PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 42200

Waves & Oscillations

Lecture 30 – Geometric Optics

Spring 2016 Semester

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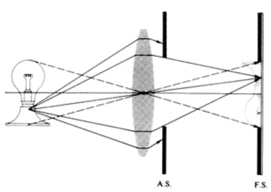
Apertures and Stops



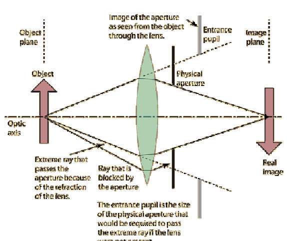
Field stop - an element limiting the size, or angular breadth of the image (for example film edge in camera)

Aperture stop - an element that determines the amount of light reaching the image

- Field stop determines the field of view and limits the size of objects that can be imaged.
- Aperture determines amount of light only

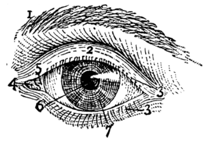
Entrance Pupil

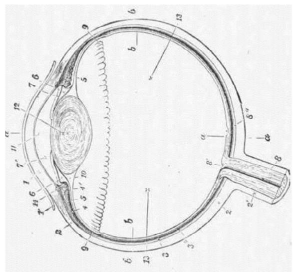
- How big does the aperture stop appear when viewed from the position of the object?



(Aperture stop is behind the lens)

Entrance Pupil

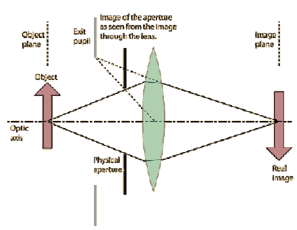




- If the cornea were removed, the pupil would appear smaller
- The cornea magnifies the image of the pupil

Exit Pupil

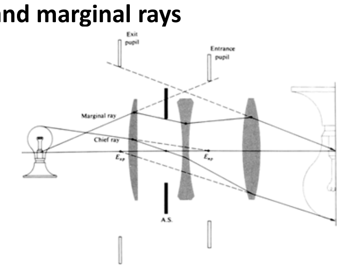
- How big does the aperture stop appear when viewed from the image plane?



(Aperture stop is in front of the lens)

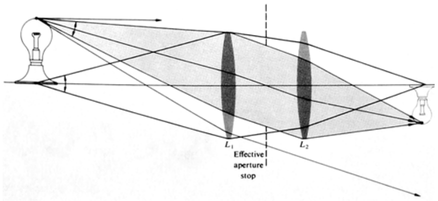
Chief and marginal rays

Marginal ray: the ray that comes from a point on object and marginally passes the aperture stop



Chief ray: any ray from an object point that passes through the middle of the aperture stop
It is effectively the central ray of the bundle emerging from a point on an object that can get through the aperture.
Importance: aberrations in optical systems

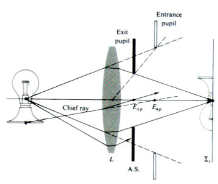
Vignetting



The cone of rays that reaches image plane from the top of the object is smaller than that from the middle. There will be less light on the periphery of the image - a process called **vignetting**

Example: entrance pupil of the eye can be as big as 8 mm. Telescopes are designed to have exit pupil of 8 mm for maximum brightness of the image

Relative Aperture



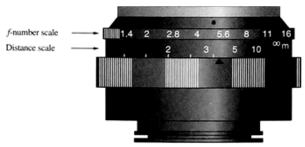
- The area of the entrance pupil determines how much light will reach the image plane.
- Pupils are typically circular: the area varies as the square of the diameter, D.
- The image area varies as the square of the lateral dimension, $A \sim f^2$
- Light intensity at the image plane varies as $(D/f)^2$
- (D/f) is called the *relative aperture*

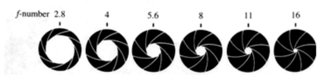
Relative Aperture

- Relative aperture: $f/D =$ (focal length/diameter)
- For optical equipment (camera lenses) this is usually labeled as $f/\#$
- Example:
  - $f = 50\ mm$
  - $D = 25\ mm$

  $f/D = 2$ denoted "$f/2$"
- This provides a standard way to reference the intensity of light shining on film or other photosensitive material.

f-number of a camera lens

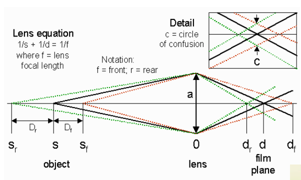




Change in neighboring numbers is $\sqrt{2}$

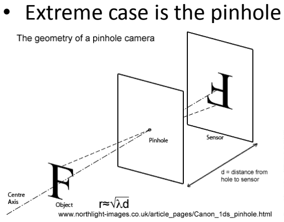
Intensity is ~1/(*f*/#)^2: changing diaphragm from one label to another changes light intensity on film 2 times

Depth of Field



Depth of Field

- Extreme case is the pinhole camera



Aberrations

- We have continued to make approximations:
  - Paraxial rays
  - Spherical lenses
  - Index of refraction independent of wavelength
- How do these approximations affect images?
  - There are several ways…
  - Sometimes one particular effect dominates the performance of an optical system
  - Useful to understand their source in order to introduce the most appropriate corrective optics
- How can these problems be reduced or corrected?

Aberrations

- Limitations of paraxial rays:

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \cdots$$

- Paraxial approximation:

$$\sin\theta \approx \theta$$

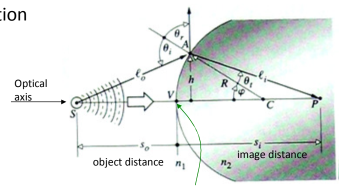
- Third-order approximation:

$$\sin\theta \approx \theta - \frac{\theta^3}{3!}$$

- The optical equations are now non-linear
  - The lens equations are only approximations
  - Perfect images might not even be possible!
  - Deviations from perfect images are called aberrations
  - Several different types are classified and their origins identified.

Aberrations

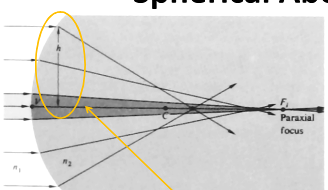
- Departure from the linear theory at third-order were classified into five types of ***primary aberrations*** by Phillip Ludwig Seidel (1821-1896):
  - Spherical aberration
  - Coma
  - Astigmatism
  - Field curvature
  - Distortion



Spherical Aberration

- We first derived the shape of a surface that changes spherical waves into plane waves
  - It was either a parabola, ellipse or hyperbola
- But this only worked for light sources that were on the optical axis
- To form an image, we need to bring rays into focus from points that lie off the optical axis
- A sphere looks the same from all directions so there are no "off-axis" points
- It is still not perfect – there are aberrations

Spherical Aberration



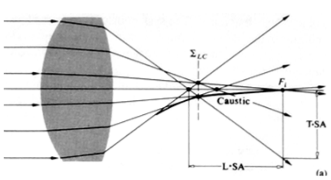
Paraxial approximation:

$$\frac{n_1}{s_o} + \frac{n_2}{s_i} = \frac{n_2 - n_1}{R}$$

Third order approximation:

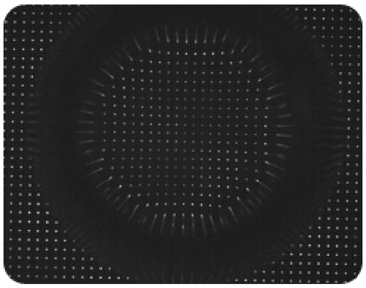
$$\frac{n_1}{s_o} + \frac{n_2}{s_i} = \frac{n_2 - n_1}{R} + \underbrace{h^2\left[\frac{n_1}{2s_o}\left(\frac{1}{s_o} + \frac{1}{R}\right)^2 + \frac{n_2}{2s_i}\left(\frac{1}{R} - \frac{1}{s_i}\right)^2\right]}_{\text{Deviation from first-order theory}}$$

Spherical Aberrations



- Longitudinal Spherical Aberration: $\mathrm{L \cdot SA}$
  - Image of an on-axis object is longitudinally stretched
  - Positive $\mathrm{L \cdot SA}$ means that marginal rays intersect the optical axis in front of F_i (paraxial focal point).
- Transverse Spherical Aberration: $\mathrm{T \cdot SA}$
  - Image of an on-axis object is blurred in the image plane
- Circle of least confusion: Σ_{LC}
  - Smallest image blur

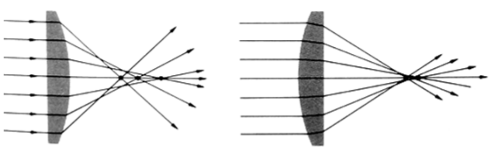
Spherical Aberration



Example from http://www.spot-optics.com/index.htm

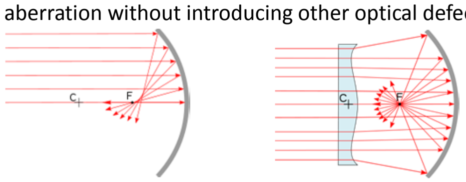
Spherical Aberration

- In third-order optics, the orientation of the lenses does matter
- Spherical aberration depends on the lens arrangement:

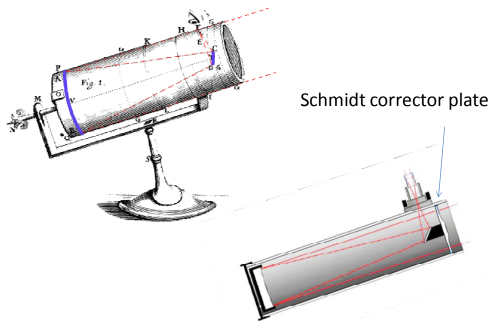


Spherical Aberration of Mirrors

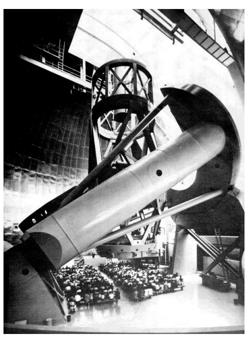
- Spherical mirrors also suffer from spherical aberration
  - Parabolic mirrors do not suffer from spherical aberration, but they distort images from points that do not lie on the optical axis
- ***Schmidt corrector plate*** removes spherical aberration without introducing other optical defects.



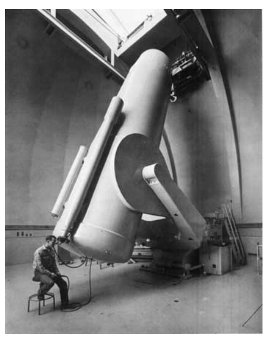
Newtonian Telescope



Schmidt 48-inch Telescope



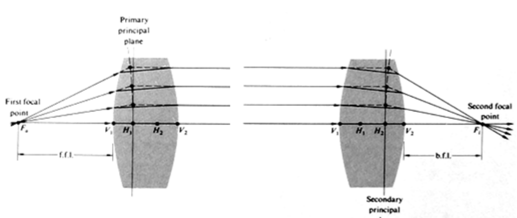
200 inch Hale telescope



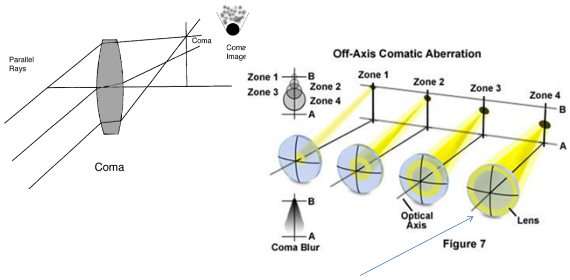
48-inch Schmidt telescope

Coma (comatic aberration)

- Principle planes are not flat – they are actually curved surfaces.
- Focal length is different for off-axis rays

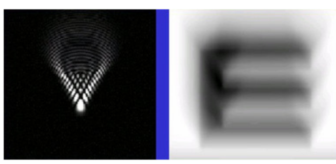


Coma

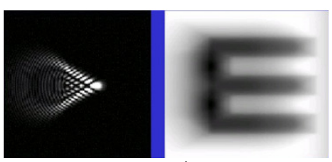


- Negative coma: meridional rays focus closer to the principal axis

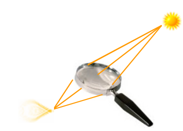
Coma



Vertical coma



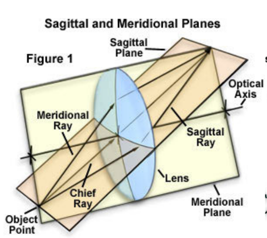
Horizontal coma

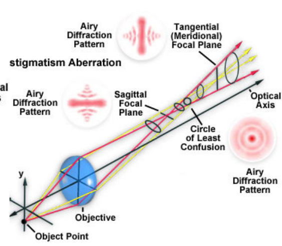


Coma can be reduced by introducing a stop positioned at an appropriate point along the optical axis, so as to remove the appropriate off-axis rays.

Astigmatism

- Parallel rays from an off-axis object arrive in the plane of the lens in one direction, but not in a perpendicular direction:

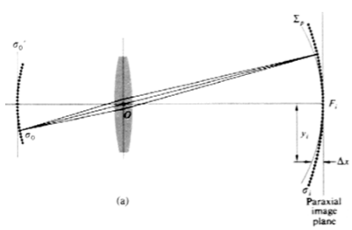




Astigmatism

- This formal definition is different from the one used in ophthalmology which is caused by non-spherical curvature of the surface and lens of the eye.

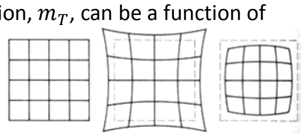
Field Curvature



- The focal plane is actually a curved surface
- A negative lens has a field plane that curves away from the image plane
- A combination of positive and negative lenses can cancel the effect

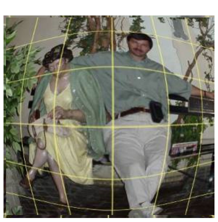
Field Curvature

- Transverse magnification, m_T, can be a function of the off-axis distance:



Positive (pincushion) distortion

Negative (barrel) distortion



Correcting Monochromatic Aberrations

- Combinations of lenses with mutually cancelling aberration effects
- Apertures
- Aspherical correction elements.