Sequential Ray Tracing

Lecture 2
Sequential Ray Tracing

• Rays are traced through a pre-defined sequence of surfaces while travelling from the object surface to the image surface.
• Rays hit each surface once in the order (sequence) in which the surfaces are defined. Particularly well-suited to imaging systems (including spectrometers).
• Numerically fast and extremely useful for the design, optimization and tolerancing of such systems.
• Aberrations evaluated using spot diagrams, ray fan plots, OPD plots, geometrical image analysis and MTF (physical optics) calculations.
Example Imaging Systems

Double Gauss lens

Schmidt-Cassegrain telescope
Objectives: Lecture 2

At the end of this lecture you should:

1. Be able to use ZEMAX to design and optimise a simple singlet lens to specified parameters.
2. Understand the use of meridional plane layouts, spot diagrams, and ray fan plots to evaluate performance.
3. Design and optimise a Cassegrain reflecting telescope to specified parameters.
4. Understand the way that conic and higher order surfaces are specified in ZEMAX.
5. Understand how to achromatise a doublet lens.
## Lens Data Editor (LDE)

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<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Material</th>
<th>Coating</th>
<th>Semi-Diameter</th>
<th>Conic</th>
<th>TCE x 1E-6</th>
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Singlet Lens Parameters

- Focal ratio is F/4.
- Glass is N-BK7.
- Effective focal length = 100mm.
- Field-Of-View = 10 degrees.
- Wavelength = 632.8nm (HeNe).
- Centre thickness of lens: 3mm to 12mm.
- Edge thickness of lens: minimum 2mm.
- Lens should be optimized for smallest RMS spot size averaged over the field of view at the given wavelength.
- Object is at infinity.
System Settings

• Entrance Pupil Diameter (EPD) is the diameter of the pupil in chosen lens units as seen from object space.
• Effective focal length (efl) is distance along optical axis from the effective refracting surface (principal plane) to the paraxial focus.

\[
F/\# = \frac{efl}{EPD}
\]

• So EPD = 25mm.
System Explorer (Setup)

- Aperture Type: Entrance Pupil Diameter
- Aperture Value: 25
- Apodization Type: Uniform
- Semi Diameter Margin Millimeters: 0
- Semi Diameter Margin %: 0
- Global Coordinate Reference Surface: 2
- Telecentric Object Space
- Afocal Image Space
- Iterate Solves When Updating
- Fast Semi-Diameters
- Check GRIN Apertures

- Wavelengths
  - Field 1 (X = 0.0, Y = 0.0, Weight = 1.0)
  - Field 2 (X = 0.0, Y = 2.5, Weight = 1.0)
  - Field 3 (X = 0.0, Y = 5.0, Weight = 1.0)

- Settings
  - Preset: HeNe (.6328)
  - Enable
  - Primary
  - Wavelength (μm): 0.6328
  - Weight: 1.0
  - Add Wavelength

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# Lens Data & Solves

**Optimize -> Quick Focus**  
[Ctrl+Shift+Q]

**N.B. use of comments field**

<table>
<thead>
<tr>
<th>Surf:Type</th>
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*February 15, 2016*  
Optical Systems Design
Performance Evaluation (Analyze)

Layout

Spots

Ray Fan

Optical Path Difference
Variables for Optimisation

• Thickness of lens
• Front radius of curvature
• Back focal distance (from Surface 2 to IMA plane)
Optimize Wizard (Default Merit Function)

Optical Systems Design
Final System Results (Optimize)

Final System Results (Optimize)

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Optical Systems Design
More Optical Concepts

• Effective Refracting Surface
  – Virtual surface at which entering and exiting rays meet. A plane for paraxial (first order) rays close to the axis.

• Zones
  – Annular regions of constant distance from the optical axis. Can apply to lens surfaces, stops, pupils, objects & images.

• Paraxial rays
  – Rays close to the optical axis for which first order (linear) equations can be used for the ray transport calculations.
More Optical Concepts

[Diagram of optical system with labeled parts: "Effective Refracting Surface" and "Real Lens"]
Tangential & Sagittal Planes

• Tangential plane is identical to the meridional plane for an axially symmetric system. Tangential rays lie within the tangential plane.

• Sagittal plane is orthogonal to the tangential plane and intersects it along the chief ray. All sagittal rays are skew rays. The sagittal pane changes its tilt after each surface to follow the direction of the chief ray.
Tangential & Sagittal Planes
Back Focal Length & Effective Focal Length

- Back focal length (BFL) is the distance along the optical axis from the vertex of the rear lens surface to the on-axis paraxial focus for an object at infinity.
- Effective focal length (EFL) is the distance along the optical axis from the vertex of the effective refracting surface to the on-axis paraxial focus for an object at infinity.
- BFL controls the longitudinal location of the focus
- EFL controls the transverse image scale at focus
# BFL, EFL & Aberrations

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<th>BFL</th>
<th>EFL</th>
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<td>With wavelength</td>
<td>Longitudinal chromatic aberration</td>
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<tr>
<td>With pupil zone</td>
<td>Spherical aberration</td>
<td>Coma</td>
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<tr>
<td>With field zone</td>
<td>Astigmatism &amp; field (focal plane) curvature</td>
<td>Distortion</td>
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Basic Zemax Analysis Tools

- Layout plots (cross-section/shaded)
- Spot diagrams
- Ray-aberration plot
  - Optical path plot (OPD)
  - Field curvature & distortion plot
  - Point Spread Function (diffraction PSF)
  - Modulation transfer function (MTF)
  - Enclosed energy plot
I: Layout

• Good for basic check of obvious mistakes (e.g. data entry sign errors)
• Sanity check after optimisation e.g. excessive surface curvatures, inappropriate glass/air thicknesses, negative edge thicknesses etc
• Check on mechanical vignetting
I: Layout

TESSAR 50/3.5
TUE FEB 24 2009
TOTAL AXIAL LENGTH: 67.19800 MM

TESSAR1.ZMX
CONFIGURATION 1 OF 1
II: Spot Diagram

• Analog of the geometrical PSF
• Shows the intersection points where a ray bundle which fills the entrance aperture meets the image plane
• For polychromatic (white light) systems these must be generated at representative wavelengths
II: Spot Diagram

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SURFACE: IMA

MATRIX SPOT DIAGRAM

TESSAR 50/3.5
TUE FEB 7th 2009  UNITS ARE μm.

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III: Ray Aberration Plots

- Spot diagrams give little information about which parts of the entrance pupil particular rays pass through.
- A given ray passes through the entrance pupil at a particular height $P$ (-1<$P$<+1) and intercepts the image plane at a separation $\Delta h$ from the chief ray.
- Ray aberration plots (ray fan plots) present the transverse ray height errors $\Delta h$ as a function of pupil zone height $P$.
- Customary to present these separately for the tangential (meridional) fan and the sagittal fan.
III: Ray Fan Plots
III: Ray Fan Plots

- Slope of ray fan plot reflects whether image plane is close to focus (inside focus $\rightarrow$ positive slope and vice versa)
- If effective refractive surface is curved or image surface is curved then ray fan plot also curved
- Behavior close to origin reflects whether image plane is close to the paraxial focus
- Each Seidel aberration has a characteristic appearance in the ray fan plot
III: Ray Fan Plots

TRANSVERSE RAY FAN PLOT

TESSAR 50/3.5
THU FEB 26 2009
MAXIMUM SCALE: ± 200,000 μm,
0.436 0.436 0.588 0.656
SURFACE: IMAGE

TESSAR,ZMX
CONFIGURATION 1 OF 1
Spherical Aberration
Coma
Astigmatism

0 deg

5 deg

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Optical Systems Design
Distortion
Lateral Colour
Glass Dispersion Curve

Dispersion:

\[ V_d = \frac{n_d - 1}{n_2 - n_1} \]

d=587.6 nm
1=486.1 nm
2=656.3 nm

[Abbé number]
Abbé Diagram

Crown glass – low dispersion

Flint glass – high dispersion

Use easily available glasses when possible: BK7, LLF1, F2, SF2, SF57, SK16, KzFSN4. CaFl often used as crown. Large Δn is good.

Final optimization is usually done on actual melt data.
Aspheric Surfaces

- Most optical surfaces are spherical
- By far the easiest surfaces to manufacture using conventional polishing techniques
- General rotationally symmetric optical surface has departure from plane (sag) given by:

\[ z = \frac{ch^2}{1 + [1 - ((1 + k)c^2h^2)^{1/2}]} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} \]

where \( h^2 = x^2 + y^2 \) is the axial height, \( c = 1/R \) is the surface curvature at the vertex, and \( k \) the conic constant. \( A, B, C, D \) are 4\textsuperscript{th}, 6\textsuperscript{th}, 8\textsuperscript{th}, 10\textsuperscript{th} order coeffs.

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<th>(-1 &lt; k &lt; 0 )</th>
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<td>prolate</td>
<td>paraboloid</td>
<td>hyperboloid</td>
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Cassegrain Telescope

• Start with a 30cm diameter F/2 spherical primary (RoC=120cm) and a spherical secondary. Adjust the radius of curvature of the secondary to put the focus in the plane of the primary.
• Glass Type = MIRROR for reflecting surfaces; distances change sign after each reflection.
• Use a Quick-focus or M-solve to locate paraxial focus and single variables in any optimization.
• Now make primary a parabola (K=-1).
• Adjust conic constant on secondary to get best on-axis performance.
Summary: Lecture 2

- Sequential ray tracing is the main mode of Zemax for the design of optical systems.
- Zemax has a range of optimising tools to improve the performance of the basic design.
- The major tools for assessing performance are the layout plots, the spot diagrams and the ray fan plots.
- All the main Seidel aberrations have characteristic forms in these plots which can be used to decide how to improve the design.
- Careful choice of glasses is required to remove longitudinal and lateral colour effects.
Exercises: Lecture 2

• Input the parameters of a 50mm diameter F/10 optimised (R1=265mm) achromatic doublet from Lecture 4 of the Optical Engineering Course (Dr Rolt). Take the lens thicknesses as 8mm (crown) and 4mm (flint). Investigate the axial colour over the wavelengths 0.486, 0.587 and 0.656 µm. Can you improve the performance?

• Investigate the performance of the Cassegrain telescope for off-axis (1 deg) field points. What is the main off-axis aberration?

• Try to minimize this aberration by making both the primary and secondary hyperbolic.