Aberrations

• Chromatic
  – is due to the fact that the refractive index of lenses, etc. varies with wavelength; therefore, focal lengths, imaging conditions, etc. are wavelength-dependent

• Geometrical
  – are due to the deviation of non-paraxial rays from the approximations we have used so far to derive focal lengths, imaging conditions, etc.; therefore, rays going through imaging systems typically do not focus perfectly but instead scatter around the “paraxial” (or “Gaussian”) focus
Chromatic Aberration

(aka dispersion)

FIGURE 9X
(a) Cromatic aberration of a singel lens. (b) A cemented doublet corrected for chromatic aberration. (c) Illustrating the difference between longitudinal chromatic aberration and lateral chromatic aberration.

FIGURE 9Y
Graphs of the refractive indices of several kinds of optical glass. These are called dispersion curves.
**Geometrical aberrations**

- Deviation of the wavefront from its "ideal" spherical shape due to imperfect refraction by the optical elements.

  - Perfect spherical wavefront (focuses to a point)
  - Aberrated wavefront does not come to a focus → image is blurred

Optical elements (lenses, mirrors) produce perfect (non-aberrated) wavefronts only in the paraxial approximation (i.e., for angles of propagation near the optical axis).

At larger angles, 5 kinds of aberration (called "Seidel" aberrations) occur.
Primary (Seidel) aberrations

Spherical

Coma

Astigmatism

Field curvature

Distortion
Spherical

\[ q = \frac{r_2 + r_1}{r_2 - r_1} \]

\[ p = \frac{s - s'}{s + s'} \]

FIGURE 9F
(a) Lenses of different shapes but with the same power or focal length. The difference is one of bending. (b) Focal length versus ray height \( h \) for these lenses.

FIGURE 9G
A plot of the net axial aberration for lenses of different shape but the same

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

\[ s = \frac{2f}{1+p} \quad s' = \frac{2f}{1-p} \quad \eta = \frac{2f(n-1)}{q+1} \quad r = \frac{2f(n-1)}{q+1} \]
Coma

FIGURE 9I
Coma, the second of the five monochromatic aberrations of a lens. Only the tangential fan of rays is shown.

FIGURE 9K
Geometry of coma, showing the relative magnitudes of sagittal and tangential magnifications.

\[ C_T = 3C_s \]

Equation of comatic figure

\[ y = C_s(2 + \cos 2\psi) \]

\[ z = C_s \sin \psi \]
Simultaneous compensation of spherical and coma, using the lens form factor

**FIGURE 9L**
Graphs comparing coma with longitudinal spherical aberration for a series of lenses having different shapes.
field curvature

astigmatism

FIGURE 9Q
Astigmatic images of a spoked wheel.
FIGURE 9R
Diagrams showing the astigmatic surfaces $T$ and $S$ in relation to the fixed Petzval surface $P$ as the spacing between lenses (or between lens and stop) is changed.

FIGURE 9S
(a) A properly located stop may be used to reduce field curvature. (b) Astigmatic surfaces for an anastigmat camera lens.
Distortion

FIGURE 9T
(a) A pinhole camera shows no distortion. Images of a rectangular object screen shown with (b) no distortion, (c) barrel distortion, and (d) pincushion distortion.

FIGURE 9U
(a) A stop in front of a lens giving rise to barrel distortion. (b) A stop behind a lens giving rise to pincushion distortion. (c) A symmetrical doublet with a stop between is relatively free of distortion.
Optical design

Exact ray-tracing
Optical design

Exact ray-tracing

ray scatter diagram (↔ defocus)
## Optical design

![Optical design diagram](image)

<table>
<thead>
<tr>
<th>Surface name</th>
<th>Curvature</th>
<th>Index to the right</th>
<th>Distance to next element</th>
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<td>0.1</td>
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<td>-21.6</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>S3</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>S4</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Features of optical design software

• Databases of common lenses and elements sold by vendors
• Simulate aberrations and ray scatter diagrams for various points along the field of the system
• Standard optical designs (e.g. achromatic doublet, Cooke triplet)
• Permit optimization of design parameters (e.g. curvature of a particular surface or distance between two surfaces) vs designated functional requirements (e.g. field curvature and astigmatism coefficients)
• Also account for diffraction by calculating the modulation transfer function (MTF) at different points along the field
Vendors

• Optical design
  – Code V
  – Oslo
  – Zemax
  – Accos
  – Asap
  – consultants

• Optics & opto-mechanics
  – Newport
  – Newfocus
  – Coherent
  – Opto-Sigma
  – Thorlabs
  – Edmund
  – specialized shops

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