



EPFL

MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 4

30.09.2024

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Sciences et techniques de l'ingénieur
École Polytechnique Fédérale de Lausanne
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Outline

Theory

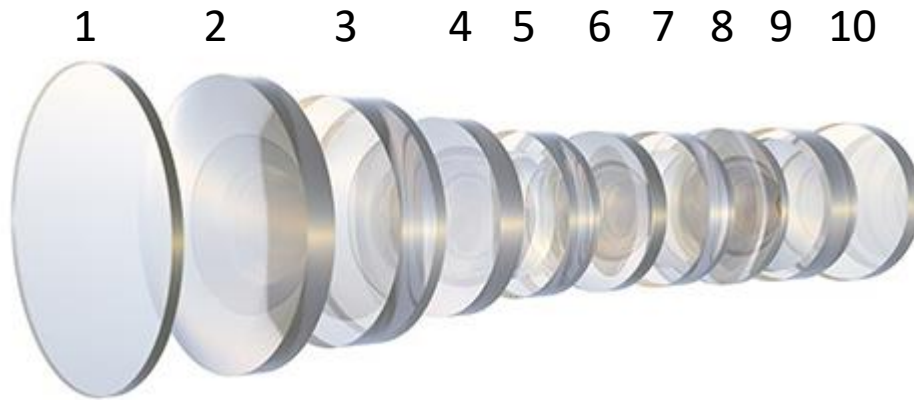
- Review of aperture and field
- Wave aberration function
- Seidel aberration coefficients
- Spot diagrams and images under aberrations

ZEMAX Practice

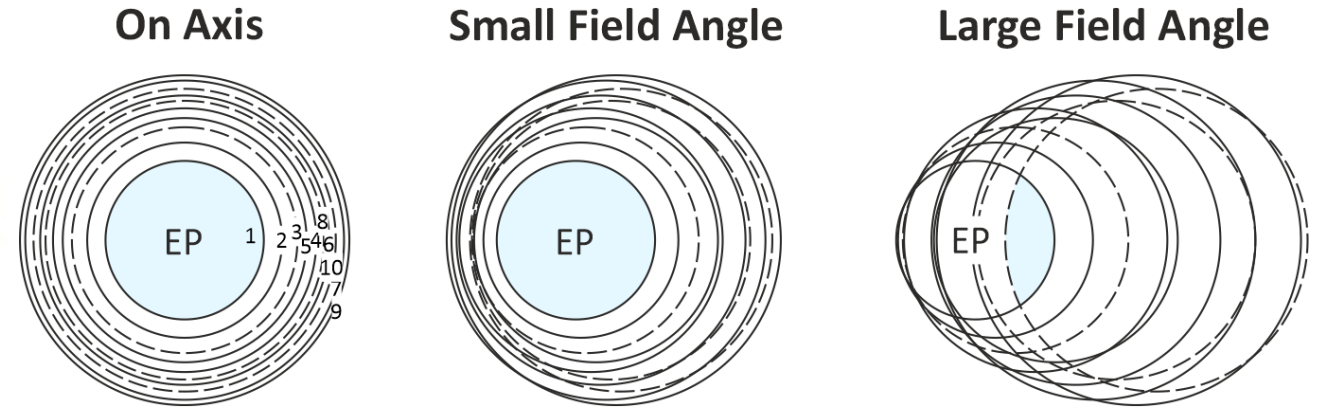
- Aberration assessment

Review of Aperture, Field, and Vignetting

Axially symmetric optical system



Images of lens edges



Theory of Aberrations

Learning approach

- Historically, the understanding of aberrations progressed from particular to general
- For learning, it is best to begin from general to particular
- Ways to describe optical aberrations
 - **Wave aberration function**
 - Angular ray aberration
 - Transverse ray aberration
 - Longitudinal ray aberration

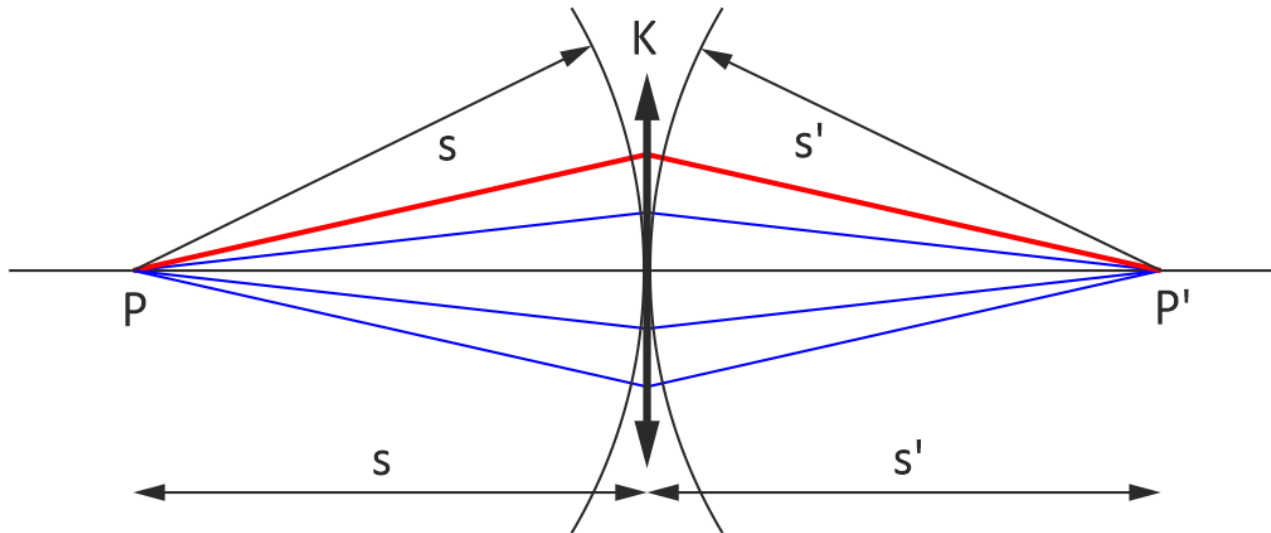
Heuristics from axial symmetry

- **On-axis object point:** only have an axially symmetric wavefront deformation (quadratic, quartic, ...) with respect to the aperture
- **Off-axis object point:** axial symmetry in the wavefront deformation is reduced to plane or double plane symmetry

Paraxial Imaging Condition

Modeling imaging process

- **Objects:** composed of numerous abstract points
- **Each point:** a spherical wave front emanating from that point
- **Each image:** a spherical wave front converging to or diverging from the image point
- **Aberrations:** deviations (errors) from the spherical wave front



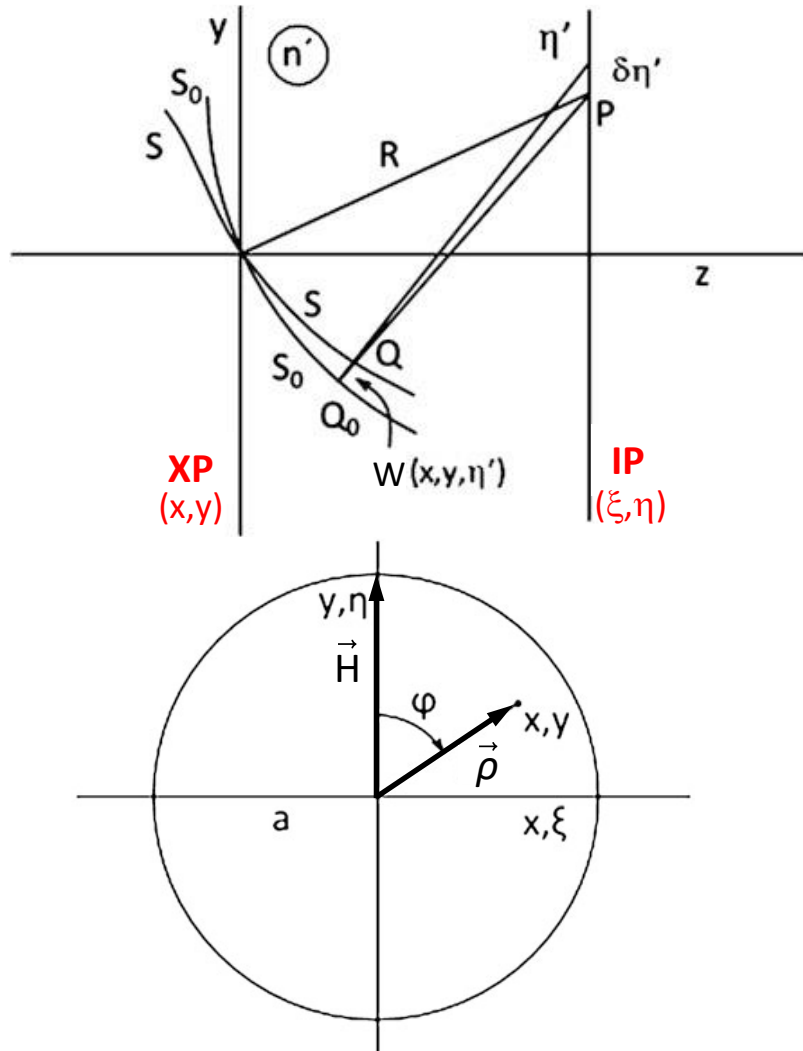
Fermat's Principle

Optical Path Length (OPL) = constant

$$\frac{1}{s'} - \frac{1}{s} = \frac{1}{f} \quad \Rightarrow \quad c' = K + c$$

$$c = \frac{1}{s} \quad c' = \frac{1}{s'} \quad K = \frac{1}{f}$$

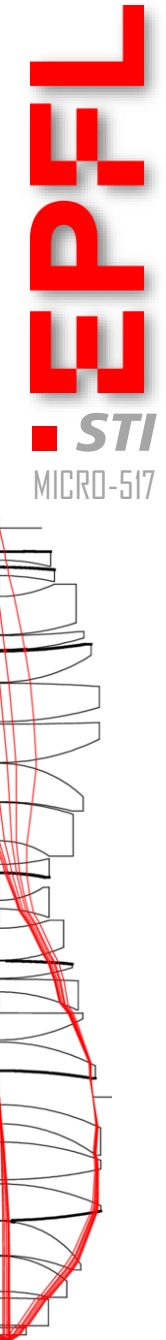
Wave Fronts and Aberrations



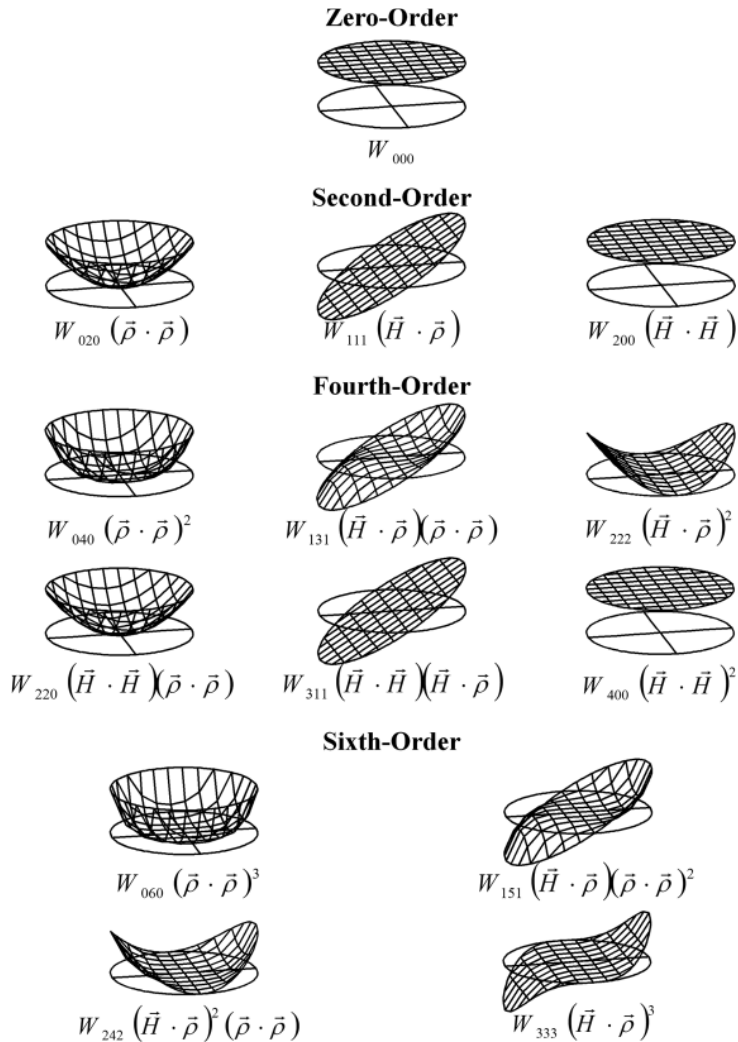
Wave aberration function: $W(\vec{H}, \vec{\rho})$ **Wave front error RMS**
 $\vec{H}$ Normalized field vector $\vec{\rho}$ Normalized aperture vector

Power expansion up to the 6th order

$$\begin{aligned}
 W(\vec{H}, \vec{\rho}) &= \sum_{j,m,n} W_{k,l,m} (\vec{H} \cdot \vec{H})^j (\vec{H} \cdot \vec{\rho})^m (\vec{\rho} \cdot \vec{\rho})^n \\
 &= W_{000} + W_{200}(\vec{H} \cdot \vec{H}) + W_{111}(\vec{H} \cdot \vec{\rho}) + W_{020}(\vec{\rho} \cdot \vec{\rho}) \\
 &\quad + W_{040}(\vec{\rho} \cdot \vec{\rho})^2 + W_{131}(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho}) + W_{222}(\vec{H} \cdot \vec{\rho})^2 \\
 &\quad + W_{220}(\vec{H} \cdot \vec{H})(\vec{\rho} \cdot \vec{\rho}) + W_{311}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho}) + W_{400}(\vec{H} \cdot \vec{H})^2 \\
 &\quad + W_{240}(\vec{H} \cdot \vec{H})(\vec{\rho} \cdot \vec{\rho})^2 + W_{331}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho}) \\
 &\quad + W_{422}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho})^2 \\
 &\quad + W_{420}(\vec{H} \cdot \vec{H})^2(\vec{\rho} \cdot \vec{\rho}) + W_{511}(\vec{H} \cdot \vec{H})^2(\vec{H} \cdot \vec{\rho}) + W_{600}(\vec{H} \cdot \vec{H})^3 \\
 &\quad + W_{060}(\vec{\rho} \cdot \vec{\rho})^3 + W_{151}(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho})^2 + W_{242}(\vec{H} \cdot \vec{\rho})^2(\vec{\rho} \cdot \vec{\rho}) \\
 &\quad + W_{333}(\vec{H} \cdot \vec{\rho})^3
 \end{aligned}$$



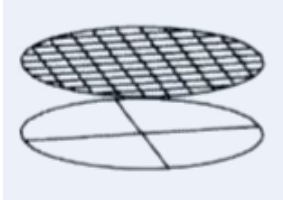
Wave Fronts and Aberrations



Aberration name	Vector form	Algebraic form	j	m	n
<i>Zero order</i>					
Uniform piston	W_{000}	W_{000}	0	0	0
<i>Second order</i>					
Quadratic piston	$W_{200}(\vec{H} \cdot \vec{H})$	$W_{200}H^2$	1	0	0
Magnification	$W_{111}(\vec{H} \cdot \vec{\rho})$	$W_{111}H\rho \cos(\phi)$	0	1	0
Focus	$W_{020}(\vec{\rho} \cdot \vec{\rho})$	$W_{020}\rho^2$	0	0	1
<i>Fourth order</i>					
Spherical aberration	$W_{040}(\vec{\rho} \cdot \vec{\rho})^2$	$W_{040}\rho^4$	0	0	2
Coma	$W_{131}(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho})$	$W_{131}H\rho^3 \cos(\phi)$	0	1	1
Astigmatism	$W_{222}(\vec{H} \cdot \vec{\rho})^2$	$W_{222}H^2\rho^2 \cos^2(\phi)$	0	2	0
Field curvature	$W_{220}(\vec{H} \cdot \vec{H})(\vec{\rho} \cdot \vec{\rho})$	$W_{220}H^2\rho^2$	1	0	1
Distortion	$W_{311}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho})$	$W_{311}H^3\rho \cos(\phi)$	1	1	0
Quartic piston	$W_{400}(\vec{H} \cdot \vec{H})^2$	$W_{400}H^4$	2	0	0
<i>Sixth order</i>					
Oblique spherical aberration	$W_{240}(\vec{H} \cdot \vec{H})(\vec{\rho} \cdot \vec{\rho})^2$	$W_{240}H^2\rho^4$	1	0	2
Coma	$W_{331}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho})$	$W_{331}H^3\rho^3 \cos(\phi)$	1	1	1
Astigmatism	$W_{422}(\vec{H} \cdot \vec{H})(\vec{H} \cdot \vec{\rho})^2$	$W_{422}H^4\rho^2 \cos^2(\phi)$	1	2	0
Field curvature	$W_{420}(\vec{H} \cdot \vec{H})^2(\vec{\rho} \cdot \vec{\rho})$	$W_{420}H^4\rho^2$	2	0	1
Distortion	$W_{511}(\vec{H} \cdot \vec{H})^2(\vec{H} \cdot \vec{\rho})$	$W_{511}H^5\rho \cos(\phi)$	2	1	0
Piston	$W_{600}(\vec{H} \cdot \vec{H})^3$	$W_{600}H^6$	3	0	0
Spherical aberration	$W_{060}(\vec{\rho} \cdot \vec{\rho})^3$	$W_{060}\rho^6$	0	0	3
Un-named	$W_{151}(\vec{H} \cdot \vec{\rho})(\vec{\rho} \cdot \vec{\rho})^2$	$W_{151}H\rho^5 \cos(\phi)$	0	1	2
Un-named	$W_{242}(\vec{H} \cdot \vec{\rho})^2(\vec{\rho} \cdot \vec{\rho})$	$W_{242}H^2\rho^4 \cos^2(\phi)$	0	2	1
Un-named	$W_{333}(\vec{H} \cdot \vec{\rho})^3$	$W_{333}H^3\rho^3 \cos^3(\phi)$	0	3	0

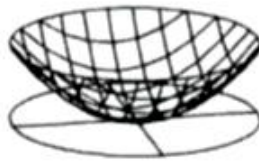
Lower-order Wave Aberration Function Terms

Zero-order

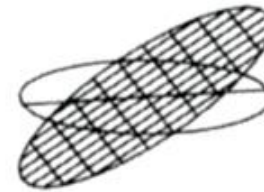


W_{000}
Piston

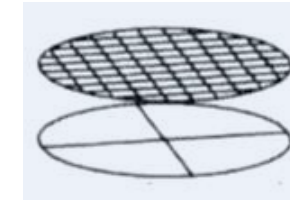
Second-order



$W_{020}\rho^2$
Defocus

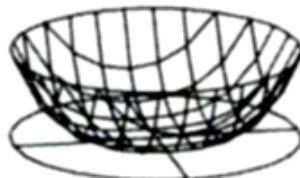


$W_{111}H\rho\cos\varphi$
Tilt

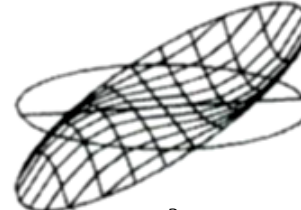


$W_{200}H^2$
Quadratic piston

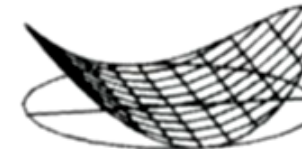
Fourth-order



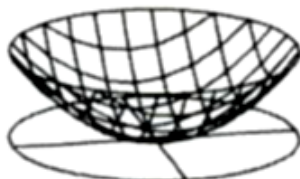
$W_{040}\rho^4$
Spherical



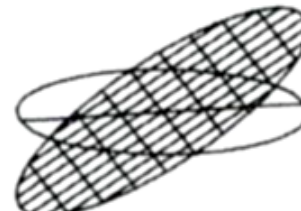
$W_{131}H\rho^3\cos\varphi$
Coma



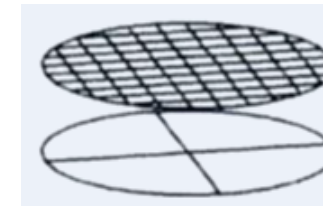
$W_{222}H^2\rho^2\cos^2\varphi$
Astigmatism



$W_{220}H^2\rho^2$
Field Curvature



$W_{311}H^3\rho\cos\varphi$
Distortion

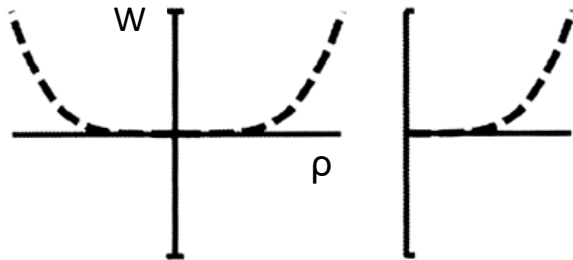


$W_{400}H^4$
Quartic piston

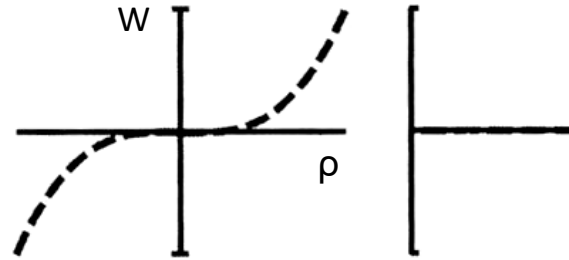
**Seidel
Aberrations**

Wave Fan Plot

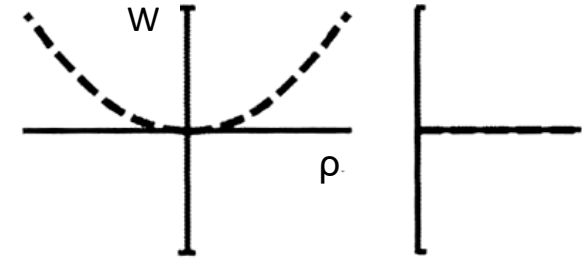
Wave fan: plot of wave front aberration vs the normalized pupil coordinate ρ in the tangential and sagittal planes. The field (H) dependence is not shown explicitly (H changes the scale of the wave fan but not the shape).



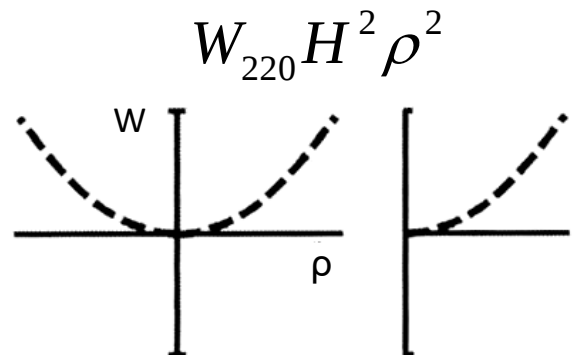
$$W_{040}\rho^4$$



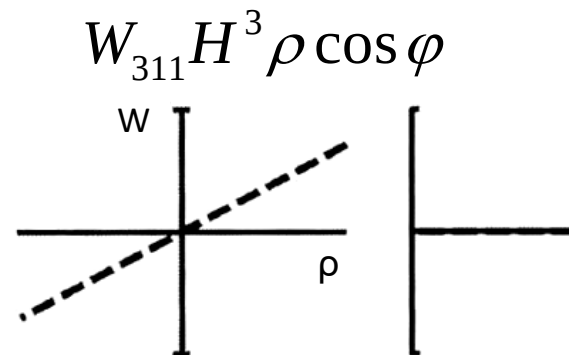
$$W_{131}H\rho^3\cos\varphi$$



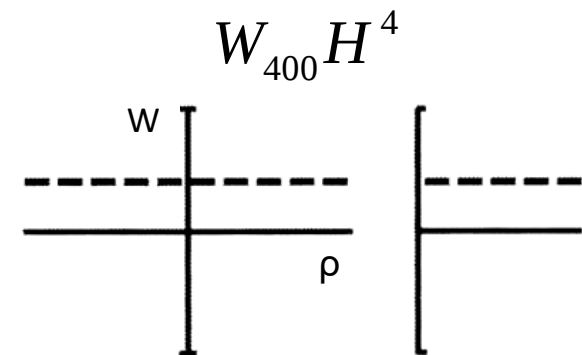
$$W_{222}H^2\rho^2\cos^2\varphi$$



$$W_{220}H^2\rho^2$$

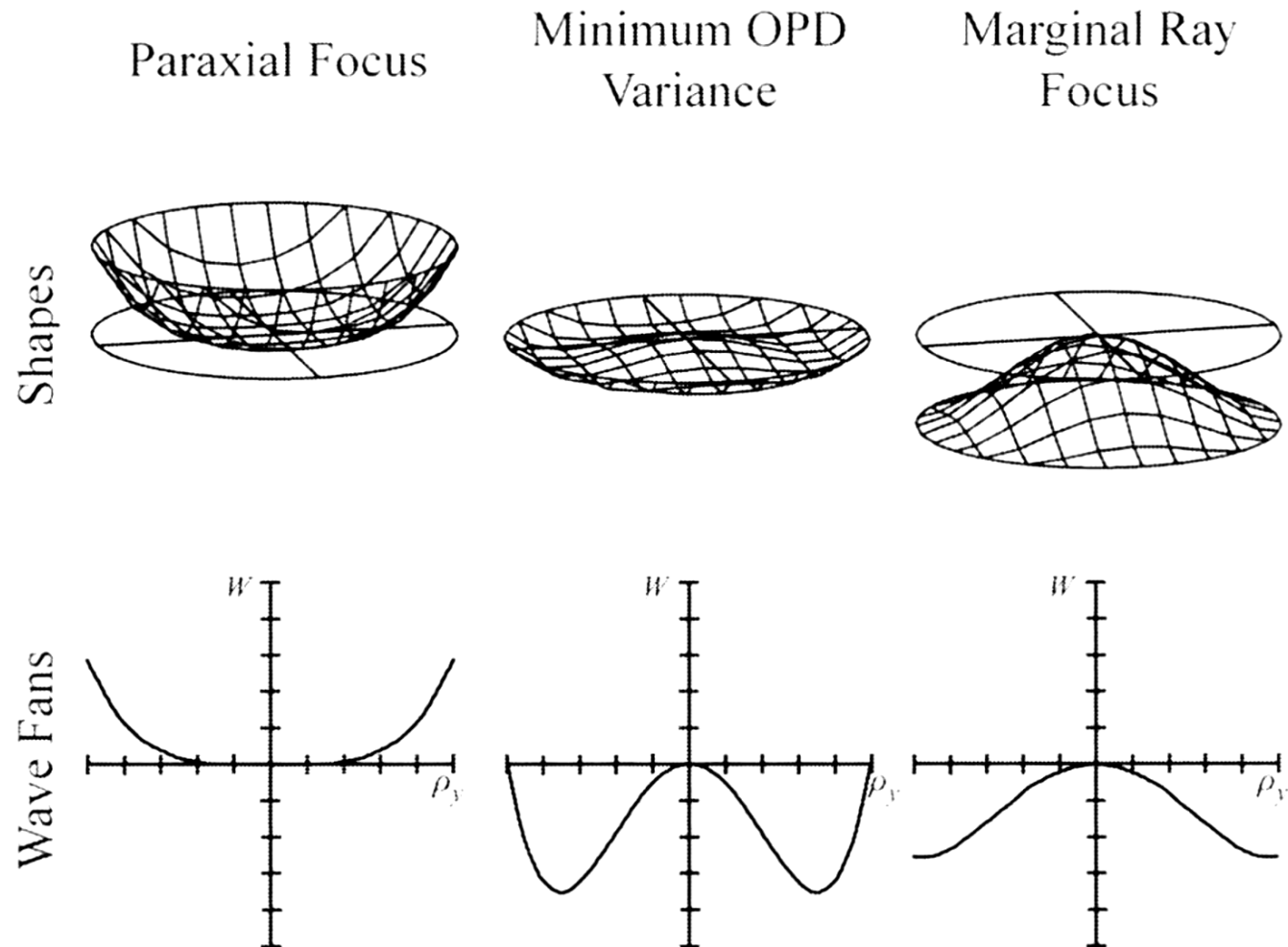


$$W_{311}H^3\rho\cos\varphi$$



$$W_{400}H^4$$

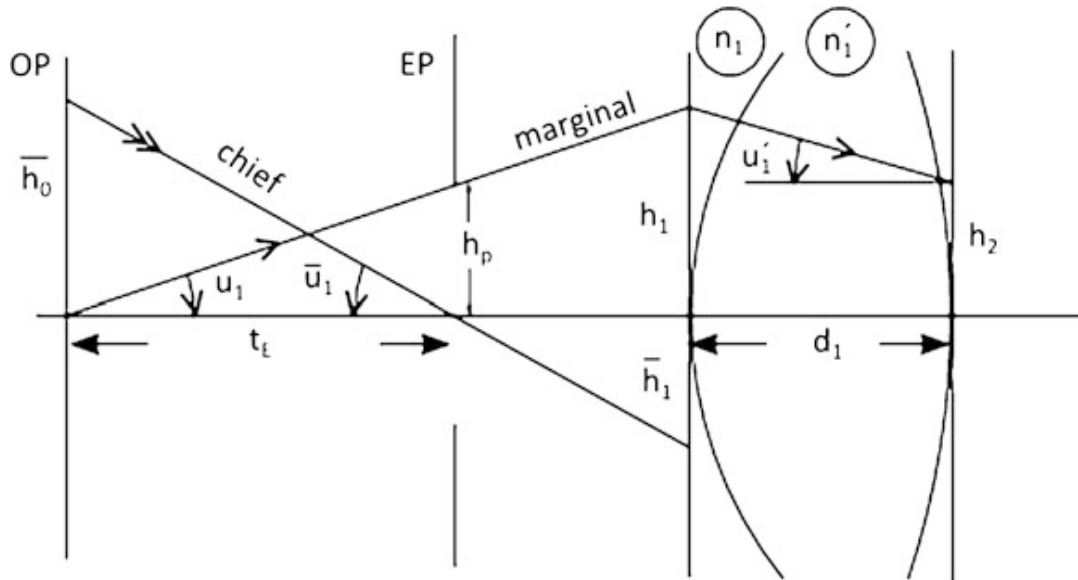
Spherical Aberration Balanced with Defocus



Seidel Coefficients

Calculation

Trace a marginal ray and a chief ray through the system, using the paraxial ray tracing equations, at surface i



$$A_i = n_i i_i = n'_i i'_i = n_i \left(u_i + \frac{h_i}{r_i} \right) \quad \bar{A}_i = n_i \bar{i}_i = n'_i \bar{i}'_i = n_i \left(\bar{u}_i + \frac{\bar{h}_i}{r_i} \right)$$

$$\Delta_i^{(u,n)} = \frac{u'_i}{n'_i} - \frac{u_i}{n_i} \quad \Delta_i^{(n)} = \frac{1}{n'_i} - \frac{1}{n_i}$$

Spherical: $S_{1,i} = -A_i^2 h_i \Delta_i^{(u,n)}$

Coma: $S_{2,i} = -A_i \bar{A}_i h_i \Delta_i^{(u,n)}$

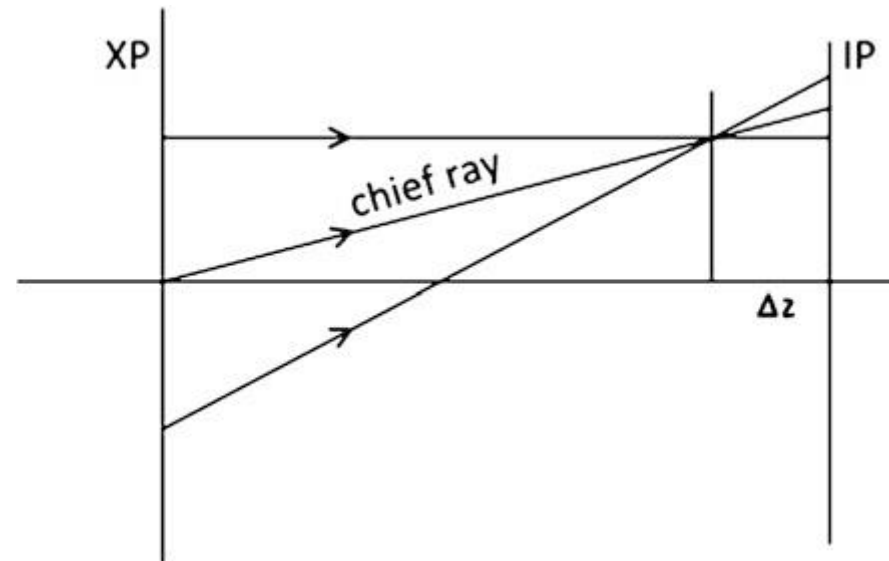
Astigmatism: $S_{3,i} = -A_i^2 h_i \Delta_i^{(u,n)}$

Field curvature: $S_{4,i} = -H^2 c_i \Delta_i^{(n)} \quad c_i = 1/r_i$

Distortion: $S_{5,i} = -\frac{\bar{A}_i}{A_i} (S_{3,i} + S_{4,i})$

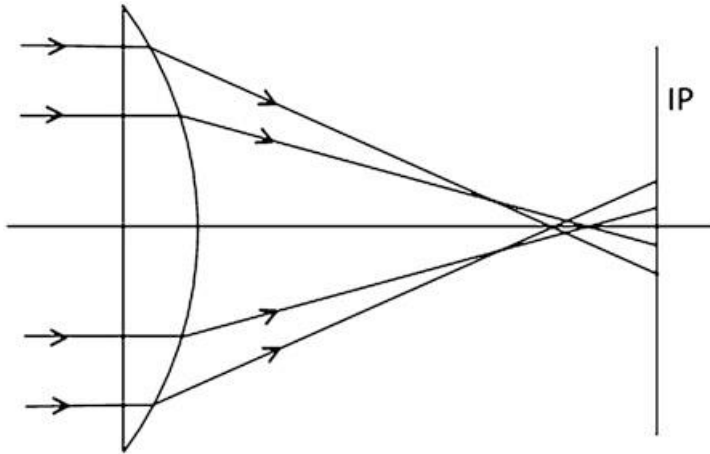
System level (Seidel sum): $S_m = \sum_i S_{m,i} \quad m = 1, 2, \dots, 5$

First-order Errors

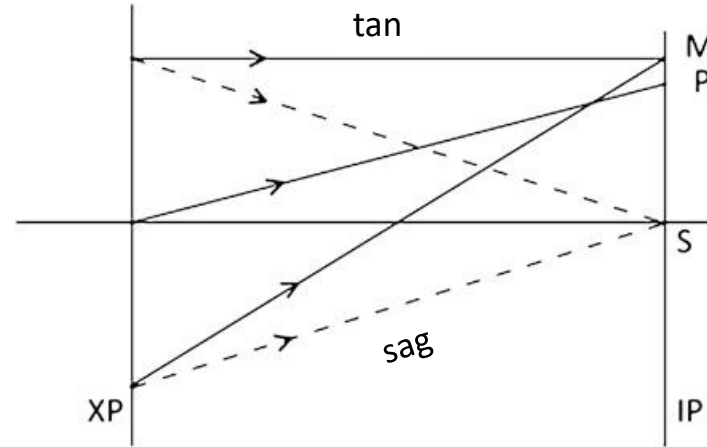


**Defocusing
Magnification**

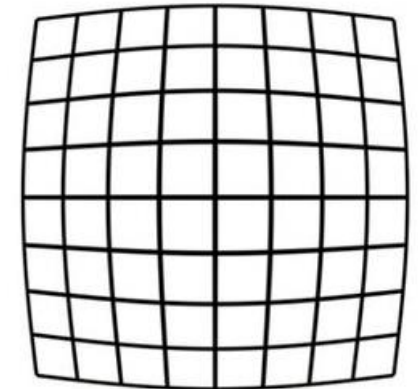
Third-order Aberrations



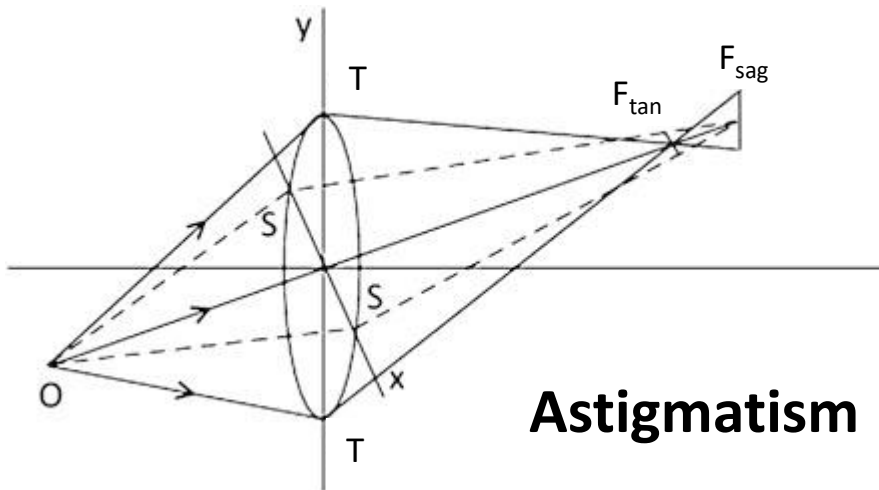
Spherical aberration



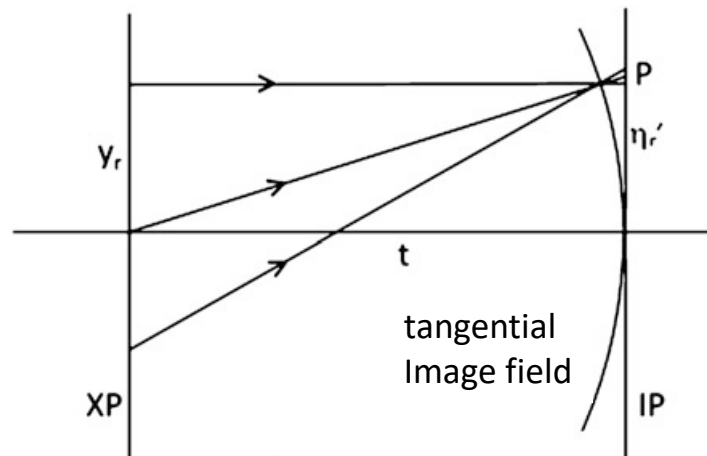
Coma



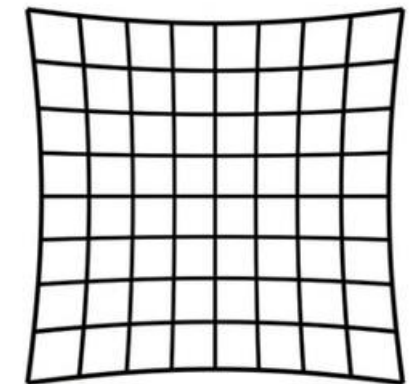
Barrel Distortion



Astigmatism



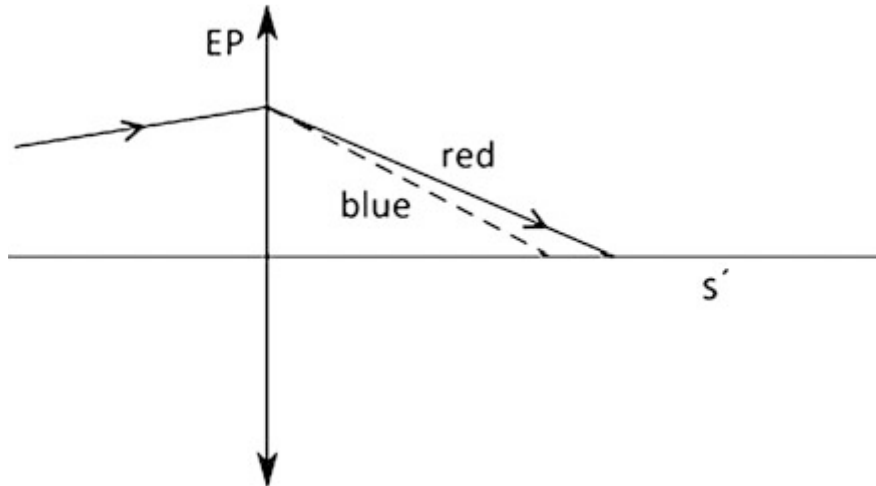
Field curvature



Pincushion Distortion

Distortion

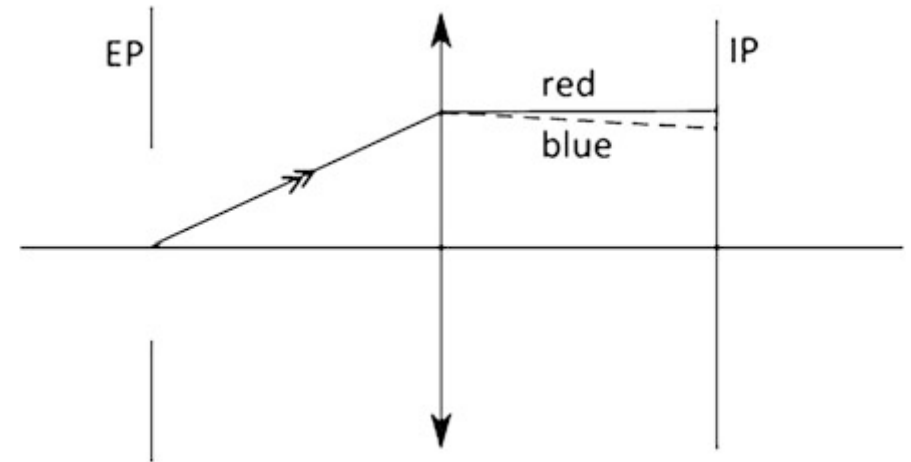
Chromatic Aberration



Longitudinal Chromatic Aberration

$$\frac{\delta s'}{s} = -\frac{\delta n}{n-1}$$

$$C_{1,i} = A_i h_i \Delta_i^{(n)}$$



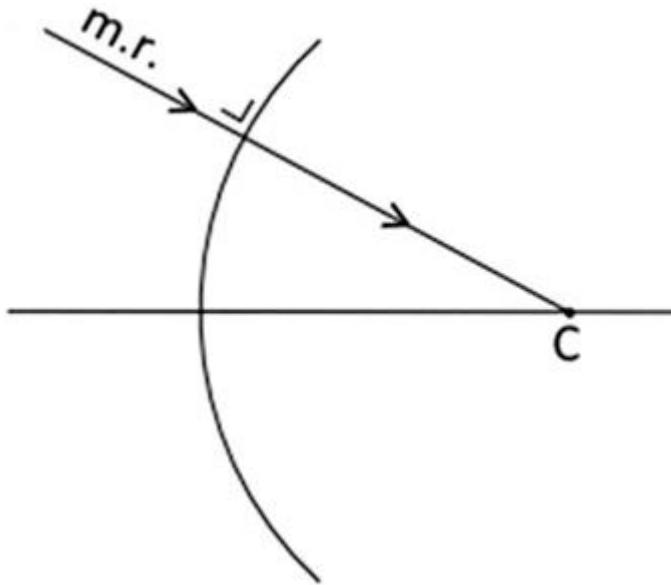
Transverse Chromatic Aberration

$$\frac{\delta M}{M} = -\frac{\delta n}{n-1}$$

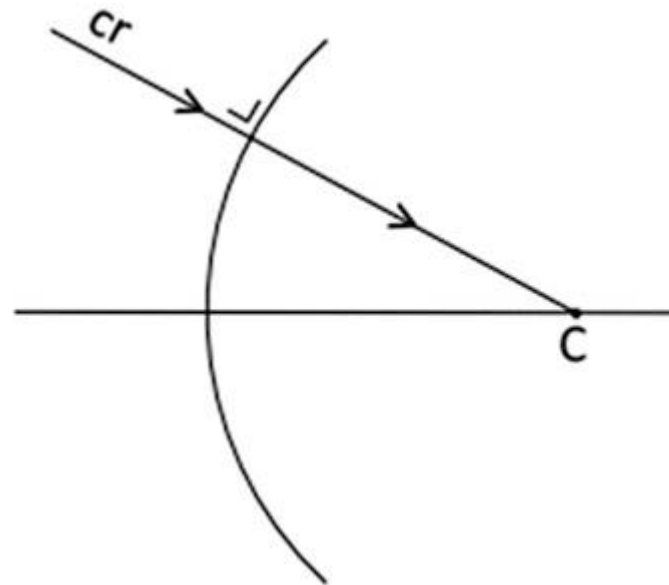
$$C_{2,i} = \bar{A}_i h_i \Delta_i^{(n)}$$

**Seidel
Coefficients**

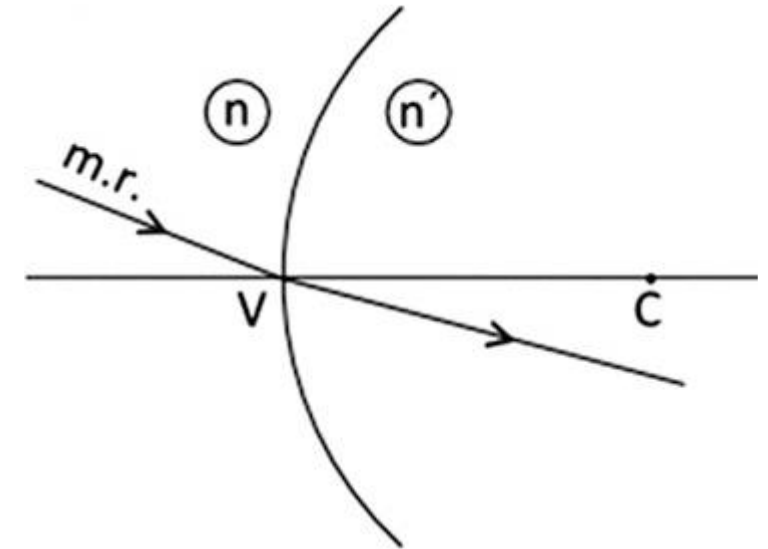
Zero-Seidel Conditions



$$\begin{aligned} A &= 0 \\ S_1 = S_2 &= 0 \\ C_1 &= 0 \end{aligned}$$



$$\begin{aligned} \bar{A} &= 0 \\ S_2 = S_3 = S_5 &= 0 \\ C_2 &= 0 \end{aligned}$$



$$\begin{aligned} h &= 0 \\ S_1 = S_2 = S_3 &= 0 \\ C_1 = C_2 &= 0 \end{aligned}$$

Zero-Seidel Conditions

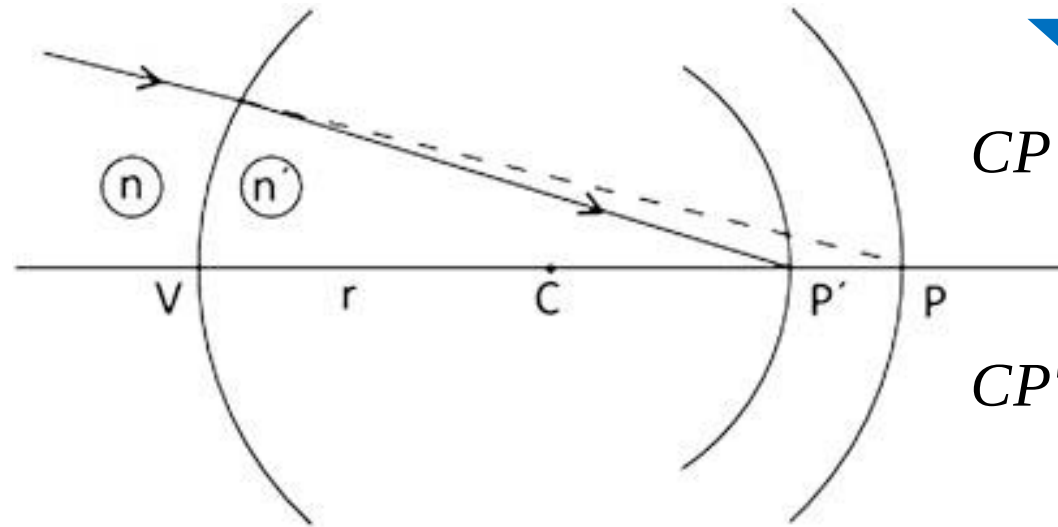
Aplanatic surface

$$s = r(1 + n'/n)$$



$$CP = \frac{n'}{n}r$$

$$CP' = \frac{n}{n'}r$$



$$\Delta^{(u,n)} = 0$$

$$S_1 = S_2 = S_3 = 0$$

Wave Aberration Function and Zernike Coefficients

Zernike Polynomial

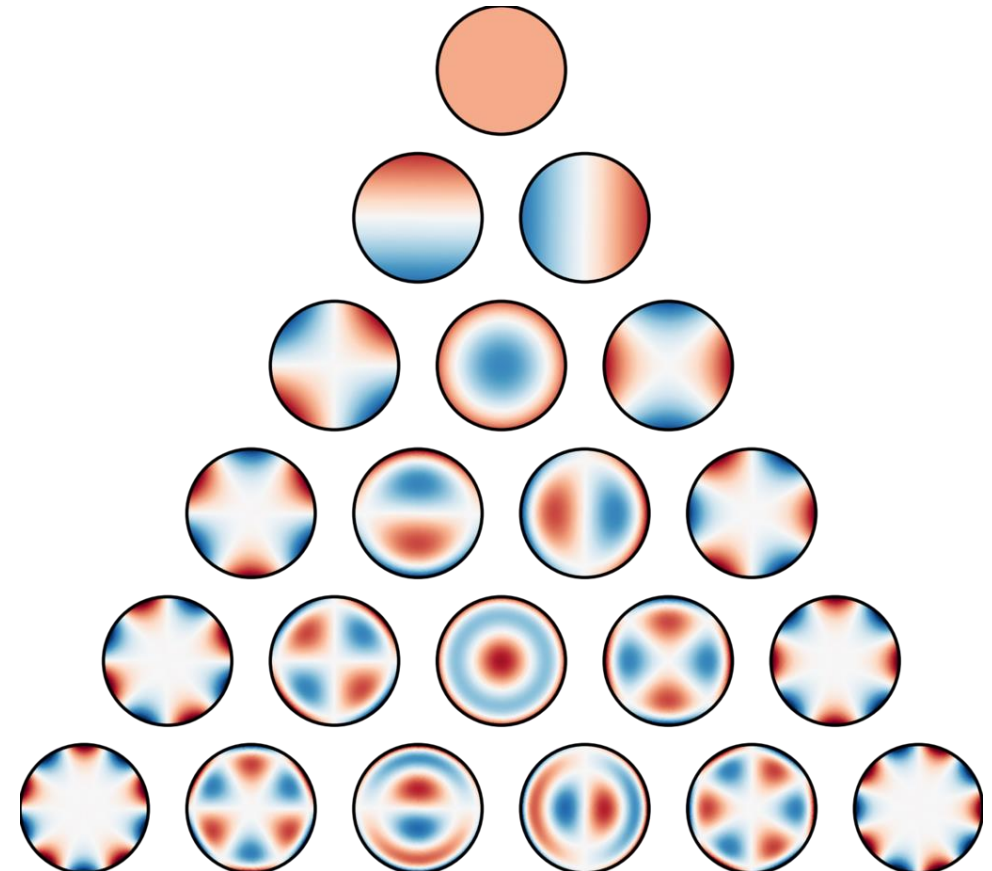
$$Z_n^m(\rho, \varphi) = R_n^m(\rho) \cos m\varphi \quad m \geq 0$$

$$Z_n^{-m}(\rho, \varphi) = R_n^m(\rho) \sin m\varphi \quad m < 0$$

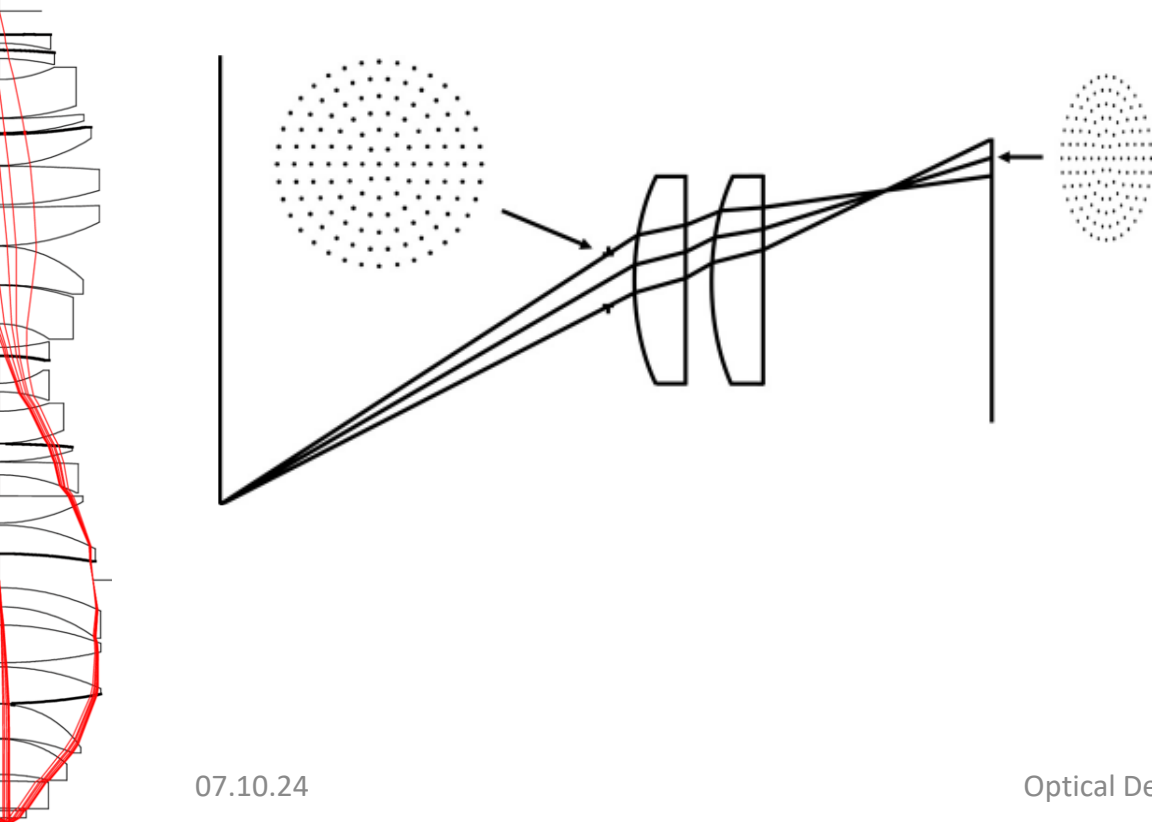
$$W(\rho, \varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^n c_{nm} Z_n^m(\rho, \varphi)$$

- Orthogonal over the continuous unit circle.
- Continuity of derivatives
- Representation of common wave front errors
- Completeness (represent arbitrarily complex continuous surfaces)

The first 21 Zernike polynomials



Spot Diagrams



Spherical Aberration



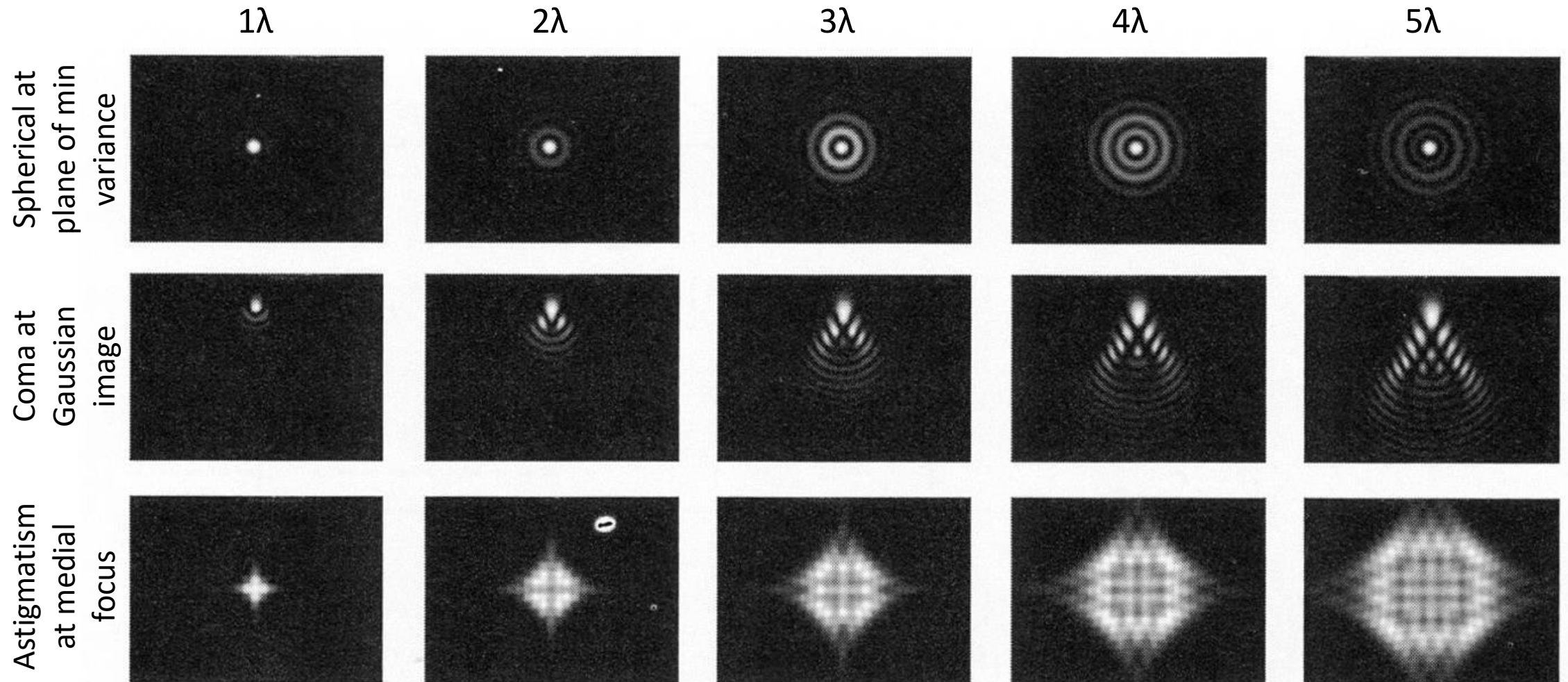
Coma



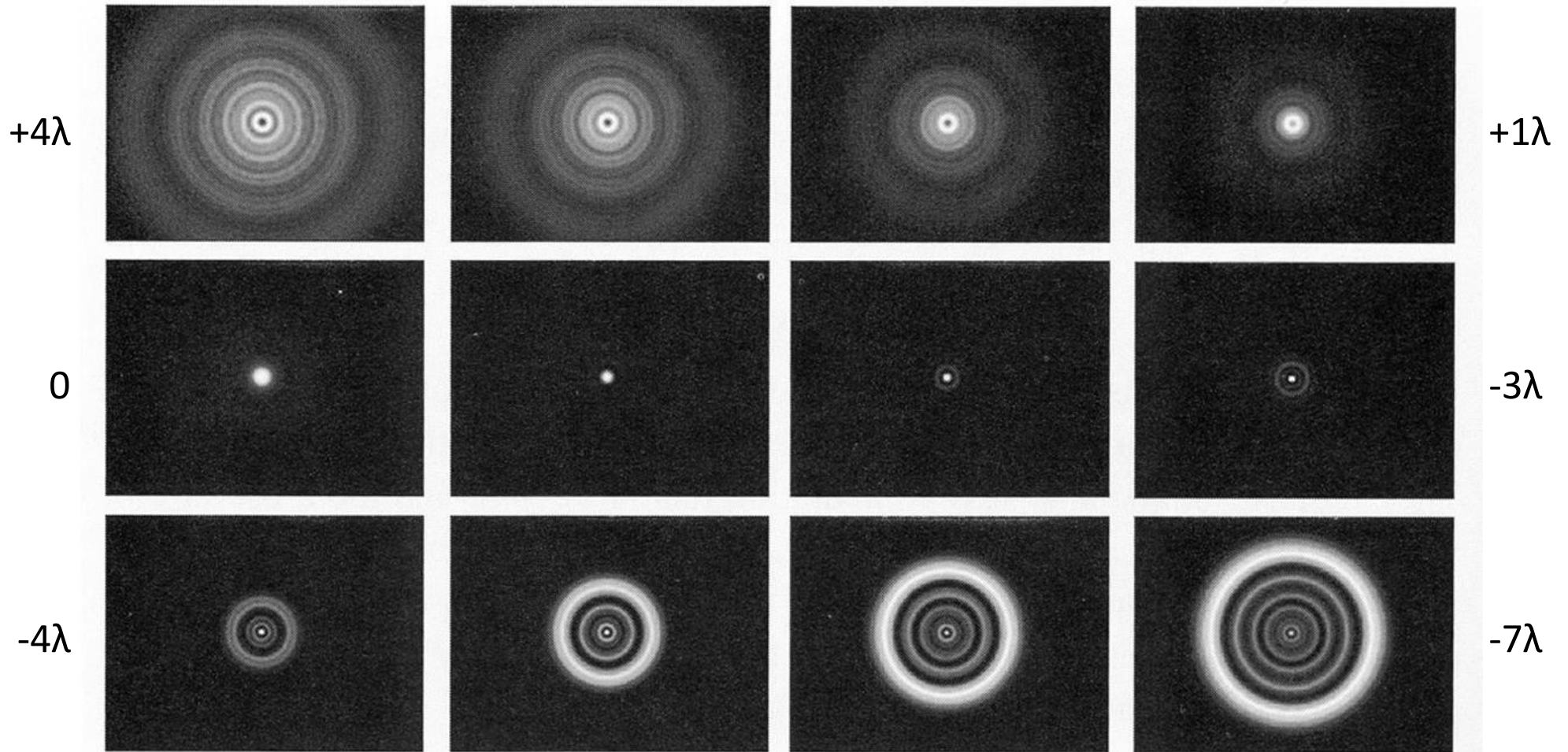
Astigmatism



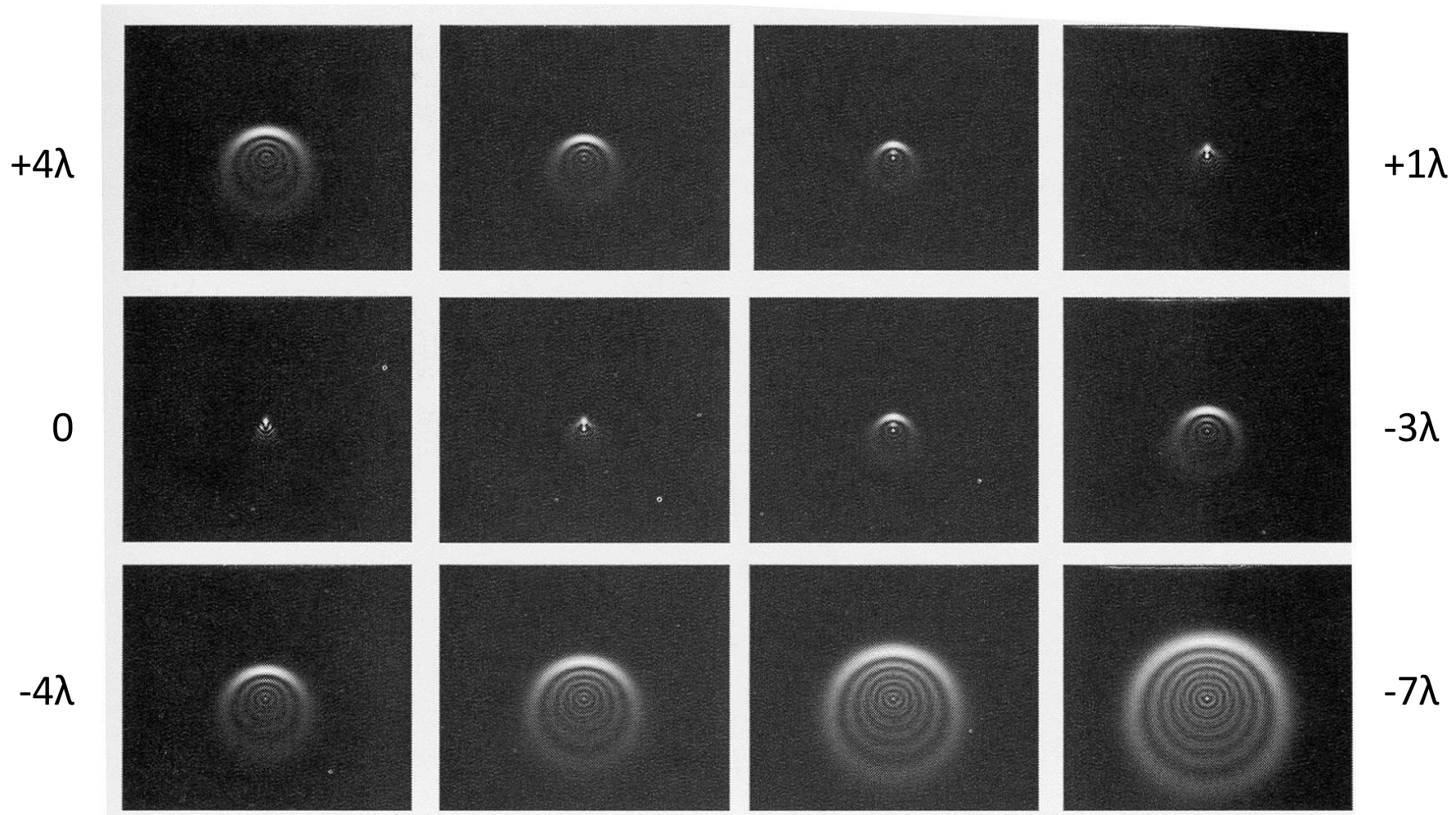
Point Images with Pure Aberrations



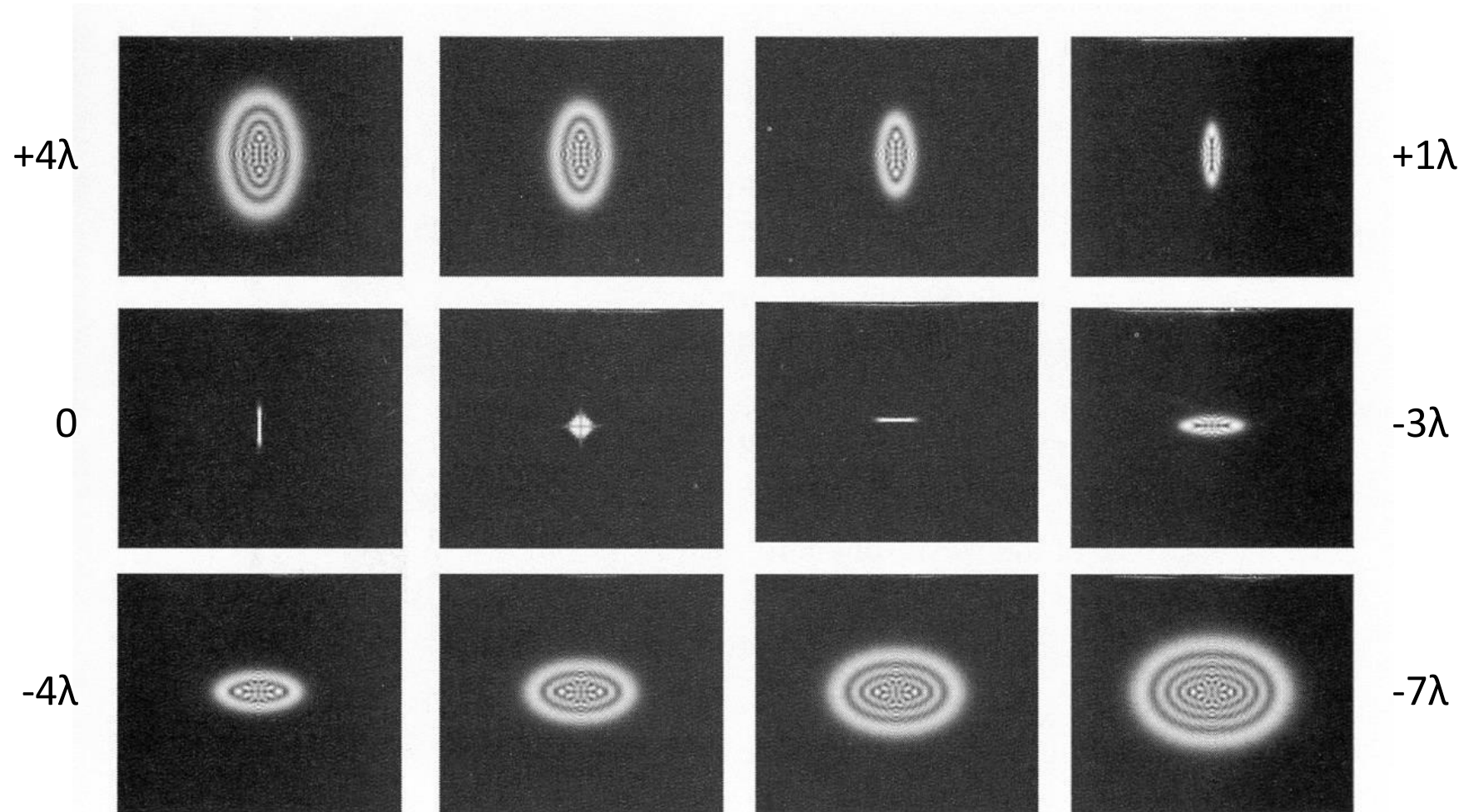
Through Images with Pure Spherical $W_{040} = 2\lambda$



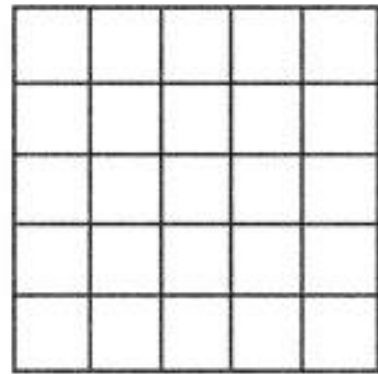
Through Images with Pure Coma $W_{131} = 2\lambda$



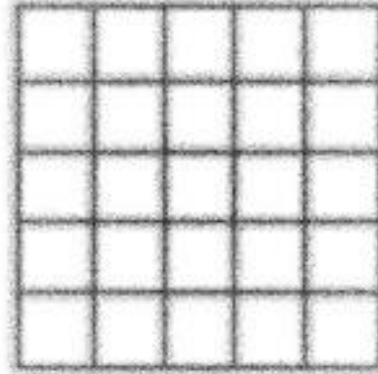
Through Images with Pure Astigmatism $W_{222} = 2\lambda$



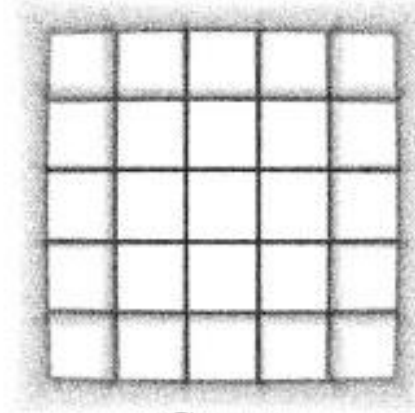
Grid Images under Pure Aberrations



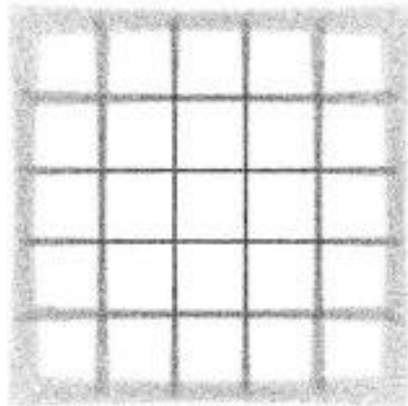
No Aberration



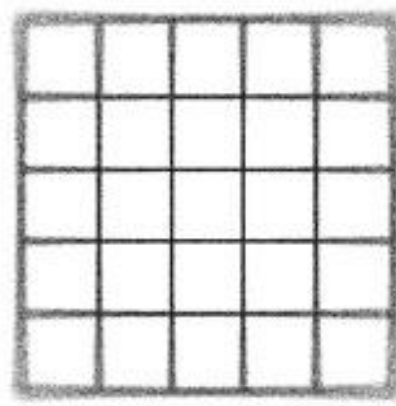
Spherical Aberration



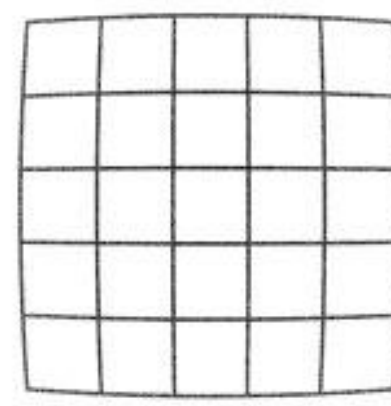
Coma



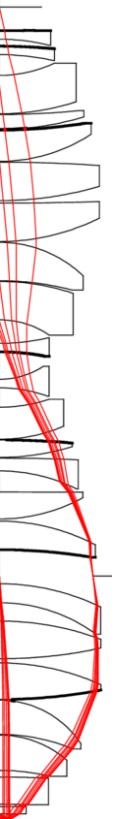
Astigmatism



Field Curvature



Barrel Distortion



ZEMAX

OpticStudio

Hands-on Time

Homework

Objective

- Acquire a thorough understanding of aberrations
- Learn to use product catalogs
- Understand the influence of lens form on aberrations

Investigate the aberrations in lenses of typical forms. **Task:** Use one zos file for each lens investigated. For each investigation, insert one lens of 25 mm (or 1 inch) diameter from a product catalog of your choice and investigate its optical aberration in terms of standard spot diagrams, ray aberrations, optical path, pupil aberration, field curvature and distortion, longitudinal aberration, lateral color, chromatic focal shift, Seidel coefficients, and Seidel diagram (dock all windows). **Wavelengths and fields:** Use full FdC wavelengths with the object at negative infinity and field angles of 1, 5, and 10 degrees. **Lenses:** Study lenses from each categories of meniscus convex, planoconvex, and biconvex type, each with 50 mm and 100 mm focal length. If you cannot find an exact match in the focal length, a close approximate can be used. **Orientation:** Repeat the assessments with the lens flipped. You can use the “Reverse Elements” button in the lens data editor for this. Use a separate file for the reversed orientation.

Pay attention to the scale of the plots. Compare and summarize your assessments in a table in terms of the five Seidel aberrations and the two chromatic aberrations on a level of A – D with A the best and D the worst. You should make a folder in your shared OneDrive and upload the ZEMAX design files (.zos) and a word comparison summary file to that folder.