Telescopes and Telescope Optics I
Intro optics, configurations, design issues

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Content

• A bit of history:
  • The Galilean and Keplerian refracting telescopes
  • Chromatic aberrations of refractors
  • Newton’s reflecting telescopes
• Geometric optics primer
• Telescope design considerations
Ibn Sahl (AD 940-1000), Persian, Muslim mathematician, physicist and optical engineer of the Islamic Golden Age. He is credited with first discovering the law of refraction, usually called Snell’s law.
Ibn al-Haytham (AD 965 – 1040), also known by the Latinization Alhazen or Alhacen, was an Arab, Muslim scientist, mathematician, astronomer, and philosopher. Ibn al-Haytham made significant contributions to the principles of optics (and his famous book of optics), astronomy, mathematics, visual perception, and the scientific method.

In his book of optics (Kitab al-Manazir), Alhazen reports experiments on lenses, mirrors, refraction, reflection, and spectroscopy.

Great influence on Leonardo Da Vinci, Galileo Galilei, Huygens, Kepler, …
The (refractive) telescope

Dutch eyeglass maker Hans Lippershey applied for a patent on the refractive telescope in 1608, and got denied:

The telescope was “common knowledge” in the early 1600s! As common as eyeglasses.
Galileo Galilei circa 1609-1610
first (reported) astronomical use of the telescope

Image by Hulton Archive/Getty Images
The Galilean telescope

+ upright image
+ $M = \frac{|f_o|}{f_e}$
- small field of view
GALILEO, 1610

Phases of Venus
GALILEO, 1610

Mountains, craters on the Moon
GALILEO, 1610

Moons orbiting around Jupiter
The Keplerian telescope

- Intermediate focus
- Large magnification easier
- Larger FoV
- Image inverted
  (needs an erector)
Yerkes 40” refractor, 1897, Williams Bay (Wisconsin)

World’s largest refractor!
Chromatic aberrations of refractors

- Due to the wavelength dependence of the refractive index of all glass materials $n(\lambda)$

- Glass is also very heavy, big lenses are hard to manufacture and mount (different gravity vectors cause sagging)
Refractive index dispersion for typical glasses
Newton’s reflector / telescope

Uses mirror to prevent chromatic aberrations present in refractors: $n_{\text{glass}}(\lambda)$

Reflection is achromatic!
Geometric optics primer
Ray optics cheat sheet

Positive lens

Rule 1: A light ray passing through the center of lens is not deviated.

Rule 2: A light ray parallel with axis will, after refraction, pass through the rear focal point.

Rule 3: A light ray through the first focal point will be refracted parallel with the axis.

The intersection of any two of the three light rays shown will locate the position of the image.

Negative lens

Rule 1: A light ray passing thru the center of lens is not deviated.

Rule 2: A light ray parallel to the axis will, after refraction, appear to come from the front focal point.

Rule 3: A ray directed toward the rear focal point will be refracted parallel to the axis. A backward extension of this ray will pass thru the image point.

The intersection of any two of the three rays shown will locate the position of the image (is virtual).
Fermat’s Principle or principle of least time

For a single plane reflecting or refracting surface, the actual path that a light ray follows, from one point to another via the surface, is one for which the time required is a minimum.

\[ d \, (O \, P \, L) = c \, dt = (c/v) \, v \, dt = n \, ds \]

\[ OPL = \int c \, dt = \int n \, ds \]

Fermat’s principle \( \delta T = \delta (OPL) = 0 \)
Snell’s law of refraction
(can be derived from Fermat’s principle, see Schroeder, p. 28)

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Reflection: $n_1 = -n_2$ in Snell’s law

\[ \theta_2 = -\theta_1 \]
Fig. 2.1. Refraction at spherical interface. All angles and distances are positive in diagram; see text for discussion.
Paraxial optics

- Other names: 1st order/small angle/Gauss approximation
- \( \sin \theta \sim \tan \theta \sim \theta, \cos \theta \sim 1 \)
- Paraxial equation for refraction:
  - \( \frac{n'}{s'} - \frac{n}{s} = \left( \frac{n'}{n} \right) / R = P \) for Power
  - B’ @ s’ and B @ s are **conjugate** points/distances
  - *If either s or s’ = \( \infty \), then the conjugate distance is the focal length f* => \( P = \left( \frac{n'}{n} \right) / R = \frac{n'}{f'} = \frac{n}{f} \)
Mirror equation

2.3. Paraxial Equation for Reflection

Fig. 2.4. Reflection at spherical surface. Here $B$ and $B'$ are conjugate axial points.

- $\frac{1}{s'} + \frac{1}{s} = \frac{2}{R}$

- Assuming $s = \infty$, we learn that the focal length of a spherical mirror is given by $f = s' = \frac{R}{2}$
Two-mirror system, effective focal length

From $n'/s' - n/s = (n' - n)/R = P$ we have for each surface:

- $n/s_1' - 1/s_1 = (n - 1)/R_1 = P_1$
- $1/s_2' - n/s_2 = (1 - n)/R_2 = P_2$

The ray in the figure has $s_1 = \infty$ intersecting the first surface at $y_1$ and the second at $y_2$.

From two sets of similar right triangles, both sets including either $y_2$ or $y_1$ as one side,

- $y_2/y_1 = s_2/s_1' = (s_1' - d)/s_1' = s_2'/f'$

where $f'$ is the effective focal length of the whole system, and, the net power is $P = 1/f'$.

We can find the effective focal length by setting $s_1 = \infty$ and $s_2 = s_1' - d$ in the equations for $P_1$ and $P_2$ and combining the results with the previous equation to solve for $P = 1/f'$:

- $P = 1/f' = (1/s_2')( (s_1' - d)/s_1' ) = P_1 + P_2 - (d/n)P_1P_2$

This is the equation for a thick lens, or for a two-mirror system (like a reflecting telescope), or, as it turns out, two thin lenses in series.
**Lens-maker equation**

- Derived from paraxial equation for refraction
- Thin lens approximation (surface separation small compared to lens diameter)
- $d$ is small, so $s_2 = s_1'$ and we can directly coadd the equations for each surface given above to get the lens-makers formula:

\[
\frac{1}{s'} - \frac{1}{s} = (n - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) = P_1 + P_2 = \frac{1}{f'} = -\frac{1}{f}
\]
Transverse Magnification

- We describe the transverse magnification as the ratio of heights of the image to object: \( m = h' / h \).
- But \( h' = (s' - R) \tan \phi \) and \( h = (s - R) \tan \phi \) and this can be used to show (see Schroeder Section 2.2.b):
  \[ m = h' / h = \frac{s' - R}{s - R} = \frac{n s'}{n' s} \]
  where the last bit comes from the application of the refraction at a spherical surface equation.
- Since \( h \) and \( h' \) are in opposite z directions, \( m < 0 \) and the image is inverted.
- For the thin lens case we have two surfaces and we have \( m_1 = s'_1 / n s_1 \) and \( m_2 = n s'_2 / s_2 \).
- The net magnification is \( m = m_1 m_2 = s' / s \).
- For a mirror in air, \( m = - s' / s \).

![Fig. 2.2. Conjugate points in the paraxial region. Here B and B', Q and Q' are pairs of conjugate points. See Eq. (2.2.7) for definition of transverse magnification.](image-url)
Telescope design considerations
The two-mirror telescope

- Easy analysis when starting from the two-mirror/thick lens equation

- The power of such a system is given by:

  \[ P = P_1 + P_2 - \left( \frac{d}{n} \right) P_1 P_2 \]

- The final focal length is given by

  \[ P = \frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \left( \frac{d}{n} \right) / f_2 f_1 \]

- \( n = -1 \) for a mirror, and \( d < 0 \), we have \( \left( \frac{d}{n} \right) > 0 \), or

  \[ f = \frac{f_1 f_2}{(f_1 + f_2 - |d|)} \]

Note that the power of each mirror is given by the spherical mirror equation, \( P = \frac{1}{f} = \frac{2}{R} \).
Telescope design considerations

• F number / plate scale / field of view
• Collecting area \# D^2
• Thermal considerations
• Focus configuration
• Mounting
• Angular resolution \# \lambda/D (diffractive optics 101)
• Image quality (aberrations)
F number (focal ratio)

- Telescopes are often characterized by their F number:
  - $F = \frac{f}{D}$, ratio of effective focal length to primary diameter
  - F small => “fast”
  - F large => “slow”
Plate scale

- Since the rays from the two sources going through the optical center vertex are undeviated, they preserve $\theta$ upon exit from the lens.
- In the paraxial regime $\tan \theta \sim \theta \sim x / f$.
- Thus, the plate scale is given by $\theta / x = 1 / f$.
- Note that it is common to quote plate scales in arcsec/mm, which is then given by scaling the above equation by 206265 arcsec/radian, so that $\theta / x = 206265 \text{ arcsec} / f \text{ (mm)}$. 

$f = \text{effective focal length}$

\[ x \]

\[ \theta \]
Field of view (FoV)

- Want large plate scale ⇒ faster primary (small F)
- Prime focus usually has smallest F, and thus largest FoV
- Issues to consider:
  - Vignetting: the size of the secondary mirror is the first limiting factor for FoV at Cass focus
  - Image quality: deviation from paraxial approximation ⇒ aberrations
  - Control of focal surface: many wide-field telescopes produce good images but have very curved focal surfaces (less problematic these days)
- Telescope design fundamental trade-off: FoV vs image quality
Collecting area

- Number of collected photons grow as $D^2$: size matters!
- Gap between 1949 (Palomar 200-inch Hale telescope) and 1992 (Keck telescopes)
  - Difficulty in manufacturing large pieces of glass
  - Difficulty in supporting large mirrors (gravity sag)
  - Thermal properties difficult to manage
Thermal considerations

- $\Delta h/h = \alpha \Delta T$, with $\alpha =$ coefficient of thermal expansion

- $\alpha$ (pyrex,P200) = $3e^{-6}$/K

- $\alpha$ (zerodur,Keck) = $1e^{-7}$/K (expensive!)

- Example (P200):
  - $\Delta l < 100$ nm = $100e^{-9}$ m over mirror thickness of 26” (66e-2 m)
  - $\Delta T < 100e^{-9}/66e^{-2} / 3e^{-6} < 0.05$ °K (!!!)

- Thermal equilibrium timescales $\# h^2$, needs typically hours / °K
Solution for large telescopes: Segmented mirrors (e.g. Keck, SALT, JWST, TMT)

Keck primary mirror:

Each segment is 1.8 meter; active control system keeps segments to proper figure under gravity (edge sensors)

Optically aligned (co-phased) every week/month
Solution for large telescopes:  
Thin meniscus (e.g. 8-meter Very Large Telescope)

Thin cast mirror is deliberately flexible (~18 cm thick), controlled via actuators on back side of primary

ACTIVE OPTICS
Solution for large telescopes:
Borosilicate honeycomb (e.g. Magellan, MMT, LBT, GMT)

Rigid mirror, relatively thick, well controlled in temperature
Telescope focus configurations

Prime

Newtonian

Cassegrain

Coude

prime focus

primary mirror

secondary mirror

newtonian focus

convex mirror

cassegrain focus

coude focus

coude mirror
Telescope mounts

Equatorial

Altitude-Azimuth (altaz)
Equatorial mount example:
Mt Wilson 100-inch Hale telescope (1917)
Equatorial mount example:
Palomar 200-inch Hale telescope (1948)

- Pointing: axis motion in declination (dec) and right ascension (RA)
- Tracking in RA
Altaz mount example: Keck telescope (1992)

- Need to point and track in both elevation and azimuth
- Two axis motion
- Field of view rotates with Parallactic angle as the telescope tracks!
  - Needs image derotator!
Altaz mount example: Keck telescope
Altaz mount example: Very Large Telescope (1998)
Sources

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• Basic optics for the astronomical sciences, J. B. Breckinridge

• Telescope optics, Rutten & van Venrooij

• Observational Astrophysics (Astronomy and Astrophysics Library), P. Lena, F. Lebrun, F. Mignard (Author), S. Lyle (Translator)

• Majewski lecture notes (based on Schroeder): http://www.faculty.virginia.edu/ASTR5110/lectures/optics1/optics1.html

• http://www.telescope-optics.net