain telescope. The primary mirror is F/2, the telescope is used in the visible ($\lambda = 0.5\mu$).



1. The diffraction limited ($\lambda/4$) depth of focus at the large image plane of the Cassegrain is given by

   $\Delta f = \pm F/\#^2$ (in microns) (when $\lambda = 0.5\mu$)
   $= \pm 100$ microns

2. The secondary mirror converts an F/2 beam into an F/10 beam. Thus, the magnification of the secondary mirror is

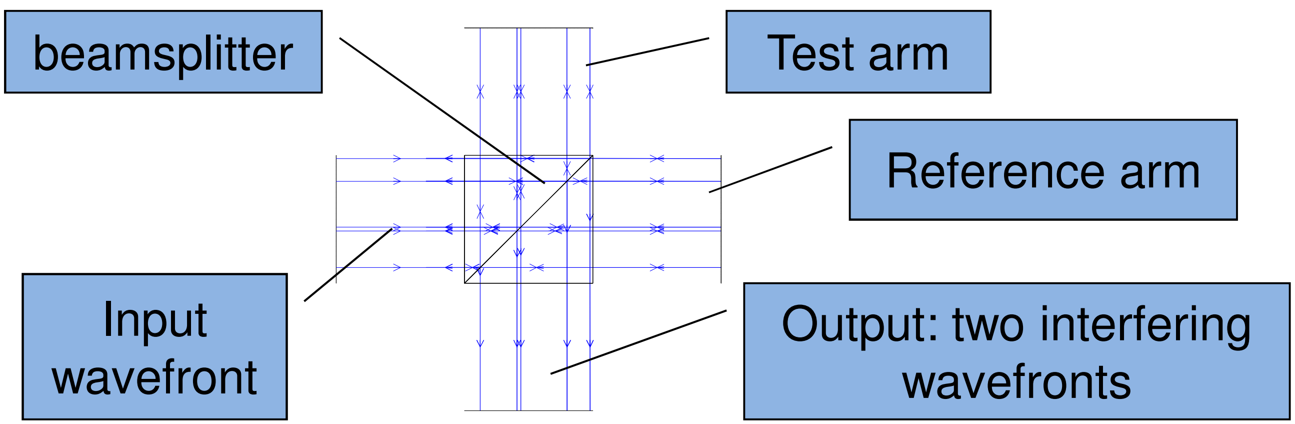
$$M = \frac{F/10}{F/2} = 5$$

3. The longitudinal magnification $M_L = M^2 = 5^2 = 25$

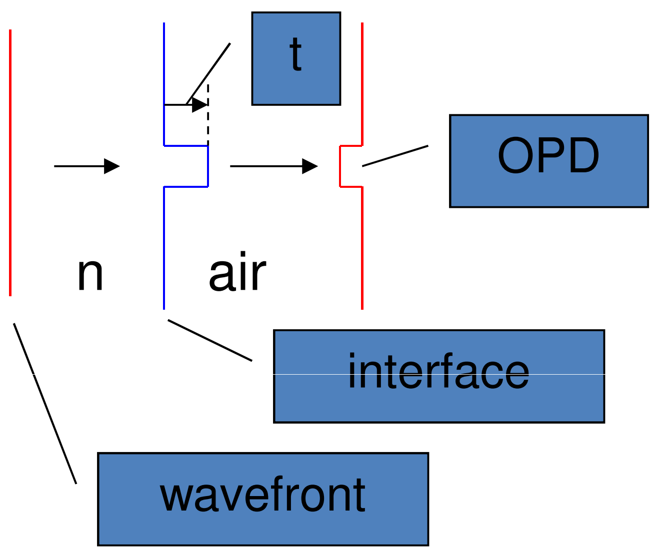
4. A 100μ change in focus will occur if ΔS changes by $100/25 = 4\mu$ = spacing tolerance

Interferometer: Optical Testing Tool

- An interferometer compares a wavefront reflected off a test component with that reflected from a well-known and perfect (to required tolerances) reference component (usually a flat mirror);
- The wavefronts are derived from a single input wavefront via a beamsplitter;
- The two wavefronts interfere; any errors in the test piece create optical path differences (relative to the test component) that show up as interference fringes in the interferometer output;
- Note: 1 fringe represents an optical path difference of 1 wavelength between the test and reference wavefronts;
- Typically, a laser is used as the light source. If the laser is single-mode (long coherence length), then the test and reference arms may be of significantly different lengths – Laser Unequal Path Interferometer (LUPI).



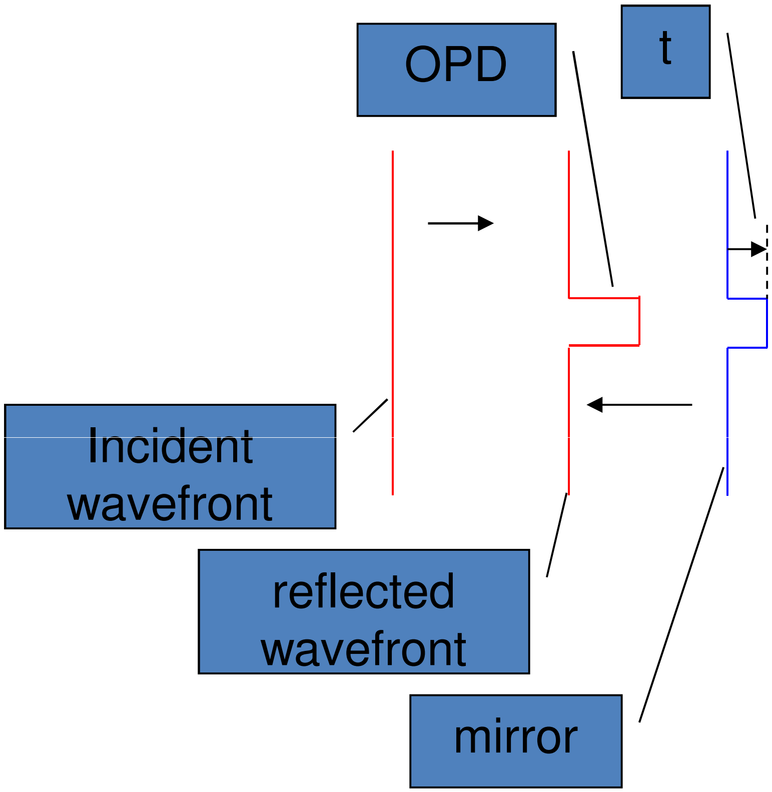
OPD for Surface Defects, *Refractive*



$$OPD = (n-1)\cdot t$$

- Surface defects cause wavefront errors and therefore a degradation of the image quality;
- At a glass (index n) to air interface, a bump in the surface causes a dip in the wavefront (light is faster in air):
- For typical optical glass (n=1.5), OPD = 0.5t
- However, for infrared materials (e.g. Ge, n=4), OPD = 3t !!
- Thus, surface quality specs must be tighter in the infrared than in the visible. But this is mitigated by the wavelength being longer!

OPD for Surface Defects, *Reflective*

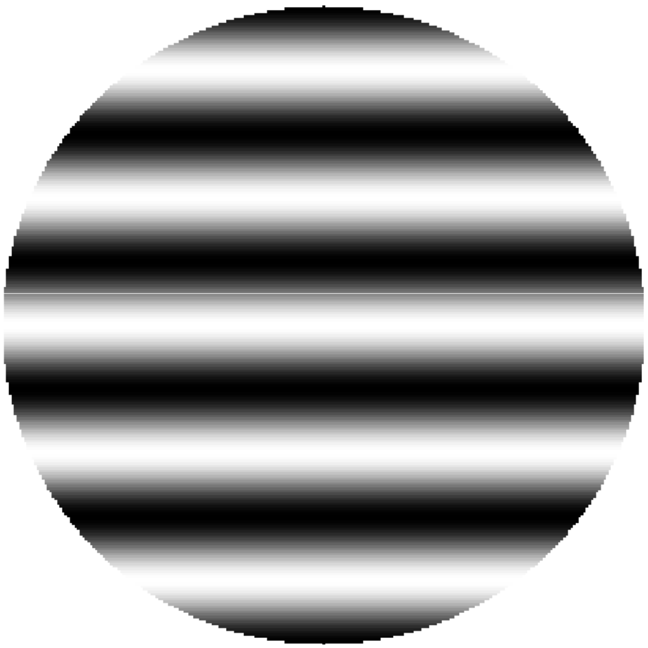


- The effective index of a mirror in air is -1;
- At a mirror surface, a dip in the surface causes a dip in the wavefront:
- Thus, OPD = -2t !!
- Thus, surface quality specs must be fairly tight for mirrors; comparison with infrared materials depends on the material.

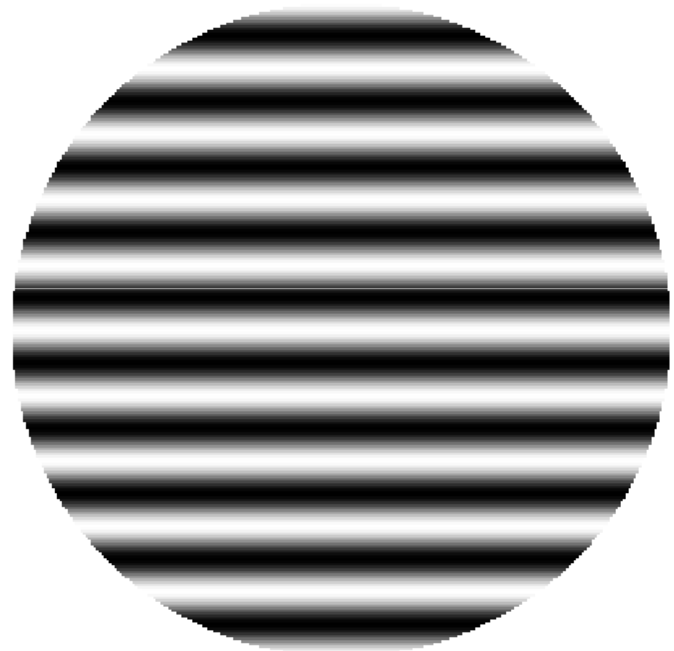
$$OPD = (n-1)\cdot t$$

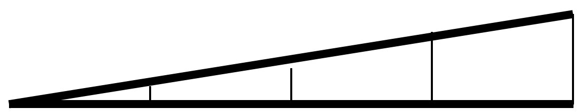
$A_{011} = ?\lambda$

5λ

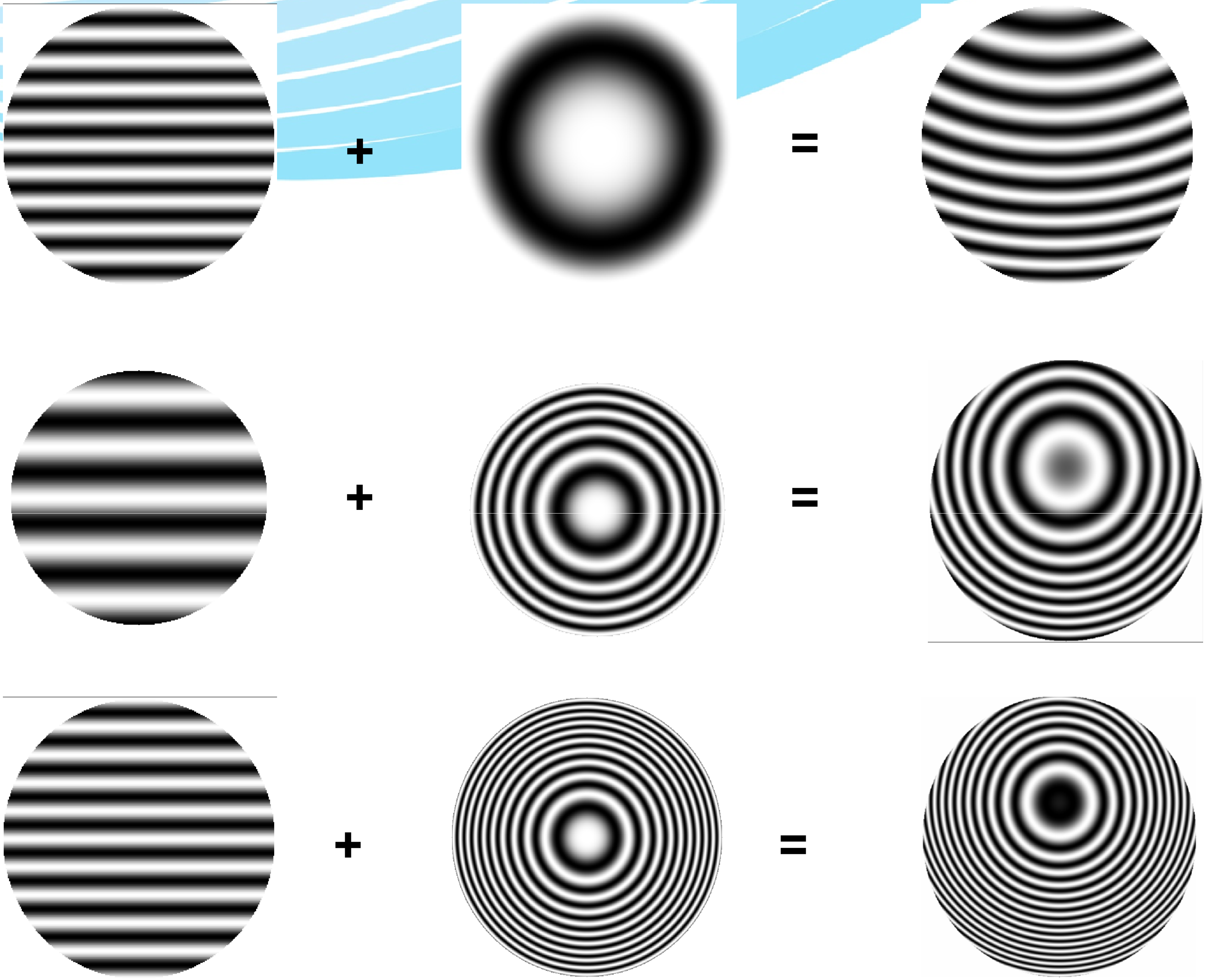


10λ





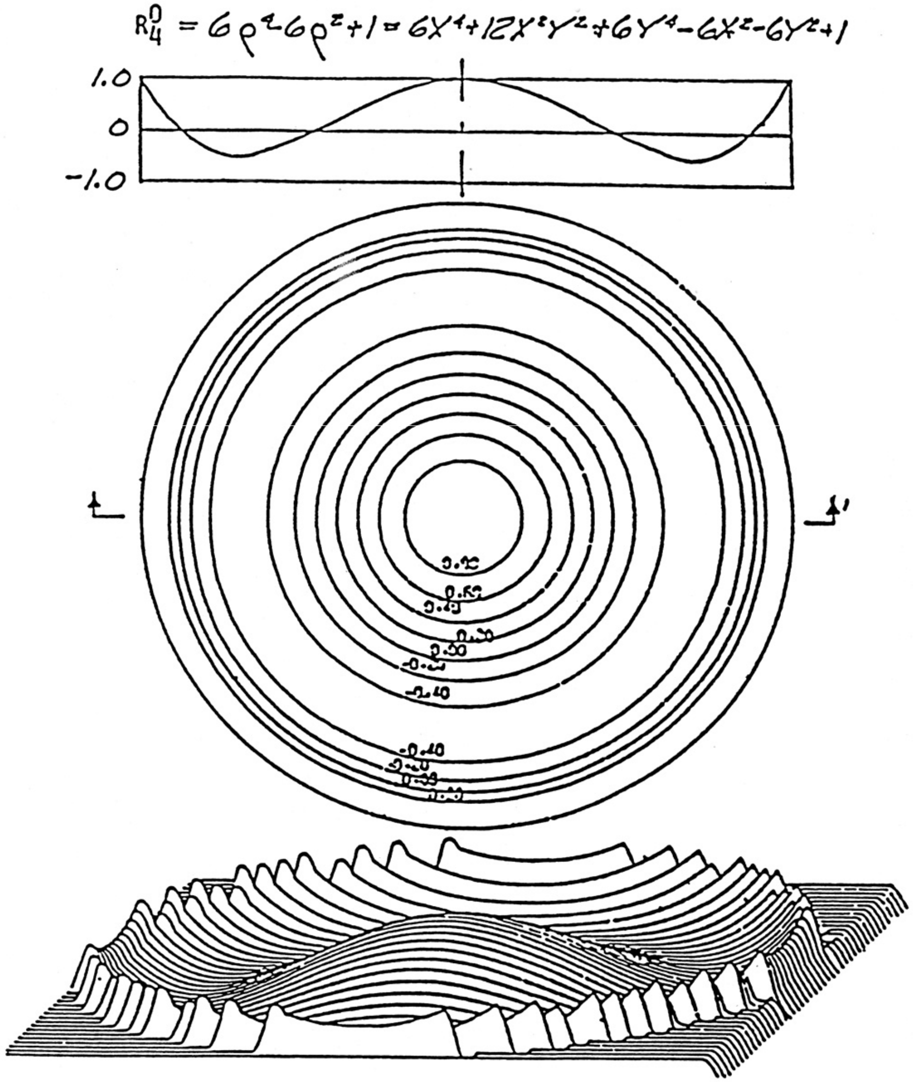
Tilt between the two plane wavefronts



Spherical Aberration

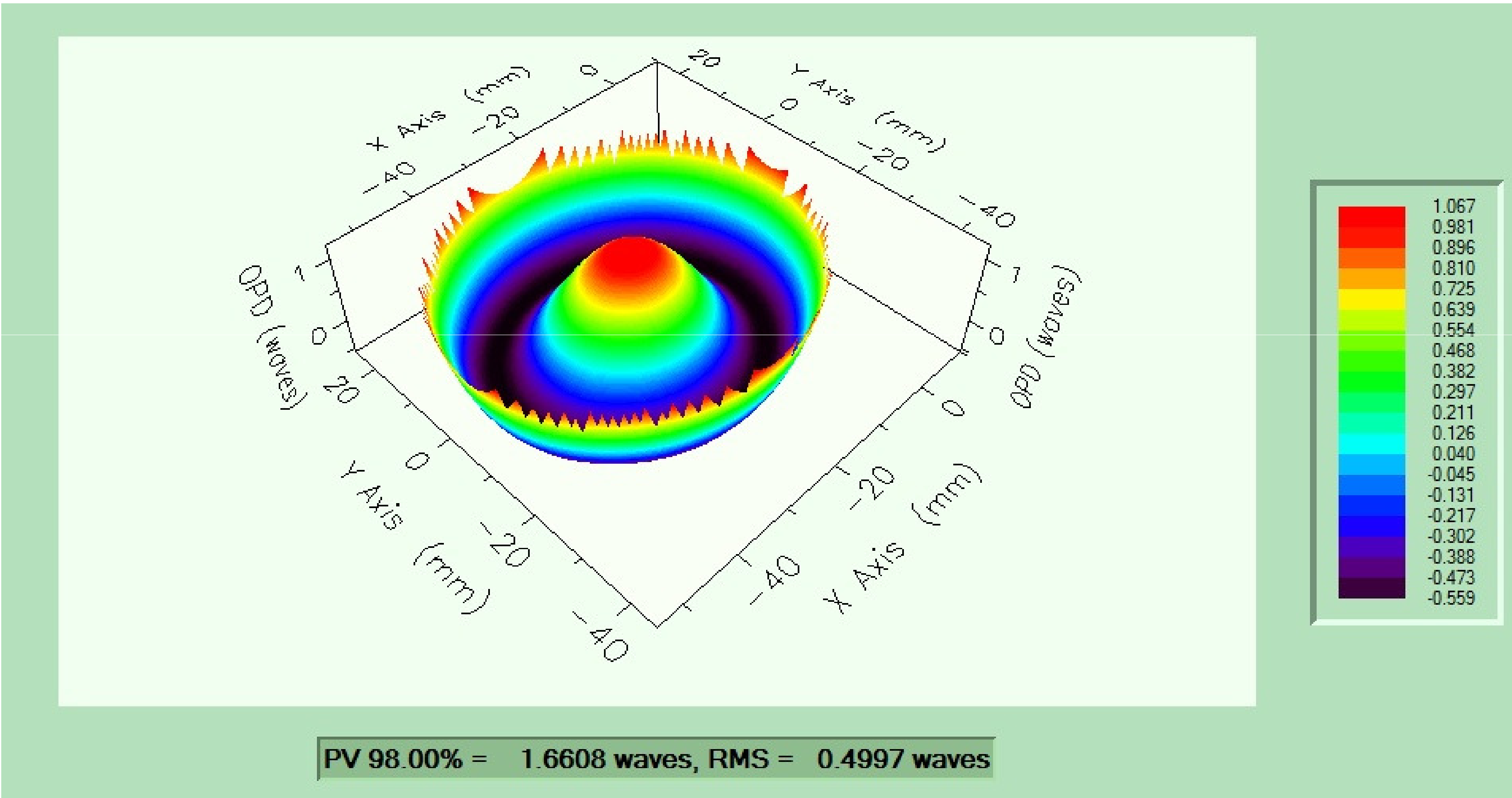
- Granddaddy of all aberrations
- Mathematically:
  - **$W = W_{040} = a_{040}\rho 4$**
- Interferometrically:
  - Concentric rings (similar to defocus). However the number increases as ρ^4
  - Can be minimized by adding defocus
- Star Test – Very Interesting
  - Rays from different annuli or "zones" have different focal points
  - Has very characteristic "thru focus" pattern
  - Unlike defocus, "black dot" is not visible, even for small amounts of spherical aberration

Spherical Aberration (Best Focus)

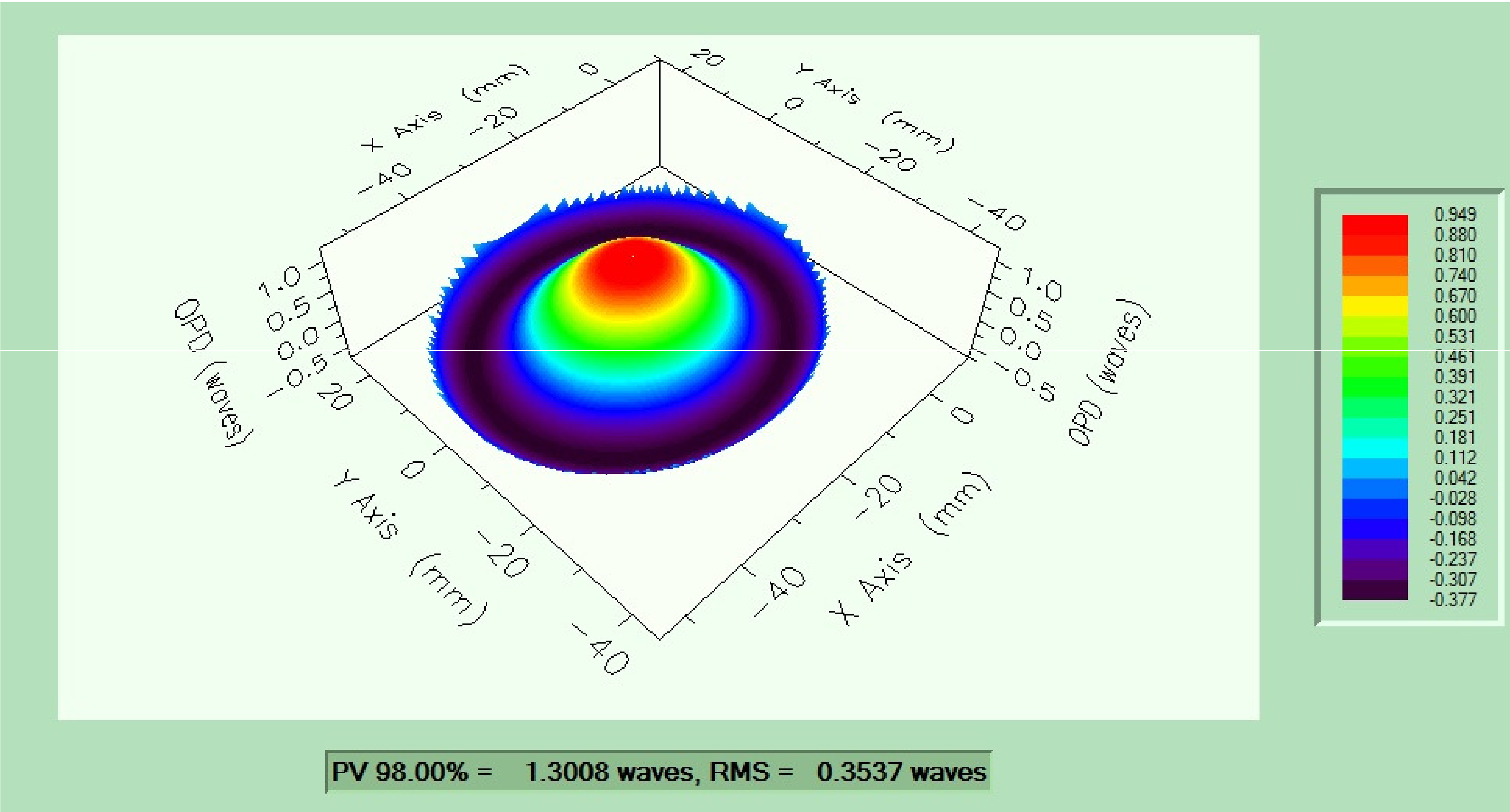


Zernike polynomial R^0_4

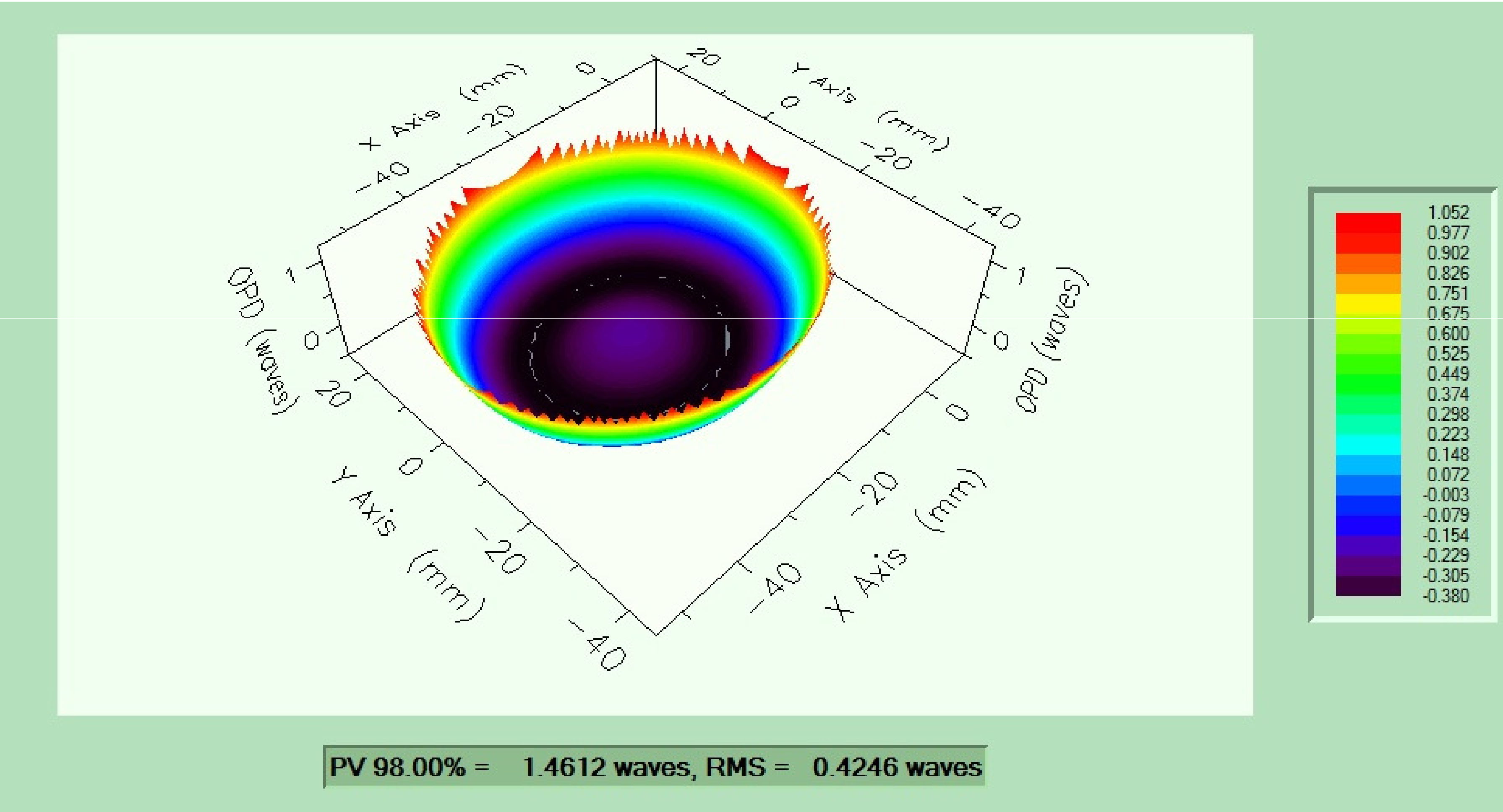
Spherical Aberration (Best Focus)

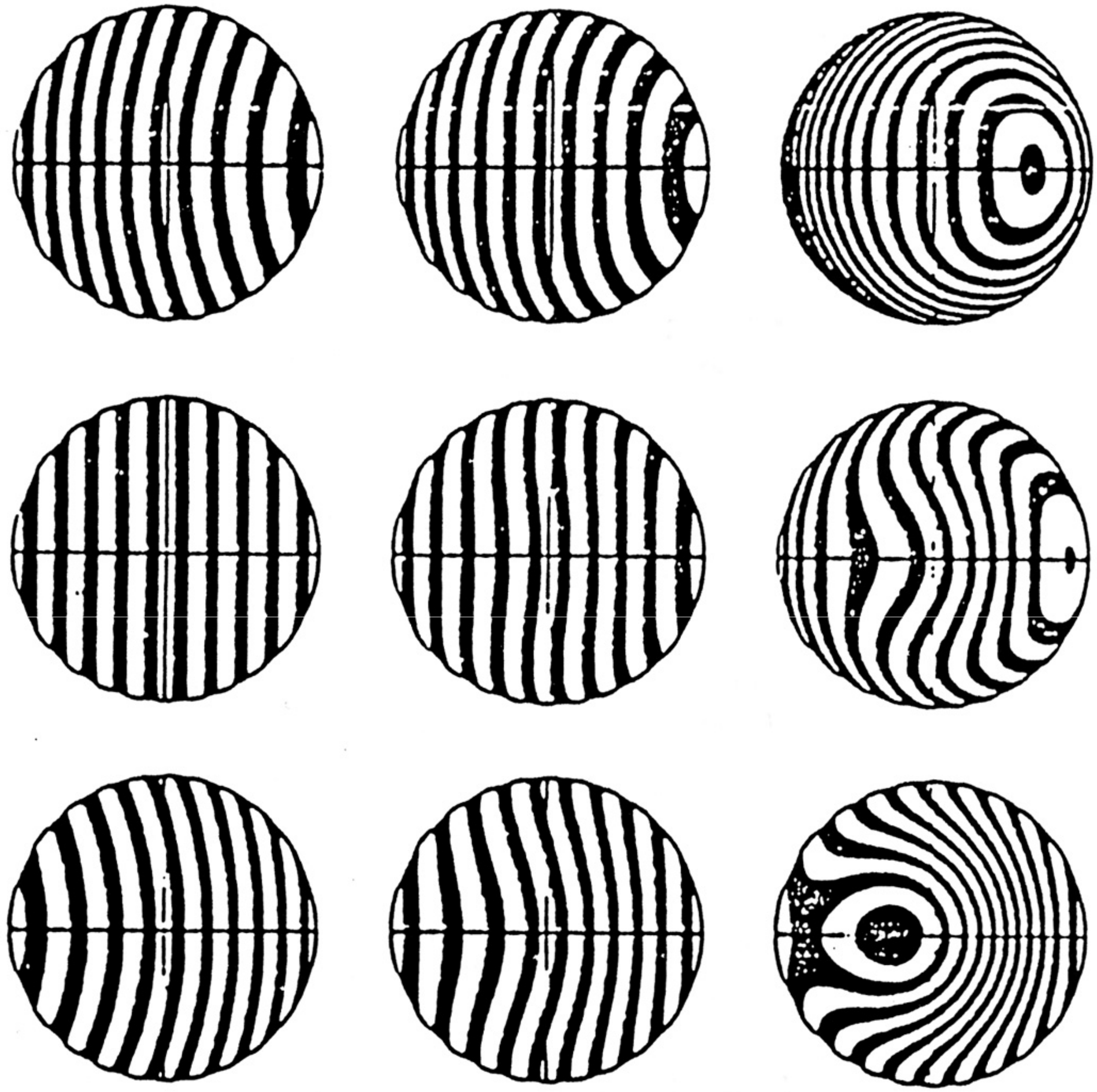


Spherical Aberration (Marginal Focus)



Spherical Aberration (Paraxial Focus)





Paraxial Focus

Mid Focus

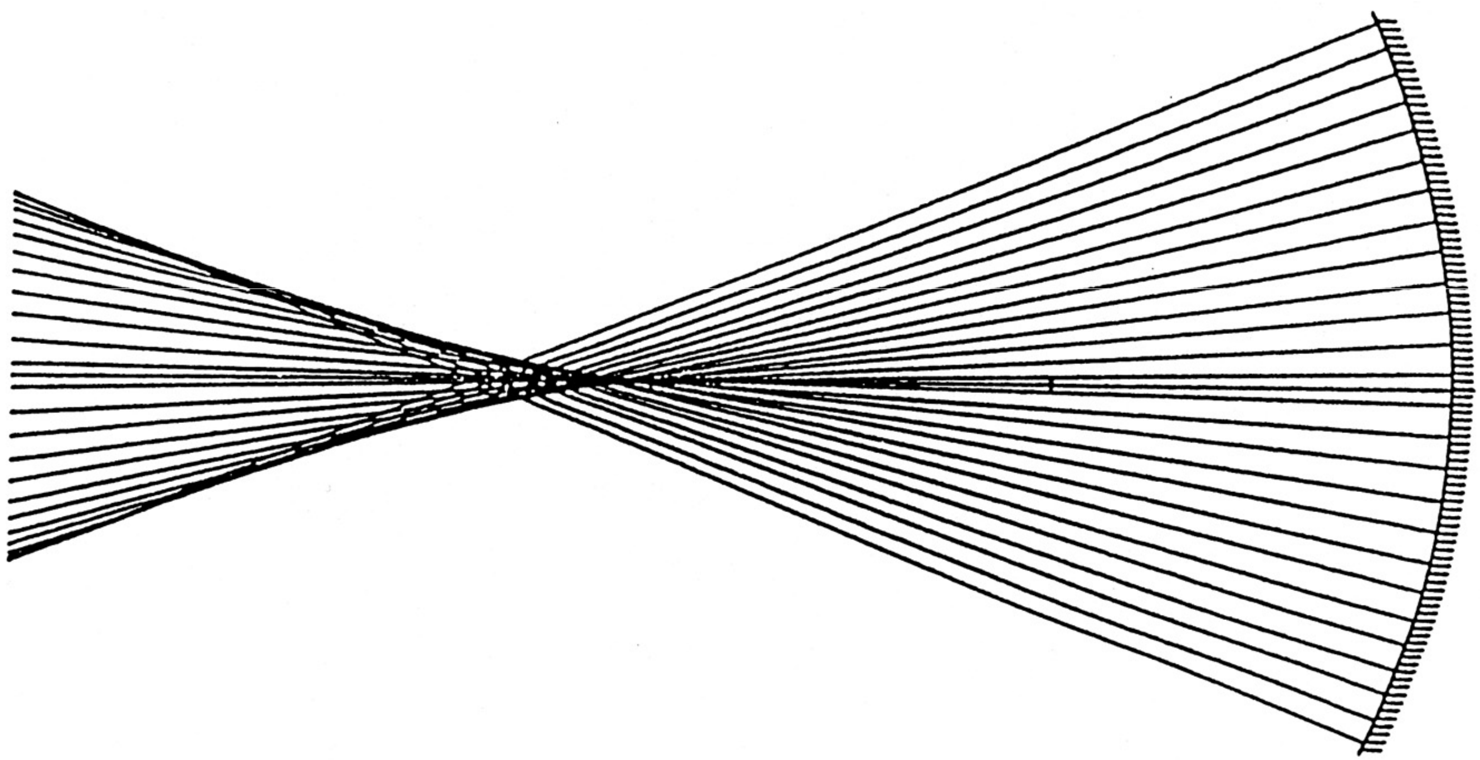
Marginal Focus

No Aberration, Focal Shift

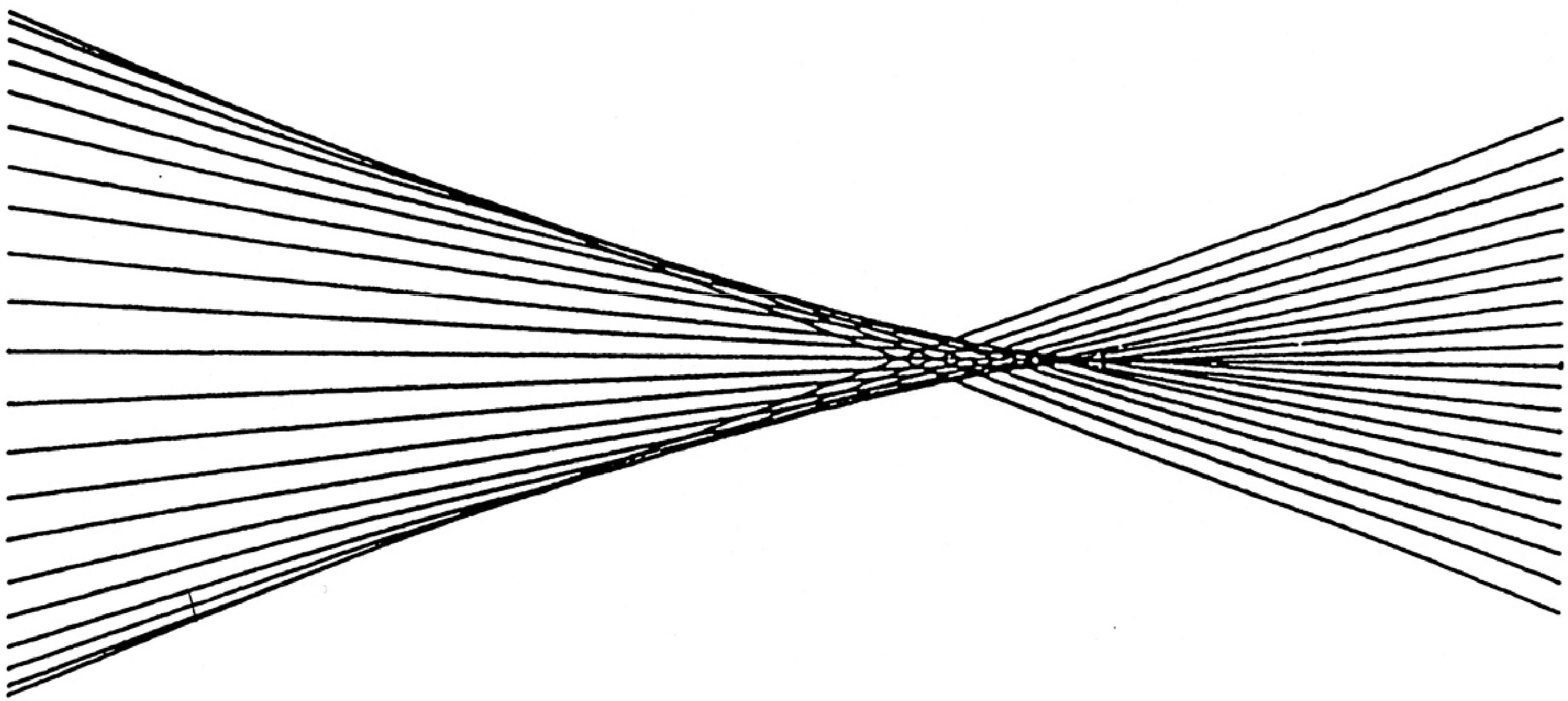
Small Spherical Aberration

Larger Spherical Aberration

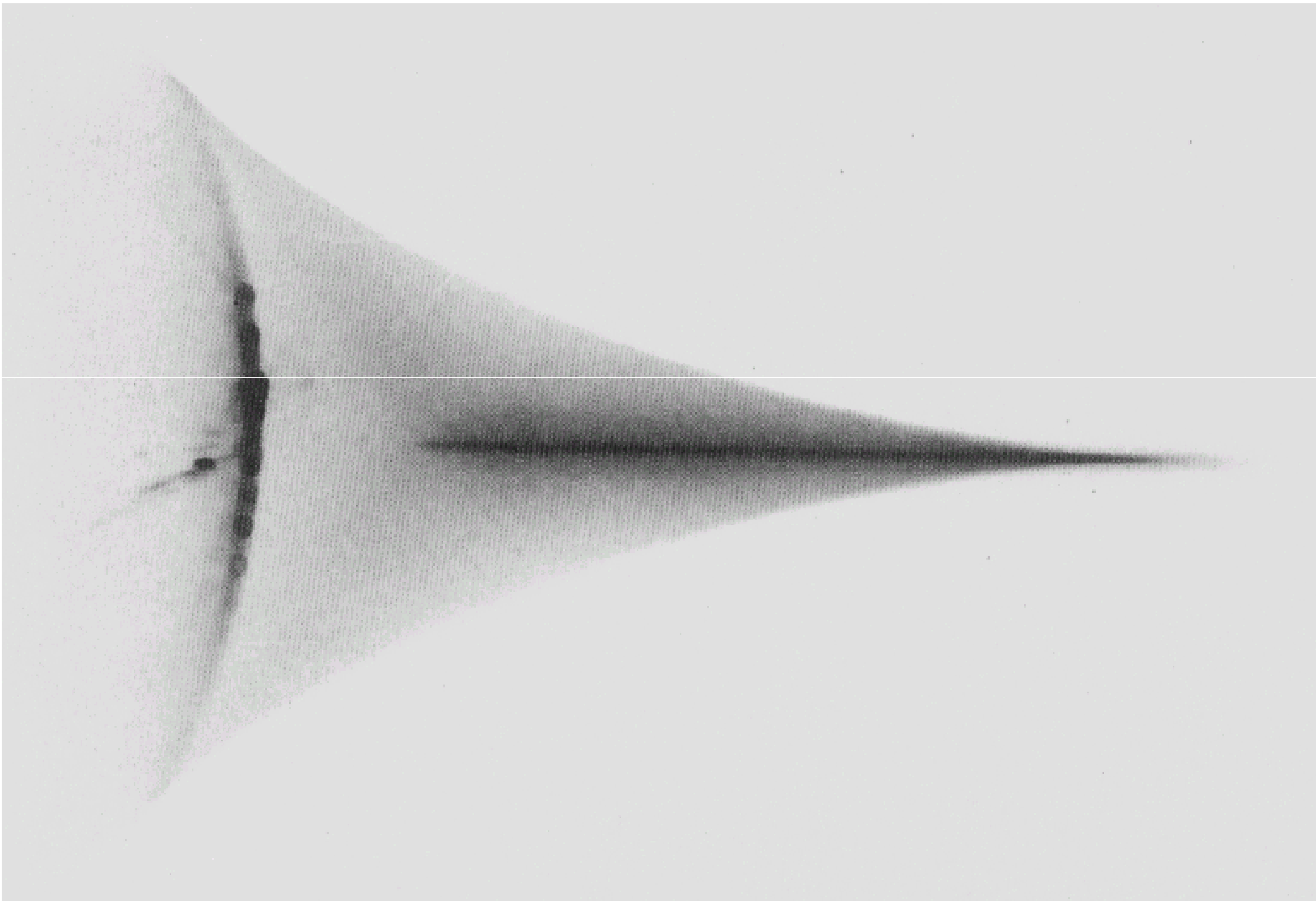
A Parabolic Mirror
and its
Caustic Surface (Due to Spherical Aberration)



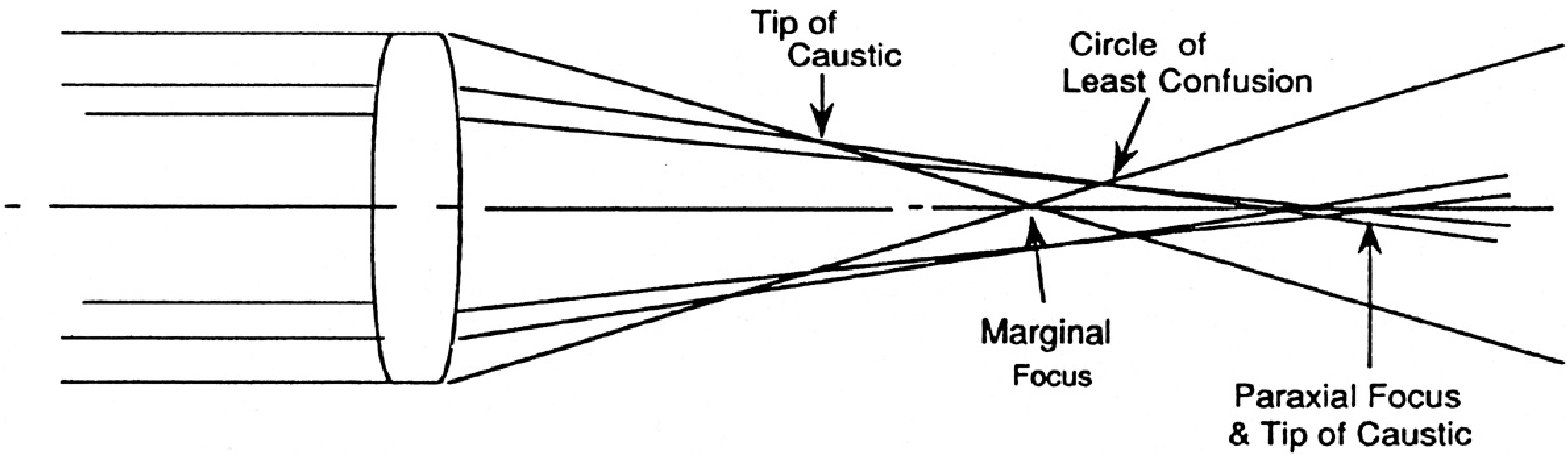
Details of the Spherical Aberration Caustic



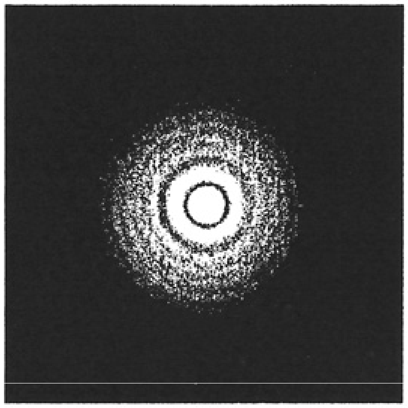
The inner & outer caustic

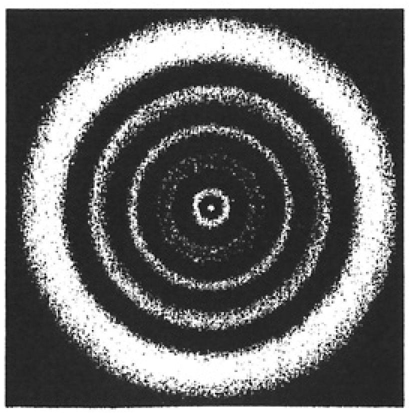


Spherical Aberration



Spherical Aberration Blur (Star Test)



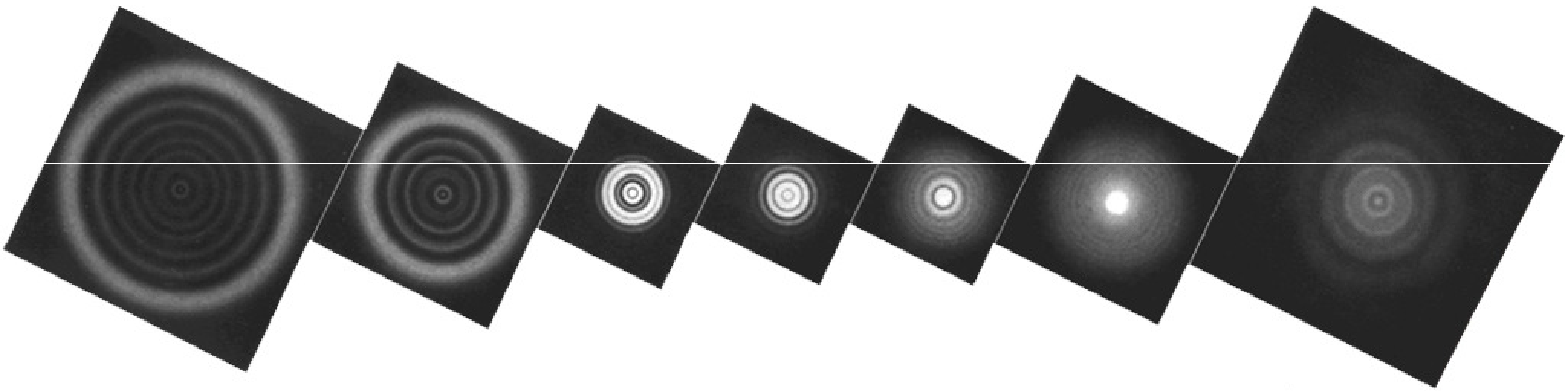


- At paraxial focus, a pronounced halo surrounds Airy disk

- At marginal focus, little energy is in core but a bright annulus is visible

RUDA CARDINAL

Thru Focus Spherical Aberration (Star Test)



Causes of (Extraneous) Spherical Aberration

- How can spherical aberration indicate the presence of misalignments or other errors?
  - Lens is reversed
  - Spacing error between lenses
  - Optical surface radius incorrect
  - Wrong aspheric
    - Null test error (Think Hubble Space Telescope)
    - Aspheric coefficient sign flip
  - Pupil diameter error
  - Wrong glass material