Design and Correction of Optical Systems

Lecture 3: Paraxial optics
2019-04-29
Herbert Gross

Summer term 2019
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1. Paraxial approximation
2. Ideal surfaces and lenses
3. Imaging equation
4. Matrix formalism
5. Lagrange invariant
6. Phase space considerations
7. Delano diagram
Paraxial Approximation

- Paraxiality is given for small angles relative to the optical axis for all rays.
- Large numerical aperture angle $u$ violates the paraxiality, spherical aberration occurs.
- Large field angles $w$ violates the paraxiality, coma, astigmatism, distortion, field curvature occurs.
Paraxial approximation:

- Law of refraction for finite angles $I, I'$
  
  \[ n \cdot \sin I = n' \cdot \sin I' \]

- Sin-expansion
  
  \[ \sin i = i - \frac{i^3}{6} + \frac{i^5}{120} - \frac{i^7}{5040} + \frac{i^9}{362880} - ... \]

- Small incidence angles allows for a linearization of the law of refraction

- Small angles of rays at every surface

- All optical imaging conditions become linear (Gaussian optics), calculation with ABCD matrix calculus is possible

- No aberrations occur in optical systems

- There are no truncation effects due to transverse finite sized components

- Serves as a reference for ideal system conditions

- Is the fundament for many system properties (focal length, principal plane, magnification, ...)

- The sag of optical surfaces (difference in $z$ between vertex plane and real surface intersection point) can be neglected

- All waves are plane of spherical (parabolic)

- The phase factor of spherical waves is quadratic

  \[ E(x) = E_0 \cdot e^{-\frac{i \pi x^2}{\lambda R}} \]
Paraxial approximation

- Taylor expansion of the sin-function
- Definition of allowed error $10^{-4}$
- Deviation of the various approximations:
  - linear: $5^\circ$
  - cubic: $24^\circ$
  - 5th order: $542^\circ$
Paraxial Approximation

- Law of refraction
  \[ n \cdot \sin I = n' \cdot \sin I' \]
- Expansion of the sine-function:
  \[ \sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \ldots \]
- Linearized approximation of the law of refraction: \( I \to i \)
  \[ n \cdot i = n' \cdot i' \]
- Relative error of the approximation
  \[ \varepsilon = \frac{i' - I'}{I'} = \frac{n \cdot i}{n'} \arcsin\left(\frac{n \cdot \sin i}{n'}\right) - 1 \]
Generalized Paraxiality

- Pitfalls in the classical definition of paraxiality:

1. Central obscurartion and ring-shaped pupil:
   - Paraxial marginal ray of no relevance
   - Reference on centroid ray

2. General 3D system without straight axis:
   Central ray as reference, calculated finite parabasal rays in the neighborhood of the real chief ray
   Distortion information is lost

- General quasi-parabasal rays:
  - macroscopic astigmatism
  - aberrations reference definition more complicated
  - separated view on cheif ray / marginal ray
Optical Image formation:
All ray emerging from one object point meet in the perfect image point

Region near axis:
gaussian imaging
ideal, paraxial

Image field size:
Chief ray

Aperture/size of light cone:
marginal ray defined by pupil stop
Formulas for surface and lens imaging

- Single surface imaging equation
  \[ \frac{n'}{s'} - \frac{n}{s} = \frac{n' - n}{r} = \frac{1}{f'} \]

- Thin lens in air focal length
  \[ \frac{1}{f'} = (n-1) \cdot \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \]

- Thin lens in air with one plane surface, focal length
  \[ f' = \frac{r}{n-1} \]

- Thin symmetrical bi-lens
  \[ f' = \frac{r}{2 \cdot (n-1)} \]

- Thick lens in air focal length
  \[ \frac{1}{f'} = (n-1) \cdot \left( \frac{1}{r_1} - \frac{1}{r_2} \right) + \frac{(n-1)^2 \cdot d}{n \cdot r_1 r_2} \]
Single Surface

- Single surface between two media
  - Radius $r$, refractive indices $n, n'$

- Imaging condition, paraxial

- Abbe invariant
  - alternative representation of the imaging equation

\[
\frac{n'}{s'} - \frac{n}{s} = \frac{n' - n}{r} = \frac{1}{f'}
\]

\[
Q_s = n \cdot \left(\frac{1}{r} - \frac{1}{s}\right) = n' \cdot \left(\frac{1}{r} - \frac{1}{s'}\right)
\]
Imaging by a Lens

- Imaging with a lens

- Location of the image:
  lens equation
  \[
  \frac{1}{s'} - \frac{1}{s} = \frac{1}{f}
  \]

- Size of the image:
  Magnification
  \[
  m = \frac{y'}{y} = \frac{s'}{s}
  \]
Imaging by a Lens

- Ranges of imaging
  - Location of the image for a single lens system

- Change of object location

- Image could be:
  1. real / virtual
  2. enlarged/reduced
  3. in finite/infinite distance
- Imaging by a lens in air: lens makers formula

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

- Magnification

\[ m = \frac{s'}{s} \]

- Real imaging:
  \( s < 0 \), \( s' > 0 \)

- Intersection lengths \( s, s' \) measured with respective to the principal planes \( P, P' \)
Distance object-image: (transfer length)
$L = |s| + |s'|$

Two solution for a given $L$ with different magnifications

$$m = \frac{L}{2f'} - 1 \pm \sqrt{\left(\frac{L}{2f'}\right)^2 - \frac{L}{f'}}$$

No real imaging for $L < 4f$
Magnification

- Lateral magnification for finite imaging
- Scaling of image size

\[ m = \frac{y'}{y} = -\frac{f \cdot \tan u}{f' \cdot \tan u'} \]
Afocal systems with object/image in infinity
Definition with field angle w
angular magnification

 Relation with finite-distance magnification

\[ \Gamma = \frac{\tan w'}{\tan w} = \frac{nh}{n'h'} \]

\[ m \cdot \Gamma = -\frac{f}{f'} \]
Imaging equation according to Newton: distances $z$, $z'$ measured relative to the focal points

$$z \cdot z' = f \cdot f'$$
Graphical Image Construction after Listing

- Graphical image construction according to Listing by 3 special rays:
  1. First parallel through axis, through focal point in image space F'
  2. First through focal point F, then parallel to optical axis
  3. Through nodal points, leaves the lens with the same angle

- Procedure work for positive and negative lenses
  For negative lenses the F / F' sequence is reversed
General Graphical Ray Construction

- First ray parallel to arbitrary ray through focal point, becomes parallel to optical axis

- Arbitrary ray:
  - constant height in principal planes $S \rightarrow S'$
  - meets the first ray in the back focal plane, desired ray is $S'Q$
Two lenses with distance $d$:

$$F = F_1 + F_2 - \frac{d \cdot F_1 \cdot F_2}{n}$$

Focal length distance of inner focal points $e$:

$$f = \frac{f_1 \cdot f_2}{f_1 + f_2 - d} = \frac{f_1 \cdot f_2}{e}$$

Sequence of thin lenses close together:

$$F = \sum_k F_k$$

Sequence of surfaces with relative ray heights $h_j$, paraxial:

$$F = \sum_k \frac{h_k}{h_1} \cdot (n'_k - n_k) \cdot \frac{1}{r_k}$$

Magnification:

$$m = \frac{s'_1}{s_1} \cdot \frac{s'_2}{s_2} \cdots \frac{s'_k}{s_k} \cdot \frac{n_1}{n'_k}$$
Principal Planes

- System of two separated thin lenses
- Variation of the back principal plane as a function of the distribution of refractive power
- Imaging with tilted object plane

- If principal plane, object and image plane meet in a common point: Scheimpflug condition, sharp imaging possible

- Scheimpflug equation

\[
\frac{s}{s'} = \frac{\tan \theta - \tan \varphi}{\tan \theta' - \tan \varphi}
\]
Scheimpflug System

- General:
  1. Image plane is tilted
  2. Magnification is anamorphic
- Example:
  Scheimpflug-Imaging

\[ m_y = m_o^2 \cdot \frac{\sin \theta}{\sin \theta'} \]
\[ m_x = m_o = \frac{s'}{s} = \frac{\tan \theta'}{\tan \theta} \]
Matrix Formulation of Paraxial Optics

- Linear relation of ray transport
- Simple case: free space propagation
- Advantages of matrix calculus:
  1. simple calculation of component combinations
  2. Automatic correct signs of properties
  3. Easy to implement
- General case: paraxial segment with matrix ABCD-matrix:

\[
\begin{pmatrix} x' \\ u' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x \\ u \end{pmatrix} = M \begin{pmatrix} x \\ u \end{pmatrix}
\]
Matrix Calculus

- Paraxial raytrace transfer
  \[ y_j = y_{j-1} + d_{j-1} \cdot U_{j-1} \quad U_j' = U_{j-1} \]

- Matrix formulation
  \[
  \begin{pmatrix}
  y'_j \\
  U'_j
  \end{pmatrix}
  =
  \begin{pmatrix}
  1 & d_{j-1} \\
  0 & 1
  \end{pmatrix}
  \begin{pmatrix}
  y_j \\
  U_j
  \end{pmatrix}
  \]

- Matrix formalism for finite angles
  \[
  \begin{pmatrix}
  y'_j \\
  \tan u'_j
  \end{pmatrix}
  =
  \begin{pmatrix}
  A & B \\
  C & D
  \end{pmatrix}
  \begin{pmatrix}
  y_j \\
  \tan u_j
  \end{pmatrix}
  \]

- Paraxial raytrace refraction
  \[ y_j = y_{j-1} \quad i_j = \rho_j \cdot y_j + U_{j-1} \quad i'_j = \frac{n_j}{n_j'} i_j \]
  \[ U_j' = U_{j-1} - i_j + i'_j \]

- Inserted
  \[ U_j' = -\frac{\rho_j \cdot (n_{j'} - n_j)}{n_j} y_j + \frac{n_j}{n_{j'}} U_{j-1} \]

- Matrix formulation
  \[
  \begin{pmatrix}
  y'_j \\
  U'_j
  \end{pmatrix}
  =
  \begin{pmatrix}
  -\frac{\rho_j \cdot (n_{j'} - n_j)}{n_j} & 0 \\
  \frac{n_j}{n_{j'}} & \frac{n_j}{n_{j'}}
  \end{pmatrix}
  \begin{pmatrix}
  y_j \\
  U_j
  \end{pmatrix}
  \]
Matrix Formulation of Paraxial Optics

- Linear transfer of spation coordinate $x$ and angle $u$
  \[ x' = Ax + Bu \]
  \[ u' = Cx + Du \]

- Matrix representation

- Lateral magnification for $u=0$

- Angle magnification of conjugated planes

- Refractive power for $u=0$

- Composition of systems

- Determinant, only 3 variables

\[ \det M = AD - BC = \frac{n}{n'} \]
Matrix Formulation of Paraxial Optics

- System inversion

\[ M^{-1} = \begin{pmatrix} D & -B \\ -C & A \end{pmatrix} \]

- Transition over distance \( L \)

\[ M = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \]

- Thin lens with focal length \( f \)

\[ M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \]

- Dielectric plane interface

\[ M = \begin{pmatrix} 1 & 0 \\ 0 & \frac{n}{n'} \end{pmatrix} \]

- Afocal telescope

\[ M = \begin{pmatrix} 1 & L \\ \frac{1}{\Gamma} & L \end{pmatrix} \]
- Calculation of intersection length
  \[ s' = \frac{A \cdot s + B}{C \cdot s + D} \]

- Magnifications:
  1. lateral
  \[ m = \frac{AD - BC}{C \cdot s + D} \]
  2. angle
  \[ \Gamma = C \cdot s + D = \frac{AD - BC}{A - C \cdot s'} \]
  3. axial, depth
  \[ \alpha = \frac{ds'}{ds} = \frac{AD - BC}{(C \cdot s + D)^2} \]

- Principal planes
  \[ a_H = \frac{AD - BC - D}{C} \]
  \[ a_H' = \frac{A - 1}{C} \]

- Focal points
  \[ a_F' = \frac{A}{C} \]
  \[ a_F = -\frac{D}{C} \]
Decomposition of ABCD-Matrix

- 2x2 ABCD-matrix of a system in air: 3 arbitrary parameters
- Every arbitrary ABCD-setup can be decomposed into a simple system
- Decomposition in 3 elementary partitions is always possible

- Case 1: C ≠ 0
  one lens, 2 transitions

\[
M = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & L_1 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & L_2 \\ 0 & 1 \end{pmatrix}
\]

- System data

\[
L_2 = \frac{A - 1}{C}
\]

\[
f = -\frac{1}{C}
\]

\[
L_1 = \frac{D - 1}{C}
\]
Decomposition of ABCD-Matrix

- **Case 2: B ≠ 0**
  two lenses, one transition

\[
M = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} -\frac{1}{f_2} & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} -\frac{1}{f_1} & 0 \\ 0 & 1 \end{pmatrix}
\]

- **System data:**

\[
f_1 = -\frac{B}{A - 1}
\]

\[
L = B
\]

\[
f_2 = -\frac{B}{D - 1}
\]
Helmholtz-Lagrange Invariant

- Product of field size $y$ and numerical aperture is invariant in a paraxial system
- Derivation at a single refracting surface:
  1. Common height $h$:
  
  \[ h = s \cdot u = s' \cdot u' \]

  2. Triangles

  3. Refraction:

  \[ w = \frac{y}{s}, \quad w' = \frac{y'}{s'} \]

  \[ nw = n'w' \]

- The invariance corresponds to:
  1. Energy conservation
  2. Liouville theorem
  3. Invariant phase space volume (area)
  4. Constant transfer of information

\[ L = n \cdot y \cdot u = n' \cdot y' \cdot u' \]
- Product of field size $y$ and numerical aperture is invariant in a paraxial system

$$L = n \cdot y \cdot u = n' \cdot y' \cdot u'$$

- The invariant $L$ describes the phase space volume (area)

- The invariance corresponds to:
  1. Energy conservation
  2. Liouville theorem
  3. Constant transfer of information
Basic formulation of the Lagrange invariant:
Uses image height, only valid in field planes

General expression:

1. Triangle SPB
   \[ w' = \frac{y_{CR}}{s'_{\text{Exp}}} \]

2. Triangle ABO'
   \[ y'_{CR} = w' \left( s' - s'_{\text{Exp}} \right) \]

3. Triangle SQA
   \[ u' = \frac{y_{MR}}{s'} \]

4. Gives
   \[ L = n' u' y'_{CR} = n' \frac{y_{MR}}{s'} w' \left( s' - s'_{\text{Exp}} \right) = n' \left( y_{MR} w' - u' w' s'_{\text{Exp}} \right) \]

5. Final result for arbitrary z:
   \[ L = n' \left[ w' y'_{MR}(z) - u' y'_{CR}(z) \right] \]
Simple example:
- A microscope is a 4f-system with
  objective lens \( f_{\text{obj}} = 3 \text{ mm} \) and tube lens \( f_{\text{obj}} = 180 \text{ mm} \)
- the numerical aperture is \( \text{NA} = 0.9 \) and the intermediate Image size \( D = 2y_{\text{ima}} = 25 \text{ mm} \)
- magnification
  \[ m = \frac{f_{\text{TL}}}{f_{\text{obj}}} = 60 \]
- image sided aperture
  \[ u_{\text{ima}} = \frac{u_{\text{obj}}}{m} = 0.015 \]
- pupil size
  \[ D_{\text{pup}} = f_{\text{obj}} \cdot \text{NA} = 2.7 \text{ mm} \]
- object field
  \[ y_{\text{obj}} = y_{\text{ima}} \cdot \frac{u_{\text{ima}}}{u_{\text{obj}}} = 0.42 \text{ mm} \]
• Geometrical optic: Etendue, light gathering capacity

• Paraxial optic: invariant of Lagrange / Helmholtz

• General case: 2D

• Invariance corresponds to conservation of energy

• Interpretation in phase space: constant area, only shape is changed at the transfer through an optical system

\[ L_{Geo} = \frac{D_{field}}{2} \cdot n \cdot \sin u \]

\[ L = n \cdot y \cdot u = n' \cdot y' \cdot u' \]
Direct phase space representation of raytrace: spatial coordinate vs angle
Direct phase space representation of raytrace: spatial coordinate vs angle
Grin lens with aberrations in phase space:
- continuous bended curves
- aberrations seen as nonlinear angle or spatial deviations
1. Slit diffraction
   Diffraction angle inverse to slit width $D$
   \[ \theta = \frac{\lambda}{D} \]

2. Gaussian beam
   Constant product of waist size $w_o$ and divergence angle $\theta_o$
   \[ w_o \theta_o = \frac{\lambda}{\pi} \]
• Angle $u$ is limited
• Typical shapes:
  Ray: point (delta function)
  Coherent plane wave: horizontal line
  Extended source: area
  Isotropic point source: vertical line
  Gaussian beam: elliptical area with minimal size

• Range of small etendues: modes, discrete structure
• Range of large etendues: quasi continuum
Simplified pictures to the changes of the phase space density.
Etendue is enlarged, but no complete filling.
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Delano Diagram

- Special representation of ray bundles in optical systems:
  marginal ray height \( y = y_{MR} \)
  vs.
  chief ray height \( y = y_{CR} \)

- Delano diagram gives useful insight into system layout
- Every \( z \)-position in the system corresponds to a point on the line of the diagram
- Interpretation needs experience
Delano Diagram

Delano ray (blue)= Chief ray (red) in $x$ + Marginal ray (green) in $y$

Delano Diagram = Delano ray projected into the $xy$-Plane

Substitution
$x \rightarrow \bar{y}$

$y = $ Pupil coordinate $\bar{y} = y_c$ Field coordinate

Delano diagram: projection along $z$

Ref.: M. Schwab / M. Geiser
- Pupil locations: intersection points with y-axis

- Field planes/object/image: intersection points with y-bar axis

- Construction of focal points by parallel lines to initial and final line through origin
- Influence of lenses: diagram line bended
- Location of principal planes

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<th>strong positive refractive power</th>
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- y: Image space
- y: Object space

- y: Principal plane
- y: Image space

- Afocal Kepler-type telescope

- Effect of a field lens
Microscopic system
- Conjugated point are located on a straight line through the origin.
- Distance of a system point from origin gives the system's half diameter.
Delano Diagram

- Location of principal planes in the Delano diagram

- Triplet
  Effect of stop shift
- Vignetting:
  ray height from axis
  
  \[ a = |y| + |\bar{y}| \]

- Marginal and chief ray considered

- Line parallel to -45° maximum diameter

Delano Diagram

- Object
- Pupil
- Chief ray
- Marginal ray
- Coma ray
- System polygon line
- Maximum height at lens 2
- Lens 1
- Lens 2
- Lens 3
- D/2