Hubble Telescope

It was probably the most precisely figured mirror ever made, with variations from the prescribed curve of only 10 nanometers. It was too flat at the edges by about 2.2 microns. Source: wikipedia
When Paraxial Approximation Fails: Ray Tracing + Diffraction

- Databases of common lenses and elements
- Simulate aberrations and ray scatter diagrams for various points along the field of the system (PSF, point spread function)
- Standard optical designs (e.g. achromatic doublet)

- 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 at different points along the field modulation transfer function (MTF) [Fourier Optics]
Numerical Aperture

Paraxial approximation

\[
\sin(\theta) \approx \tan(\theta) \approx \theta
\]

\[
\rightarrow NA = \frac{D}{2f} = \frac{1}{2f/\#}
\]

\(\theta\): half-angle subtended by the imaging system from an axial object

**Numerical Aperture**

\((NA) = n \sin \theta\)

**Speed** \((f/#) = 1/2(NA)\)

pronounced f-number, e.g. f/8 means \((f/#) = 8\).

**Aperture stop**

the physical element which limits the angle of acceptance of the imaging system

The spatial resolution limit due to diffraction \(\approx 1.22 \times \frac{\lambda}{D} = 0.61 \times \frac{\lambda}{NA}\) [Rayleigh Criterion].
Thin Lenses \(\rightarrow\) Thick Lenses

Paraxial approximation

\[
\sin(\theta) \approx \tan(\theta) \approx \theta
\]
\[
\cos(\theta) \approx 1
\]

Review the following equations in Ch. 2.

\[
\frac{1}{f} = \frac{1}{s_0} + \frac{1}{s_i}
\]

\[
x_0x_i = f^2
\]

\[
M_T = \frac{y_i}{y_0} = -\frac{s_i}{s_o}
\]

\[
M_L = \frac{dx_i}{dx_0} = -\frac{f^2}{x_0^2}
\]

“Sign” convention is of paramount importance! (See Pedrotti^3, Table 2-1)
Ray and Wave Aberrations

Ray Aberrations:
- Longitudinal aberration
- Transverse or lateral aberration

Optical system

Ideal wavefront
Actual wavefront
Paraxial image plane

Detail
Aberrations (a brief description)

- 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 (monochromatic)
  - 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

  Departures from the idealized conditions of Gaussian Optics (e.g. paraxial regimes).

  \[
  \sin \varphi = \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \cdots
  \]

  \[
  \cos \varphi = 1 - \frac{\varphi^2}{2!} + \frac{\varphi^4}{4!} - \cdots
  \]

  Paraxial approximation

  \[
  \sin(\varphi) \approx \tan(\varphi) \approx \varphi
  \]

  \[
  \cos(\varphi) \approx 1
  \]

Refractive index n is dispersive!

\[
 n(\omega)
\]

Third-order or Seidel aberrations

Deteriorate the image:
- Spherical aberration
- Coma
- Astigmatism

Deform the image:
- Field curvature
- Distortion

\[
\sin \varphi = \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \cdots
\]

\[
\cos \varphi = 1 - \frac{\varphi^2}{2!} + \frac{\varphi^4}{4!} - \cdots
\]
The Five monochromatic, or Seidel, Aberrations

The aberration at Q

\[ a(Q) = (PQI - POI)_{opd} \]

opd: the optical-path difference

\[ r^4 \]
Spherical aberration

\[ h'r^3 \cos \theta \]
Coma

\[ h'^2 r^2 \cos^2 \theta \]
Astigmatism

\[ h'^2 r^2 \]
Curvature of field

\[ h'^3 r \cos \theta \]
Distortion
Lens Aberrations

Spherical & chromatic

Astigmatism

Coma
Chromatic Aberration

Pedrotti^3, Ch. 3-2 & Ch. 20-7

\[
\frac{1}{f} \approx (n - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right).
\]

Different glasses for use in lenses.

Fraunhofer designations.

C H \hspace{1cm} 656.3 \text{ nm}
D Na \hspace{1cm} 589.2
F H \hspace{1cm} 486.1
G' H \hspace{1cm} 434.0
Chromatic Aberration

Solutions:
1. Combine lenses (achromatic doublets)
2. Use mirrors

Melles Griot “Fundamental Optics”
Spherical Aberration

Solution I: Aspheric Mirrors or Lenses
Hubble Telescope

It was probably the most precisely figured mirror ever made, with variations from the prescribed curve of only 10 nanometers, it was too flat at the edges by about 2.2 microns.

Source: wikipedia
Lens Shape

Solution II: Chose a proper shape of a singlet lens for a given image-object distance.

For a given desired focal length, there is freedom to choose one of the radii for a singlet. The spherical aberration and coma depend on the particular choice, so these aberrations can be minimized by the designed form.

\[
\frac{1}{f} \approx (n - 1) \left[ \frac{1}{R_1} - \frac{1}{R_2} \right].
\]

\[
q = \frac{(R_1 + R_2)}{(R_2 - R_1)}
\]
Lens Selection Guide

http://www.newport.com/Lens-Selection-Guide/140908/1033/catalog.aspx#
Astigmatism

Figure 1.16 Astigmatism represented by sectional views
Coma and Deformation

Figure 1.18  **Positive transverse coma**

Figure 1.19  **Field curvature**

Figure 1.20  **Pincushion and barrel distortion**