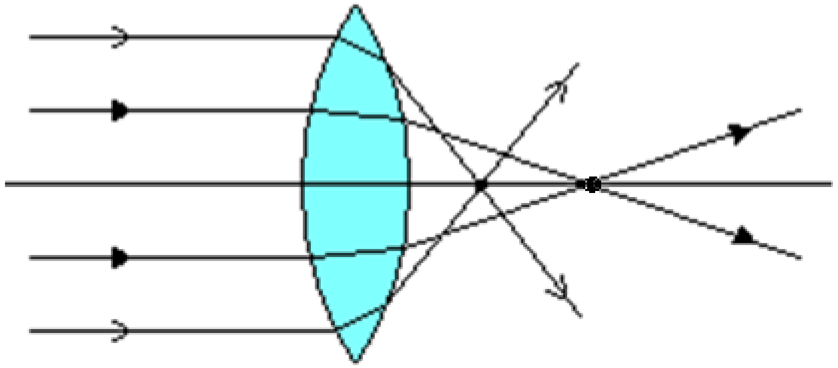
Lectures Notes on Optical Design using Zemax OpticStudio

Lecture 8

Monochomatic Aberrations



Ahmet Bingül

Gaziantep University
Department of Optical Engineering

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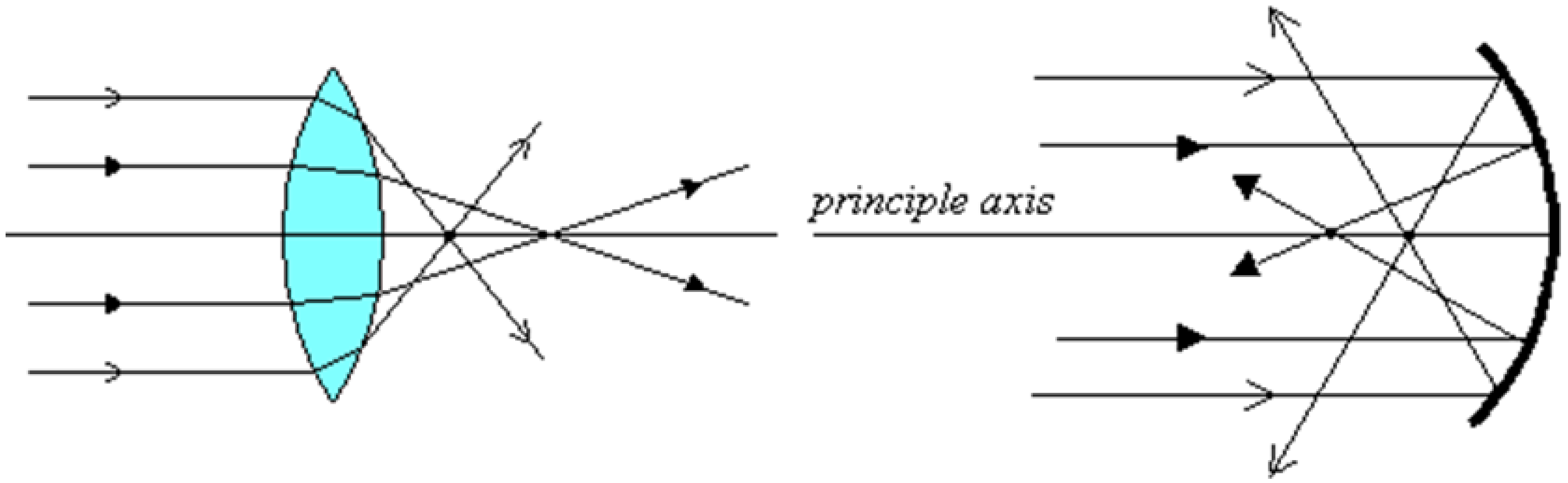
What is aberration?

- Paraxial approximations result in perfect image!
- Imperfect images caused by geometric factors are called aberrations.
- Aberration leads to blurring of the image produced by an image-forming optical system.



Aberration Types

1. Spherical aberration
2. Coma
3. Astigmatism
4. Field Curvature
5. Distortion
6. Chromatic Aberration

occur with monochromatic light (1–5)

due to dispersion of optical material (6)

Origin of Aberrations

Snell's law of refraction: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Taylor series of expansion: $$\sin(\theta) = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \cdots$$

Taking only first term → We arrive first order optics which is the study of perfect optical systems without aberrations.

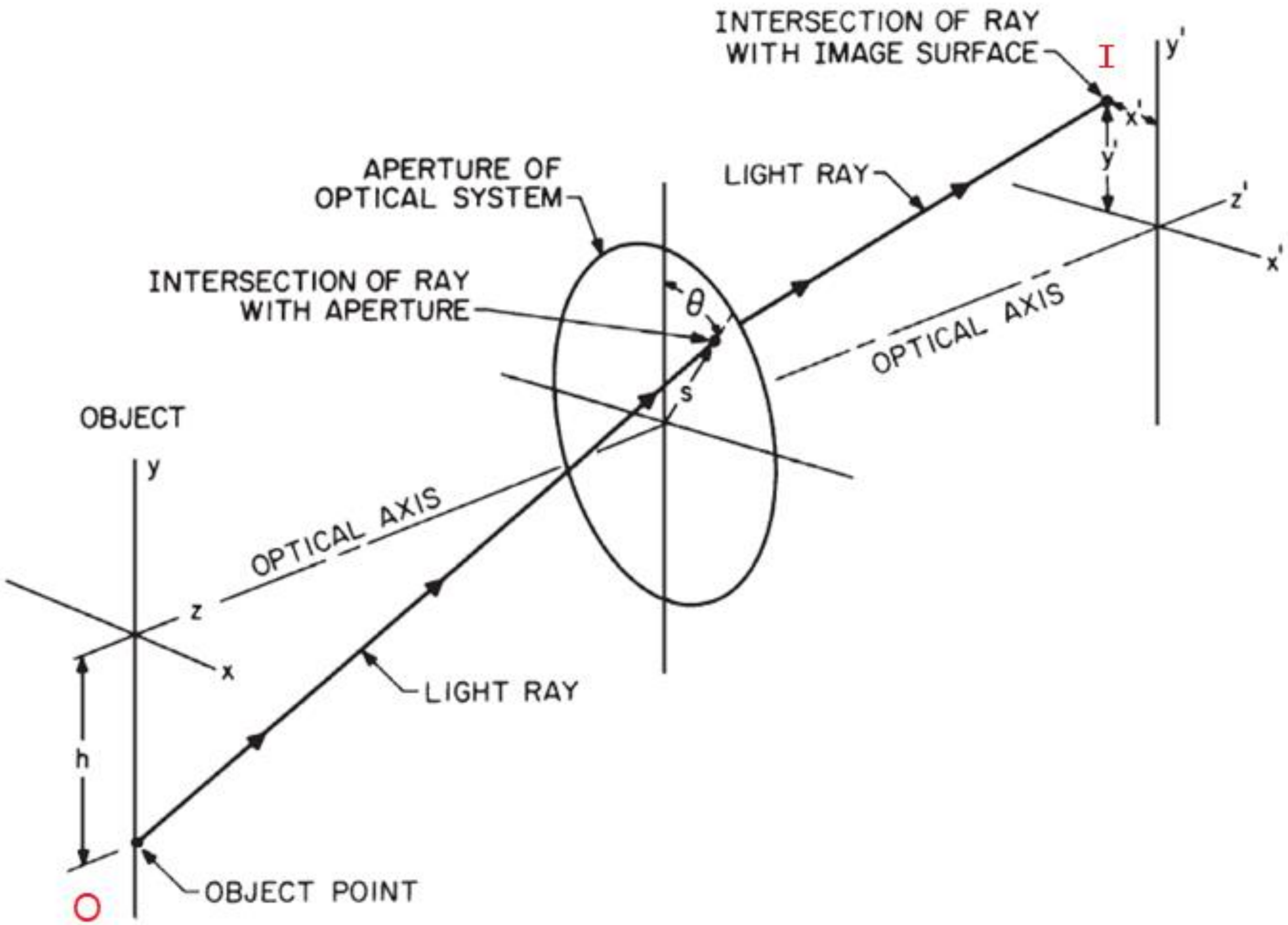
Including third order terms → We arrive third order optics.

- In 3rd order optics, we have set of equations for describing lens aberrations as departures from paraxial theory.
- These equations are called Siedel Aberrations.

Seidel Coefficients

Consider a ray originates from object point at **O**(0, -h, 0). The ray hits image surface at **I**(x', y', z).

Question: What are the mathematical relations between these two points?



Seidel Coefficients

The solution is given below. The coefficients of

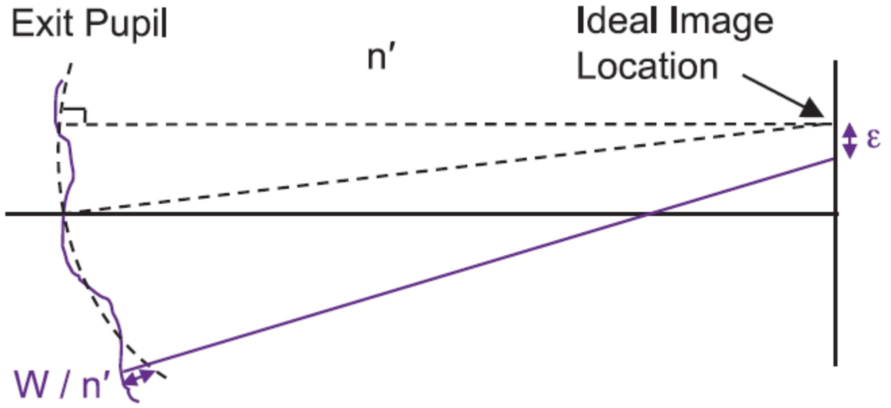
- 1st order terms: A_1, A_2 are related to perfect imaging.
- 3rd order terms: B_1, B_2, B_3, B_4, B_5 are Seidel Coefficients. They are related to 3rd order departure from perfect imaging. (Higher order terms can also be included).

$$
\begin{aligned}
y' &= A_1 s \cos\theta + A_2 h \\
&+ B_1 s^3 \cos\theta + B_2 s^2 h (2 + \cos 2\theta) + (3B_3 + B_4) s h^2 \cos\theta + B_5 h^3 \\
&+ C_1 s^5 \cos\theta + (C_2 + C_3 \cos 2\theta) s^4 h + (C_4 + C_6 \cos^2\theta) s^3 h^2 \cos\theta \\
&+ (C_7 + C_8 \cos 2\theta) s^2 h^3 + C_{10} s h^4 \cos\theta + C_{12} h^5 + D_1 s^7 \cos\theta + \cdots
\end{aligned}
$$

$$
\begin{aligned}
x' &= A_1 s \sin\theta \\
&+ B_1 s^3 \sin\theta + B_2 s^2 h \sin 2\theta + (B_3 + B_4) s h^2 \sin\theta \\
&+ C_1 s^5 \sin\theta + C_3 s^4 h \sin 2\theta + (C_5 + C_6 \cos^2\theta) s^3 h^2 \sin\theta \\
&+ C_9 s^2 h^3 \sin 2\theta + C_{11} s h^4 \sin\theta + D_1 s^7 \sin\theta + \cdots
\end{aligned}
$$

Wave Aberration

Wave aberration function **W** is the optical length, measured along a ray, from the aberrated wavefront to the reference sphere.
The distance ε is called the transverse ray error.

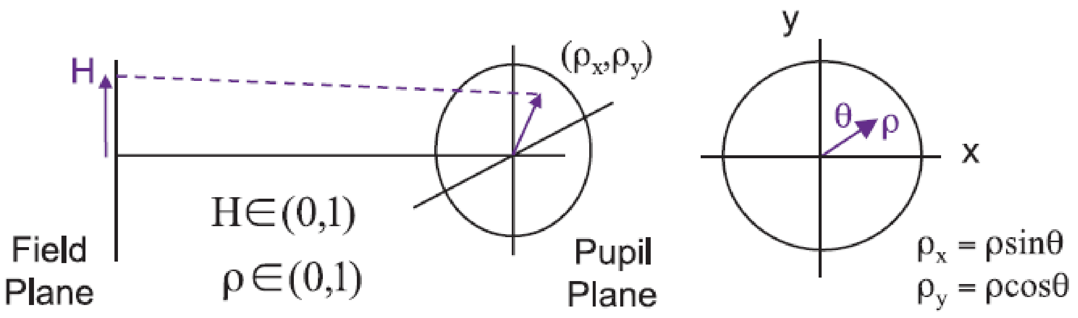


Monochromatic aberrations can also be described by expanding **W** in a power series of aperture and field coordinates, ρ, θ and H:

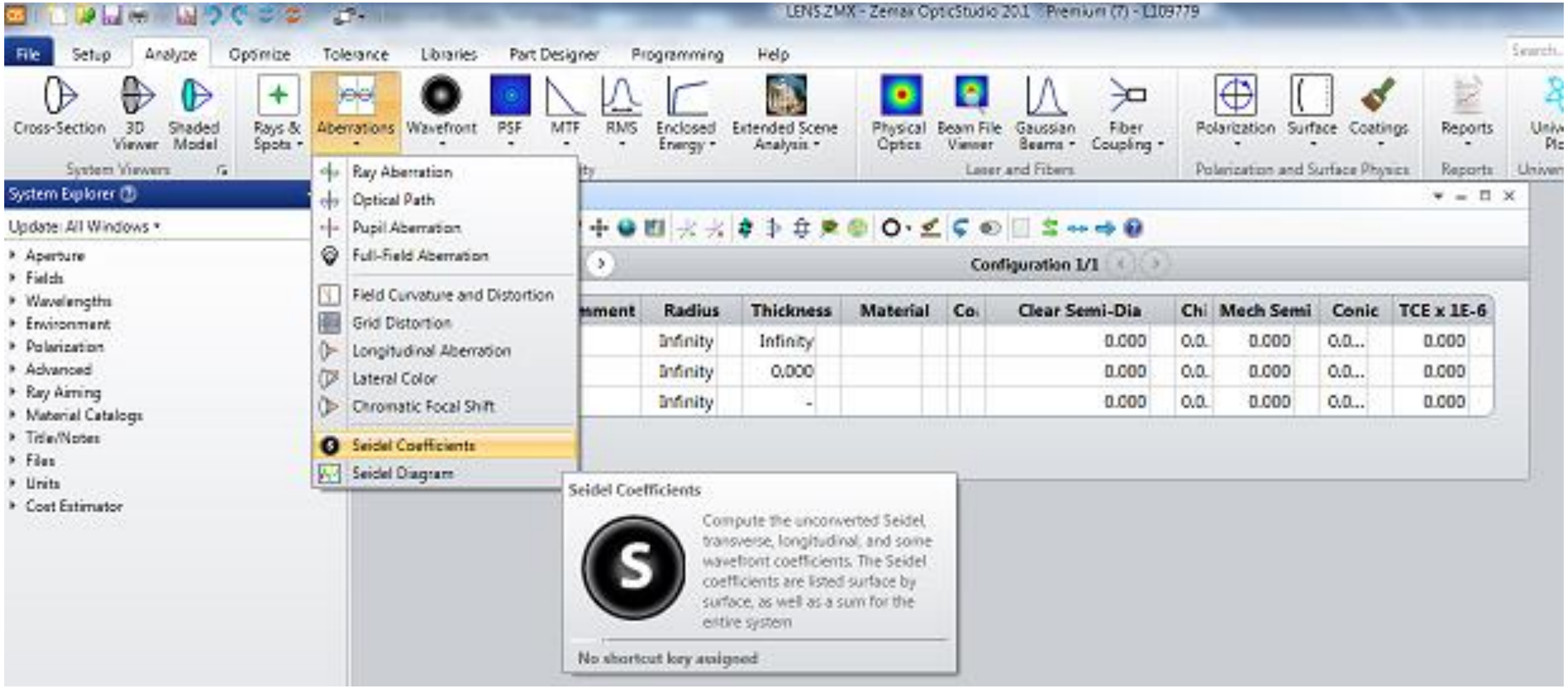
$$W_{IJK} \Rightarrow H^I \rho^J \cos^K \theta$$

$$W(H,\rho,\theta) = W_{020}\rho^2 + W_{111}H\rho\cos\theta + W_{040}\rho^4 + W_{131}H\rho^3\cos\theta + W_{222}H^2\rho^2\cos^2\theta + W_{220}H^2\rho^2 + W_{311}H^3\rho\cos\theta + O(6)$$

W_{020}: Defocus
W_{111}: Wavefront tilt
W_{040}: Spherical aberration
W_{131}: Coma
W_{222}: Astigmatism
W_{220}: Field curvature
W_{311}: Distortion



Aberration Plots & Seidel Coefficients



Monochromatic Aberration Demo in Zemax

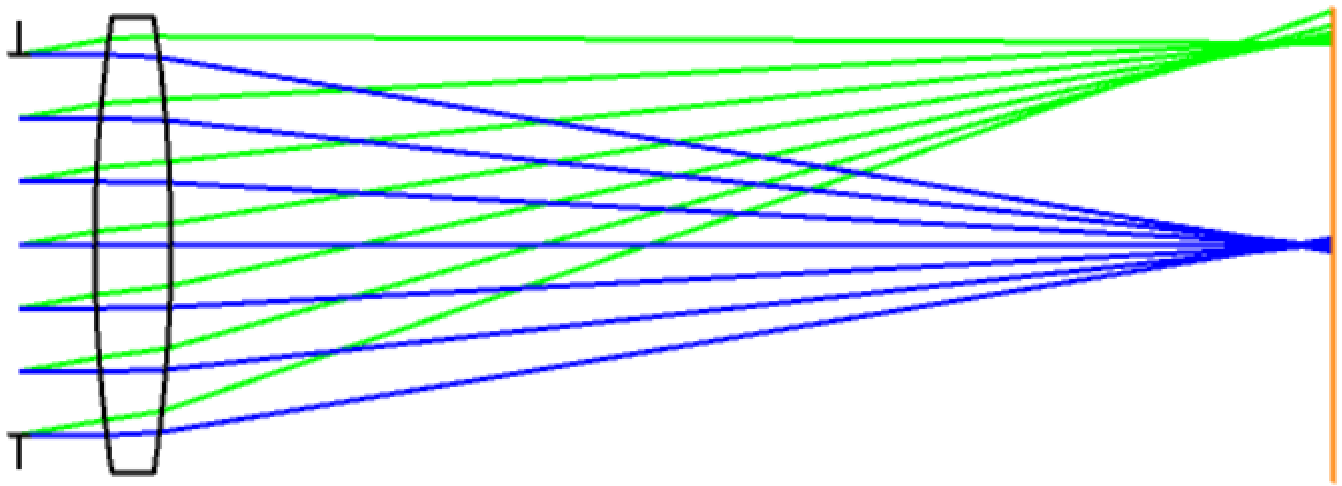
λ = 550 nm, ENPD = 25 mm, SFOV = 0^{o} and 10^{o}.

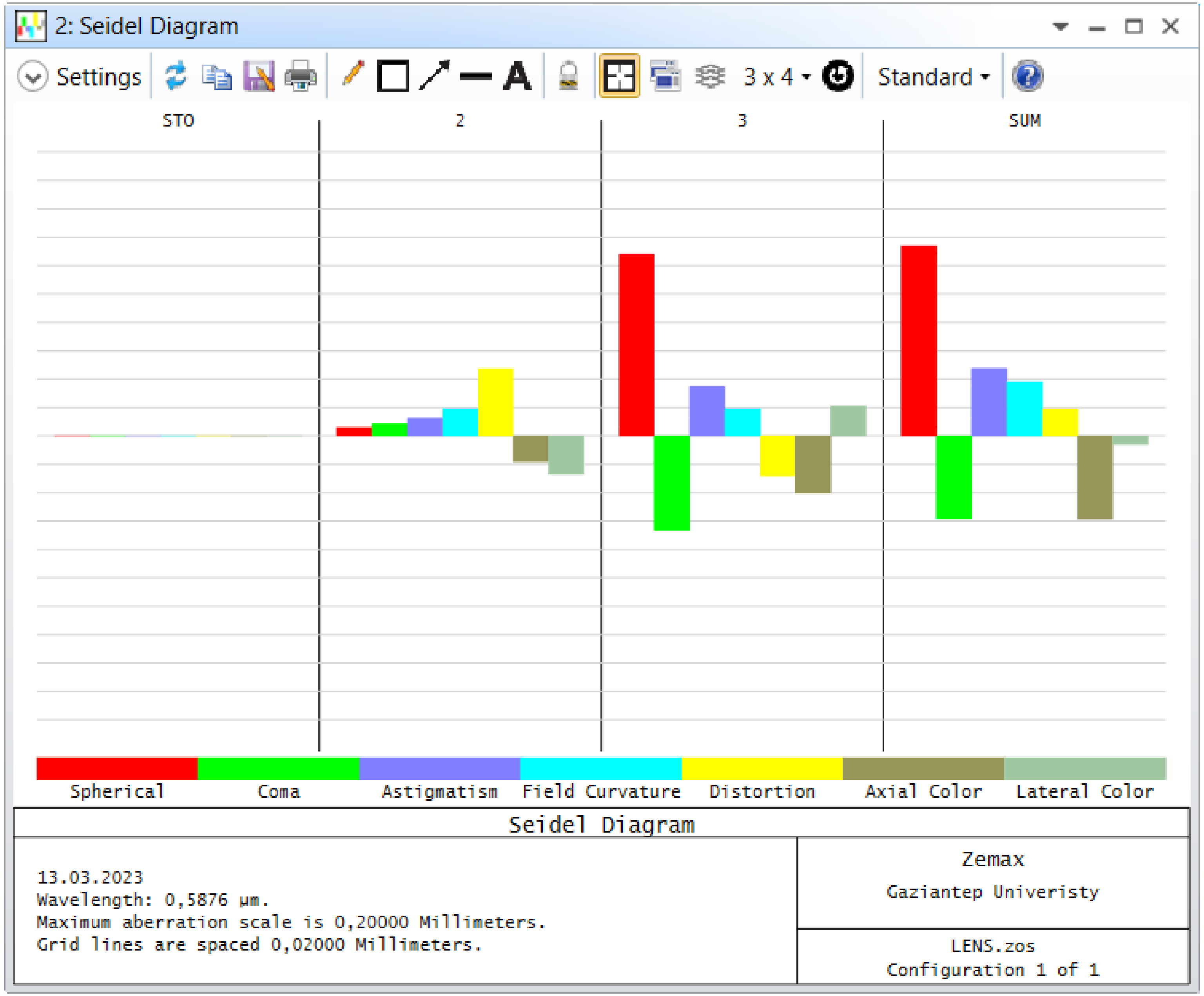
Lens Data

Update: All Windows

Surface 4 Properties | Configuration 1/1

	Surface Type		Comment	Radius	Thickness		Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia
0	OBJECT	Standard		Infinity	Infinity				Infinity		0,000	Infinity
1	STOP	Standard		Infinity	5,000				12,500		0,000	12,500
2	(aper)	Standard		100,000	5,000		N-SF2		15,000	U	0,000	15,000
3	(aper)	Standard		-100,000	76,431	M			15,000	U	0,000	15,000
4	IMAGE	Standard		Infinity	-				15,672		0,000	15,672




2: Seidel Diagram
Settings
3 x 4
Standard
STO
2
3
SUM
Spherical
Coma
Astigmatism
Field Curvature
Distortion
Axial Color
Lateral Color
Seidel Diagram
13.03.2023
Wavelength: 0,5876 µm.
Maximum aberration scale is 0,20000 Millimeters.
Grid lines are spaced 0,02000 Millimeters.
Zemax
Gaziantep Univeristy
LENS.zos
Configuration 1 of 1

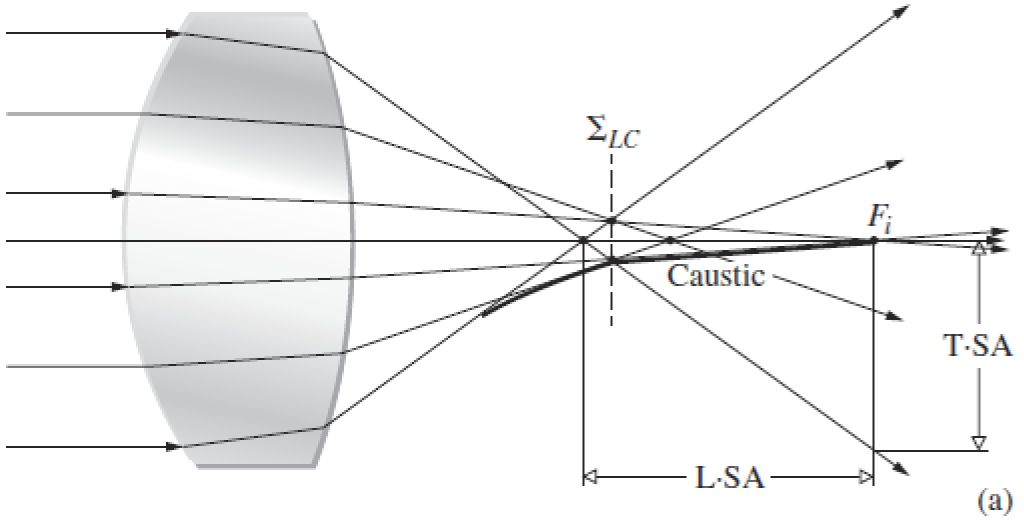
Spherical Aberration

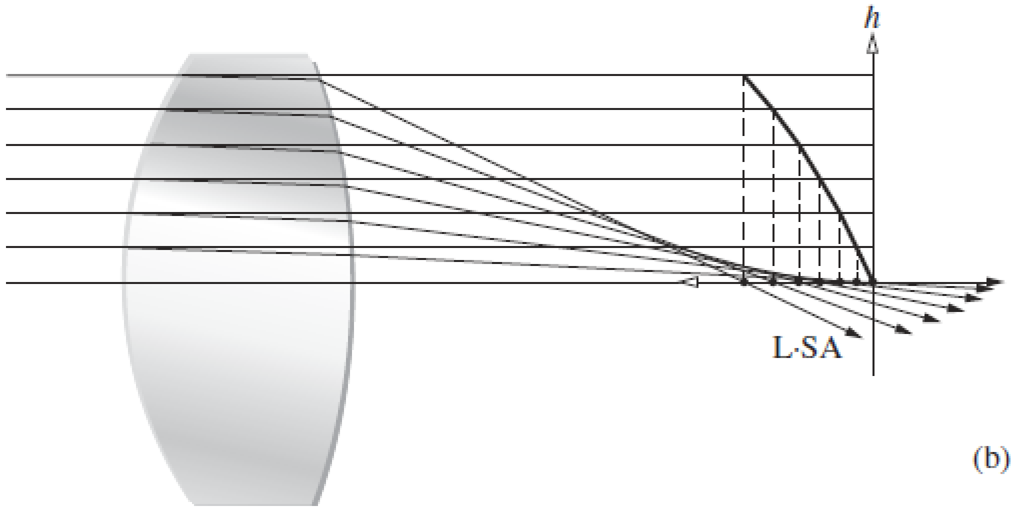
SA is occurs only on-axis.

We have two types of spherical aberrations:

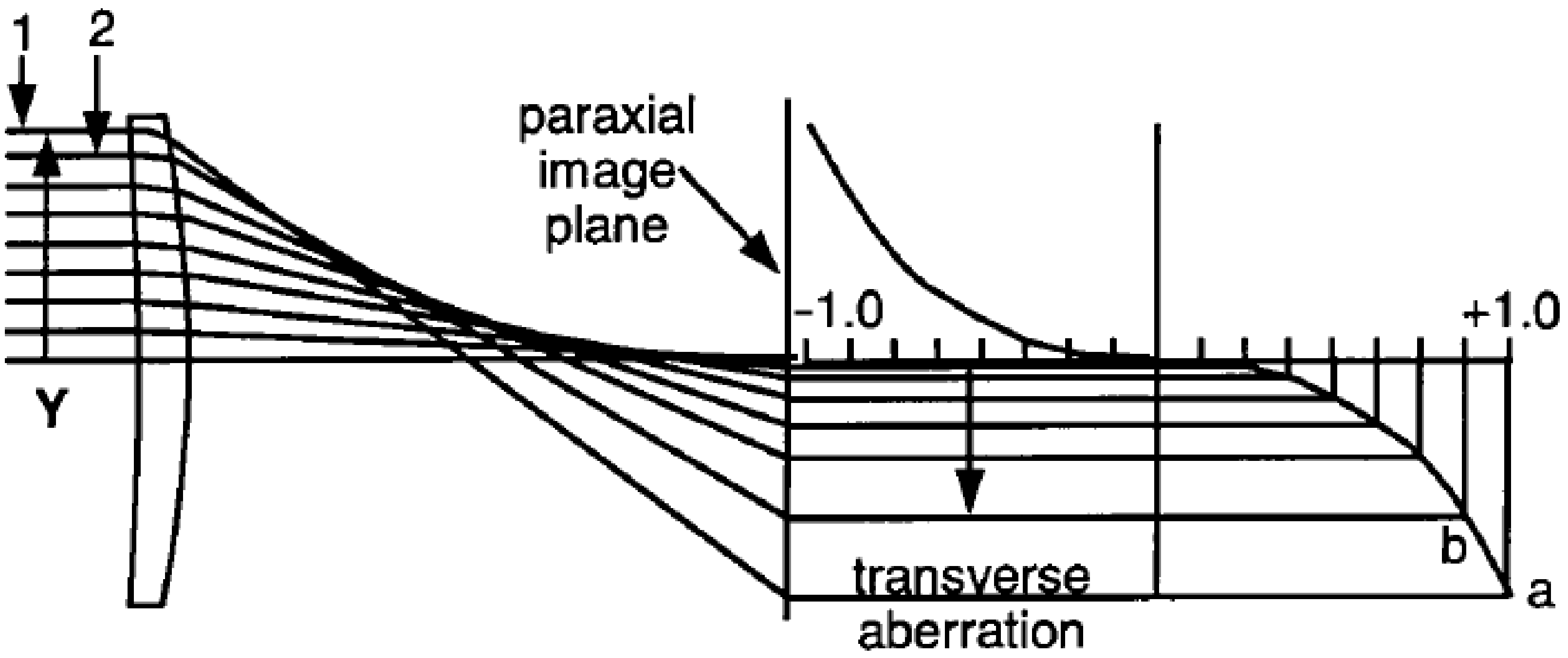
Longitudinal Aberration (L.SA)

Transverse Aberration (T.SA)





Ray Fan Plot



Aspherical Surfaces

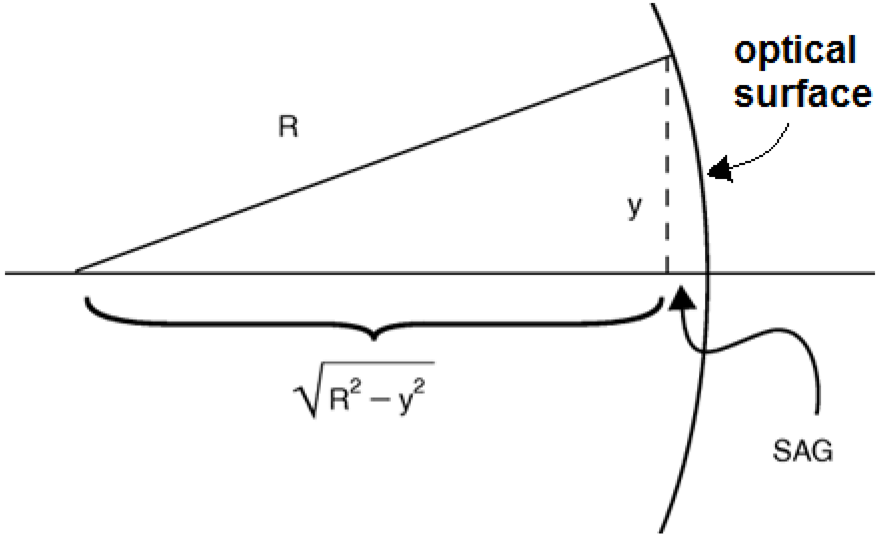
Using Aspherical surfaces one can reduce S.A.

- Aspherical surface is relatively harder to make and measure.
- Aspheric lenses improve image quality and reduce the number of required optical elements.

An important property of an optical surface is sag defined by:

$$z = \frac{Cy^2}{\sqrt{1+(1+k)C^2y^2}} + A_2y^2 + A_4y^4 + A_6y^6 + \cdots$$

z = sag of surface parallel to the optical axis
y = radial distance from the optical axis
C = curvature, inverse of radius ($C = 1/R$)
k = conic constant
A_i = i^{th} order aspheric coefficient



Geometric meaning of conic constant:

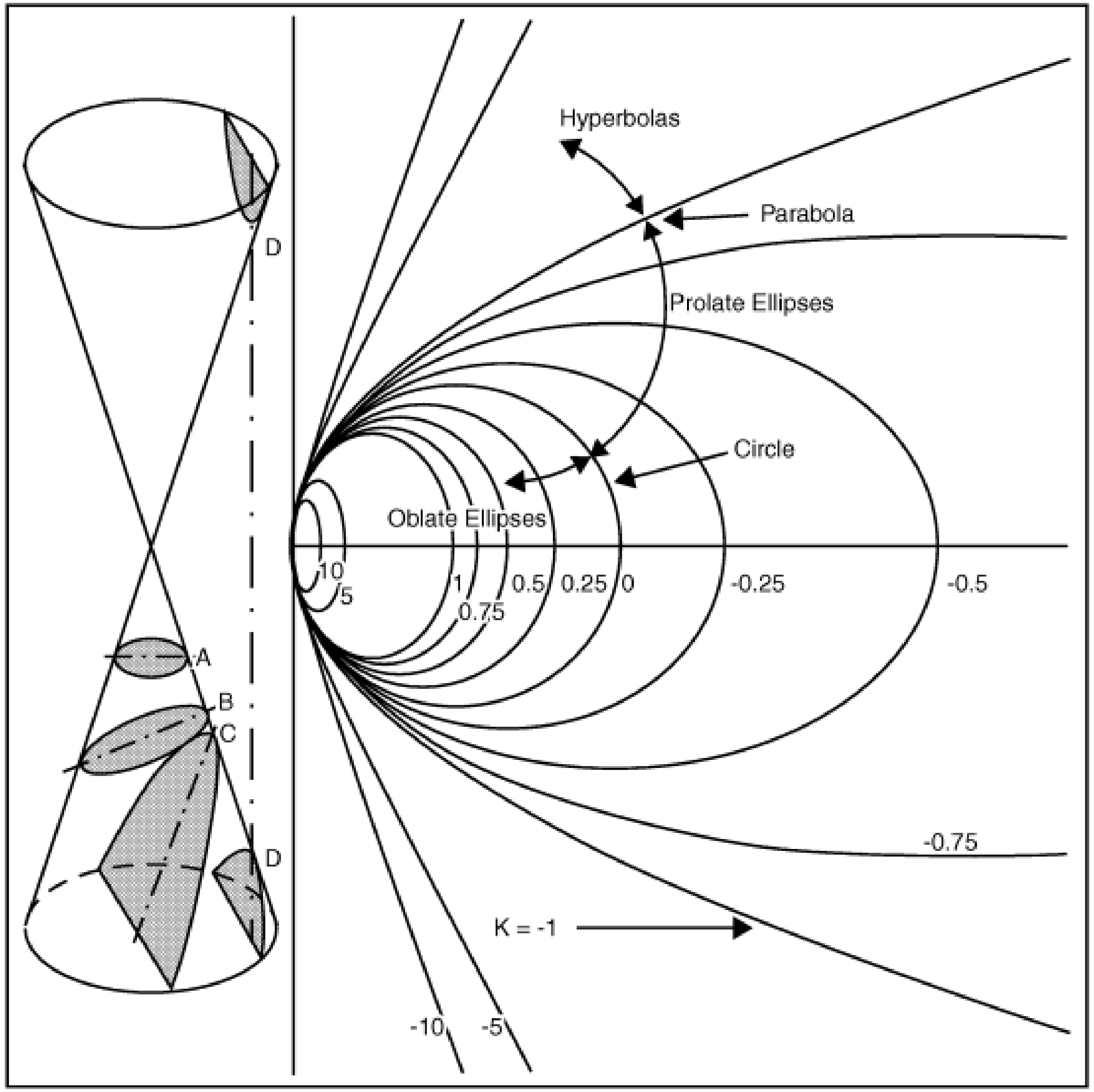
k = 0 => *circle*

k = -1 => *parabola*

k < -1 => *hyperbola*

k > 0 => *ellipse*

-1 < *k* < 0 => *ellipse*



Suggestions in use of Aspheric Surfaces

1. If possible, optimize your design first using spherical surfaces, and then use the conic and/or aspheric coefficients in the final stages of optimization. This may help in keeping the asphericities to a more manageable level.

2. Conic surfaces can be used for correcting third-order spherical aberration and other low-order aberrations.

3. If you have a nearly flat surface, then use A_4 and higher-order terms rather than a conic.

How to Get Rid Off Spherical Aberration

To reduce spherical aberration:

- Reduce size (diameter) of the lens
- Change bending (radii of curvatures) of the lens
- Use more than one spherical lens
- Use aspherical surface(s)

Example 1: Three Lenses to reduce SA

In this example, we will use three N-BK7 glasses separated by 5 mm and 7 mm.

ENPD = 25 mm, F/# = 4 and λ = 550 nm.

Diameter of each lens is D = 30 mm and $ct_1 = ct_2 = ct_3$ = 6 mm

(*Note that for optomechanical reasons center thickness must satisfy* $ct > D/10$).

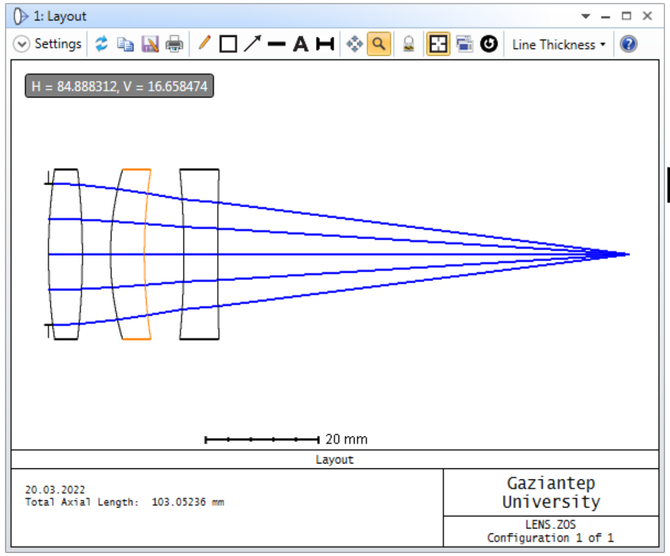
An example recipie is as follows:

Step 1: We have only one lens. Do not insert other lenses.
R_{11} = 90 mm and R_{12} is variable.
Optimize (min spot) such that focal length of the lens is f_1 = 120 mm.

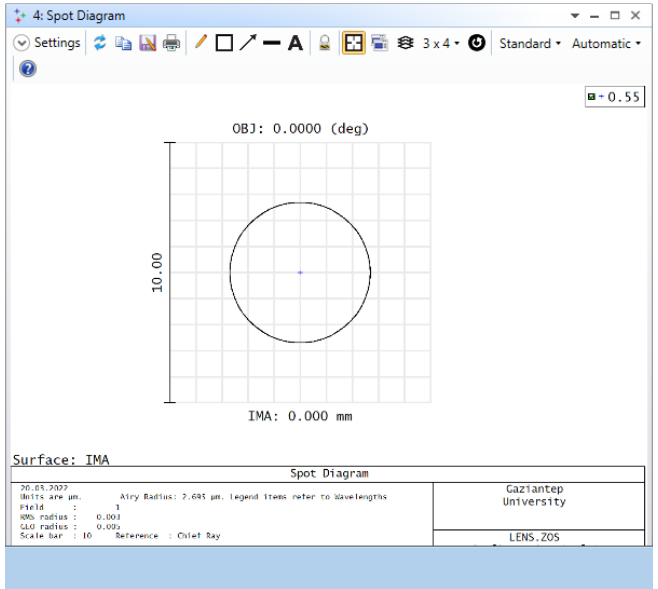
Step 2: Insert new lens 5 mm away from first lens. Now, we have two lenses.
R_{11}, R_{12} are fixed. R_{21} and R_{22} are variable.
Optimize (min spot) such that focal length of the two lenses is f_{12} = 80 mm.

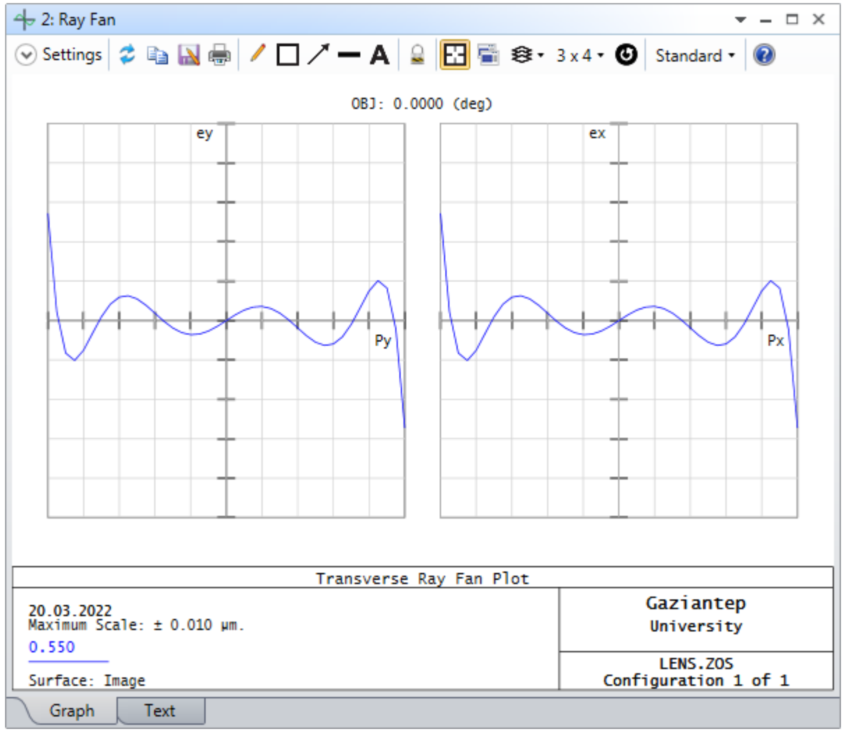
Step 3: Insert new lens 7 mm away from second lens. Now, we have three lenses.
R_{11}, R_{12}, R_{21}, R_{22} are fixed. R_{31} and R_{32} are variable.
Optimize (min spot) such that focal length of lenses is f_{123} = 100 mm.

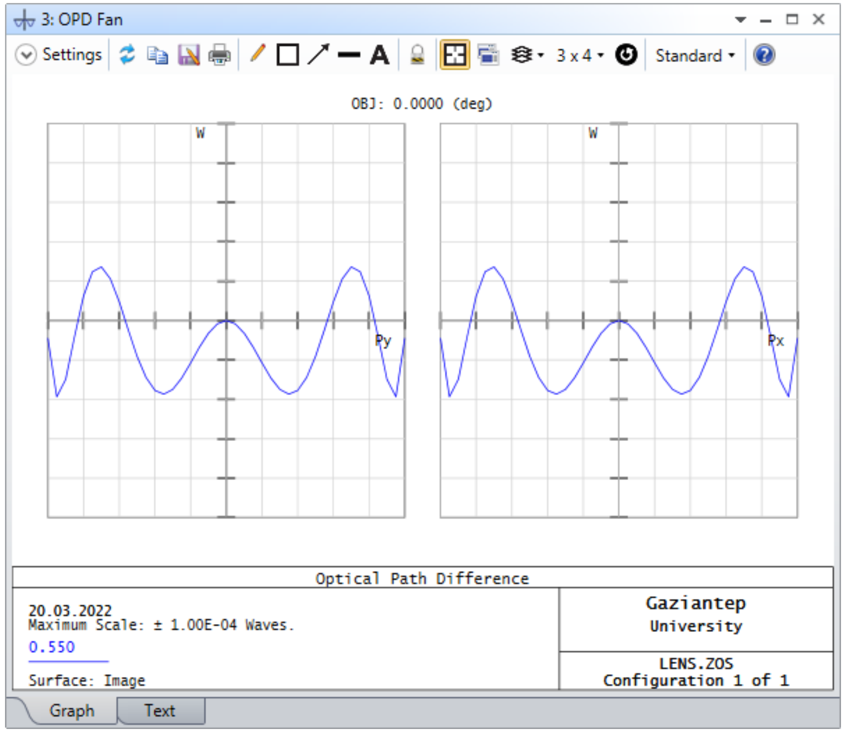
Step 4: Set all 6 radii variables.
Optimize (min spot) such that focal length of lenses is f_{123} = 100 mm.



ptimization:







Example 2: Even Asphere Surface

In some cases, use of the conic constant may not be enough to remove S.A. An alternative way is to use even aspheric surface which is a standard surface plus polynomial asphere terms (See Page 13). In Zemax OpticStudio, this surface is defined as **Even Asphere**. In this example, we'll consider a plano convex aspherical lens whose focal length is 100 mm and ENPD = 25 mm.

Lens Data

Update: All Windows

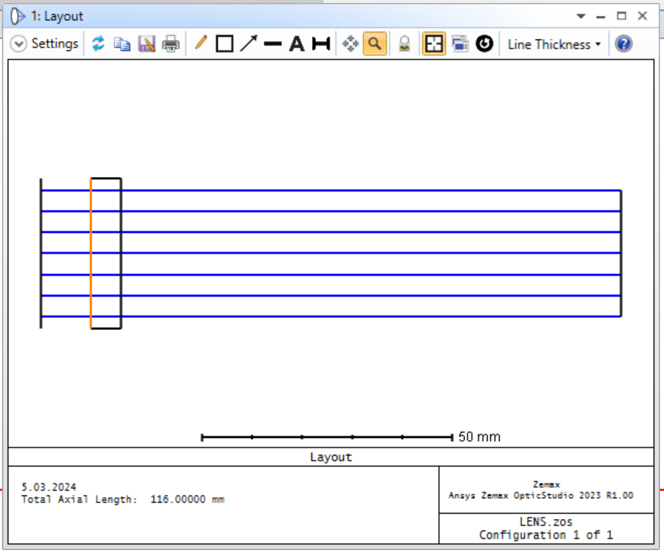
Surface 2 Properties — Configuration 1/1

	Surface Type		Co	Radius	Thickness	Material	Clear Semi-	Chip Zone	Mech Semi-Dia	Conic	Coati	TCE x 1E-6	2nd Order Term	4th Order Term	6t
0	OBJECT	Standard		Infinity	Infinity		0.000	0.000	0.000	0.000		0.000			
1	STOP	Standard		Infinity	10.000		12.500	0.000	12.500	0.000		0.000			
2	(aper)	Even Asphere		Infinity V	6.000	N-BK7	15.000 U	0.000	15.000	0.000		-	0.000 V	0.000 V	
3	(aper)	Standard		Infinity	100.000 V		15.000 U	0.000	15.000	0.000		0.000			
4	IMAGE	Standard		Infinity	-		12.500	0.000	12.500	0.000		0.000			

Merit Function Editor

Wizards and Operands — Merit Function: 3705435992.59739

	Type		Wave	Hx	Hy	Px	Py		Target	Weight	Value	% Contrib
1	EFFL		1						100.000	1.000	1.000E+10	100.000
2	DMFS											
3	BLNK	Sequential merit function: RMS spot x+y centroid X Wgt = 1.0000 Y Wgt = 1.0000 GQ 3 rings 6 arms										
4	BLNK	No air or glass constraints.										
5	BLNK	Operands for field 1.										
6	TRCX		1	0.0...	0.0...	0.3...	0.000		0.000	0.873	4.196	1.537E-17
7	TRCY		1	0.0...	0.0...	0.3...	0.000		0.000	0.873	0.000	0.000
8	TRCX		1	0.0...	0.0...	0.7...	0.000		0.000	1.396	8.839	1.091E-16
9	TRCY		1	0.0...	0.0...	0.7...	0.000		0.000	1.396	0.000	0.000
10	TRCX		1	0.0...	0.0...	0.9...	0.000		0.000	0.873	11.775	1.210E-16
11	TRCY		1	0.0...	0.0...	0.9...	0.000		0.000	0.873	0.000	0.000



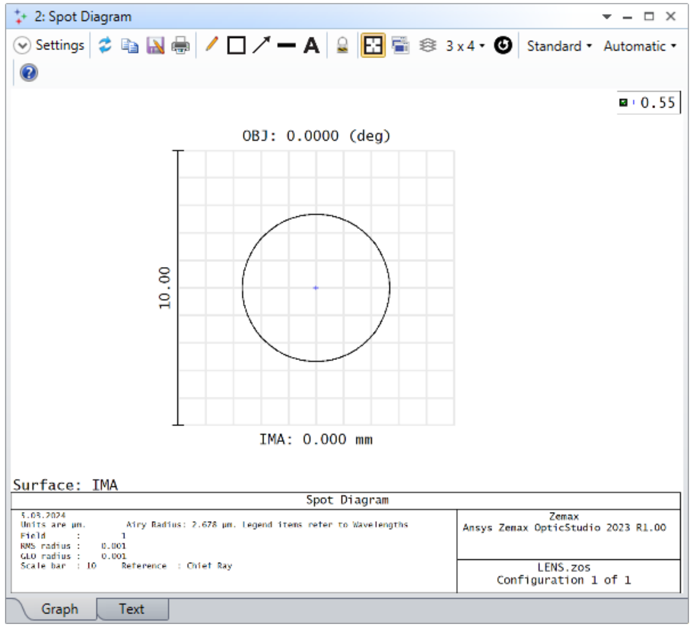
After optimization, we have a perfect form. Compare the solution with Example 1.

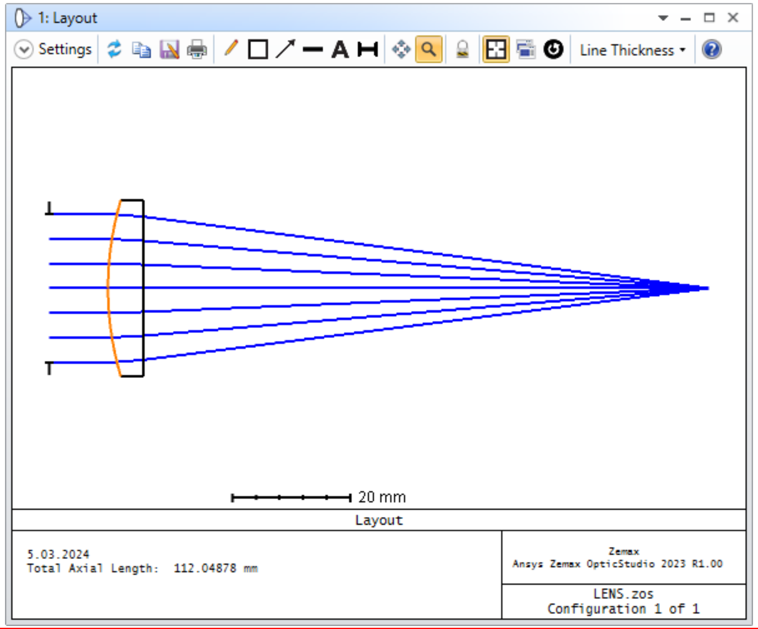
Lens Data

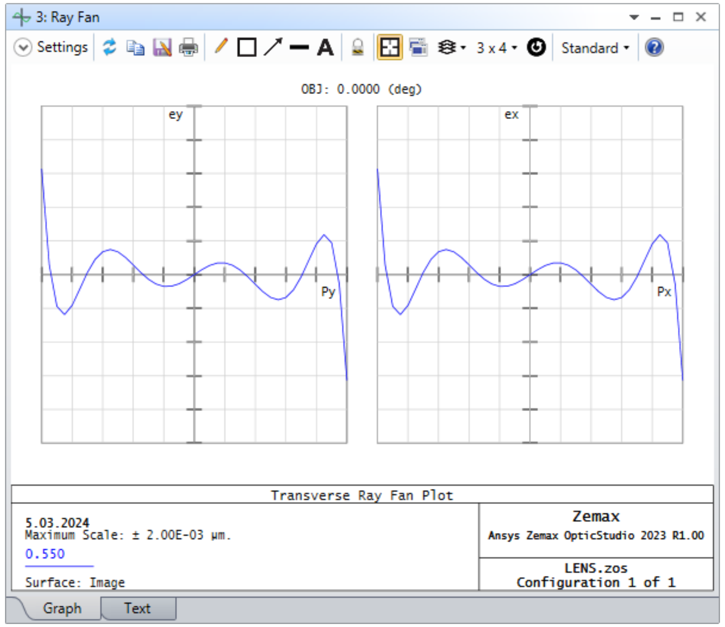
Update: All Windows

Surface 2 Properties — Configuration 1/1

	Surface Type		Co	Radius	Thickness	Material	Clear Semi-	Chip Zone	Mech Semi-Dia	Conic	Coati	TCE x 1E-6	2nd Order Term	4th Order Term	6t
0	OBJECT	Standard		Infinity	Infinity		0.000	0.000	0.000	0.000		0.000			
1	STOP	Standard		Infinity	10.000		12.500	0.000	12.500	0.000		0.000			
2	(aper)	Even Asphere		78.802 V	6.000	N-BK7	15.000 U	0.000	15.000	0.000		-	3.298E-03 V	1.212E-07 V	
3	(aper)	Standard		Infinity	96.049 V		15.000 U	0.000	15.000	0.000		0.000			
4	IMAGE	Standard		Infinity	-		1.255E-06	0.000	1.255E-06	0.000		0.000			



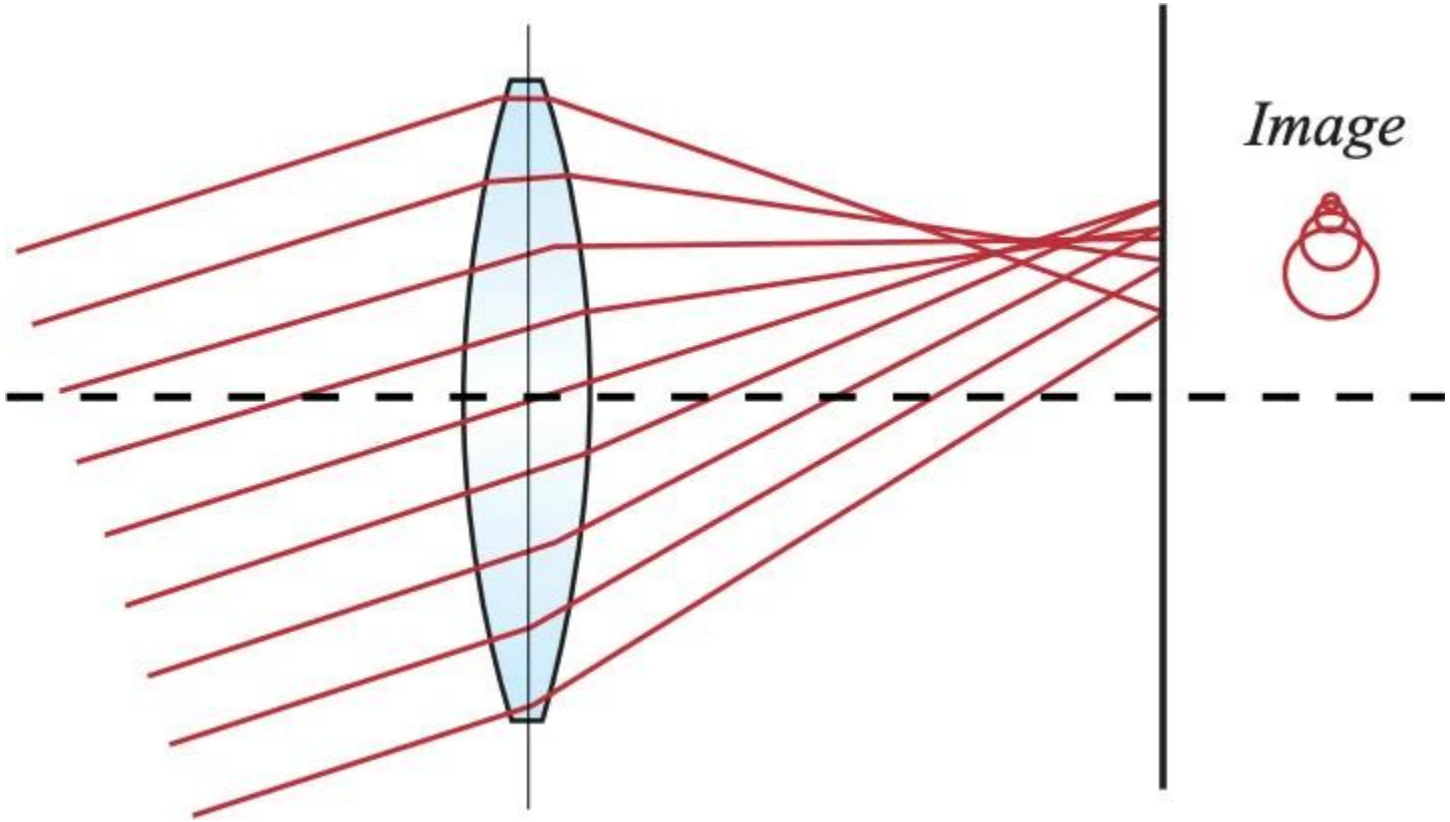




Coma

Coma is similar to SA but in addition the rays come from off-axis points.

Coma increases rapidly as the third power of the lens aperture.

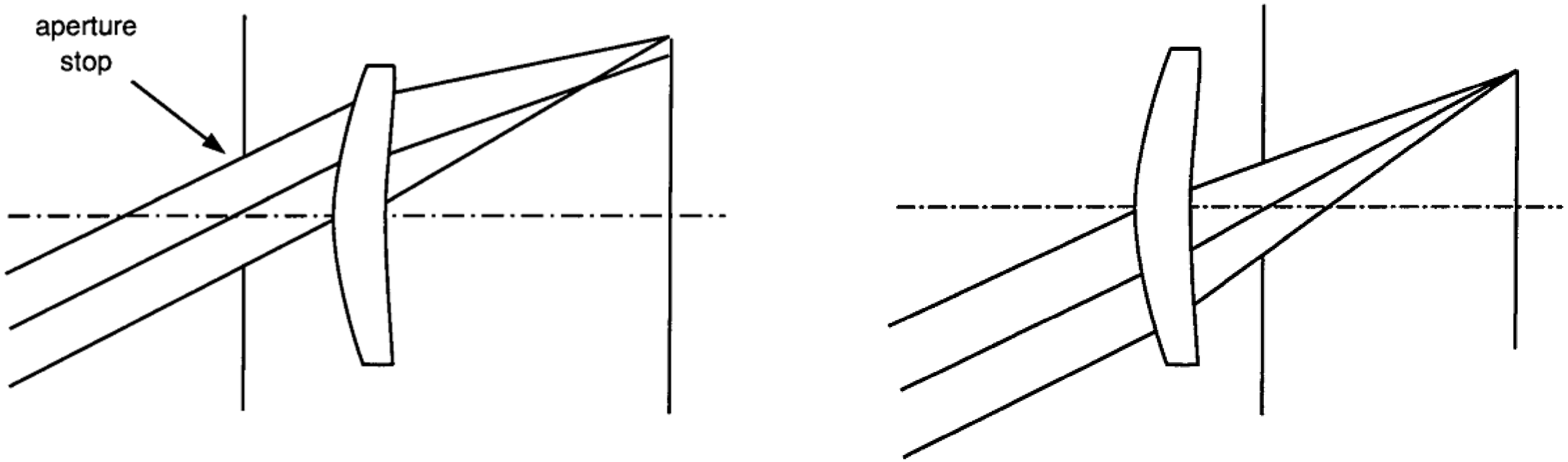


The term coma comes from comet due to the shape of the spot diagram.

Coma

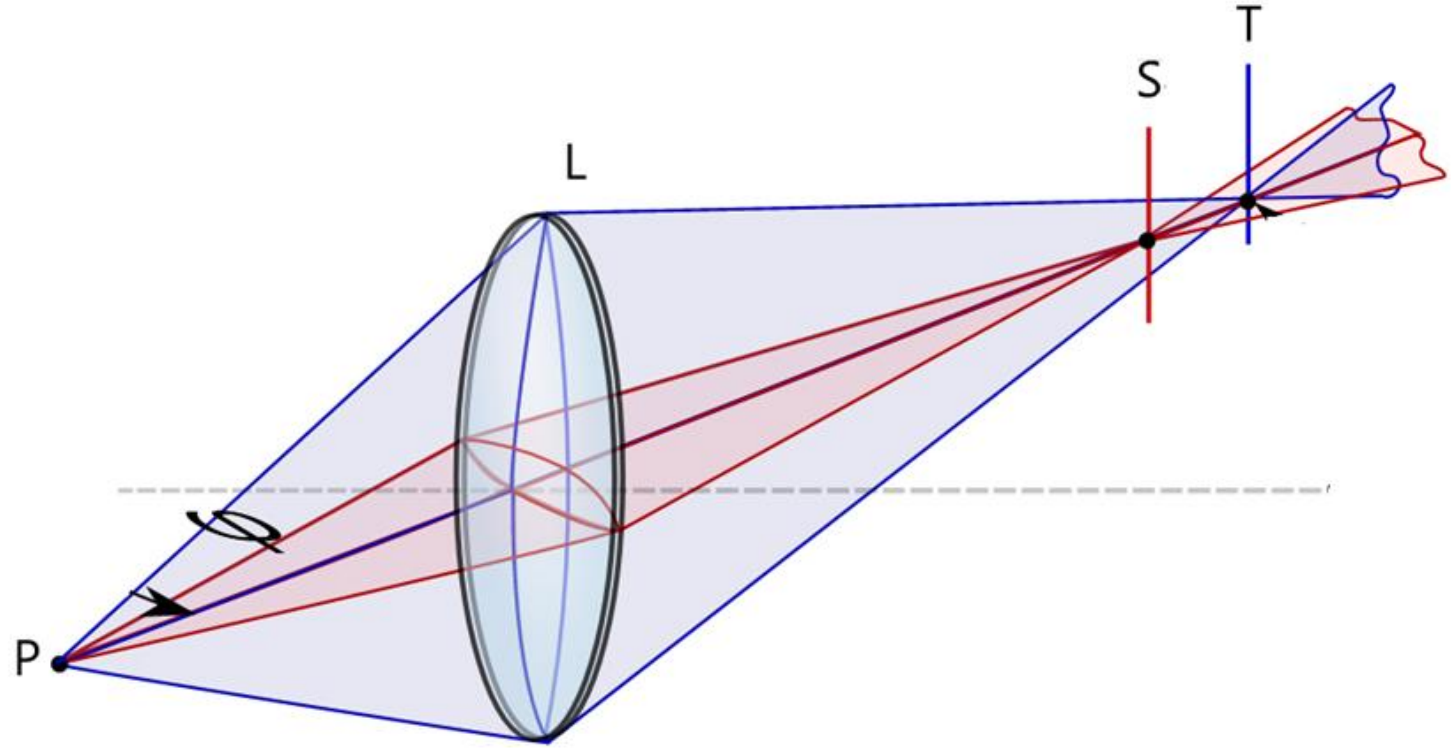
To correct coma,

- Change bending of the lens or
- Change the position and/or diameter of the aperture stop



Astigmatizm

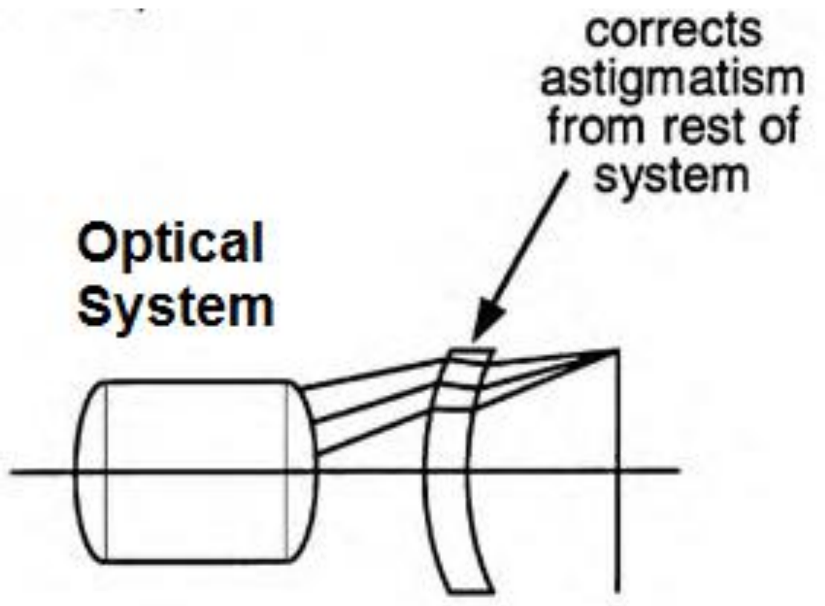
- Astigmatism is another off-axis aberration.
- Tangential and Sagital rays for oblique rays are focused at dierent points.



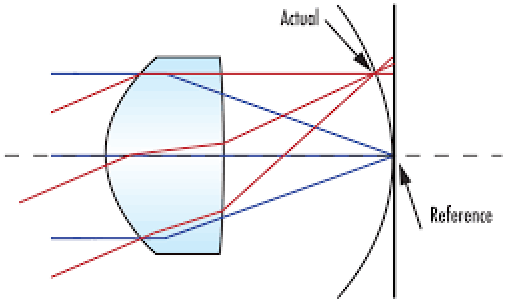
Astigmatizm

To correct or reduce astigmatizm

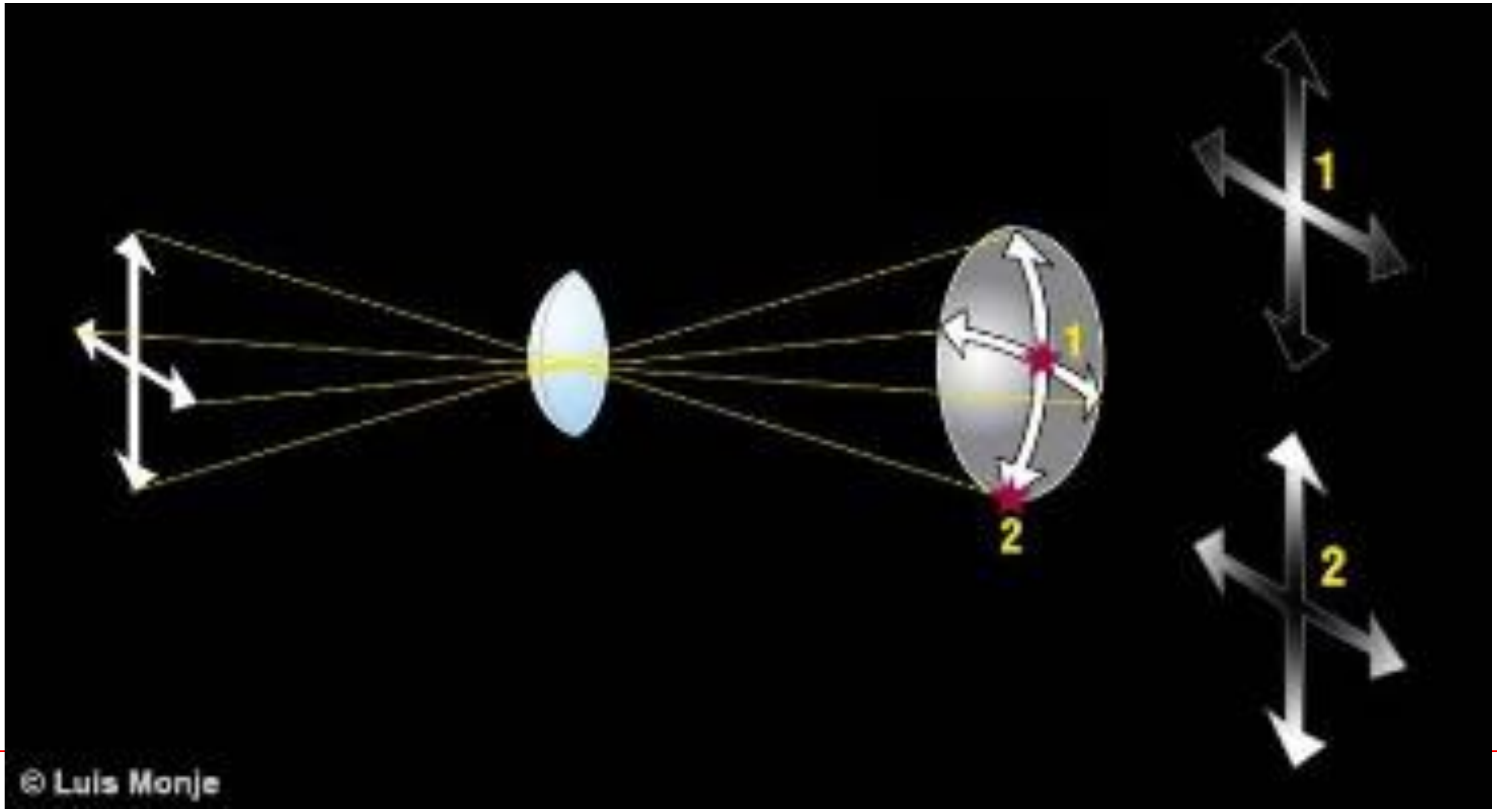
- Change the shape of the lens
- Change its distance from the aperture stop
- Use spaced doublet lens with stop in center
- Place a weak menuscus lens before image plane



Field Curvature



- For a light ray comes from off-axis, a positive lens appears to be thicker than really it is.
- As a results, for oblique rays we have different focal lengths.
- The points on a plane object, then form a curved image, a deciency is called **field curvature.**
- This aberration is important in camera systems and projectors: **image is expected to be flat**.



Field Curvature

To correct curvature of field (known as Field flattening)

- Change the position and/or diameter of the aperture stop.
- Try to obey the Petzval Condition in your system, that is:

$$\textbf{Petzval sum} = P = n_m \sum_{i=1}^{m} \frac{n_i - n_{i-1}}{n_i n_{i-1} R_i} = 0$$

n_{i-1} and n_i	are refractive indexes before and after the surface number i.
R_i	is the radius of curvature of the surface number i.
m	is the surface number of image surface.
n_m	is the index of image surface

For a system of thin lenses of focal lengths f_i the Petzval sum is given by: $P = \sum_{i=1}^{m} \frac{1}{n_i f_i} = 0$

*In Zemax help, see operands: **PETC** and **PETZ** and topic **Petzval Radius**.*

Distortion

- Distortion occurs as variation in the lateral magnication.
- If the magnication decreases with distance from the axis, the images appears as barrel distortion.
- If the magnication increases with the from axis, the image appears as pincushion distortion.
- Distortion increases with the cube of the field of view.

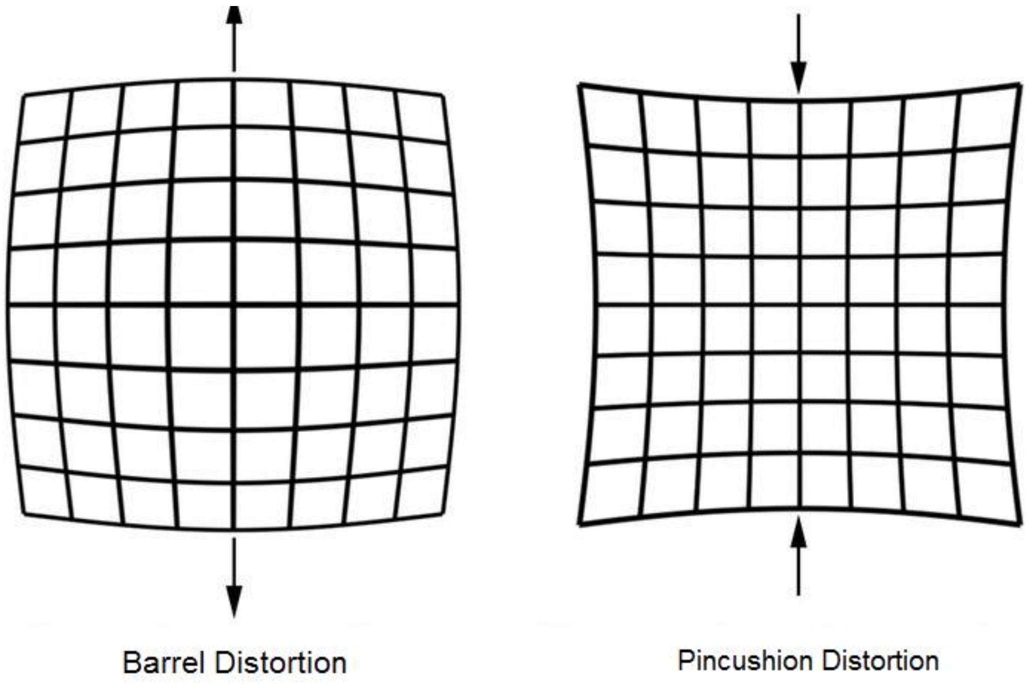
- Distortion is defined as

$$D = \frac{y - y_p}{y_p}$$

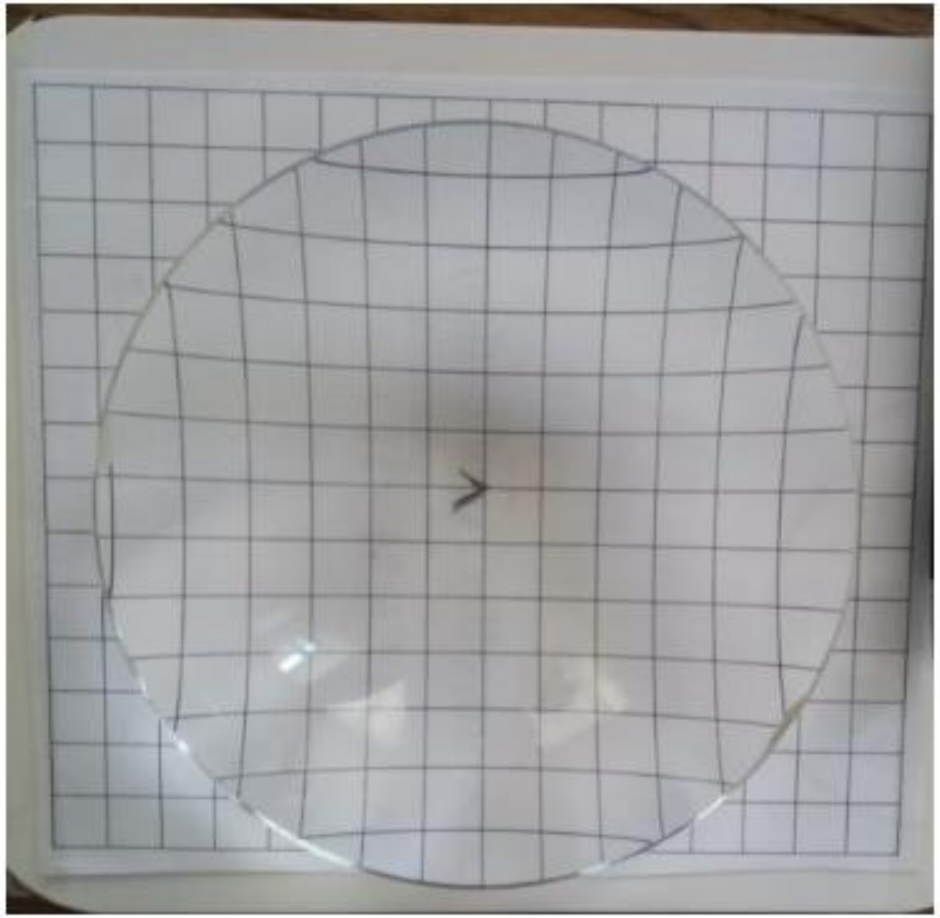
y is the height in the image plane

y_p is the paraxial height

Generally, distortion in the order of 2-3% is acceptable visually.



Distortion

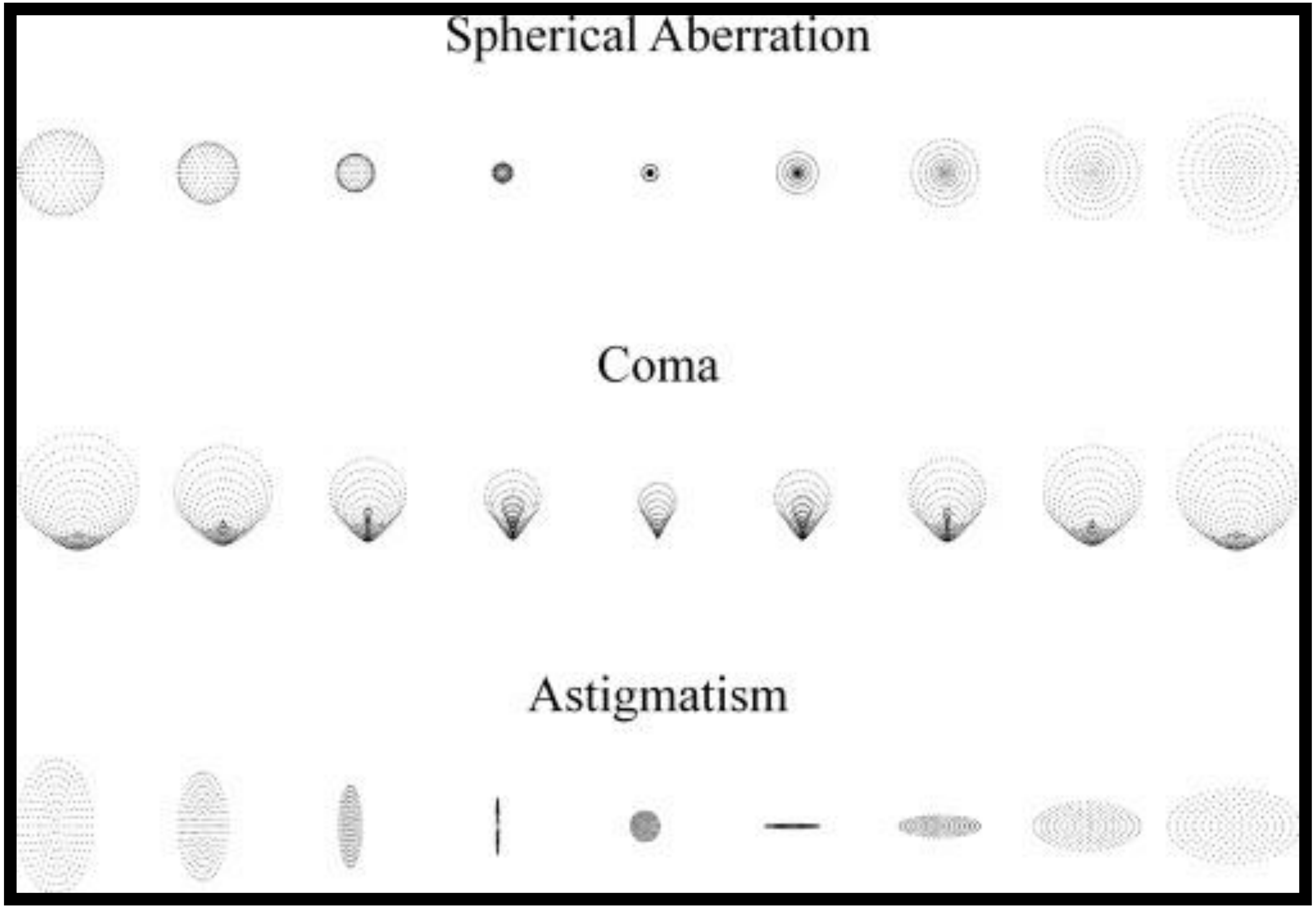


Distortion

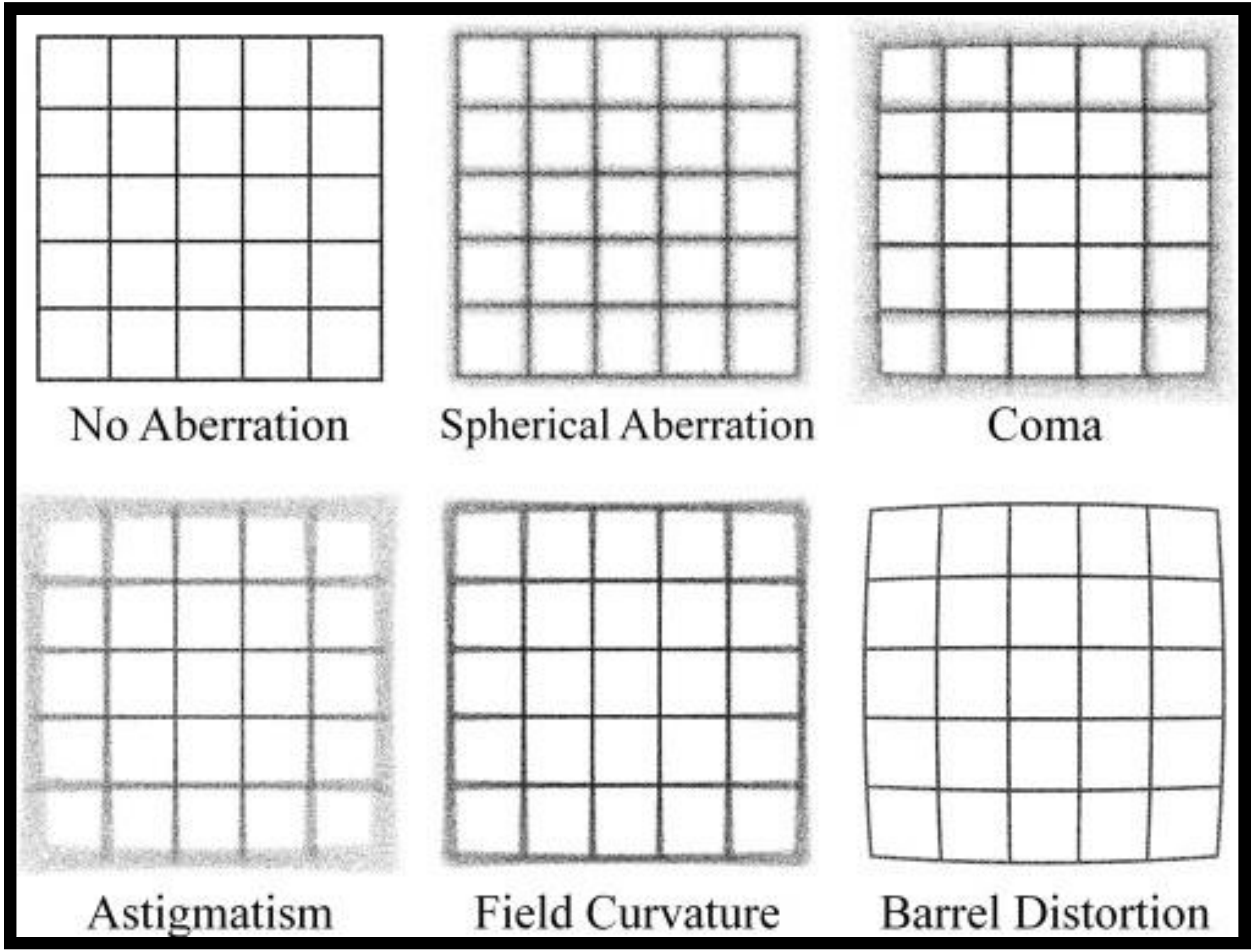
To correct or reduce distortion

- Change the shape of the lens.
- Change the position of the aperture stop.
- Use spaced doubled lens system after placing aperture stop in the center of the system.
- Use image processing softwares in digital systems.

Typical Spot Diagrams



Sasián, J. (2012). Ray aberrations. In *Introduction to Aberrations in Optical Imaging Systems* (pp. 100-118). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511795183.012



Sasián, J. (2012). Ray aberrations. In *Introduction to Aberrations in Optical Imaging Systems* (pp. 100-118). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511795183.012

Example 3: Aperture Size and Position

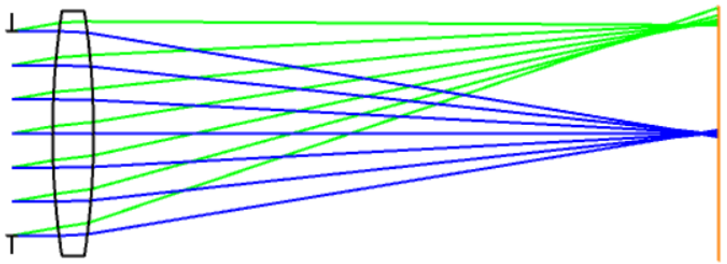
In this example, we will investigate the effect of aperture size and postion on the monochromatic aberrations for the demo example.

(λ = 550 nm, ENPD = 25 mm, SFOV = 0^{o} and 10^{o}).

Lens Data

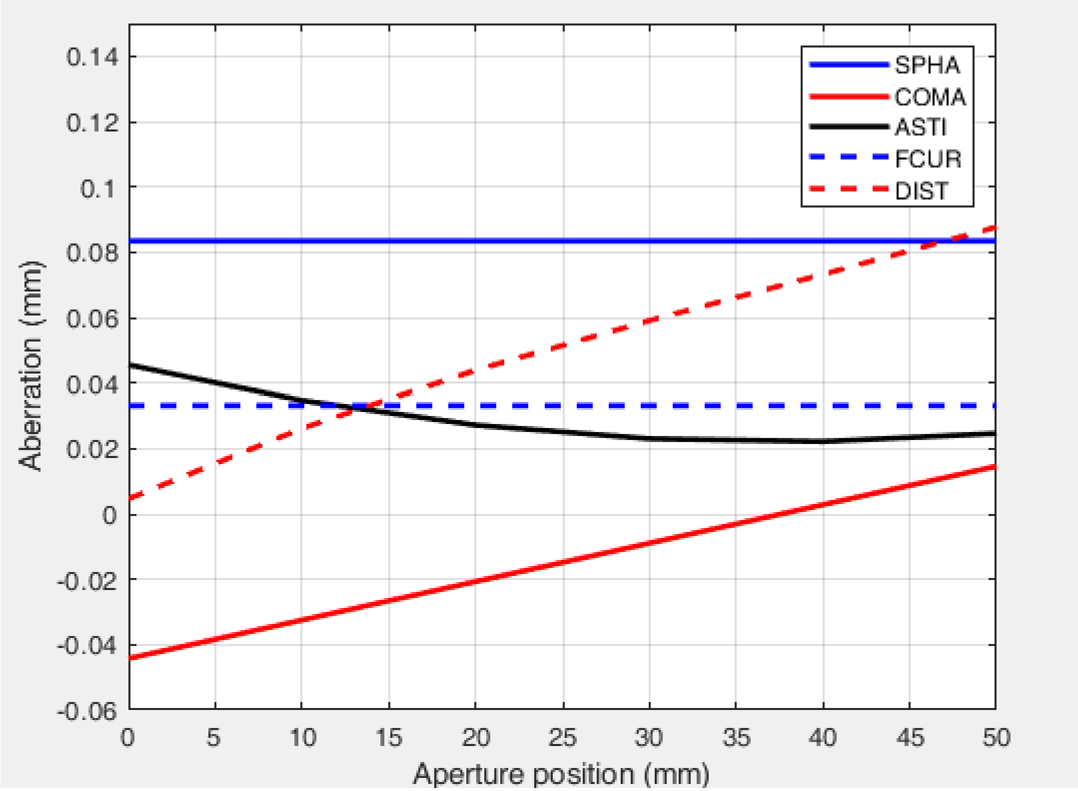
Surface 4 Properties — Configuration 1/1

	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia
0	OBJECT	Standard		Infinity	Infinity			Infinity	0,000	Infinity
1	STOP	Standard		Infinity	5,000			12,500	0,000	12,500
2	(aper)	Standard		100,000	5,000	N-SF2		15,000 U	0,000	15,000
3	(aper)	Standard		-100,000	76,431 M			15,000 U	0,000	15,000
4	IMAGE	Standard		Infinity	-			15,672	0,000	15,672



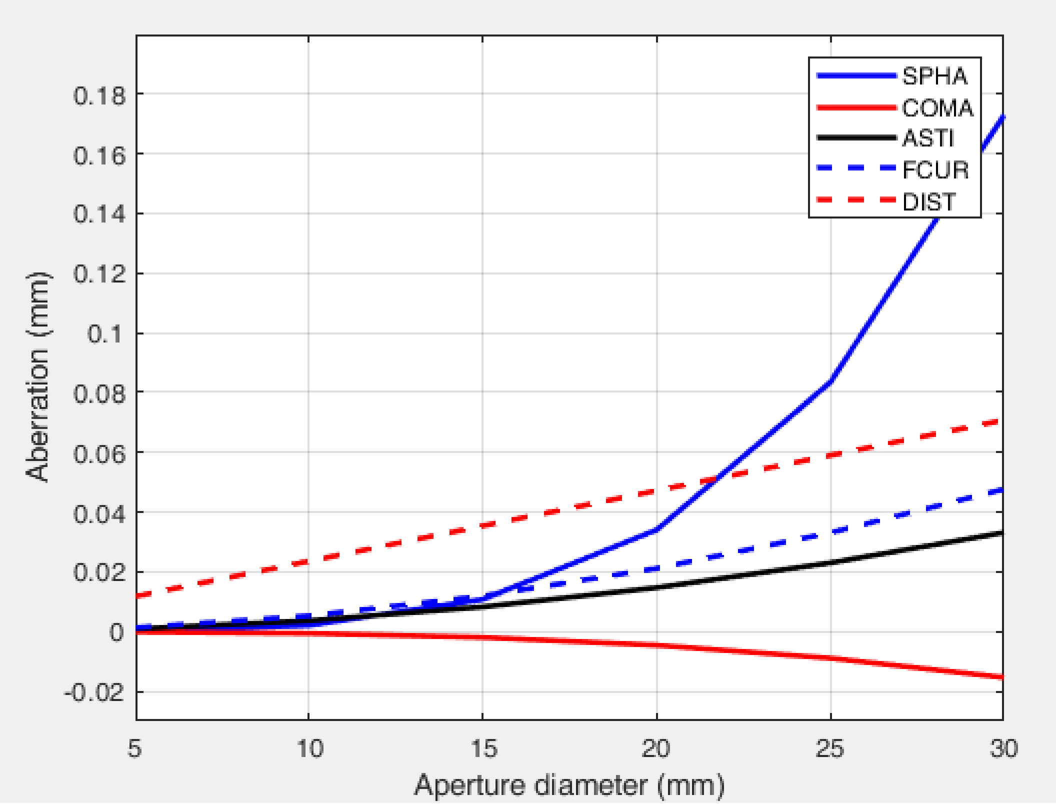
First, change the positon of STOP from 0 to 50 mm with step 10 mm.
Extract the Seidel coeffcients (Total value on image plane).

position	SPHA	COMA	ASTI	FCUR	DIST
0	0.083460	-0.044210	0.045543	0.033177	0.004688
10	0.083460	-0.032437	0.034731	0.033177	0.026236
20	0.083460	-0.020664	0.027241	0.033177	0.043912
30	0.083460	-0.008891	0.023071	0.033177	0.059120
40	0.083460	0.002882	0.022224	0.033177	0.073267
50	0.083460	0.014655	0.024697	0.033177	0.087758



Second, change the diameter of STOP from 5 to 25 mm with step 5 mm for the stop position 30 mm in front of the lens. Extract the Seidel coeffcients (Total value on image plane).

diameter	SPHA	COMA	ASTI	FCUR	DIST
5	0.000134	-0.000071	0.000923	0.001327	0.011824
10	0.002137	-0.000569	0.003691	0.005308	0.023648
15	0.010816	-0.001921	0.008306	0.011944	0.035472
20	0.034185	-0.004552	0.014766	0.021233	0.047296
25	0.083460	-0.008891	0.023071	0.033177	0.059120
30	0.173063	-0.015364	0.033223	0.047775	0.070944

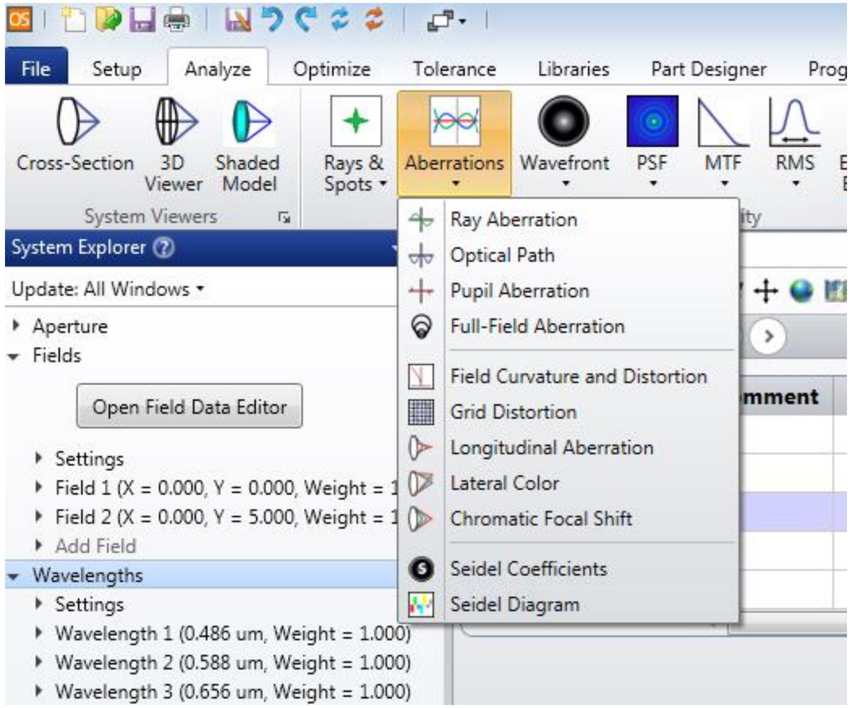


Summary of Monochomatic Aberrations

Summary of Third-Order Monochromatic Aberration Dependence on Aperture and Field Angle

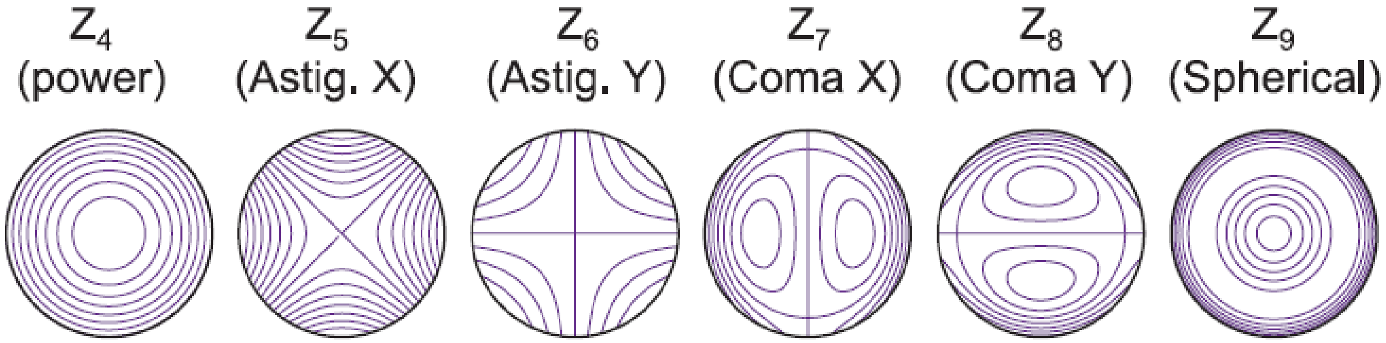
Aberration	Aperture Dependence	Field Dependence
Spherical	Cubic	—
Coma	Quadratic	Linear
Astigmatism	Linear	Quadratic
Field curvature	Linear	Quadratic
Distortion	—	Cubic

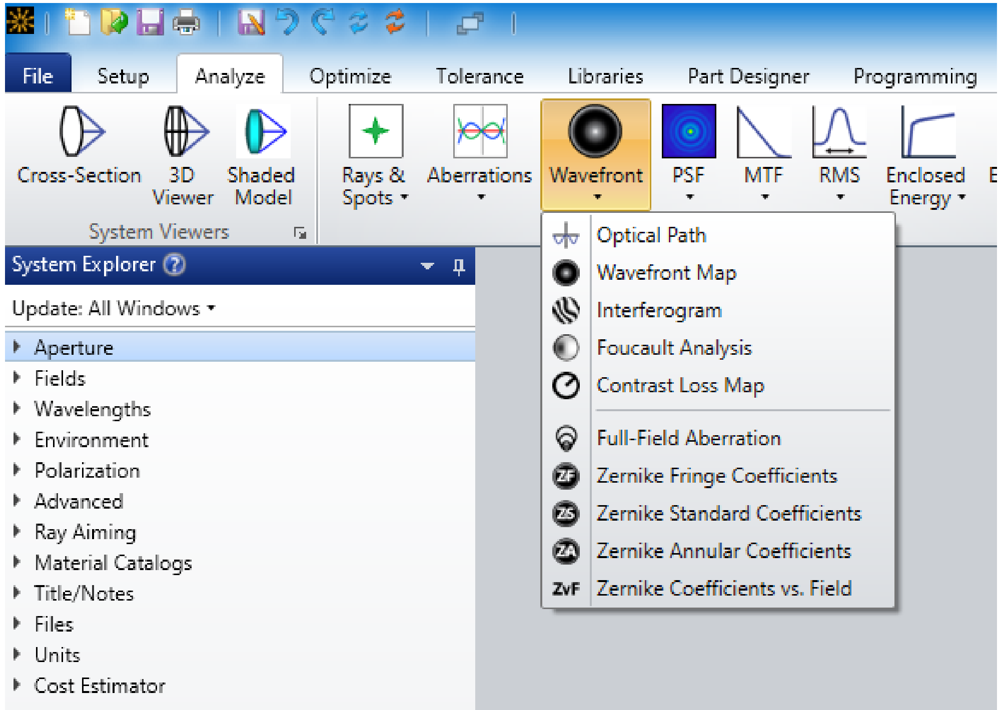
Aberration Performance Plots
in Zemax OpticStudio



Zernike Polynomials

Zernike polynomials are a set of circularly symmetric orthogonal basis functions defined over a unit circle. They are 2D functions of both radial and azimuthal coordinates. In optical design, Zernikes are used to describe either surface irregularity or system wavefront (measured in the pupil).





See additional documents on the course web page.

http://www1.gantep.edu.tr/~bingul/opac202/docs/A1-zernike_polynomials.pdf