OPTICAL DESIGN

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Matrix methods

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Definitions Fundamentals
- Introduction Ray Tracing
- Exercises telescopes
- Exercises field lens
- Telescopes

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Elements Systems

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OUTLOOK

IOA - Th. Lasser
Chief ray: field point > center of pupil
Marginal ray: fieldpoint > pupiledge
Meridional ray: element of chief plane
Sagittal ray: perpendicular to chief plane
Coma ray: field point > any pupil border
Rays

Meridional - Sagittal plane

Optical Axis

Object plane

Pupil plane

axis point

axis ray

x

y

yp

xp

yp

yp
Rays

Meridional - Sagittal plane

Optical Axis

Chief ray

Field point

Axis point

Axis ray

Object plane

Pupil plane

y_p

x_p

y

x
Definitions

Tangential (Meridional) plane
defined by optical axis and chief ray.
Definitions

**Tangential (Meridional) plane**
Defined by optical axis and chief ray.
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**Sagittal plane:**
perpendicular to the tangential plane and contains chief ray.
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Rays

Meridional - Sagittal plane

Definitions

Tangential (Meridional) plane
defined by optical axis and chief ray.

Sagittal plane:
perpendicular to the tangential plane and contains chief ray.
Rays
Aperture, pupils & field

Marginal ray
Chief ray

OA
OF

IF
IA

Stop
Rays

Aperture, pupils & field

Marginal ray

Chief ray

OA

OF

Stop

Entrance Pupil

IF

IA

Aperture, pupils & field
Rays

Aperture, pupils & field

Marginal ray

Chief ray

Stop

Exit Pupil

Entrance Pupil

IF

IA

OA

OF
Rays

Aperture, pupils & field

Pupils in optical Systems
- Image Brightness / Energy Transmission
- Effective aberrations on image quality
- Resolution power
- Perspective

Rays
Aperture, pupils & field

Pupils in optical Systems
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Rays
Aperture, pupils & field

Pupils in optical Systems
- Image Brightness / Energy Transmission
- Effective aberrations on image quality
- Resolution power
- Perspective
Rays

Aperture, pupils & field

Pupil in optical Systems

∑ Image Brightness / Energy Transmission
∑ Resolution power
∑ Effective aberrations on image quality
∑ Perspective
**Rays**

Raytracing

**Raytracing through a sequence of optical surfaces**

- $j$: surface index $j$
- $r$: surface curvature
- $n_j$: index of refraction
- $u$: ray slope angle (rel. to optical axis)
- $y$: ray height (intersection point > optical axis)
- $d$: distance (along optical axis)
- $d_s$: Skew distance (intersection to intersection)

**ZEMAX Sign Conventions**

- Surface: $r > 0$ CC to the right  $r < 0$ CC to the left
- Slope angle (rel. to optical axis)
- $y$: ray height (intersection point > optical axis)  (intersection point < optical axis)
- $d$: distance (along optical axis)

**ZEMAX**

Light propagation
From LEFT to RIGHT
Sequential raytracing

Step #j

Ray Transfer
skew distance

Homogeneous medium propagation

Inhomogeneous medium
Eikonal and Runge-Kutta

Sequential Raytracing
Next surface

Non-Sequential Raytracing
next surface
smallest distance

Aspherical surface
numerical iterative solution
for intersection

surface 2. Order
analytical solution
for intersection

Calculation
next surface
next intersection

Test correct intersection

Calculation new direction
new medium

Step #j+1

ray > out of aperture

ray out of surface

refraction

reflection

ERROR: total reflection

Rays
**Rays**

*f-Number (f/#), numerical aperture*

*light gathering power*

The **numerical aperture** of an optical system

\[ NA = n \cdot \sin u \]

(Usually used in microscopy > finite object distance).

The **F-Number** (f/#)

\[ F \# = \frac{f}{\varnothing_{EP}} \]

(Usually used for telescopes, photography etc.)

Caution: small f/# > large entrance pupil diameter
(example f=10 cm, P.D.=2 cm > f/5)

For small u

\[ F\# = \frac{1}{2n \cdot \sin u} \]

The **F-Number** (f/#) is defined for infinity object distance

The numerical **Aperture** is not defined for infinity object distance.
**SCALE - FACTOR**

\[
M = \frac{U' + U}{U' - U} = \frac{1 + \beta}{1 - \beta} = -\frac{2f}{s} + 1 = \frac{2f'}{s'} - 1
\]

**FORM - FACTOR**

\[
X = \frac{R_2 + R_1}{R_2 - R_1}
\]
$M = -1$

$s = f$

$M = +1$

$sí = fí$
Significance of formfactor I

Object Distance = $\infty$
Effective Focal Length = 100 mm
Field Angle = 17°

\[
\begin{align*}
R_1 &= -25\text{mm} \\
R_2 &= -17.3\text{mm} \\
X &= \frac{R_1 + R_2}{R_2 - R_1} = -5.49
\end{align*}
\]
Significance of formfactor II

Object Distance = ∞
Effective Focal Length = 100 mm
Field Angle = 17°

\begin{align*}
R_1 &= -50 \text{mm} \\
R_2 &= -25.8 \text{mm} \\
X &= \frac{R_1 + R_2}{R_2 - R_1} = -3.13 \\
\end{align*}
Significance of formfactor III

Object Distance = ∞
Effective Focal Length = 100 mm
Field Angle = 17°

\[ R_1 = \infty \]
\[ R_2 = -51.8 \text{mm} \]
\[ X = \frac{R_1 + R_2}{R_2 - R_1} = -1 \]

\[ \infty = \infty + (-51.8) \]

\[ 12 \]

\[ 2 \]

\[ 1 \]

\[ + = \]

\[ - = \]

\[ ∞ = \]

\[ 2 \]

\[ 12 \]

\[ 1 \]

\[ 2 \]

\[ 1 \]

\[ + = \]

\[ - = \]

\[ ∞ = \]
Significance of formfactor IV

Object Distance = ∞
Effective Focal Length = 100 mm
Field Angle = 17°

\[ R_1 = +50 \text{mm} \]
\[ R_2 = +1380 \text{mm} \]
\[ X = \frac{R_1 + R_2}{R_2 - R_1} = +1.08 \]
Significance of formfactor \( V \)

Object Distance = \( \infty \)
Effective Focal Length = 100 mm
Field Angle = 17\(^\circ\)

\[
\begin{align*}
R_1 &= +25\text{mm} \\
R_2 &= +47\text{mm} \\
X &= \frac{R_1 + R_2}{R_2 - R_1} = +3.27
\end{align*}
\]
Object Distance = $\infty$
Effective Focal Length = 100 mm
Field Angle = 17°

$R_1 = +16.7\text{mm}$
$R_2 = +23.6\text{mm}$
$X = \frac{R_1 + R_2}{R_2 - R_1} = +5.84$
Variation Form factor

R₁ = - 25 mm
R₂ = - 17.3 mm
X = - 5.49

R₁ = + 50 mm
R₂ = + 1380 mm
X = + 1.08

R₁ = - 50 mm
R₂ = - 25.8 mm
X = - 3.13

R₁ = + 25 mm
R₂ = + 47 mm
X = + 3.27

R₁ = - 1 mm
R₂ = - 51.8 mm
X = - 1

R₁ = ± 16.7 mm
R₂ = ± 23.6 mm
X = ± 5.84
Object Distance = $\infty$

$EFL = 100 \text{ mm}$

Field Angle = 17°

$R_1 = +50 \text{ mm}$

$R_2 = +1380 \text{ mm}$

$X = \frac{R_1 + R_2}{R_1 - R_2} = +1.08$

Plot through focus spot
Primary wave-aberration
single surface

\[ Q(r, \theta) \]

paraxial image plane

\[ P_0 \quad V_0 \quad B \quad C \quad P_{i0} \]

\[ n \quad n_i \]

AS EnP ExP

\[ r, \theta \]
Primary wave-aberration single surface

\[ W_0(r) = \left[ P_0 Q P_0' \right] - \left[ P_0 V_0 P_0' \right] \]

\[ W_0(r) = (nP_0Q + n'QP_0') - (n'S' - nS) \]
Primary wave-aberration single surface

$$W(y', r_p, \theta) = W_{040} r_p^4 + W_{131} y' r_p^3 \cos \theta + W_{222} y'^2 r_p^2 \cos^2 \theta + W_{220} y'^2 r_p^2 + W_{311} y'^3 r_p \cos \theta$$

**Spherical aberration**

$$W_{040} \Rightarrow A_s = -\frac{n'(n' - n)}{8n^2} \left( \frac{1}{R} - \frac{1}{s'} \right)^2 \left( \frac{n'}{R} - \frac{n + n'}{s'} \right) \left( \frac{s'}{p'} \right)^4$$

**Coma**

$$W_{131} \Rightarrow A_c = 4 \cdot \frac{R - s' + p'}{s' - R} \cdot A_s$$

**Astigmatism**

$$W_{222} \Rightarrow A_d = 4 \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s$$

**Distortion**

$$W_{311} \Rightarrow A_p = 2 \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s - \frac{n'(n' - n)}{4nR^2}$$

**Petzval Curvature**

$$W_{220} \Rightarrow A_d = 4 \left( \frac{R - s' + p'}{s' - R} \right)^3 \cdot A_s - \frac{n'(n' - n)}{2nRp^2} \cdot \frac{R - s' + p'}{s' - R}$$
Primary wave-aberration
single surface

\[ W(y', r_p, \theta) = W_{040} r_p^4 + W_{131} y' r_p^3 \cos \theta + W_{222} y'^2 r_p^2 \cos^2 \theta + W_{220} y^2 r_p^2 + W_{311} y'^3 r_p \cos \theta \]

Spherical aberration

\[ W_{040} \Rightarrow A_s = \frac{n(n' - n)}{8n^2} \left( \frac{1}{R} - \frac{1}{s} \right)^2 \frac{\left( n' - n + n' \right)}{R - s'} \frac{\left( s' \right)^4}{p^4} \]

Coma

\[ W_{131} \Rightarrow A_c = \frac{R - s' + p'}{s' - R} A_s \]

Astigmatism

\[ W_{222} \Rightarrow A_d = 4 \left( \frac{R - s' + p'}{s' - R} \right)^2 A_s \]

Anastigmatic

Petzval Curvature

\[ W_{220} \Rightarrow A_d = 4 \left( \frac{R - s' + p'}{s' - R} \right)^3 A_s - \frac{n(n' - n)}{2nR p^2} \frac{R - s' + p'}{s' - R} \]

Distortion

\[ W_{311} \Rightarrow A_p = 2 \left( \frac{R - s' + p'}{s' - R} \right)^3 A_s - \frac{n(n' - n)}{4nR p^2} \]
Primary wave-aberration
single surface

\[ W(y', r_p, \theta) = W_{040} r_p^4 + W_{131} y' r_p^3 \cos \theta + W_{222} y'^2 r_p^2 \cos^2 \theta + W_{220} y'^2 r_p^2 + W_{311} y'^3 r_p \cos \theta \]

**Spherical aberration**
\[ W_{040} \Rightarrow A_s = -\frac{n'(n' - n)}{8n^2} \left( \frac{1}{R} - \frac{1}{s'} \right)^2 \cdot \frac{1}{s'} \left( \frac{n'}{R} - \frac{n + n'}{s'} \right) \cdot \left( \frac{s'}{p'} \right)^4 \]

**Coma**
\[ W_{131} \Rightarrow A_c = 4 \cdot \frac{R - s' + p'}{s' - R} \cdot A_s \]

**Astigmatism**
\[ W_{222} \Rightarrow A_d = 4 \cdot \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s \]

**Distortion**
\[ W_{311} \Rightarrow A_p = 2 \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s - \frac{n'(n' - n)}{4nR p'^2} \]

**Sí=R >> S=R** aplanatic points
wave-aberration single lens
Form- and Scale-factors

SCALE - FACTOR

\[
M = \frac{U' + U}{U' - U} = \frac{1 + \beta}{1 - \beta} = \frac{2f}{2 + 1} = \frac{2f'}{s' - 1}
\]

FORM - FACTOR

\[
X = \frac{R_1 + R_2}{R_2 - R_1}
\]

Spherical aberration as function of X

\[
A_s = \frac{1}{32n(n-1)f^3} \left[ \frac{n^3}{n-1} + \frac{n+2}{n-1} \left\{ X - \frac{2(n^2-1)}{n+2} M \right\}^2 - \frac{n^2(n-1)}{n+2} M^2 \right]
\]

\[
X_{sph\text{ min}} = \frac{2(n^2-1)}{n+2} M \quad A_s = 0 \quad M^2 = \frac{n(n+2)}{(n-1)^2}
\]

\[
A_u = -\frac{1}{2f^4s^2}
\]

\[
A_c = \frac{1}{4nf^3s^2} \left[ \frac{n+1}{n-1} X - (2n+1)M \right]
\]

\[
X = \frac{(2n+1)(n-1)}{n+1} \cdot M
\]

\[
A_p = -\frac{n+1}{4nf^3s^2}
\]

\[
A_d = 0
\]
wave-aberration single lens
best lens shape

\[ M = \frac{U' + U}{1 + \beta} = \frac{1 + \beta}{1 - \beta} = \frac{2f}{s} + 1 = \frac{2f'}{s'} - 1 \]

\[ X = \frac{R_1 + R_2}{R_2 - R_1} \]

Spherical aberration as function of \( X \)

Minima of spherical aberration!

\[
\frac{\partial A_s}{\partial X} = 0; \quad X_{sph \, min} = \frac{2(n^2 - 1)}{n + 2} M
\]

\[
A_{s\, min} = -\frac{1}{32 f^3} \left[ \left( \frac{n}{n-1} \right)^2 - \frac{n}{n+2} \right] \left( n + 2 \right) M^2
\]

\[ A_s = 0; \quad M^2 = \frac{n(n+2)}{(n-1)^2} \]

For \( A_s = 0 \), \( M^2 > 1 \) Real object>virtuel image (or invers)
**OPTICAL DESIGN**

Scale and form factors

### SCALE - FACTOR

\[
M = \frac{U' + U}{U' - U} = \frac{1 + \beta}{1 - \beta} = -\frac{2f}{s} + 1 = \frac{2f'}{s'} - 1
\]

- **M <= -1**
- **M = -1**
- **M = 0**
- **M = +1**
- **M > +1**

### FORM - FACTOR

\[
X = \frac{R_1 + R_2}{R_2 - R_1}
\]

- **X <= -1**
- **X = -1**
- **X = 0**
- **X = 1**
- **X > 1**
wave-aberration
\text{a-} \& \text{iso-}

**Spherical aberration**

\[ W_{040} \Rightarrow A_s = -\frac{n'(n-n)}{8n^2} \left( \frac{1}{R} - \frac{1}{s'} \right)^2 \left( \frac{n'}{R} - \frac{n+n'}{s'} \right)^4 \]

**Coma**

\[ W_{131} \Rightarrow A_c = 4 \cdot \frac{R - s' + p'}{s' - R} \cdot A_s \]

**Astigmatism**

\[ W_{222} \Rightarrow A_s = 4 \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s \]

**Petzval Curvature**

\[ W_{311} \Rightarrow A_p = 2 \cdot \left( \frac{R - s' + p'}{s' - R} \right)^2 \cdot A_s - \frac{n'(n-n)}{4nRp'^2} \]

**Distortion**

\[ W_{220} \Rightarrow A_q = 4 \cdot \left( \frac{R - s' + p'}{s' - R} \right)^3 \cdot A_s - \frac{n'(n-n)}{2nRp'^2} \cdot \frac{R - s' + p'}{s' - R} \]

**anastigmatic**

\[ A_s = 0 \]

\[ \Rightarrow A_c = A_a = 0 \]

\[ s' = (n + n')R / n \]

\[ s = -(n + n')R / n \]

**Aplanatic (points)**

\[ s' = R \]

\[ s = -R \]

\[ A_s = A_c = 0 \]

\[ A_a \neq 0 \]
wave-aberration
aplanatic surface

1. Aplanatic-aplanatic
   (no significance)

2. Aplanatic-concentric
   (important)

3. Concentric-aplanatic
   (important)

4. Concentric-concentric
   (no significance)
Influence of stop position

Light cones on lens for field 10∞ and different stop positions and sizes

- ❶: at lens, big
- ❷: 15 mm in front, small
- ❸: at lens, small
- ❹: 15 mm behind, small
Influence of stop position
Stop positions and ray fans

Light cones on lens for field 10∞ and different stop positions and sizes

- : at lens, big
- : 15 mm in front, small
- : at lens, small
- : 15 mm behind, small
Ray Fan

Rays from Lens

Image Plane

Transverse $y$-aberration

Meridional deviation

Meridional deviation

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OPTICAL DESIGN

Overview

Parax Single Lens

Parax Telescope

Real Telescope

Field Lens

Telecentricity

Microscopy

Parax Galilei-Telescope

Parax Kepler Telescope

Real Galilei-Telescope

Real Kepler Telescope

Single Lens Achromat
OPTICAL DESIGN

Telescopes

**KEPLER**

![Diagram of a Kepler telescope with focal lengths $f_1$ and $f_2$.]

**GALILEI**

![Diagram of a Galilei telescope with focal lengths $f_1$ and $f_2$.]
KEPLER

\[ f_1 \]

\[ f_2 \]

\[ f_1 + f_2 \]
OPTICAL DESIGN

Telescopes Field Stop

KEPLER

Field Stop

\[ f_1 + f_2 \]
OPTICAL DESIGN

Telescopes Field lens

KEPLER

Field Lens

\[ f_1 + f_2 \]
Lens position nearest to image plane, pupil ray path strongly influenced

Field lens influences chief ray, marginal ray is not influenced

Position and size of image constant, pupil shifted and size changed

Field lens very critical to surface-tolerance of scratches and digs

Irregularities are imaged sharply
Aperture Stop
limits the solid angle of rays from a point of the object transmitted by the system

Image of Aperture Stop
in object space Entrance Pupil
in image space Exit Pupil

Aperture limits Quantity and Quality of light through the system

Field Stop
limits the solid angle of the chief rays from the object

Image of Field Stop
in object space Entrance Window
in image space Exit Window

Field stop limits part of object that is imaged
Telecentricity

**Principle of telecentricity:** A stop in the focal plane forces the chief ray to be parallel to the optical axis.

![Diagram of telecentricity](image)

**Three types of telecentric systems:**
1. Telecentric at the object side: stop in the rear focal plane
2. Telecentric at the image: stop in the front focal plane
3. Telecentric at both sides: stop in the pupil plane

**Application of telecentricity:**
1. Measuring objectives for image processing
2. Objectives with high requirements concerning the magnification (projection of masks)
3. Focussing into holes
$m_e = 1 / \nu_e$
Schott Glass Catalogue

The glass dispersion formulas
The coefficients in the catalog are used in any one of several polynomial formulas that ZEMAX recognizes. There are nine different dispersion formulas supported: the Schott constants of dispersion, the Sellmeier 1, the Sellmeier 2, the Sellmeier 3, the Sellmeier 4, the Herzberger, the Conrady, and two variations of the Handbook of Optics formulas. The reason there are more than one Sellmeier formula is due to the variations on the form of the equation common in the literature on measured index values. There is also a dispersion formula described by the six-digit MIL number, but those indices are calculated directly from the MIL number entered on the spreadsheet. The MIL number formula is not part of the glass catalog, and so it will not appear. See the last section in this chapter for a discussion of the MIL number glass formula. In all of the equations is in microns.

The Sellmeier 1 formula

\[ n^2 - 1 = \frac{K_1 \lambda^2}{\lambda^2 - L_1} + \frac{K_2 \lambda^2}{\lambda^2 - L_2} + \frac{K_3 \lambda^2}{\lambda^2 - L_3} \]
Optical Design
chromatic aberrations

Sellmeier Dispersion Formula

\[ n^2 - 1 = \frac{K_1 \lambda^2}{\lambda^2 - L_1} + \frac{K_2 \lambda^2}{\lambda^2 - L_2} + \frac{K_3 \lambda^2}{\lambda^2 - L_3} \]

<table>
<thead>
<tr>
<th>Dispersion Formula</th>
<th>Sellmeier 1</th>
<th>Sellmeier 1</th>
<th>Sellmeier 1</th>
</tr>
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<tbody>
<tr>
<td>(K_1)</td>
<td>1.04E+00</td>
<td>8.44E-01</td>
<td>1.54E+00</td>
</tr>
<tr>
<td>(L_1)</td>
<td>6.00E-03</td>
<td>4.75E-03</td>
<td>1.08E-02</td>
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<tr>
<td>(K_2)</td>
<td>2.32E-01</td>
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<td>1.57E-01</td>
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<tr>
<td>(L_2)</td>
<td>2.00E-02</td>
<td>1.50E-02</td>
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<tr>
<td>(K_3)</td>
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<td>9.11E-01</td>
<td>1.30E+00</td>
</tr>
<tr>
<td>(L_3)</td>
<td>1.04E+02</td>
<td>9.79E+01</td>
<td>1.31E+02</td>
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<tr>
<td>(\text{Lambda min})</td>
<td>0.31</td>
<td>0.28</td>
<td>0.404</td>
</tr>
<tr>
<td>(\text{Lambda max})</td>
<td>2.325</td>
<td>2.325</td>
<td>2.325</td>
</tr>
</tbody>
</table>
Optical Design
chromatic aberrations

\[ n^2 - 1 = \frac{K_1 \lambda^2}{\lambda^2 - L_1} + \frac{K_2 \lambda^2}{\lambda^2 - L_2} + \frac{K_3 \lambda^2}{\lambda^2 - L_3} \]

Kronglas(s)
Nd>
**Optical Design**

**Glass dispersion**

\[ v(\lambda) = \frac{n(\lambda) - 1}{n_P - n_C} \]

**Dispersion Number**

\[ m_{xy} = \frac{n_x - n_y}{n_e - 1} \]

\[ m_e = \frac{n_F' - n_C'}{n_e - 1} \]

\[ m_e = \frac{1}{v} \]

**Abbe Number (general)**

\[ v_e = \frac{n_e - 1}{n_P - n_C} \]

**Dispersion Number (basic color)**

\[ m_e = \frac{n_e - 1}{n_F - n_C} \]

**Optical Glass**

\[ v_e = 10 \ldots 120 \]

**Croneglass**: small Dispersion, mostly small n

**Flintglass**: large Dispersion, mostly high n
Light dispersion
- Dispersion > index of refraction as function of $\lambda$
\[
\Delta n = n(\lambda_1) - n(\lambda_2)
\]
- Normal Dispersion > n greater at shorter $\lambda$
\[
\frac{dn}{d\lambda} < 0
\]
(Blue more than red)

- Chromaticity
  - Main wavelength
    - (e, d) green
  - 2 associated wavelength
    - (F1, C1) : blue and red
Optical Design
longitudinal chromatic aberrations

\[
\frac{1}{S'} - \frac{1}{S} = \frac{1}{f} \\
\delta S \quad = \quad \frac{\delta f'}{f'^2} = - \frac{1}{f'V}
\]
Optical Design

longitudinal chromatic aberration

\[ \sum \text{Positive lens CHL under corrected} \]

\[
\frac{1}{S'} - \frac{1}{S} = \frac{1}{f}
\]

\[
\frac{\delta S}{S^2} = \frac{\delta f'}{f'^2} = -\frac{1}{f'V}
\]
Optical Design
transversal chromatic aberrations

\[ M = \frac{h'}{h} \]

\[ \frac{\delta M}{M} = \frac{\delta h'}{h'} = \frac{\delta S'}{S'} = -\frac{S'}{f'V} \]
Optical Design
chromatic aberrations

axial chromatic aberration

\[ \sum \text{Positive lens CHL under corrected} \]

\[ \frac{1}{S'} - \frac{1}{S} = \frac{1}{f} \]

\[ \delta S = \frac{\delta f'}{f'^2} = - \frac{1}{f' V} \]

lateral chromatic aberration

Chromatic difference of image magnification (CDM)

\[ \Delta y_{CHV} = y_F' - y_C' \]

Reference paraxial image size (for primary wavelength)

\[ \Delta y_{CHV} = \frac{y_F' - y_C'}{y_e'} \]

CDM depends on aperture position

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achromat

Total power :

\[ \Phi = \Phi_1 + \Phi_2 \]

Achromasie-Condition :

\[ \frac{\Phi_1}{V_1} + \frac{\Phi_2}{V_2} = 0 \]

Optical Power ind. Element

\[ \Phi_2 = \frac{1}{1 - \frac{V_1}{V_2}} \cdot \Phi \]
\[ \Phi_1 = \frac{1}{1 - \frac{V_2}{V_1}} \cdot \Phi \]

Conclusions :

1. *positive and negative Lens necessary*
2. *Ngoodi Design*  
   small power per element  
   high \( \nu \)-Difference in used glasses
3. *Achromaticity independant of individual lens-shape*
5. *2 Concepts for Achromats :*  
   "Kron in fronti" (Fraunhofer-Achromat)  
   "Flint in fronti" (Steinheil-Achromat).
Assumption: two thin lenses closely together

Condition focal length:

\[ \Phi = \Phi_1 + \Phi_2 \]

\[ \frac{1}{f'} = (n - 1) \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \]

\[ \Phi_{F'} = (n_{F'} - 1) \rho \]

\[ \Phi_{D'} = (n_{D'} - 1) \rho \]

\[ \Phi = \frac{n_{F'} - n_{D'}}{n_e - 1} \rho (n_e - 1) \]

\[ \rho = \frac{\Phi e}{v_e} \]

Condition achromatism:

\[ \frac{\Phi_1}{v_1} + \frac{\Phi_2}{v_2} = 0 \]
Assumption: two thin lenses closed together

Condition for focal length: \[ \Phi = \Phi_1 + \Phi_2 \]

Condition for achromatism: \[ \frac{\Phi_1}{\nu_1} + \frac{\Phi_2}{\nu_2} = 0 \]

Solution of the equations for the refractive powers:
\[ \Phi_2 = \frac{1}{1 - \frac{\nu_1}{\nu_2}} \cdot \Phi \]
\[ \Phi_1 = \frac{1}{1 - \frac{\nu_2}{\nu_1}} \cdot \Phi \]

Consequences & Properties:
1. Necessarily one positive and one negative Lens
2. Relaxed design with small refractive powers: glass choice, large difference of \( \nu \)-values
   The achromatism is independant of the bending of the lenses
3. Positive achromate: the positive lens contains the glass with the larger value of \( \nu \) (crone glass)
4. Two possible configurations for achromates:
   - Crone in fronti (Fraunhofer-Achromate)
   - Flint in fronti (Steinheil-Achromate).
OPTICAL DESIGN

Achromate 2

4 principle solutions crone in front:

3 principle solutions flint in front:

- border contact
- cemented
- Center contact
- Gauss-form

Solutions with cemented lenses: higher stability

Compare glass diagram
\textbf{OPTICAL DESIGN}

\textit{Achromate (3)}

\begin{itemize}
  \item \textit{Cemented achromate:}
    6 free parameters: 3 radii. 2 refractive indices, relation of the $\nu$-values
  
  \item \textit{Degrees of freedom, targets:}
    focal length, achromatism, spherical aberration corrected
  
  \item \textit{Optimale choice of glass:}
    minimal spherical zone and correction of the coma possible
  
  \item \textit{Correction of the spherical aberration:}
    $n_{\text{neg}} > n_{\text{pos}}$, diverging cemented surface
  
  \item \textit{Depending on the chosen glasses:}
    optimal bending with minimal spherical aberration or two bendings with vanishing spherical aberration
\end{itemize}
1. **Computation of a cemented achromate:**
   Defining the type of solution: flint / crone in front

2. **Choice of glasses, criteria:**
   - Large difference in $v$ values for a relaxed design
   - Correction of coma possible
   - Small spherical aberration zone
   - Small spherochromatism: $v$ small

3. **Focal lengths of the lenses: $f_1$, $f_2$**

\[
f_1 = \frac{v_1 - v_2}{v_1} \cdot f \quad f_2 = \frac{v_1 - v_2}{v_2} \cdot f'
\]

4. **Bending of the first lens:**

\[
r_1 = \frac{2(n_1 - 1)f_1}{X_1 + 1} \quad r_2 = \frac{2(n_1 - 1)f_1}{X_1 - 1} \quad r_3 = \frac{1}{1 - \frac{1}{f_2} \cdot \frac{1}{n_2 - 1}}
\]

**Optimization**
   - Correction of coma
   - Correction of spherical aberration
Geometric <> Wave Optics
Overview

**Optical path length**
- Paraxial reference ray
- Reference sphere

**Raytracing**
- Intersections
- Paraxial reference ray

**Longitudinal Aberration**
- Rayleigh units Aberration classes

**Wave Aberration W**
- Zernike coefficients
  - Exp (phase)
  - Orthogonal Transformation

**Transverse Aberration**
- Integration

**Rayleigh units**
- Aberration classes

**Pupil function**
- Fourier-transform
- Kirchhoff-integral

**Far Field Amplitude (PSF)**
- Autocorrelation-I ntegral (Duffieux)
- \( I \times \text{Fourier-transform}^2 \)

**Optical Transfer Function**
- Approximation diameter PSF

**Strehl Brightness**
- Integration f-Space

**Geometrical Spotdiagram**
- Fourier-transform

**Geometrical Optical OTF**
- Approx. Spot diameter

**Resolution**
- Cut-off spatial freq.

**Image Aberration**
- Full Aperture

**Paraxial reference ray**

**Zernike Coefficients**
- ∑ coefficients
- Marechal Approximation

**Wave Aberration W**
- rms-Value

**Integration**
- Differentiation

**Longitudinal Aberration**
- Integration

**Optical path length**
- Paraxial reference ray

**Resolution**
- Cut-off spatial freq., approx.

**Far Field Amplitude (PSF)**
- Autocorrelation-Integral (Duffieux)
- \( I \times \text{Fourier-transform}^2 \)

**Optical Transfer Function**
- Approximation diameter PSF

**Resolution**
- Cut-off spatial freq., approx.

**Geometrical Optical OTF**
- Approx. Spot diameter

**Geometrical Spotdiagram**
- Fourier-transform