<table>
<thead>
<tr>
<th>Week</th>
<th>Date</th>
<th>Topic</th>
<th>Subtopics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.10</td>
<td>Aberrations and optimization</td>
<td>Repetition</td>
</tr>
<tr>
<td>2</td>
<td>23.10</td>
<td>Structural modifications</td>
<td>Zero operands, lens splitting, lens addition, lens removal, material selection</td>
</tr>
<tr>
<td>3</td>
<td>30.10</td>
<td>Aspheres</td>
<td>Correction with aspheres, Forbes approach, optimal location of aspheres, several aspheres</td>
</tr>
<tr>
<td>4</td>
<td>06.11</td>
<td>Freeforms</td>
<td>Freeform surfaces, general aspects, surface description, quality assessment, initial systems</td>
</tr>
<tr>
<td>5</td>
<td>13.11</td>
<td>Field flattening</td>
<td>Astigmatism and field curvature, thick meniscus, plus-minus pairs, field lenses</td>
</tr>
<tr>
<td>6</td>
<td>20.11</td>
<td>Chromatical correction I</td>
<td>Achromatization, axial versus transversal, glass selection rules, burried surfaces</td>
</tr>
<tr>
<td>7</td>
<td>27.11</td>
<td>Chromatical correction II</td>
<td>Secondary spectrum, apochromatic correction, aplanatic achromates, spherochromatism</td>
</tr>
<tr>
<td>8</td>
<td>04.12</td>
<td>Special correction topics I</td>
<td>Symmetry, wide field systems, stop position, vignetting</td>
</tr>
<tr>
<td>9</td>
<td>11.12</td>
<td>Special correction topics II</td>
<td>Telecentricity, monocentric systems, anamorphic lenses, Scheimpflug systems</td>
</tr>
<tr>
<td>10</td>
<td>18.12</td>
<td>Higher order aberrations</td>
<td>High NA systems, broken achromates, induced aberrations</td>
</tr>
<tr>
<td>11</td>
<td>08.01</td>
<td>Further topics</td>
<td>Sensitivity, scan systems, eyepieces</td>
</tr>
<tr>
<td>12</td>
<td>15.01</td>
<td>Mirror systems</td>
<td>Special aspects, double passes, catadioptric systems</td>
</tr>
<tr>
<td>13</td>
<td>22.01</td>
<td>Zoom systems</td>
<td>Mechanical compensation, optical compensation</td>
</tr>
<tr>
<td>14</td>
<td>30.01</td>
<td>Diffractive elements</td>
<td>Color correction, ray equivalent model, straylight, third order aberrations, manufacturing</td>
</tr>
<tr>
<td>15</td>
<td>05.02</td>
<td>Realization aspects</td>
<td>Tolerancing, adjustment</td>
</tr>
</tbody>
</table>
Contents

1. General properties
2. Image orientation
3. Telescope systems
4. Further Examples
Fundamental Properties of Mirror Systems

- No chromatical Aberrations
- Aspherical correction of spherical aberration
- More sensitive for field aberrations:
  - Only small field of view
  - Calculation with 3. Order Seidel often possible
  - Coma dominant residual aberration
- Tolerances $2/(n-1) \approx 4$ tighter than refractive surfaces
- Combination of refractive surfaces with mirrors:
  catadioptric systems
### General Properties of Mirror Systems

**Geometry:**
1. bending needs the separation of ray bundles
2. helps in folding systems to more compact size
3. switches image orientation in the plane of incidence
4. for centered usage of mirrors: central obscuration, spider legs for mounting

**Correction:**
1. astigmatism for oblique incidence
2. no color aberrations
3. positive contribution to Pethval curvature
4. usually more sensitive for off-axis field: coma

**Miscellaneous:**
1. coating is HR, mostly metallic, no ghost images
2. surface accuracy approximately 4 times more sensitive
3. only option for very large diameter (astronomy)
4. aspherical or freeform shape easier to fabricate
5. preferred as scanning or adaptive component
6. plane bending mirrors often realized as prisms
7. only option for extreme UV due to transmission problems
Mirror inverts the system: left handed into right handed coordinate system
Vectorial calculation with tensor calculus possible

Possible solutions for correct ray tracing:
1. distances negative behind the mirror
   only obvious for normal incidence
2. refractive index negative behind the mirror
   seems to be unphysical, only formal solution

For complicated prisms with multiple reflections:
tunnel diagram with unfolded reflections
Modelling a Mirror Surface

- Problem in coordinate system based raytracing of mirror systems: right-handed systems becomes left-handed

- Possible solutions:
  1. Folding the mirror
     - light propagation direction changed
     - z-component inverted
     - tunnel diagram for prism
  2. negative refractive index
  3. inversion of the x-axis
Avoiding Mirror Obscuration

- Avoiding the central obscuration in mirror systems
- Field bias or aperture offset as opportunities

Ref.: K. Fuerschbach
Tunnel diagram:
Unfolding the ray path with invariant sign of the z-component of the optical axis

Optical effect of prisms corresponds to plane parallel plates

More rigorous model:
Exact geometry of various prisms can cause vignetting
Transformation of Image Orientation

- Modification of the image orientation with four options:
  1. Invariant image orientation
  2. Reverted image (side reversal)
  3. Inverted image (upside down)
  4. Complete image inversion (inverted-reverted image)

- Image side reversal in the principal plane of one mirror

- Inversion for an odd number of reflections

- Special case roof prims:
  Corresponds to one reflection in the edge plane,
  Corresponds to two reflections perpendicular to the edge plane
Transformation of Image Orientation

- Image reversion in the folding plane (upside down)
- Image inversion
- Original
- Image reversion perpendicular to the folding plane
- Folding plane
- Image unchanged
- Image inversion
Types of Reflection Prisms: 90° Prism

- Classical 90° prism
- Version with roof edge
- Version with arbitrary deviation angle (Amici prism)
Roof-Edge Prism

- Roof edge:
  - two reflecting surfaces with 90°
  - change of lateral coordinate in one section

- Critical in practice:
  Precision of 90° angle, typical tolerance 1“
  errors cause image split

- Coatings critical due to polarization effects
Types of Reflection Prisms: Penta Prism

- Classical penta prism
- Penta prism with roof edge
- Penta prism with arbitrary deviation angle
Types of Reflection Prisms: Bauernfeind Prism

- Classical Bauernfeind prism
- One surface used for entrance and in reflection
- Prism with roof-edge
Types of Telescopes

- basic setups

Ref.: C. Keller
Telescopic System Types

- **Cassegrain**

- **Gregorian**

- **Schmidt catadioptric**

- **Schwarzschild**
Astigmatism of Oblique Mirrors

- Mirror with finite incidence angle: effective focal lengths
  \[ f_{\text{tan}} = \frac{R \cdot \cos i}{2}, \quad f_{\text{sag}} = \frac{R}{2 \cos i} \]

- Mirror introduces astigmatism
  \[ \Delta s'_{\text{ast}} = \frac{s'^2 \cdot R \cdot \sin^2 i}{2 \cos i \cdot \left( s - \frac{R \cos i}{2} \right) \cdot \left( s - \frac{R}{2 \cos i} \right)} \]

- Parametric behavior of scales astigmatism
Non-Axisymmetric Systems: Pilot Axis Ray

- For an oblique ray, the effective curvatures of the spherical surface depend on azimuth
- Astigmatism of oblique used curved surfaces
- In particular large effects in case of mirrors
- Propagation of curvature components according to Coddington equations

\[
\begin{align*}
\frac{n'\cos^2 i'}{l'_{\tan}} - \frac{n\cos^2 i}{l_{\tan}} &= \frac{n'\cos i' - n\cos i}{R} \\
\frac{n'}{l'_{sag}} - \frac{n}{l_{sag}} &= \frac{n'\cos i' - n\cos i}{R}
\end{align*}
\]
Field Curvature of a Mirror

- Mirror: opposite sign of curvature than lens
- Correction principle: field flattening by mirror
Astigmatism at Curved Mirrors

- Image surfaces for a concave mirror
  - $y'$: image height
  - $s_{bar}$: stop position

- Special cases of flat image shells as a function of the stop position
  a) stop a center:
     - zero astigmatism
  b) stop at distance $0.42 \, R$:
     - $T=0$
  c) stop at distance $0.29 \, R$:
     - $B = 0$ (best plane)
  d) stop at mirror:
     - $S = 0$

\[ \Delta s'_r = \frac{y'^2}{R} \cdot \left[ 1 - 3 \left( \frac{s}{R} - 1 \right)^2 \right] \]

\[ \Delta s'_s = \frac{y'^2}{R} \cdot \left[ 1 - \left( \frac{s}{R} - 1 \right)^2 \right] \]
- Telescopes with tilted elements
- Anastigmatic solution for two mirrors

\[ \frac{\theta_2}{\theta_2} = \frac{\sqrt{r_1 \cdot r_2}}{r_1 - 2d} \]
Correction of 3D Mirror Systems

- Problem: oblique incidence on curved mirrors creates macroscopic astigmatism
- Different solution approaches as tradeoffs between performance vs cost/complexity

<table>
<thead>
<tr>
<th>Setup</th>
<th>Correction</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 All spherical</td>
<td>Select incidence angles to fulfill Coddington equations, compensation over all mirrors</td>
<td>1. only limited solution space (Korsch) 2. coma remains 3. induced aberrations, only small aperture possible</td>
</tr>
<tr>
<td>2 Confocal conic section</td>
<td>Perfect on axis, if focal points coincide, rotations optimized to avoid collisions</td>
<td>1. Correction offaxis hard 2. all aspheres is costly</td>
</tr>
<tr>
<td>3 Centered aspheres</td>
<td>Biased sub-aperture or field, centered surfaces</td>
<td>1. astigmatism and coma coupled</td>
</tr>
<tr>
<td>4 Spherical Toric surfaces</td>
<td>Astigmatism at any surface corrected</td>
<td>1. all non-spherical is costly 2. coma remains</td>
</tr>
<tr>
<td>5 Freeform</td>
<td>All but one surface spherical, one freeform surface compensates all coma and astigmatism</td>
<td>1. large induced aberrations 2. Simultaneous resolution and field correction needs 2 freeforms</td>
</tr>
</tbody>
</table>
Finding of Initial Systems

- Conic section initial system approach for 4-mirror system
  - $F_1$ is common to parabola and hyperbola
  - $F_2$ is common to hyperbola and ellipsoid 1
  - $F_3$ is common to ellipsoid 1 and ellipsoid 2
  - image point $F_4$ is also focal point of ellipsoid 2

- Perfect imaging on axis

TMA Schiefspiegler vs Freeform Solutions

- First approach of a corrected obscuration-free three mirror system:
  - coaxial circular symmetric system
  - one common optical axis
  - used for off-axis field part only (field biased approach)
  - typically: astigmatism corrected with incidence angle in complete system
  - coupling of astigmatism and coma at every surface (one degree of freedom lost)
  - overall performance reduced

- Second approach of a corrected onscuration-free three mirror system:
  - vertex-centered unobscured three freeform mirrors
  - low-order correction of freeform surfaces, coma and astigmatism independent corrected
  - overall performance improved in comparison to first approach

Gracing Incidence-Xray Telescope

- X-ray telescope Wolter type I
- Nested shells with grazing incidence
- Increase of numerical aperture by several shells
Gracing Incidence-Xray Telescope

- Woltertyp
- 1. Paraboloid
  2. Hyperboloid
Mangin Mirror

- **Principle:**
  - Backside mirror, catadioptric lens
- **Advantages:**
  - Mirror can be made spherical
  - Refractive surface corrects spherical
  - System can be made nearly aplanatic
- Seidel surface contributions of a real lens:
  - Spherical correction perfect
  - Residual axial chromatic unavoidable
Concentric system of Offner: relation

\[ d_1 = d_2 = \frac{r_1}{2} = r_2 \]

Due to symmetry:
Perfect correction of field aberrations in third order
- Catadioptric system with $m = -1$ according Dyson
  - Advantage: flat field
  - Application: lithography and projection
- Relation:
  $$r_L = \frac{n - 1}{n} \cdot r_M$$
- Residual aberration: astigmatism
Lithographic Optics

- I-Design
- H-Design
- X-Design
EUV - Mirror System

- System:
  Only mirrors
Microscope Objective Lens: Catadioptric Lenses

- Catadioptric lenses:
  1. Schwarzschild design: first large mirror
  2. Newton design: first small mirror

- Advantageous:
  1. Large working distance
  2. Field flattening
  3. Colour correction

- Drawback:
  central obscuration reduces contrast / resolution