Spherical Aberration

Lens Design OPTI 517

Prof. Jose Sasian

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Spherical aberration

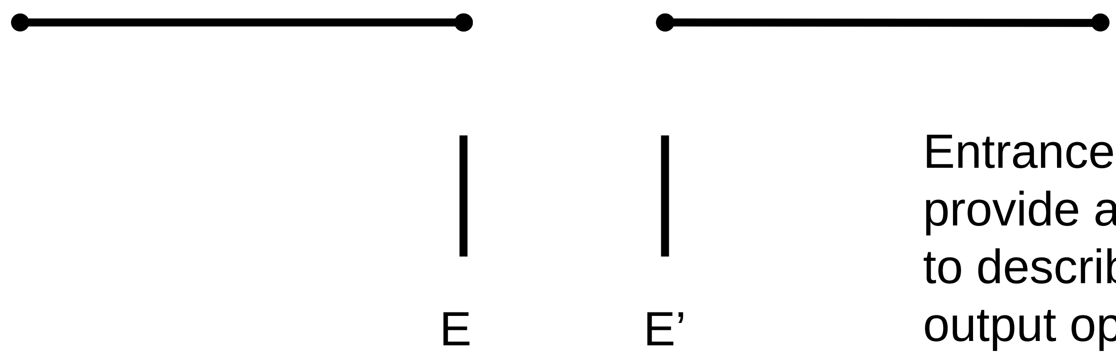
- 1) Wavefront shapes
- 2) Fourth and sixth order coefficients
- 3) Using an aspheric surface
- 3) Lens splitting
- 4) Lens bending
- 5) Index of refraction dependence
- 6) Critical air space
- 7) Field lens

8) Merte surface
9) Afocal doublet
10) Aspheric plate
11) Meniscus lens
12) Spaced doublet
13) Aplanatic points
14) Fourth-order dependence
16) Gaussian to flat top

Review of key conceptual figures

Conceptual models

First-order optics model provides a useful reference and provides graphical method to trace first-order rays



Entrance and exit pupils provide a useful reference to describe the input and output optical fields

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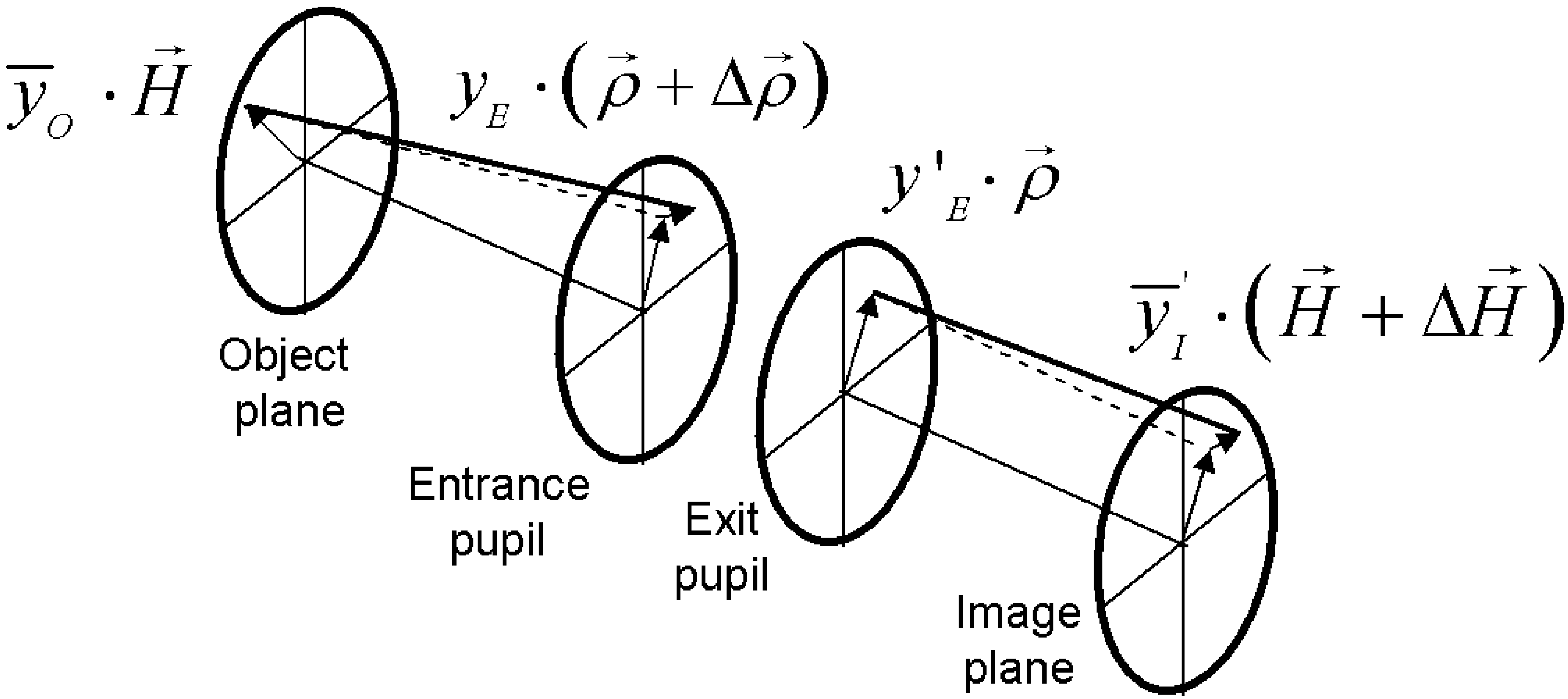
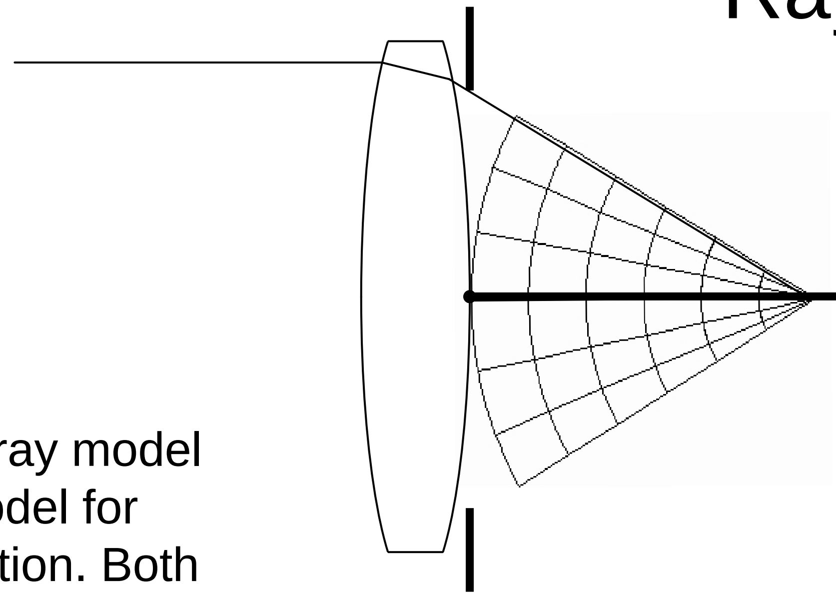
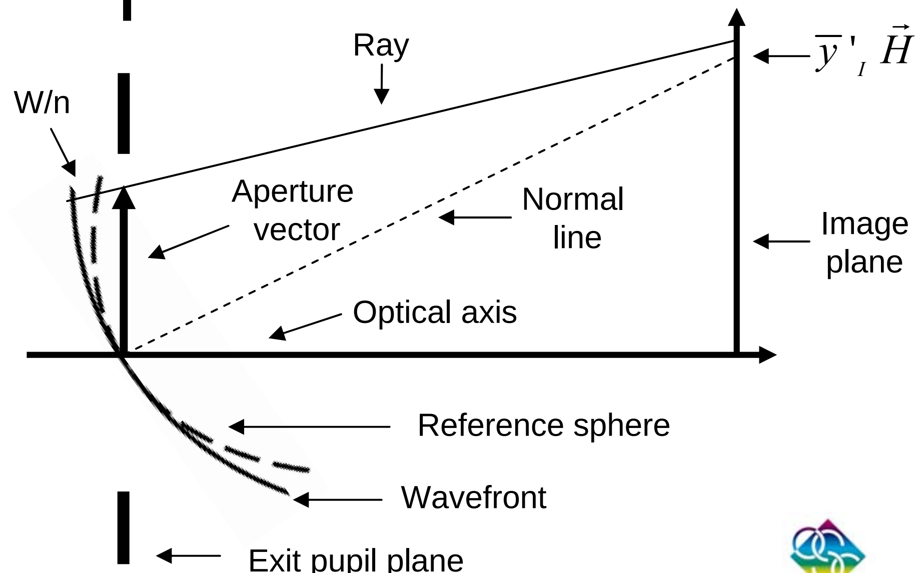
Object, image and pupil planes



Rays and waves geometry



Geometrical ray model and wave model for light propagation. Both Are consistent and are different representations of the same phenomena.



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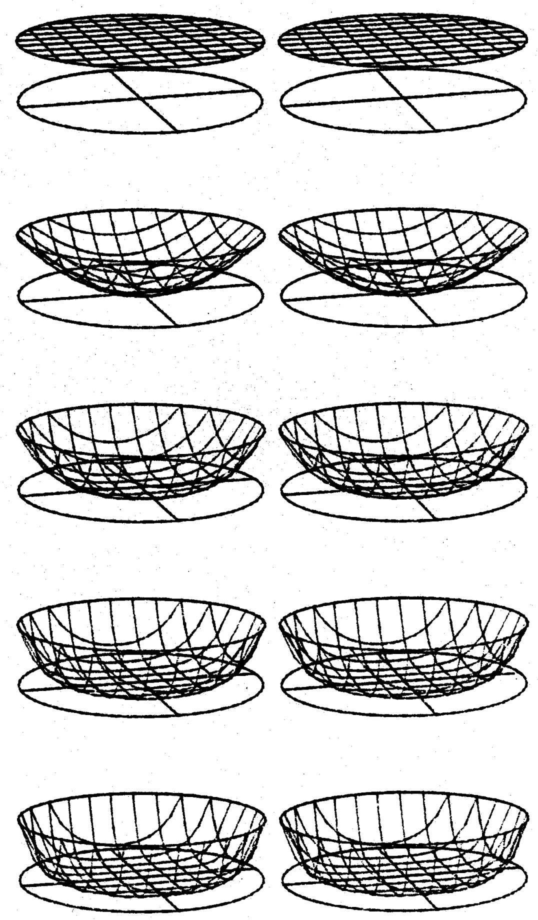
Spherical aberration



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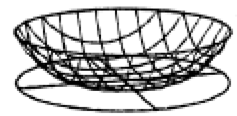
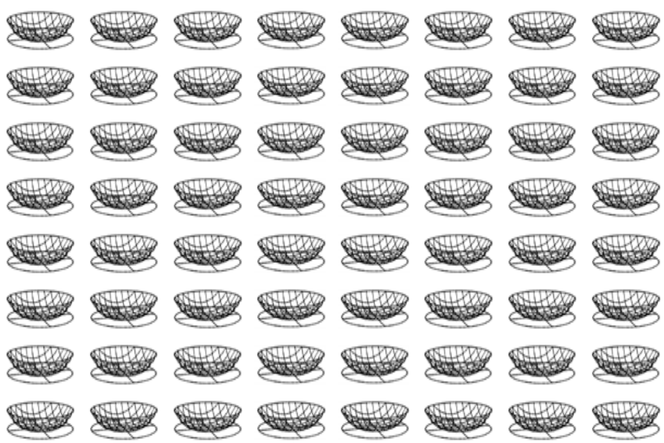
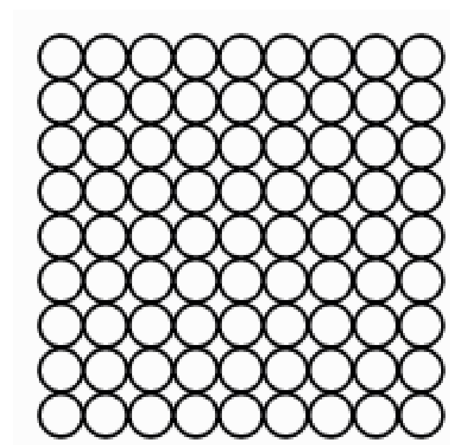
Spherical aberration is uniform over the field of view

$$W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)^{2}$$





Wavefront



Spots

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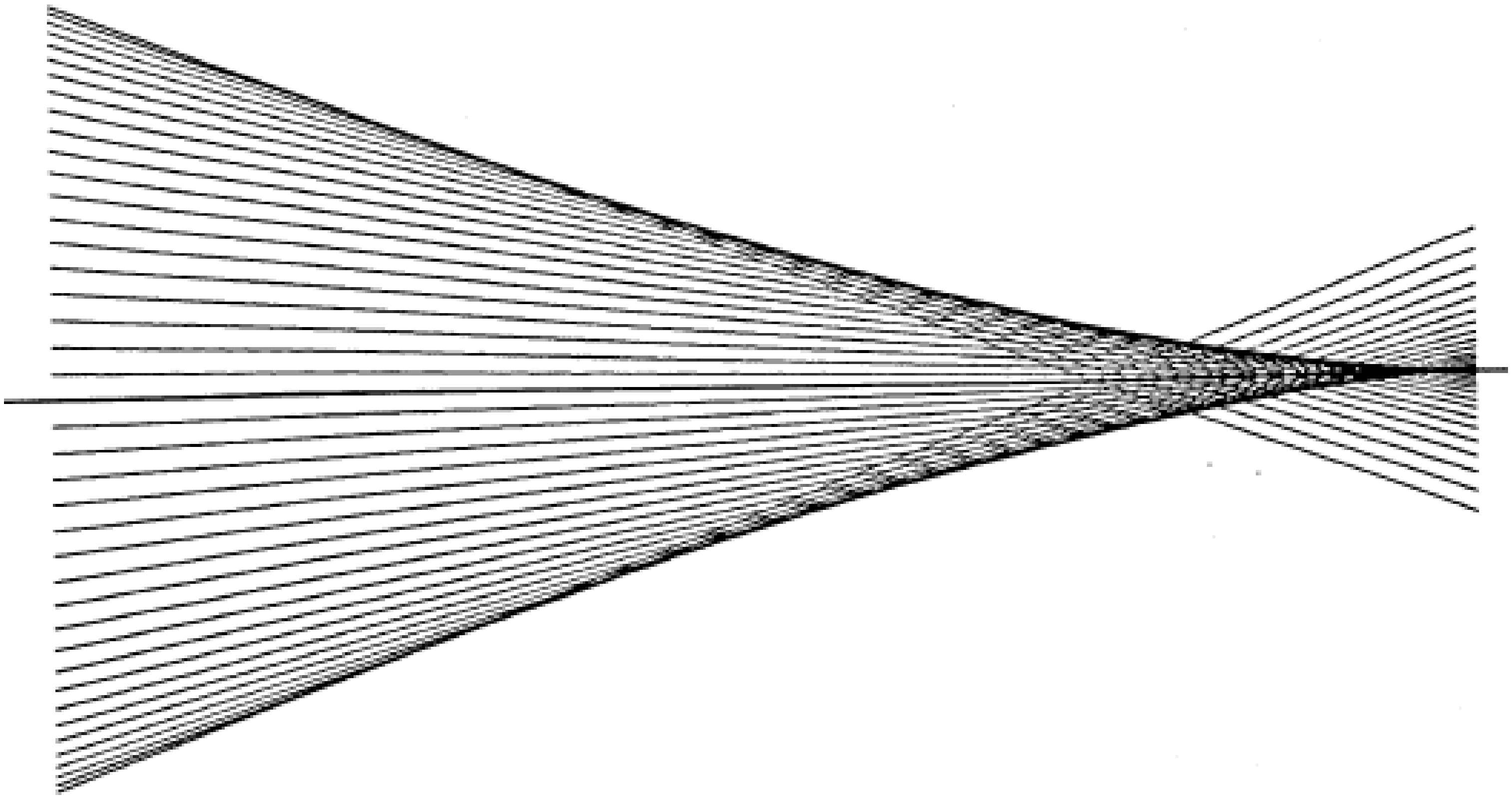
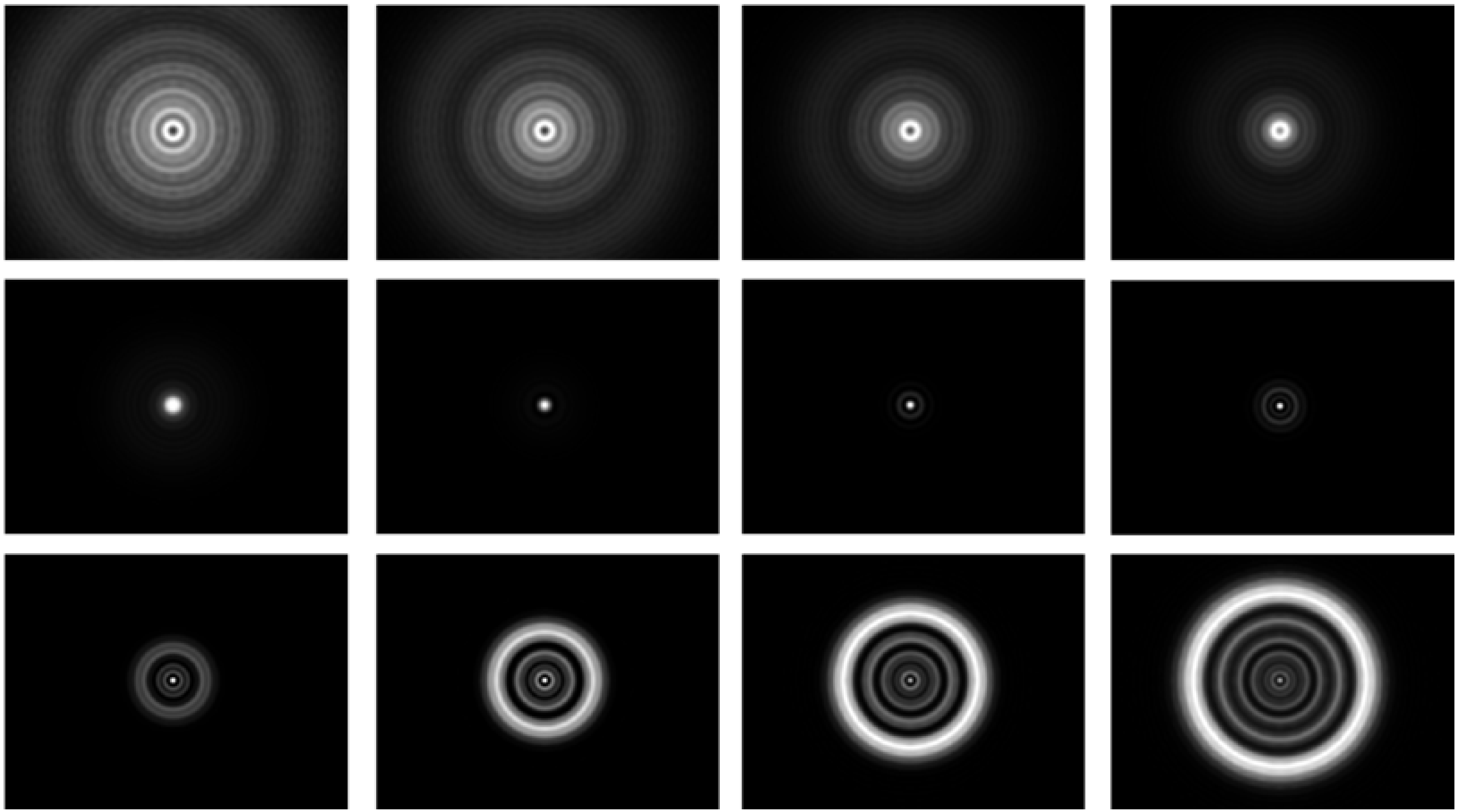
Ray caustic



Two waves of spherical aberration through focus. From positive four waves to negative seven waves, at one wave steps of defocus. The first image in the middle row is at the Gaussian image plane.



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Cases of zero spherical aberration from a spherical surface

$$W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)^2 \qquad W_{040}=\frac{1}{8}S_I \qquad S_I=-\sum A^2 y\Delta\left(\frac{u}{n}\right)$$

$$y=0$$

$$A=0$$

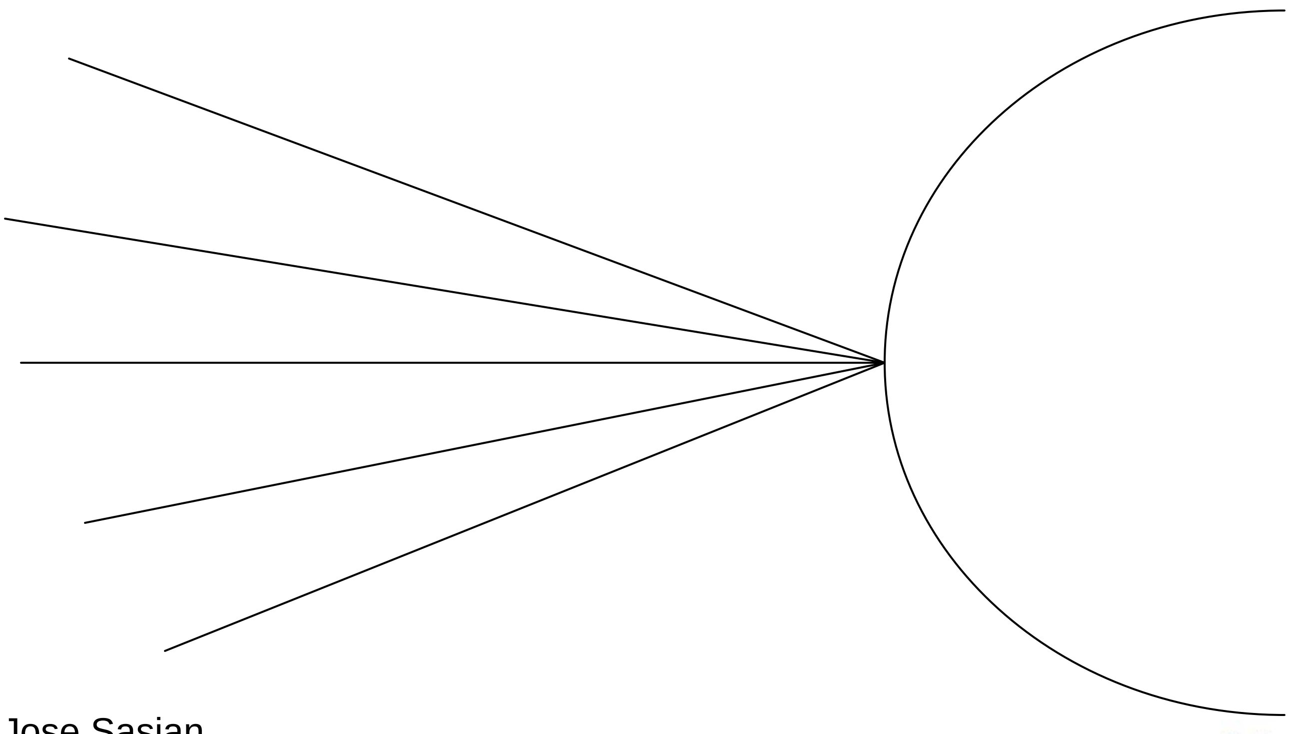
$$\Delta\left(u/n\right)=u'/n'-u/n=0$$

y=0 the aperture is zero or the surface is at an image
A=0 the surface is concentric with the Gaussian image point on axis
u'/n'-u/n=0 the conjugates are at the aplanatic points

Aplanatic means free from error;
freedom from spherical aberration and coma

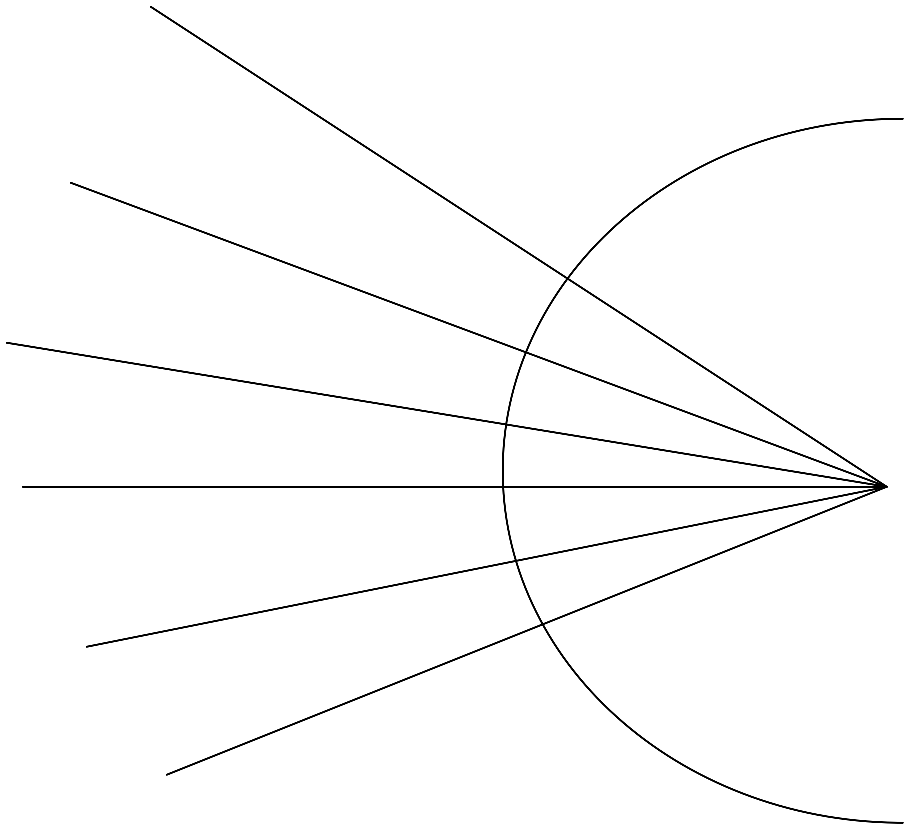
Surface at image

$$y = 0$$



Concentric surface

$$A = 0$$



Aplanatic points of a spherical surface

$$-\frac{1}{n's'}+\frac{1}{ns}=0$$

$$\frac{n'}{s'}-\frac{n}{s}=\frac{n'-n}{r}$$

$$S=r\frac{n'+n}{n}$$

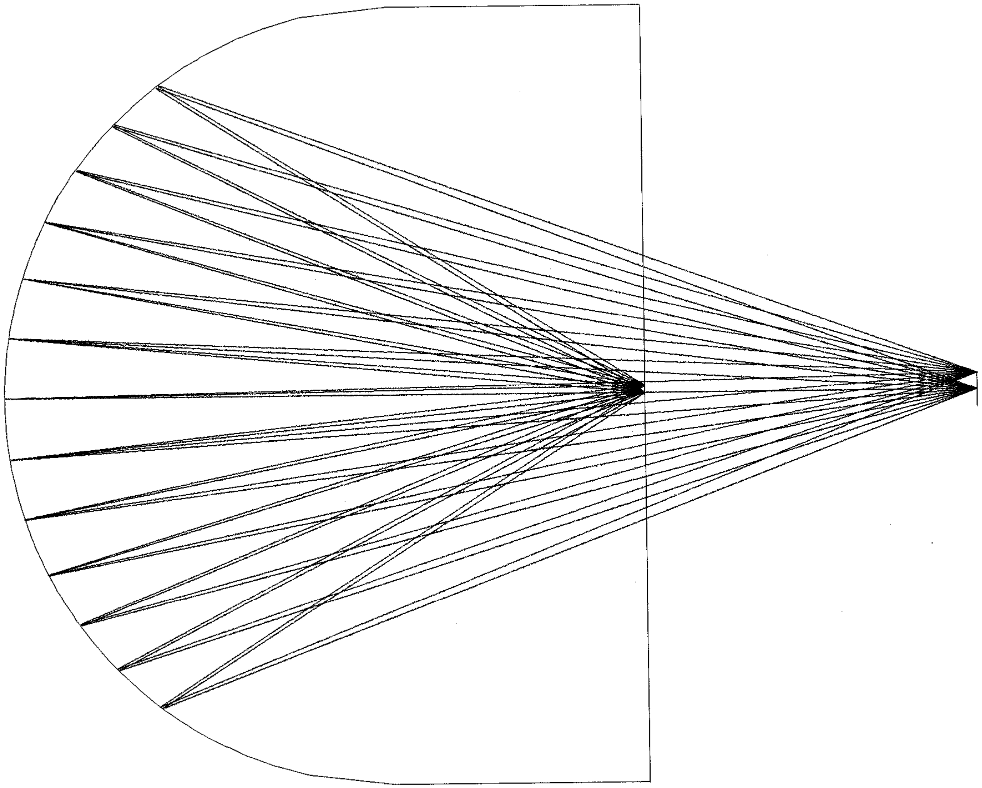
$$S'=r\frac{n'+n}{n'}$$

$$S=2.5r$$

$$S'=(5/3)r$$

$$n=1.5$$

$$\Delta(u/n)=u'/n'-u/n=0$$



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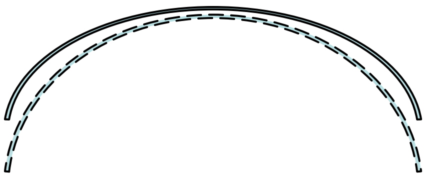
Controlling spherical aberration with an aspheric surface

$$Z(S) = \frac{cS^2}{1+\sqrt{\left[1-(K+1)c^2S^2\right]}} + A_4S^4 + A_6S^6 + A_8S^8 + A_{10}S^{10} + \ldots$$

$$S^2 = x^2 + y^2$$

$$K = -\varepsilon^2$$



K is the conic constant
K=0, sphere
K=-1, parabola
K<-1, hyperbola
-1<K<0, prolate ellipsoid
K>0, oblate ellipsoid or spheroid

C is 1/r where r is the radius of curvature; K is the conic constant; A's are aspheric coefficients

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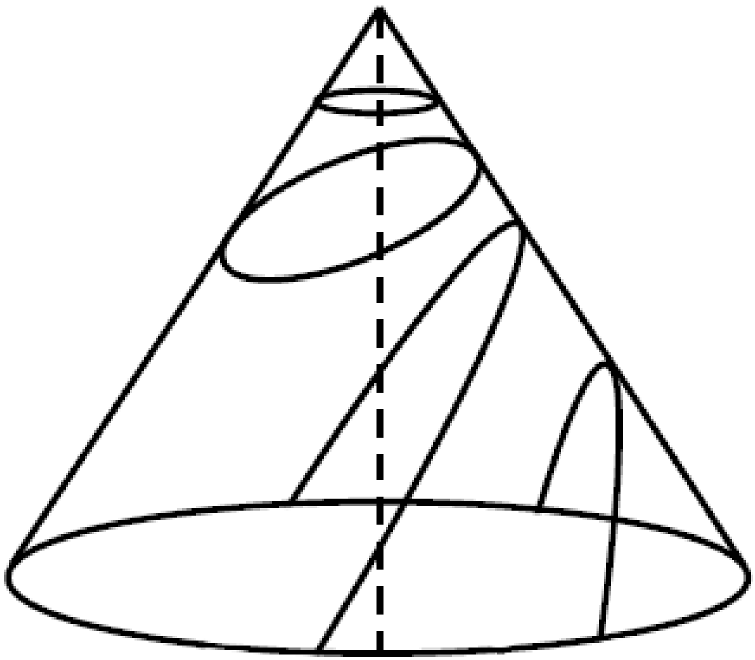
Conic sections

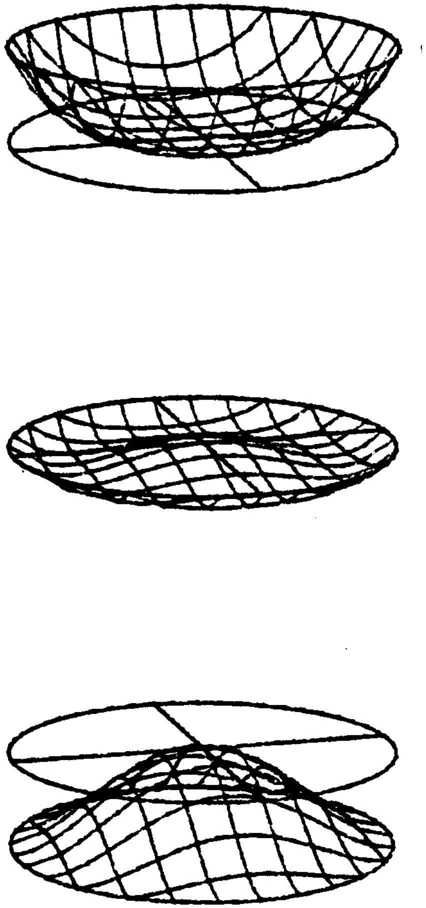


Circle
Ellipse
Parabola
Hyperbola

Some points

- Ideally by placing the aspheric surface at the stop or a pupil
- Truncate the number of significant digits to avoid operator's error
- Minimize the number of aspheric terms
- Fabricator is concerned about slope
- Should provide test configuration (null)

Spherical aberration and focus



- Minimum variance
- Zernike coefficient

- Strehl ratio

- Aperture dependence

- Depth of focus

Structural coefficient

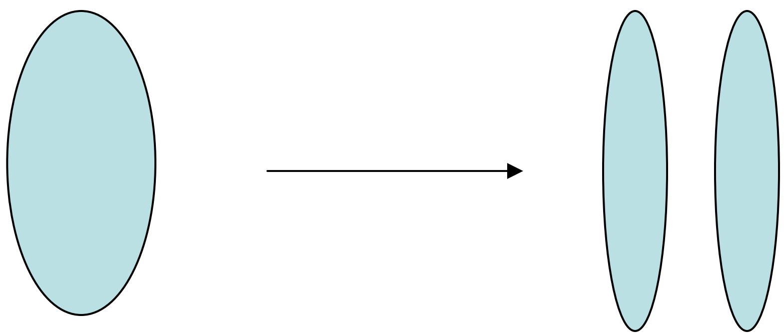
$$S_I = \frac{1}{4} y_p{}^4 \phi^3 \sigma_I$$

$$S_I = \frac{1}{4} y_p^4 \varphi^3 \left[AX^2 - BXY + CY^2 + D \right]$$

- Depends on the fourth power of the aperture!
- Depends on the cube of the optical power
- Is quadratic as a function of the shape factor
- Stop at thin lens

Lens Splitting

$$S_I = \frac{1}{4} y_p{}^4 \phi^3 \sigma_I$$

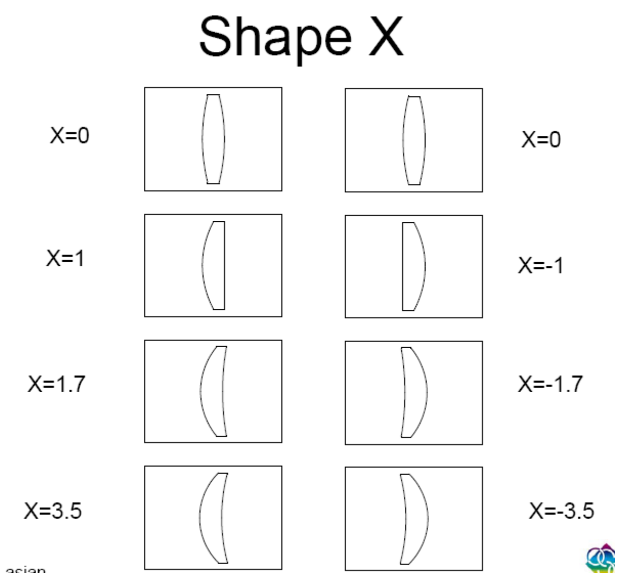


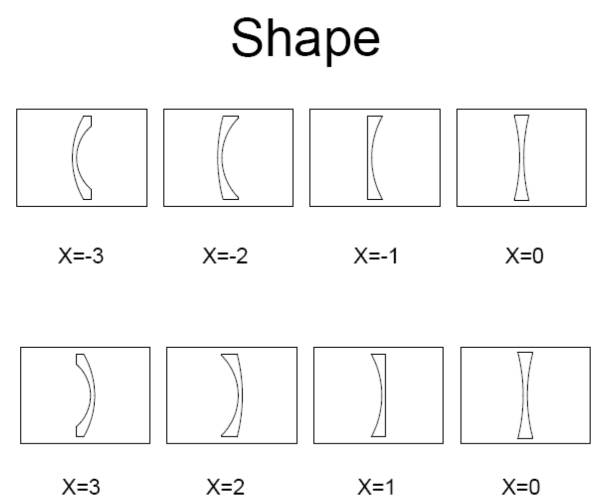
Same optical power but about ¼ (~1/3) the amount of fourth-order spherical aberration

Spherical aberration dependence on lens bending

$$S_I = \frac{1}{4} y_p^4 \varphi^3 \left[AX^2 - BXY + CY^2 + D \right]$$

$$Y = \frac{\omega' + \omega}{\omega' - \omega} = \frac{1+m}{1-m} \qquad X = \frac{c_1 + c_2}{c_1 - c_2} = -\frac{R_1 + R_2}{R_1 - R_2}$$





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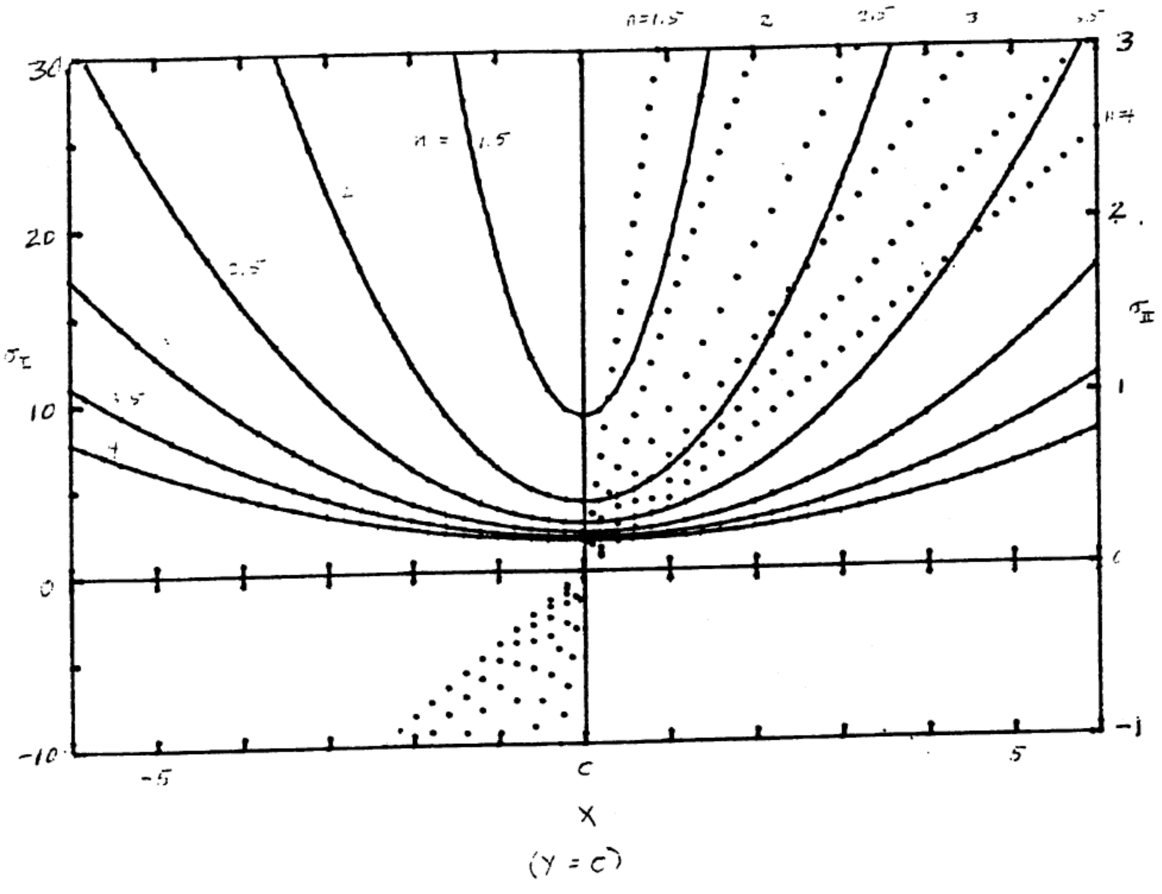
Spherical and coma

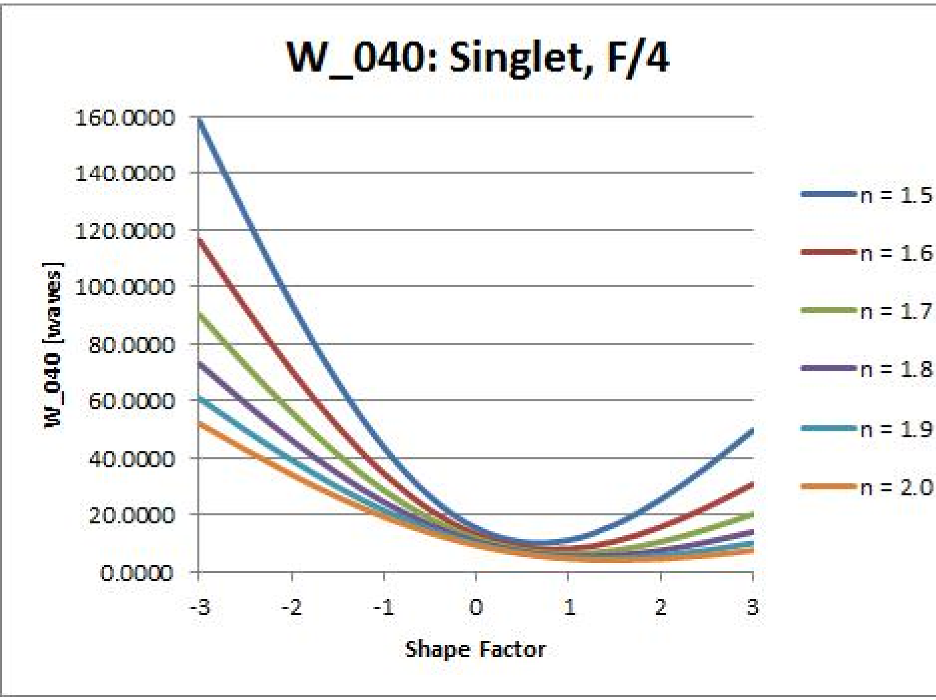
σ_I

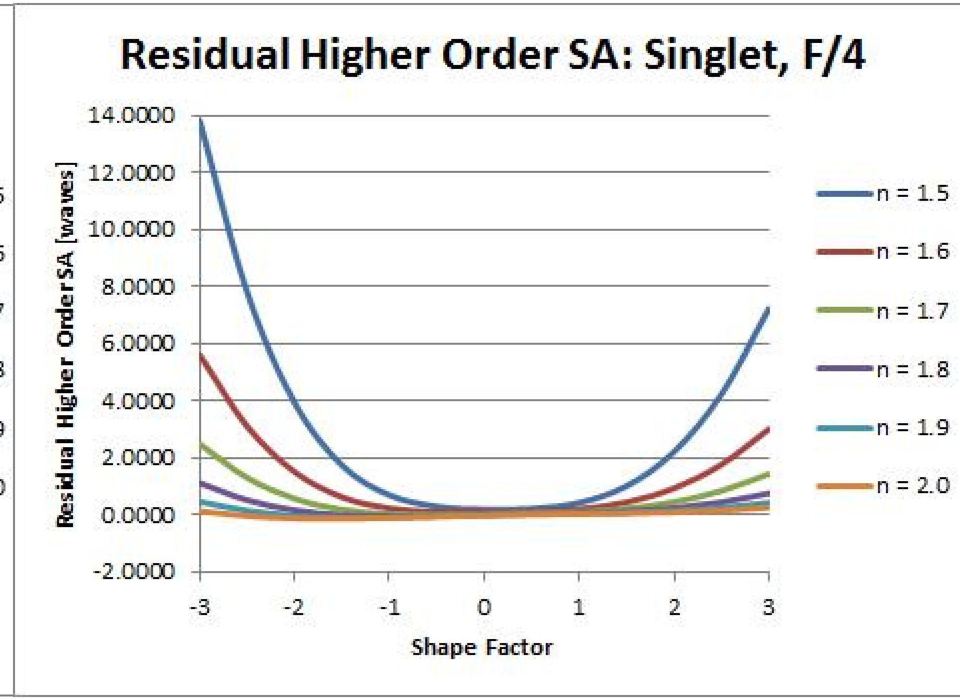


σ_{II}

From Roland Shack’s notes

Spherical aberration of a F/4 lens





- Asymmetry due to thick lens
- For high index high order is small and 4th order is a very good estimate

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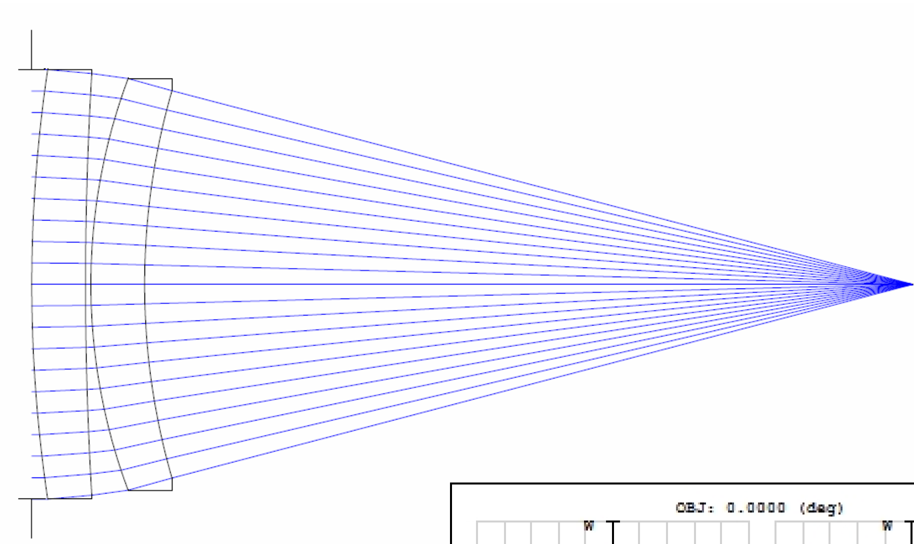
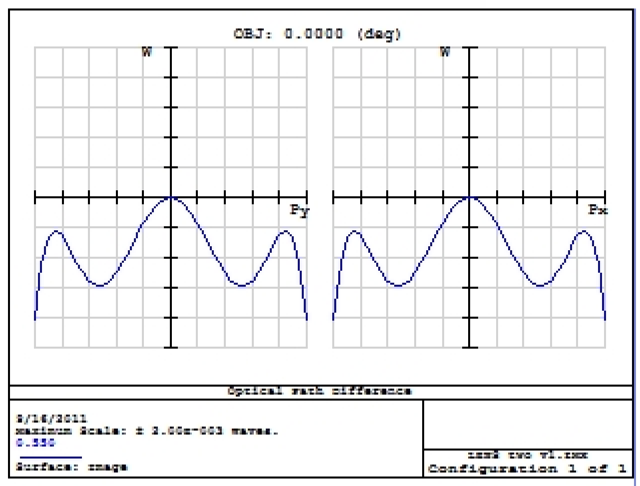
Spherical aberration vs. index



2e-3 waves n=2.51

Positive lenses



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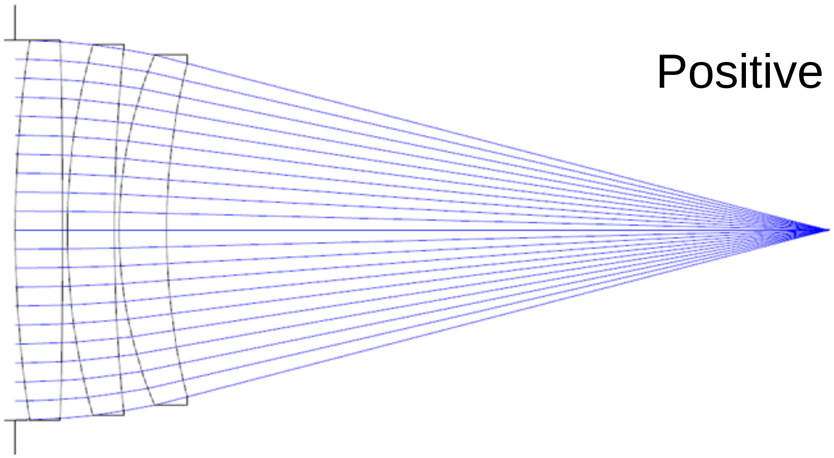
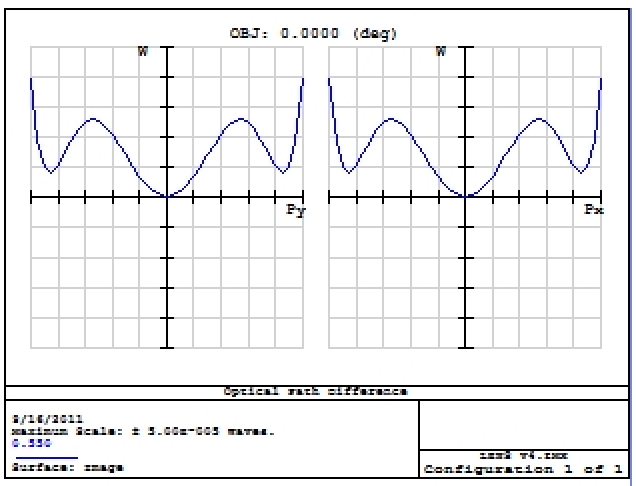
Spherical aberration vs. index



Positive lenses

5e-5 waves n=1.86

Surfaces 1,3,5 have angle solve at -0.05, -0.15, and -0.25



Spherical aberration: some fascinating observations
Fischer, R. E.; Mason, K. L.

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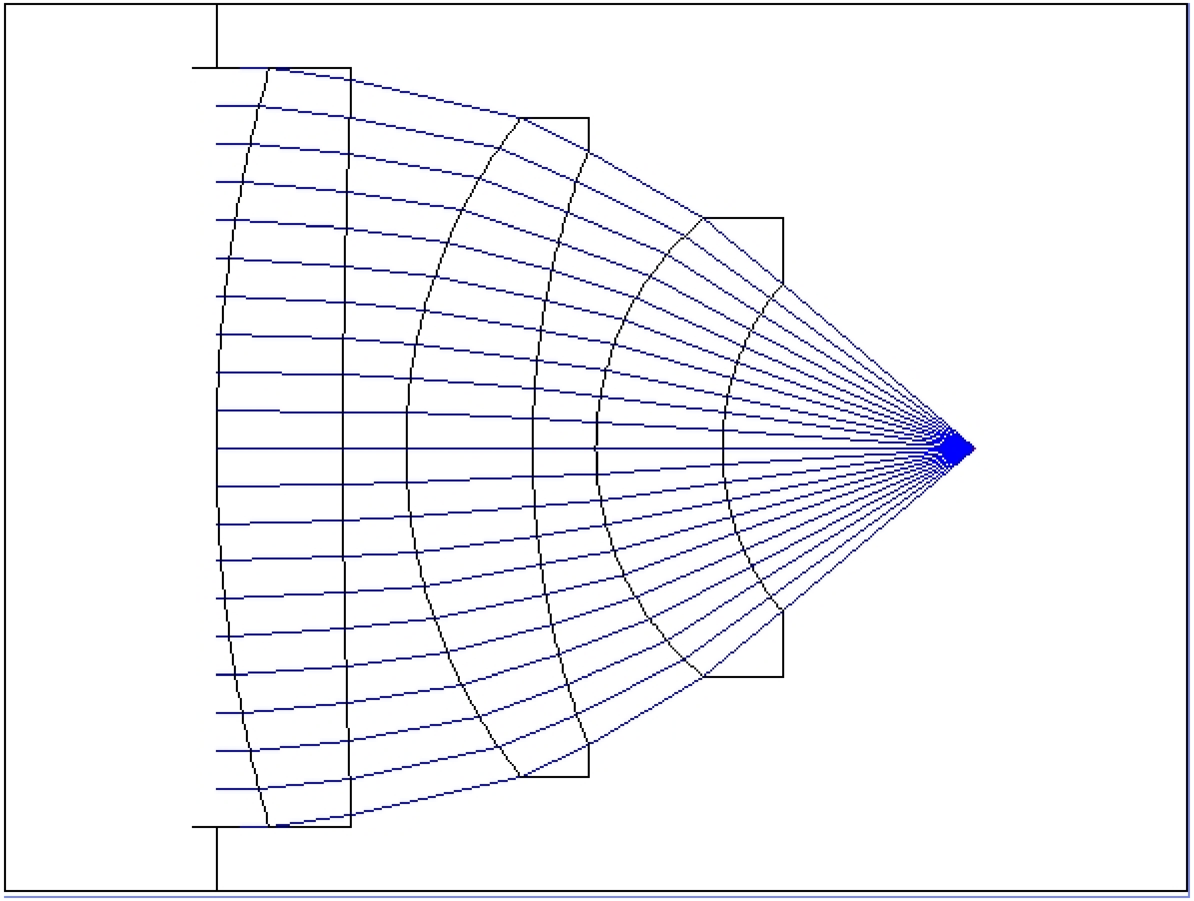
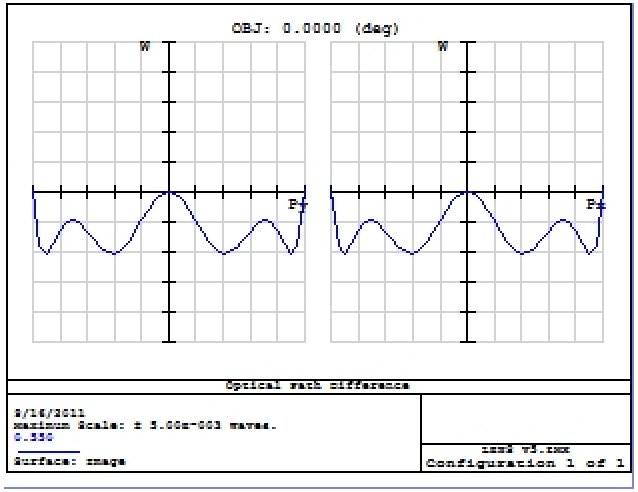
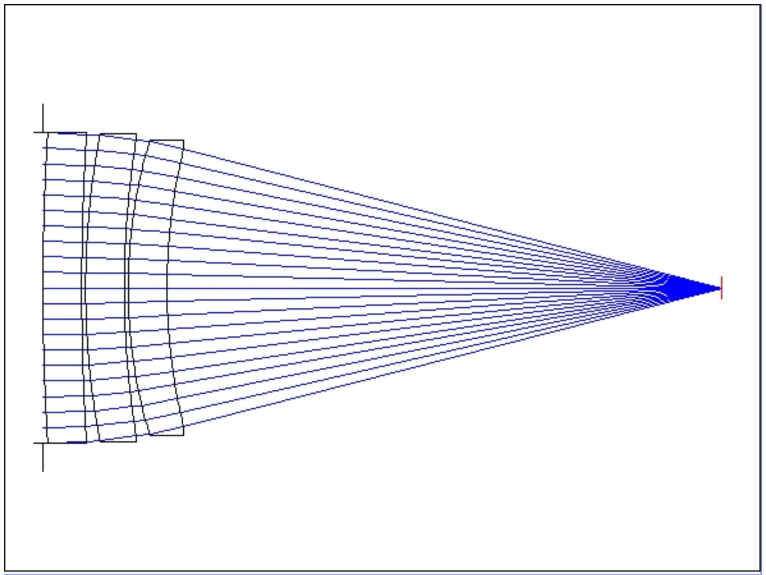
Last surface concentric

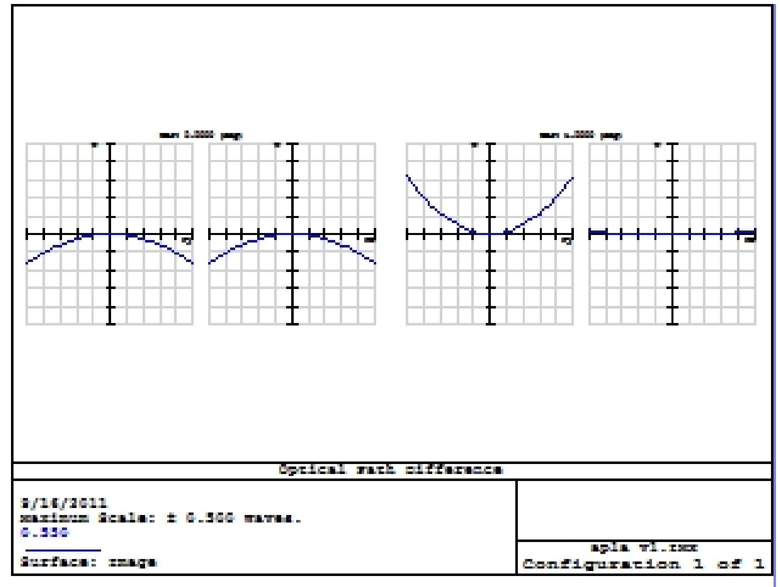


5e-3 waves n=1.97



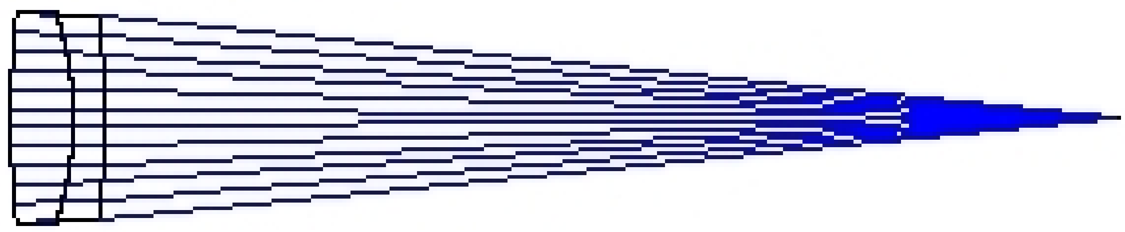
Aplanatic @ f/2

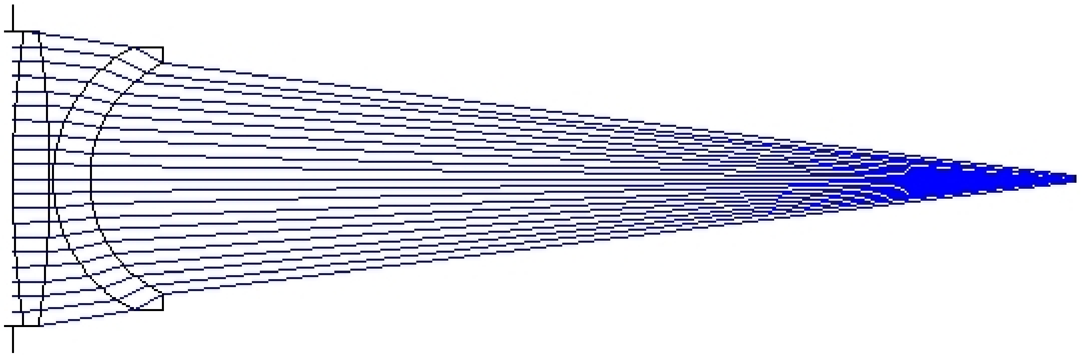


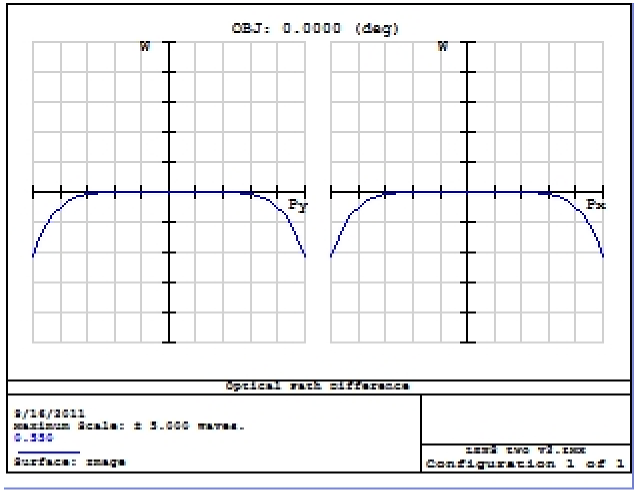


See also R. Kingslake on Fulcher aplanatic lens

Compensation

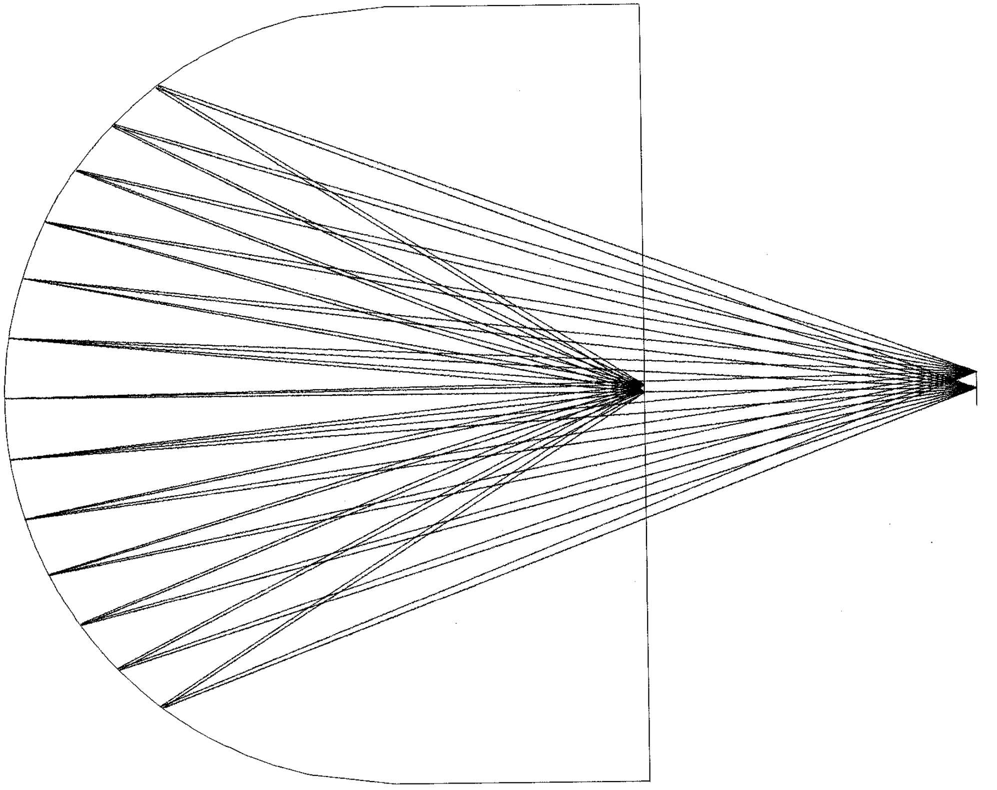




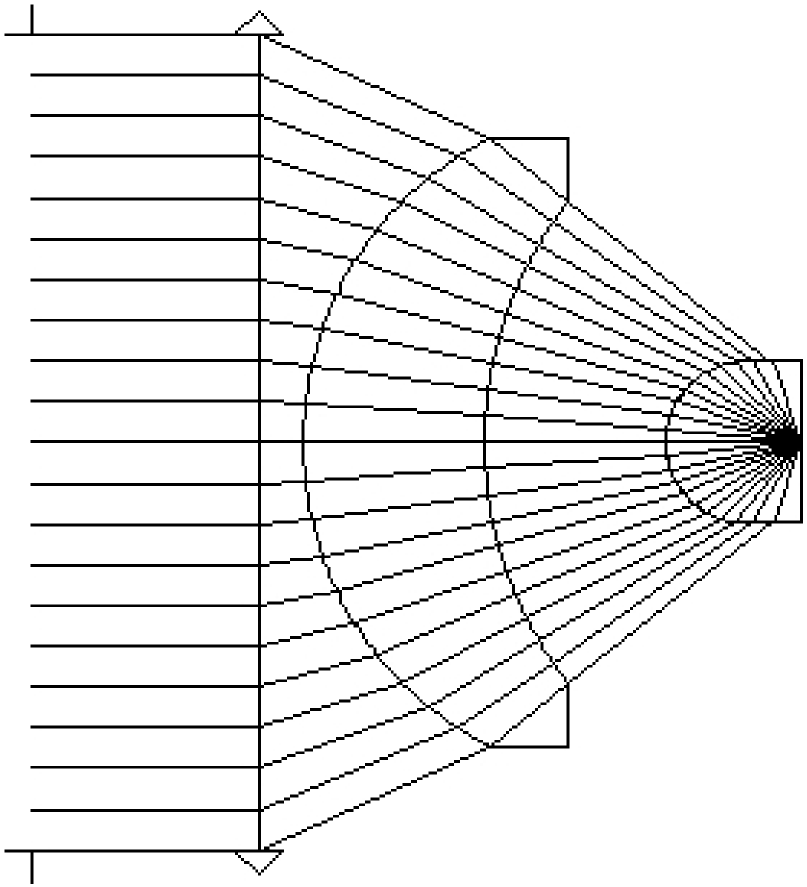


Aplanatic points

$$\Delta\left(u/n\right) = u'/n' - u/n = 0$$



Aplanatic concentric principle



No Spherical
No coma

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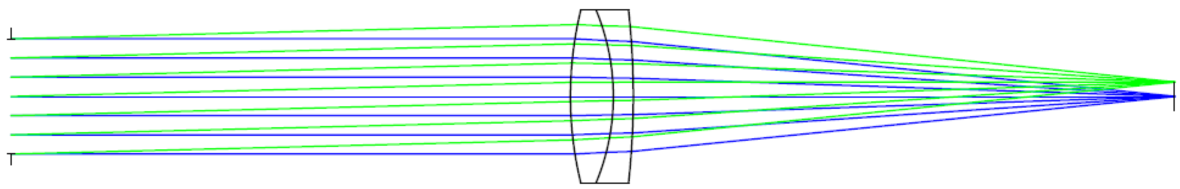
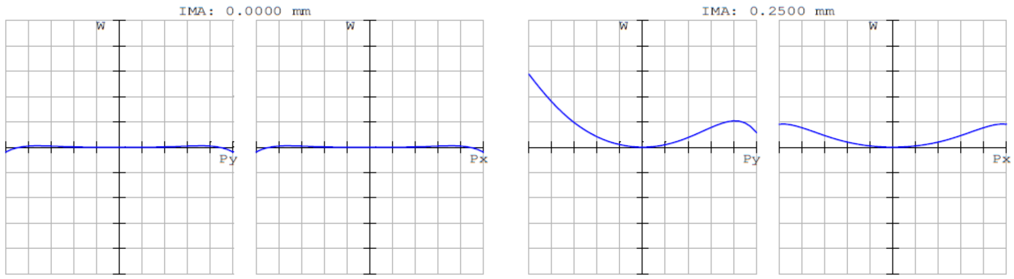
Microscope objectives

telecentric, BK7 and F2 glasses



FOV 0.5 mm @ F/5
F=10 mm



0.2 wave scale

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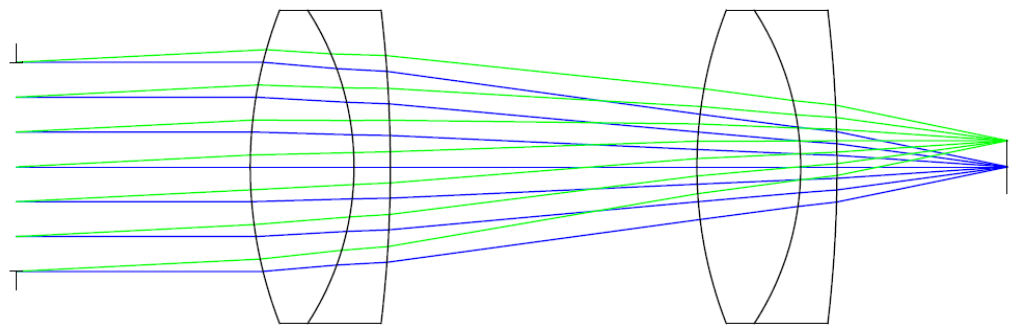
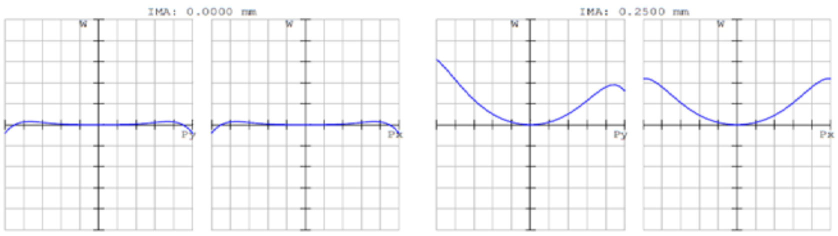
Microscope objectives

Add second doublet with same shape and glass as first



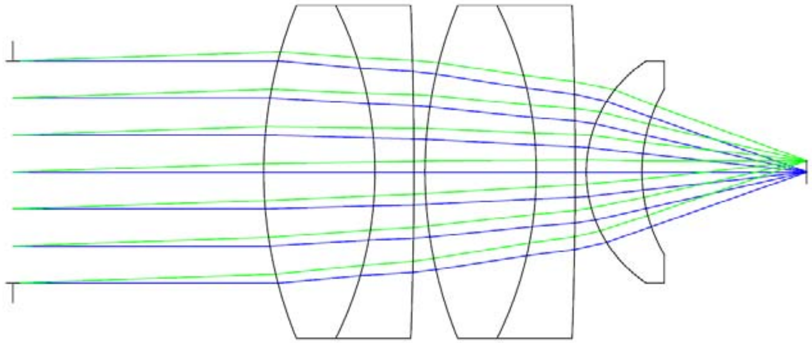
FOV 0.5 mm @ F2.5
F=5 mm



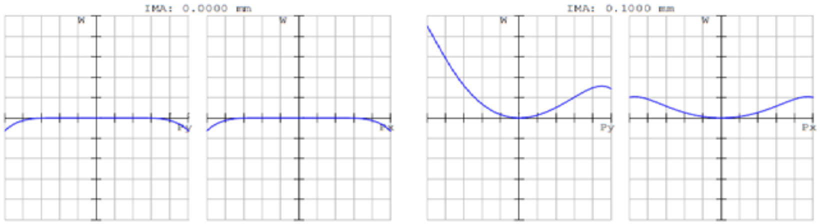
O.5 waves scale

Microscope objectives

Add aplanatic/concentric lens



FOV 0.2 mm @ F1.5
F=3 mm



One wave scale

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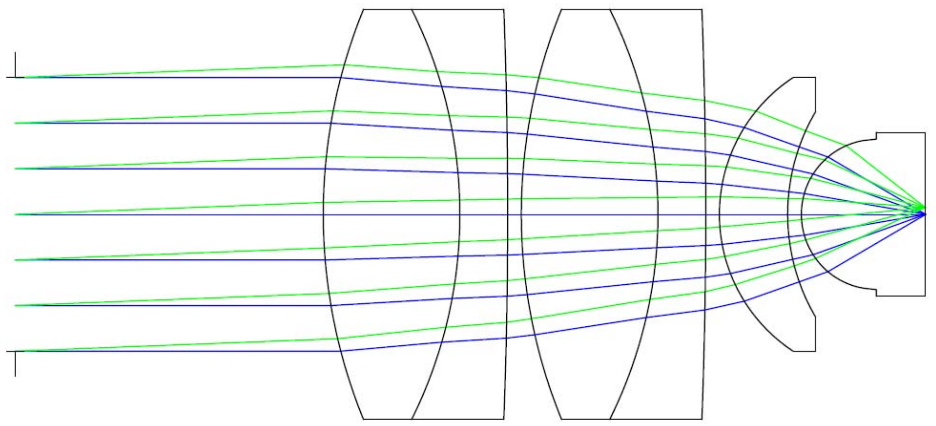
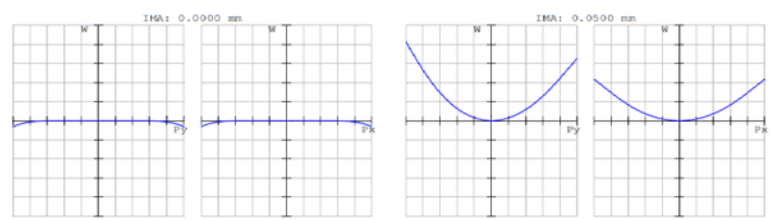
Microscope objectives

Add one more aplanatic surface and immersion



FOV 0.1 mm @ F/0.65
F=1.3 mm



Two waves scale

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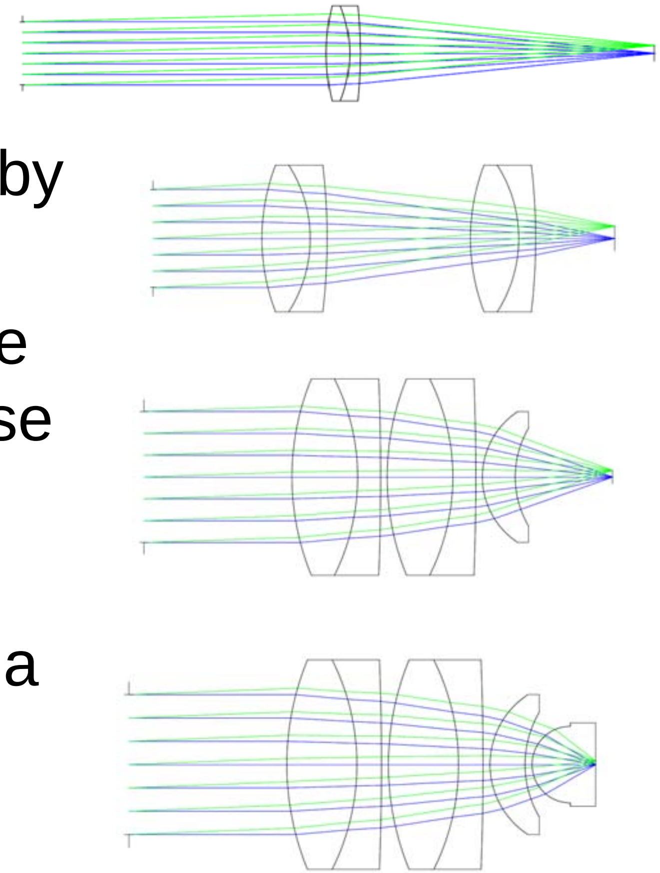
Early microscope objectives

- Specs: Diffraction limited; NA and FOV; easy to make
- Correction of chromatic change of focus; spherical aberration, and coma
- Become an expert by understanding the evolution; especially advantages and disadvantages of other combinations
- From the simple to the elaborated

Early microscope objective evolution

1. Single achromatic doublet
2. Increase NA and coma correction by using two doublets
3. Apply aplanatic concentric principle and add one lens to further increase the NA
4. Apply again an aplanatic surface and use liquid immersion for even a higher NA
5. Consider fabrication



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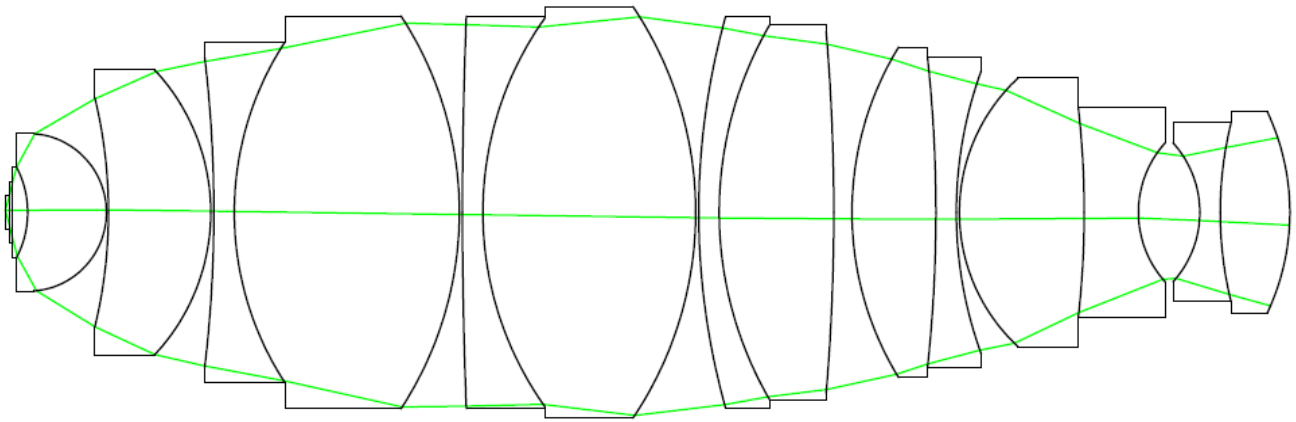
USP 7,046,451 (2006 Nikon)



NA ~1.5
Immersion

PHILOSOPHICAL

TRANSACTIONS

OF THE

ROYAL SOCIETY

OF

LONDON.

FOR THE YEAR MDCCCXXX.

PART I.

LONDON:

PRINTED BY RICHARD TAYLOR, RED LION COURT, FLEET STREET.

MDCCCXXX.

XIII. *On some properties in achromatic object-glasses applicable to the improvement of the microscope. By* JOSEPH JACKSON LISTER, *Esq. Communicated by Dr.* ROGET, *Secretary.*

Read January 21, 1830.

It is the marginal rays which contribute especially to render visible close and delicate lines, such as those on the scales of lepidopterous insects, and some of the most difficult of these are even best seen when the central light is intercepted†.

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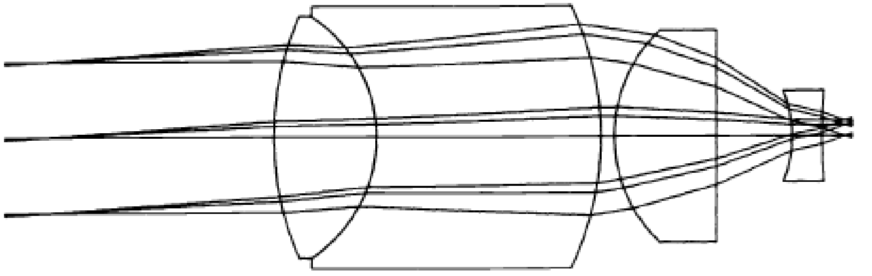
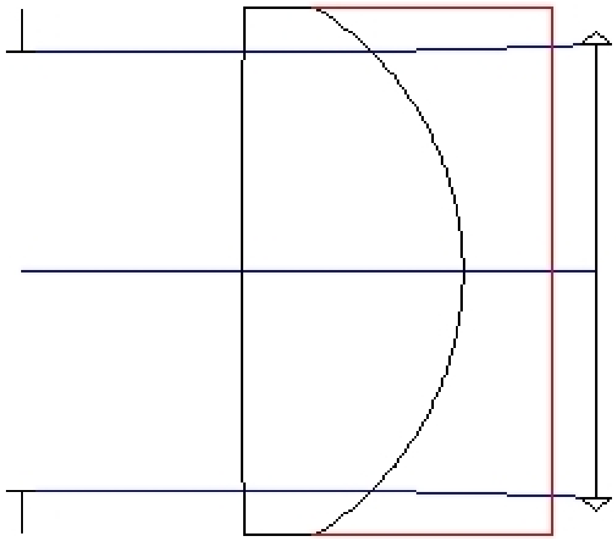
Strong index break

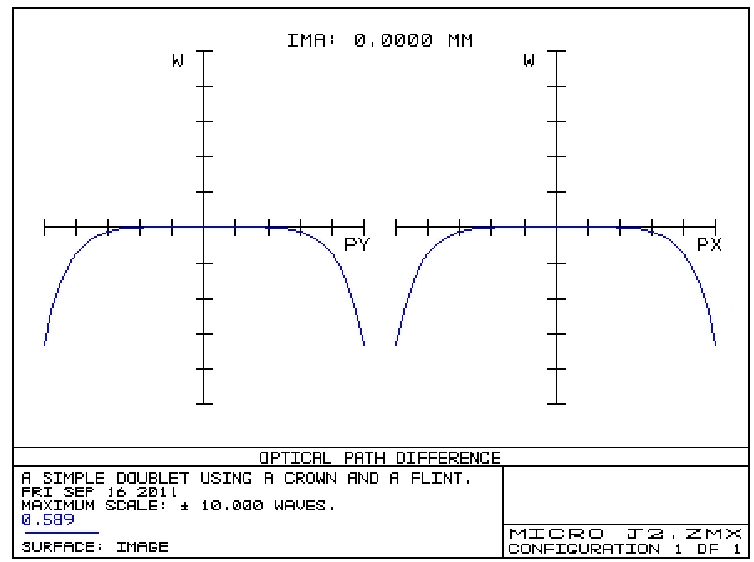


- Strong index of refraction difference
- A doublet may contribute almost no optical power
- Can control mainly fourth-order spherical aberration
- Cemented surface has a strong radius

Merte Surface

Small index difference/strong curvature high-order spherical aberration





See Warren Smith: Hector lens explanation

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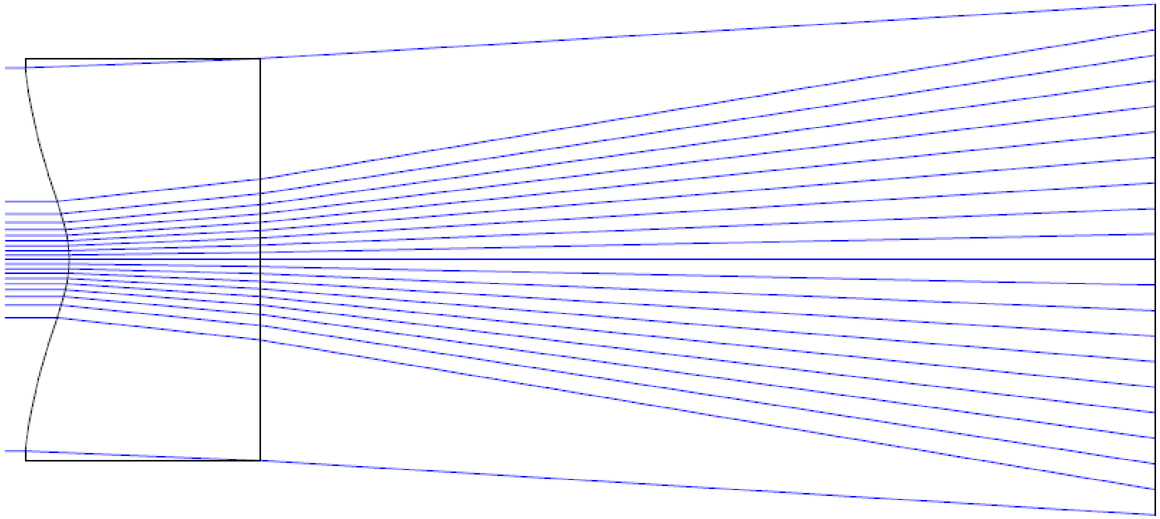
Gaussian to flat top beam



- Converting a Gaussian beam to a flat-top beam requires introducing spherical aberration and then correcting it. This is done with an afocal system of two aspheric lenses (or four spherical lenses). The first one redistributes the rays so that the irradiance is uniform at the second lens; the second lens fixes the beam phase.

Schematic figure

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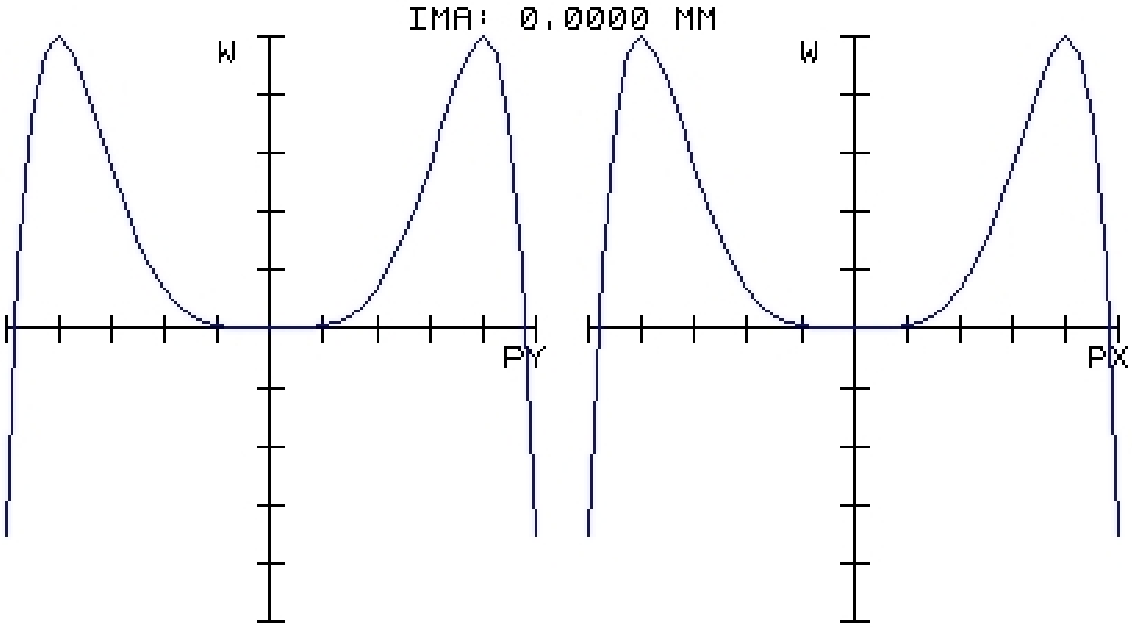
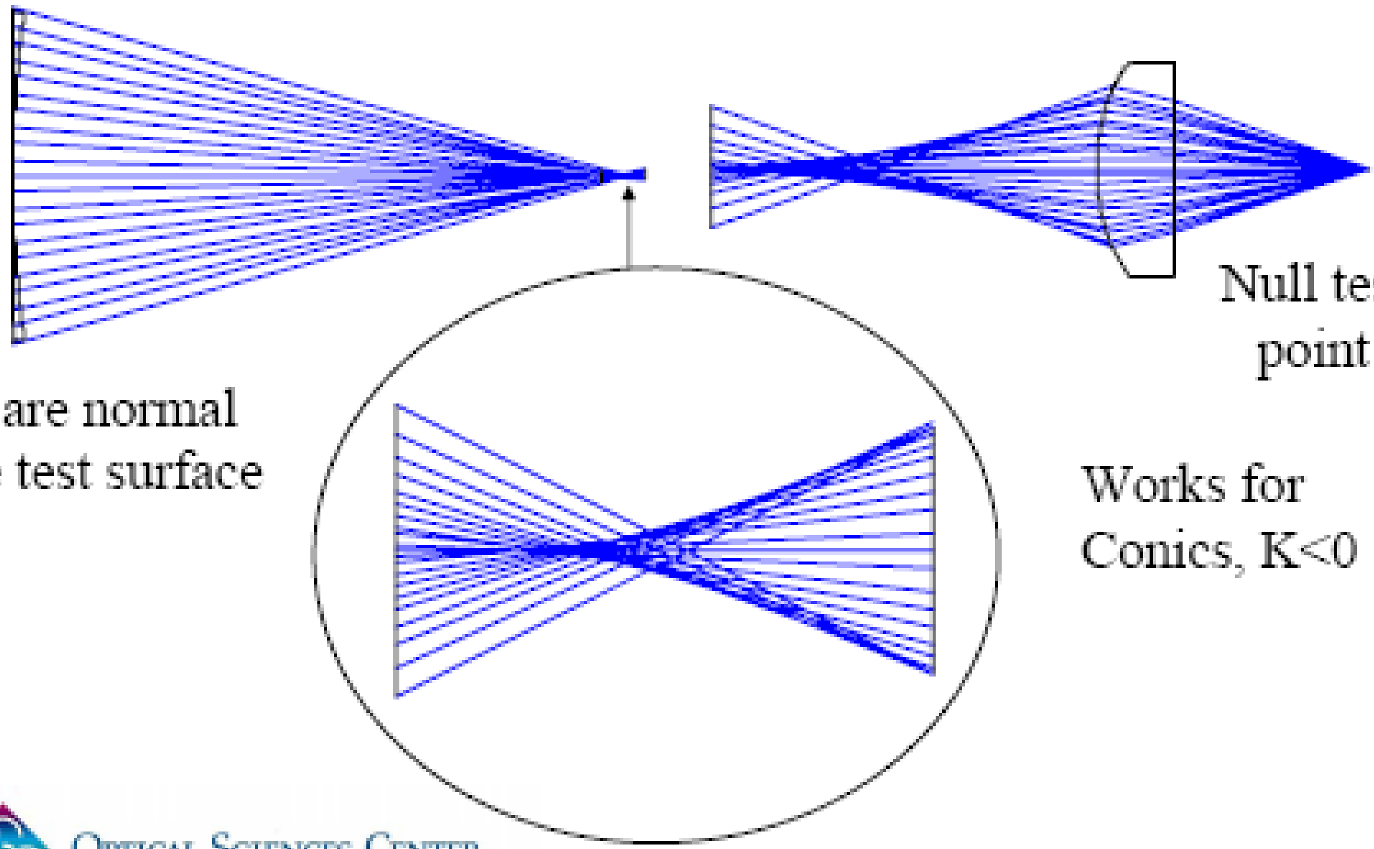
Zonal spherical aberration



Higher order spherical aberration is balanced with fourth-order

No focus error

Null corrector task: Spherical aberration compensation



Null test point

Rays are normal to the test surface

Works for Conics, K<0

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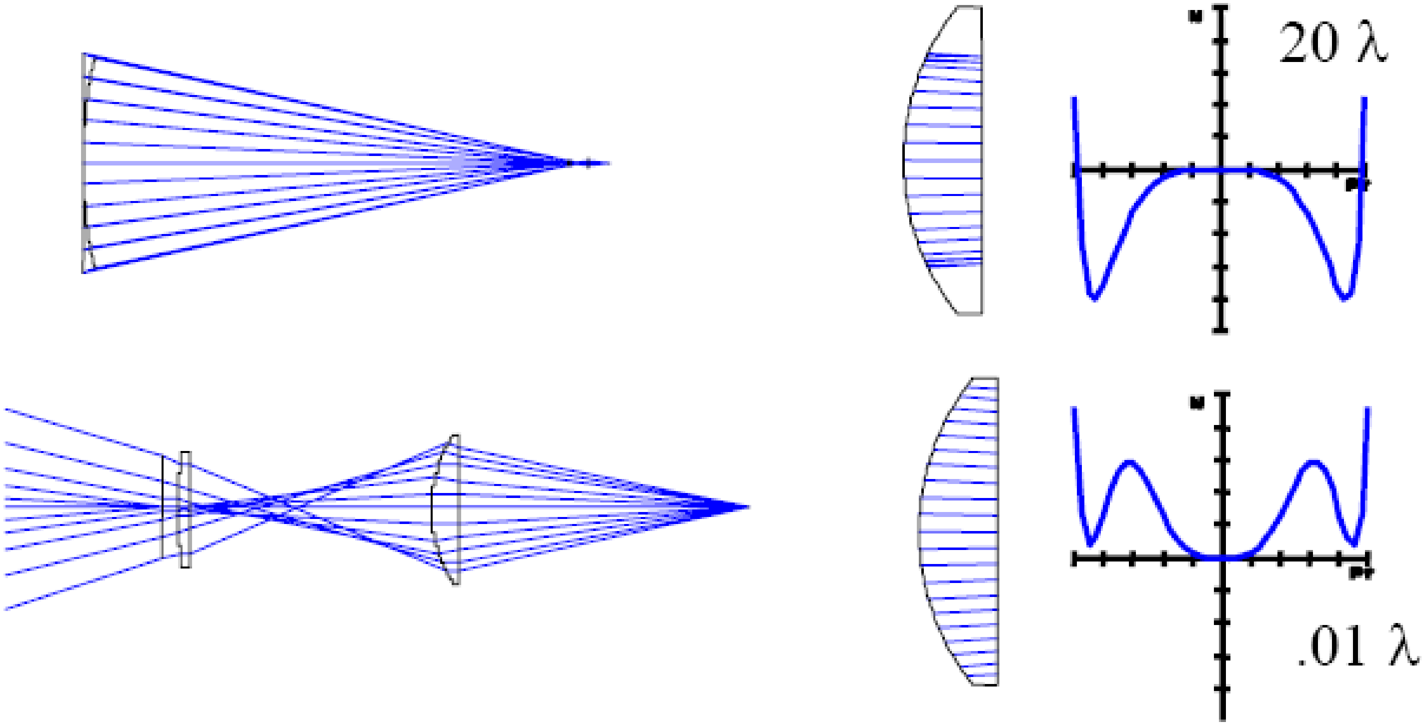
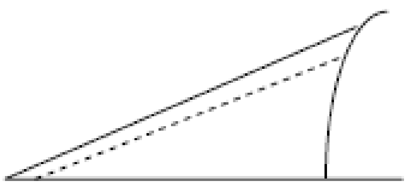
Offner null corrector (1963)



Improves on simpler null lenses

Extrinsic/induced spherical aberration

$$W_{040} = -\frac{1}{8} A^2 y \Delta\left(\frac{u}{n}\right)$$



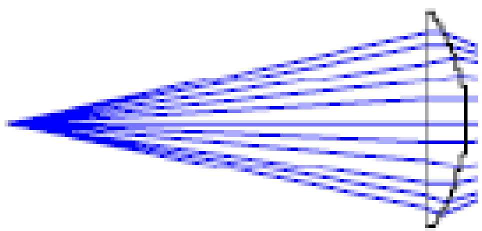
$$Y = y + c_3 y^3 + c_5 y^5 + c_7 y^7 + \ldots = y + \Delta y = y\left(1 + \frac{\Delta y}{y}\right)$$

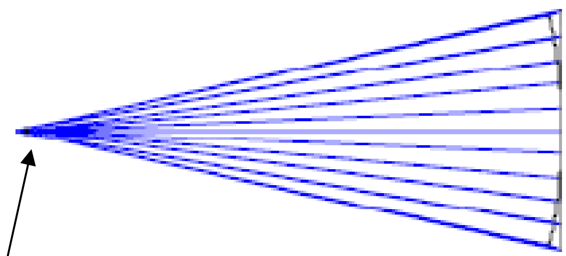
$$\bar{Y} = \bar{y} + c_3 \bar{y}^3 + c_5 \bar{y}^5 + c_7 \bar{y}^7 + \ldots = \bar{y} + \Delta \bar{y} = \bar{y}\left(1 + \frac{\Delta \bar{y}}{\bar{y}}\right)$$

Controlling delta y gives control over higher-order
Spherical aberration

$$W_{060E} = -\frac{1}{\text{Ж}}\left(4 W_{040}^{A} \bar{W}_{311}^{B}\right)$$

Extrinsic aberration





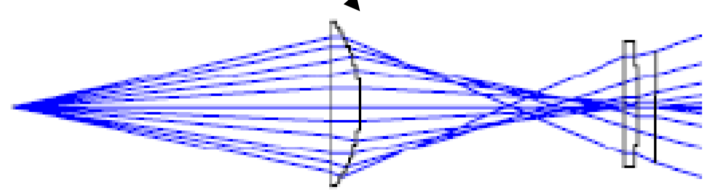
$$W_{040}^{A}$$

Distorted grid at entrance pupil

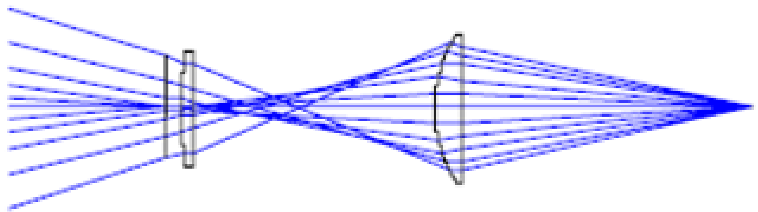
$$\bar{W}_{311}^{B}$$

Uniform grid at exit pupil

$$W_{060E} = -\frac{1}{\text{Ж}}\left(4W_{040}^{A}\bar{W}_{311}^{B}\right)$$



Offner null corrector



- Power of field lens effectively controls delta y/y. Therefore higher order spherical aberration can be controlled.
- Relay lens corrects bulk of spherical aberration
- Filed lens redistributes rays on the relay lens so that a good wavefront match can take place.
- Can test a large mirror with small lenses.

Some camera/telescope systems where spherical aberration is corrected

- Aspheric plate: Schmidt camera
- Meniscus lens: Maksutov telescope
- Spaced doublet: Houghton camera

- Some times spherical aberration is introduced on purpose.

Summary

- Origin of spherical aberration
- Control of spherical aberration
- Fourth and higher orders of spherical aberration