Optical Design with Zemax

Lecture 2: Properties of optical systems I
2012-10-23
Herbert Gross
<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Topic</th>
<th>Overview</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>16.10.</td>
<td>Introduction</td>
<td>Introduction, Zemax interface, menus, file handling, preferences, Editors, updates, windows, Coordinate systems and notations, System description, Component reversal, system insertion, scaling, 3D geometry, aperture, field, wavelength</td>
</tr>
<tr>
<td>2</td>
<td>23.10.</td>
<td>Properties of optical systems I</td>
<td>Diameters, stop and pupil, vignetting, Layouts, Materials, Glass catalogs, Raytrace, Ray fans and sampling, Footprints</td>
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<tr>
<td>3</td>
<td>30.10.</td>
<td>Properties of optical systems II</td>
<td>Types of surfaces, Aspheres, Gratings and diffractive surfaces, Gradient media, Cardinal elements, Lens properties, Imaging, magnification, paraxial approximation and modelling</td>
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<td>4</td>
<td>06.11.</td>
<td>Aberrations I</td>
<td>Representation of geometrical aberrations, Spot diagram, Transverse aberration diagrams, Aberration expansions, Primary aberrations,</td>
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<td>5</td>
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<td>Aberrations II</td>
<td>Wave aberrations, Zernike polynomials, Point spread function, Optical transfer function</td>
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<td>6</td>
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<td>Optimization I</td>
<td>Principles of nonlinear optimization, Optimization in optical design, Global optimization methods, Solves and pickups, variables, Sensitivity of variables in optical systems</td>
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<td>7</td>
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<td>Optimization II</td>
<td>Systematic methods and optimization process, Starting points, Optimization in Zemax</td>
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<td>8</td>
<td>04.12</td>
<td>Imaging</td>
<td>Fundamentals of Fourier optics, Physical optical image formation, Imaging in Zemax</td>
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<td>9</td>
<td>11.12.</td>
<td>Illumination</td>
<td>Introduction in illumination, Simple photometry of optical systems, Non-sequential raytrace, Illumination in Zemax</td>
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<td>10</td>
<td>18.12.</td>
<td>Advanced handling I</td>
<td>Telecentricity, infinity object distance and afocal image, Local/global coordinates, Add fold mirror, Scale system, Make double pass, Vignetting, Diameter types, Ray aiming, Material index fit</td>
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<td>11</td>
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<td>Advanced handling II</td>
<td>Report graphics, Universal plot, Slider, Visual optimization, IO of data, Multiconfiguration, Fiber coupling, Macro language, Lens catalogs</td>
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<td>12</td>
<td>15.01.</td>
<td>Correction I</td>
<td>Symmetry principle, Lens bending, Correcting spherical aberration, Coma, stop position, Astigmatism, Field flattening, Chromatical correction, Retrofocus and telephoto setup, Design method</td>
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<td>13</td>
<td>22.01.</td>
<td>Correction II</td>
<td>Field lenses, Stop position influence, Aspheres and higher orders, Principles of glass selection, Sensitivity of a system correction, Microscopic objective lens, Zoom system</td>
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<td>14</td>
<td>29.01.</td>
<td>Physical optical modelling I</td>
<td>Gaussian beams, POP propagation, polarization raytrace, polarization transmission, polarization aberrations</td>
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<td>15</td>
<td>05.02.</td>
<td>Physical optical modelling II</td>
<td>Coatings, representations, transmission and phase effects, ghost imaging, general straylight with BRDF</td>
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</table>
1. Diameters
2. Stops and Pupil definition
3. Vignetting
4. Layout
5. Materials and glass catalogs
6. Raytrace
7. Ray fans and sampling
8. Footprints
Pupil stop defines:
1. chief ray angle $w$
2. aperture cone angle $u$

- The chief ray gives the center line of the oblique ray cone of an off-axis object point
- The coma rays limit the off-axis ray cone
- The marginal rays limit the axial ray cone
The physical stop defines the aperture cone angle $\theta$

- The real system may be complex

- The entrance pupil fixes the acceptance cone in the object space

- The exit pupil fixes the acceptance cone in the image space

Ref: Julie Bentley
Relevance of the system pupil:

- Brightness of the image
  Transfer of energy

- Resolution of details
  Information transfer

- Image quality
  Aberrations due to aperture

- Image perspective
  Perception of depth

- Compound systems:
  matching of pupils is necessary, location and size
2 Properties of Optical Systems I

Entrance and exit pupil
- Generalization of paraxial picture: Principal surface works as effective location of ray bending
- Paraxial approximation: plane
- Real systems with corrected sine-condition (aplanatic): principal sphere
- Pupil sphere: equidistant sine-sampling

\[ \sin(U) \]

\[ \sin(U') \]

\[ \text{Object} \]

\[ \text{Entrance pupil} \]

\[ \text{Exit pupil} \]

\[ \text{Image} \]

\[ y_0 \]

\[ y' \]

\[ z \]

\[ \text{Pupil sphere} \]

\[ \text{Equidistant} \]

\[ \sin(U) \]

\[ \text{Angle U non-equidistant} \]
Different possible options for specification of the aperture in Zemax:

1. Entrance pupil diameter
2. Image space F#
3. Object space NA
4. Paraxial working F#
5. Object cone angle
6. Floating by stop size

Stop location:

1. Fixes the chief ray intersection point
2. Input not necessary for telecentric object space
3. Is used for aperture determination in case of aiming

Special cases:

1. Object in infinity (NA, cone angle input impossible)
2. Image in infinity (afocal)
3. Object space telecentric
- 3D-effects due to vignetting
- Truncation of the at different surfaces for the upper and the lower part of the cone
- Truncation of the light cone with asymmetric ray path for off-axis field points
- Intensity decrease towards the edge of the image
- Definition of the chief ray: ray through energetic centroid
- Vignetting can be used to avoid uncorrectable coma aberrations in the outer field
- Effective free area with extrem aspect ratio: anamorphic resolution
1. Determination of one surface as system stop:
   - Fixes the chief ray intersection point with axis
   - can be set in surface properties menu
   - indicated by STO in lens data editor
   - determines the aperture for the option 'float by stop size'

2. Diameters in lens data editor
   - indicated U for user defined
   - only circular shape
   - effects drawing
   - effects ray vignetting
   - can be used to draw 'nice lenses' with overflow of diameter

3. Diameters as surface properties:
   - effects on rays in drawing (vignetting)
   - no effect on lens shapes in drawing
   - also complicated shapes and decenter possible
   - indicated in lens data editor by a star
4. Individual aperture sizes for every field point can be set by the vignetting factors of the Field menu.
- Real diameters at surfaces must be set.
- Reduces light cones are drawn in the layout.
Graphical control of system and ray path

Principal options in Zemax:
1. 2D section for circular symmetry
2. 3D general drawing

Several options in settings
Zooming with mouse
Different options for 3D case
Multiconfiguration plot possible
Rayfan can be chosen
2 Properties of Optical Systems I

Layout options

- Professional graphic
- Many layout options
- Rotation with mouse or arrow buttons
Important types of optical materials:
1. Glasses
2. Crystals
3. Liquids
4. Plastics, cement
5. Gases
6. Metals

Optical parameters for characterization of materials
1. Refractive index, spectral resolved $n(\lambda)$
2. Spectral transmission $T(\lambda)$
3. Reflectivity $R$
4. Absorption
5. Anisotropy, index gradient, eigenfluorescence,…

Important non-optical parameters
1. Thermal expansion coefficient
2. Hardness
3. Chemical properties (resistence,…)

2 Properties of Optical Systems I
Optical materials
## Properties of Optical Systems I

### Test wavelengths

<table>
<thead>
<tr>
<th>$\lambda$ in [nm]</th>
<th>Name</th>
<th>Color</th>
<th>Element</th>
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</thead>
<tbody>
<tr>
<td>248.3</td>
<td>UV</td>
<td></td>
<td>Hg</td>
</tr>
<tr>
<td>280.4</td>
<td>UV</td>
<td></td>
<td>Hg</td>
</tr>
<tr>
<td>296.7278</td>
<td>UV</td>
<td></td>
<td>Hg</td>
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<td>312.5663</td>
<td>UV</td>
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<td>334.1478</td>
<td>UV</td>
<td></td>
<td>Hg</td>
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<tr>
<td>365.0146</td>
<td>i</td>
<td>UV</td>
<td>Hg</td>
</tr>
<tr>
<td>404.6561</td>
<td>h</td>
<td>violett</td>
<td>Hg</td>
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<tr>
<td>435.8343</td>
<td>g</td>
<td>blau</td>
<td>Hg</td>
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<tr>
<td>479.9914</td>
<td>F'</td>
<td>blau</td>
<td>Cd</td>
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<tr>
<td>486.1327</td>
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<td>blau</td>
<td>H</td>
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<tr>
<td>546.0740</td>
<td>e</td>
<td>grün</td>
<td>Hg</td>
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<tr>
<td>587.5618</td>
<td>d</td>
<td>gelb</td>
<td>He</td>
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<tr>
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<td>D</td>
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<td>632.8</td>
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<td>HeNe-Laser</td>
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<td>852.11</td>
<td>s</td>
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<td>Cä</td>
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<tr>
<td>1013.98</td>
<td>t</td>
<td>IR</td>
<td>Hg</td>
</tr>
<tr>
<td>1060.0</td>
<td></td>
<td></td>
<td>Nd:YAG-Laser</td>
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</tbody>
</table>
2 Properties of Optical Systems I
Dispersion and Abbe number

- Description of dispersion:
  \[ \nu(\lambda) = \frac{n(\lambda) - 1}{n_F - n_C} \]

- Visual range of wavelengths:
  \[ \nu_e = \frac{n_e - 1}{n_{F'} - n_{C'}} \]

- Typical range of glasses
  \( \nu_e = 20 \ldots 120 \)

- Two fundamental types of glass:
  Crone glasses:
  \( n \) small, \( \nu \) large
  Flint glasses
  \( n \) large, \( \nu \) small

\[ n_F - n_C \]

\[ n_e - 1 \]

\[ n_{F'} - n_{C'} \]
Material with different dispersion values:
- Different curvature of the dispersion curve
- Stronger change of index over wavelength for large dispersion
- Inversion of index sequence at the boundaries of the spectrum possible

<table>
<thead>
<tr>
<th>λ</th>
<th>n</th>
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<tr>
<td>0.5</td>
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<td>0.75</td>
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<td>1.5</td>
<td>1.75</td>
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<td>1.75</td>
<td>1.8</td>
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<tr>
<td>2.0</td>
<td>1.9</td>
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</table>
2 Properties of Optical Systems I
Dispersion formulas

- Schott formula
  empirical

- Sellmeier
  Based on oscillator model

- Bausch-Lomb
  empirical

- Herzberger
  Based on oscillator model

- Hartmann
  Based on oscillator model

\[
n(\lambda) = \sqrt{A + B \frac{\lambda^2}{\lambda^2 - \lambda_1^2} + C \frac{\lambda^2}{\lambda^2 - \lambda_2^2}}
\]

\[
n(\lambda) = \sqrt{A + B \lambda^2 + C \lambda^4 + \frac{D}{\lambda^2} + \frac{E \lambda^2}{(\lambda^2 - \lambda_o^2) + \frac{F \lambda^2}{\lambda^2 - \lambda_o^2}}}.
\]

\[
n(\lambda) = a_o + a_1 \lambda^2 + \frac{a_2}{\lambda^2 - \lambda_o^2} + \frac{a_3}{(\lambda^2 - \lambda_o^2)^2}
\]

\[
n(\lambda) = a_o + \frac{a_1}{a_3 - \lambda} + \frac{a_4}{a_5 - \lambda}
\]

\[
m_{\text{mit }} \lambda_o = 0.168 \mu m
\]
Relative partial dispersion:
Change of dispersion slope with \( \lambda \)

Definition of local slope for selected wavelengths relative to secondary colors

Special selections for characteristic ranges of the visible spectrum

\[
P_{\lambda_1\lambda_2} = \frac{n(\lambda_1) - n(\lambda_2)}{n_{F'} - n_{C'}}
\]

- \( \lambda = 656 / 1014 \text{ nm} \) far IR
- \( \lambda = 656 / 852 \text{ nm} \) near IR
- \( \lambda = 486 / 546 \text{ nm} \) blue edge of VIS
- \( \lambda = 435 / 486 \text{ nm} \) near UV
- \( \lambda = 365 / 435 \text{ nm} \) far UV
Usual representation of glasses:
diagram of refractive index vs dispersion $n(\nu)$

Left to right:
Increasing dispersion decreasing Abbe number
## Glass: LAFN7

### Part 1

<table>
<thead>
<tr>
<th>Main data</th>
<th>Refractive indices</th>
<th>Internal transmission data</th>
<th>relative partial dispersion</th>
<th>Anomalous partial dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$ [nm]</td>
<td>$n$</td>
<td>$\tau_1$ [10 mm]</td>
<td>$\Delta P_{c,t}$</td>
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<td>LAFN7</td>
<td>750350.4</td>
<td>2325.4</td>
<td>2500.0, 0.380, 0.090</td>
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<td>$n_d$</td>
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<tr>
<td>$n_e$</td>
<td>1.75458</td>
<td>1529.6</td>
<td>1970.1, 0.940, 0.850</td>
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<td>$n_F-n_c$</td>
<td>0.02145</td>
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<td>460.0, 0.993, 0.982</td>
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<tr>
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<td>435.8, 0.986, 0.965</td>
<td>$P'i,h$</td>
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<td>320.0, 0.000, 0.000</td>
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## Glass: LAFN7

### Sellmeier dispersion constants

<table>
<thead>
<tr>
<th></th>
<th>Constants of dn/dT</th>
<th>Other properties</th>
<th>Temperature coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>1.66842615E+00</td>
<td>D0 7.27E-06</td>
<td>α-30-70°C [10⁻⁶/K]</td>
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<tr>
<td></td>
<td>2.98512803E -01</td>
<td>D1 1.31E-08</td>
<td>α +20/+300°C [10⁻⁶/K]</td>
</tr>
<tr>
<td>B3</td>
<td>1.07743760E+00</td>
<td>D2 -3.32E-11</td>
<td>Tg[°C]</td>
</tr>
<tr>
<td>C1</td>
<td>1.03159999E -02</td>
<td>E0 8.88E-07</td>
<td>T10 13,0[°C]</td>
</tr>
<tr>
<td>C2</td>
<td>4.69216348E -02</td>
<td>E1 9.32E-10</td>
<td>T10 7,6[°C]</td>
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</tbody>
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### Other properties

<table>
<thead>
<tr>
<th></th>
<th>λ [W/(m·K)]</th>
<th>c_p [J/(g·K)]</th>
<th>G [10⁻³ N/mm²]</th>
<th>μ</th>
<th>K[10⁻⁶ mm²/N]</th>
</tr>
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<tbody>
<tr>
<td>C3</td>
<td>8.25078509E+01</td>
<td>2.48E-01</td>
<td>0,000</td>
<td>0,770</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>μ [g/cm³]</th>
<th>E[10³ N/mm²]</th>
<th>K [10⁻⁶ mm²/N]</th>
<th>HK0.1/20</th>
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<td></td>
<td>4,38</td>
<td>80</td>
<td>1,77</td>
<td>520</td>
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### Temperature coefficients

<table>
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<th>1060,0</th>
<th>e</th>
<th>g</th>
<th>1060,0</th>
<th>e</th>
<th>g</th>
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<tbody>
<tr>
<td>B1</td>
<td>-40/-20</td>
<td>6,00</td>
<td>7,80</td>
<td>9,70</td>
<td>3,70</td>
<td>5,40</td>
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<tr>
<td>B2</td>
<td>+20/+40</td>
<td>6,30</td>
<td>8,30</td>
<td>10,40</td>
<td>4,80</td>
<td>6,70</td>
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<tr>
<td>B3</td>
<td>+60/+80</td>
<td>6,50</td>
<td>8,60</td>
<td>10,90</td>
<td>5,30</td>
<td>7,40</td>
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<tr>
<td>C1</td>
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<td></td>
<td></td>
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<td></td>
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<td>C2</td>
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</tr>
</tbody>
</table>

### Part 2

Glass data sheet
Crown glasses

\[ \nu_e > 54.7 \quad \text{für} \quad n_e < 1.6028 \]

\[ \nu_e > 49.7 \quad \text{für} \quad n_e > 1.6028 \]

Flint glasses

\[ \nu_e < 54.7 \quad \text{für} \quad n_e < 1.6028 \]

\[ \nu_e < 49.7 \quad \text{für} \quad n_e > 1.6028 \]
- Nearly equal area in the glass diagram with available materials for all vendors
- No options with Index / dispersion
  1. high / high
  2. low / low
- Ray: straight line between two intersection points
- System: sequence of spherical surfaces
- Data: - radii, curvature $c=1/r$
  - vertex distances
  - refractive indices
  - transverse diameter
- Surfaces of 2nd order:
  Calculation of intersection points
  analytically possible: fast computation
- General 3D geometry
- Tilt and decenter of surfaces
- General shaped free form surfaces
- Full description with 3 components
- Global and local coordinate systems
- Single surface:
  - tilt and decenter before refraction
  - decenter and tilt after refraction
- General setup for position and orientation in 3D

\[ \vec{r}' = D_H \cdot R_H \cdot F \cdot R_V \cdot D_V \cdot \vec{r} \]
Restrictions:
- surfaces of second order, fast analytical calculation of intersection point possible
- homogeneous media

Direction unit vector of the straight ray
\[
\vec{s}_j = \begin{pmatrix}
\xi_j \\
\eta_j \\
\zeta_j
\end{pmatrix}
\]

Vector of intersection point on a surface
\[
\vec{r}_j = \begin{pmatrix}
x_j \\
y_j \\
z_j
\end{pmatrix}
\]

Ray equation with skew thickness \(d_{sj}\)
index \(j\) of the surface and the space behind
\[
\vec{r}_j = \vec{r}_{j-1} + d_{s,j-1} \cdot \vec{s}_{j-1}
\]

Equation of the surface 2.order
\[
H_j d^2_{s,j-1} + 2F_j d_{s,j-1} - G_j = 0
\]
The coefficients \(H\), \(F\), \(G\) contains the surface shape parameters
- Special case spherical surface with curvature $c = 1/R$
  Coefficients $H$, $G$, $F$

  Unit vector normal to the surface

- Insertion of the ray equation into surface equation:
  skew thickness

- Angle of incidence

- Refraction
  or
  reflection

\[
H_j = -c_j \\
G_j = c_j \left( x_j^2 + y_j^2 + z_j^2 \right) - 2z_j \\
F_j = \zeta_j - c_j \left( x_j \xi_j + y_j \eta_j + z_j \zeta_j \right)
\]

\[
\vec{e}_j = \begin{pmatrix} -c_j x_j \\ -c_j y_j \\ 1 - c_j z_j \end{pmatrix}
\]

\[
d_{s,j-1} = \frac{G_j}{F_j + \sqrt{F_j^2 + H_j G_j}}
\]

\[
\cos i_j = \vec{s}_j \cdot \vec{e}_j
\]

\[
\cos i'_j = \sqrt{1 - \left( \frac{n_j}{n_{j+1}} \right)^2 \left( 1 - \cos^2 i_j \right)}
\]

\[
\cos i'_j = -\cos i_j
\]
Auxiliary parameter

New ray direction vector

\[ \Phi_j = n_{j+1} \cos i'_j - n_j \cos i_j \]

\[ \tilde{s}_{j+1} = \frac{n_j}{n_{j+1}} \tilde{s}_j + \frac{\Phi_j}{n_{j+1}} \tilde{e}_j \]
- Vignetting/truncation of ray at finite sized diameter: can or can not considered (optional)
- No physical intersection point of ray with surface
- Total internal reflection
- Negative edge thickness of lenses
- Negative thickness without mirror-reflection
- Diffraction at boundaries

Intersection:
- Mathematical possible
- Physical not realized

No intersection point
- Meridional rays: in main cross section plane
- Sagittal rays: perpendicular to main cross section plane
- Coma rays: Going through field point and edge of pupil
- Oblique rays: without symmetry
2 Properties of Optical Systems I

Tangential and sagittal plane

- Off-axis object point:
  1. Meridional plane / tangential plane / main cross section plane contains object point and optical axis
  2. Sagittal plane:
     perpendicular to meridional plane through object point

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![Diagram of Optical System](image)

- Object plane
- Image plane
- Meridional plane
- Sagittal plane
- Lens
- Ray fan:
  2-dimensional plane set of rays

- Ray cone:
  3-dimensional filled ray cone
- Transverse aberrations: Ray deviation from ideal image point in meridional and sagittal plane respectively.
- The sampling of the pupil is only filled in two perpendicular directions along the axes.
- No information on the performance of rays in the quadrants of the pupil.
Pupil sampling for calculation of transverse aberrations:
all rays from one object point to all pupil points on x- and y-axis

Two planes with 1-dimensional ray fans

No complete information: no skew rays
Pupil sampling in 3D for spot diagram:
all rays from one object point through all pupil points in 2D

- Light cone completely filled with rays
Different types of sampling with pro and con's:

1. Polar grid: not isoenergetic
2. Cartesian: good for FFT, boundary discretization bad
3. Isoenergetic circular: good
4. Hexagonal: good
5. Statistical: good non-regularity, holes?
- Artefacts due to regular gridding of the pupil of the spot in the image plane
- In reality a smooth density of the spot is true
- The line structures are discretization effects of the sampling
Looking for the ray bundle cross sections