3.Telescope

・the first element of any astronomical imaging system
・the means by which the light from distant objects is collected and focused

・good tracking, minimum air turbulence in the telescope dome
→provide excellent telescope optics & good images

・consider basic optical properties and their applications to telescope design

3.1 Historical Development

- the end of 13C : convex lenses
- the middle of the 15C : concave lenses
- the beginning of the 17C : combination of convex & concave lenses
  - 1608 : Hans Lippershey made a device with a convex & concave lens (3×)
  - 1609 : Galileo Galilei made the telescope (8×, 20×)
    - small field of view of about 15 arcmin (only a quarter of the full moon)
    - produced an upright image
    - 1.52-1.83m in length
- the middle of 17C: length of astronomical telescope of 4.57-6.10m
  - 1656, Christiaan Huygens made the telescope
    - 7 meters long
    - 10cm aperture of objective lens
    - magnification 100×
    - field of view of 17 arcmin

3.1 Historical Development

・a spherical-shaped lens : rays parallel to the optical axis fail to converge
at one point

=spherical aberration

・to eliminate spherical aberration

→lens curvature : plane & hyperbolic or spherical & elliptical

・Curved lens : the colors decomposed from white light come to a focus at
a different point on the optical axis

=chromatic aberration

⇨cause the image of a star to be surrounded by circles of different colors

・to reduce spherical & chromatic aberration

→telescopes with long focal length

3.1 Historical Development

- 1672 : Isaac Newton had constructed the first reflecting telescope using a spherical mirror
  - used a 2-inch mirror blank of speculum metal
  - placed the mirror at the bottom of a tube

    →caught the reflected rays on a secondary mirror at 45° near the top of the tube

    →secondary mirror reflected the image into a convex lens outside the tube

- others were unable to grind mirrors of regular curvature & the mirror tarnished easily

  ⇨reflecting telescope remained a curiosity for decades
- around 1723 : John Hadley had perfected better polishing techniques

  →the first parabolic version of the Newtonian telescope was made

3.1 Historical Development

- the middle of 18C : many reflecting telescopes with primary mirrors up to 6-inch in diameter had been produced
- the latter half of the 18C : large reflecting telescope with parabolic ground mirrors came into their own
  - William Herschel built a reflector with a mirror diameter 1.22m and a 12.2m focal length
    - to tackle the problem of rapid tarnishing in metal mirrors, Herschel always had a spare ready to exchange

  →remained the largest telescope for over 50 years

3.1 Historical Development

・classical times : the size of a telescope was characterized by its focal length
modern telescopes : identified by diameter of the primary aperture or by the diameter of the equivalent circle with the same collecting surface area

・The largest telescope used by Galileo : diameter of 4.4cm
2008 : 10 general-purpose optical telescopes with effective diameters >8m

・the doubling time for aperture size was about 50 years up until about 1950
・after 1950, the telescopes have been doubling in size

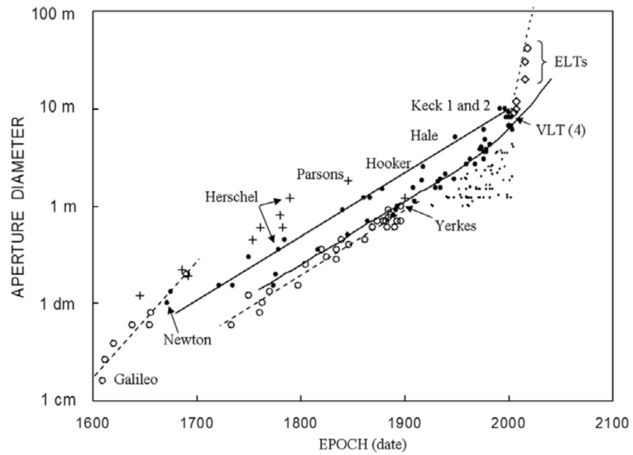


Figure 3.1. The growth of aperture size with time is plotted from the invention of the telescope to present day. Credit: René Racine.

3.1 Historical Development

・1993, the largest telescope (Keck telescope) went into operation

the first of a pair of 10m telescopes employed the “segmented mirror”

(The second telescope was inaugurated in May 1996)

・many telescopes with collecting apertures >6.5m in diameter, and employing different technologies, were under construction or being contemplated

3.1 Historical Development

・the introduction and growth of CCDs

→more and more area on the sky could be digitally imaged to deeper levels

・the use of multi-slit devices and optical fibers to observe many objects simultaneously

→the efficiency of spectroscopy had been improved

・to construct larger ground-based telescopes and to develop methods for counteracting the image-blurring effects of air turbulence

→ gain large factors in efficiency

3.1 Historical Development

・fundamental issues

(1) how to achieve a very large collecting aperture of the required optical performance

(2) how to support and control in the optimum way such a very heavy mechanical structure

(3) how to enclose a very large telescope in a cost-effective way with negligible degradation on image quality due to vibration, air disturbance, or inadequate environmental protection (wind, dust).

・new telescopes

- ・must be designed to capitalize on the best seeing conditions
- ・must be designed with remote control in mind
- ・must give sharper images than their predecessors

→ it all comes down to how the mirrors are made and supported

3.1 Historical Development

- segmented mirrors
  - smaller monolithic disks of thin polished glass
  - Each segment is individually supported and global changes are sensed at the gaps between segments.
- meniscus mirrors
  - large monolithic disks of solid glass which are so thin that it must be accepted that they will be flexible
  - must be actively controlled to maintain the required shape during operation
- honeycomb mirrors
  - thick mirrors are constructed but large pockets of mass are removed to make the mirror lightweight yet very stiff

Table 3.2. The current generation of telescopes with $D > 6.5\,\mathrm{m}$.

Telescope and date	*Primary* (m)	*Mirror technology*	*Location*
Keck I, II (1993, 1996) (CARA)	10	Hexagonal segments of Zerodur	Mauna Kea, Hawaii
Hobby–Eberly Telescope (2000)	9.2	Hexagonal segments Spherical primary	Mt. Fowlkes, Texas
South African Large Telescope (2004)	9.2	Hexagonal segments Spherical primary	Sutherland, SA
LBT (2005, 2008) (former Columbus)	2×8.4	Borosilicate honeycomb	Mt. Graham, Arizona
Subaru (2000) (Japan)	8.2	Thin meniscus	Mauna Kea, Hawaii
VLT1, 2, 3, 4 (1998, 2000, 2001, 2002) (ESO)	4×8.2	Thin meniscus	Cerro Paranal, Chile
Gemini N, S (2000, 2002) (GTP)	2×8.0	Thin meniscus	Mauna Kea, Hawaii Cerro Pachón, Chile
Magellan I, II (2002, 2003) (OCIW)	6.5	Borosilicate honeycomb	Las Campanas, Chile
MMT upgrade (2002) (SI/UA)	6.5	Borosilicate honeycomb	Mt. Hopkins, Arizona

3.1 Historical Development

- Larger and faster primary mirrors require new polishing methods.
  - the problem is the asphericity

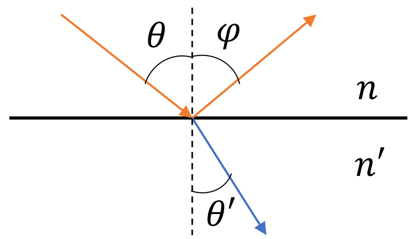
    →difference of curvature from place to place and between tangential and radial directions
  - A rigid pitch lap can't accommodate the changes of curvature of a strongly aspheric surface
  - To polish the primary mirror blank for the 4.2m Herschel Telescope

    →used lap which changed shape as it moved (stressed lap polishing)
    - The method was based on the fact that, when a full-sized lap is used to make polishing strokes across a paraboloid, the distortion required to maintain contact is that of coma.

3.2 Telescope designs

- Three basic types of telescopes
  - refractive: dioptric, using lenses
  - reflective: catoptric, using mirrors
  - hybrid: catadioptric, using a combination of lenses and mirrors
- hybrid designs are most popular for amateur astronomy
- all large professional telescopes are reflectors

3.2.1 Basic optical properties



・ when a ray of light strikes the boundary between two different transparent materials, it is divided into a reflected ray and a refracted ray

・ A ray represents the direction of flow of the energy in an electromagnetic wave and is perpendicular to the wavefront.

・the law of reflection : $\theta = \varphi$

・the law of refraction : $n\sin\theta = n'\sin\theta'$

・the refractive index : $n = \frac{c}{v} = \sqrt{\varepsilon_r \mu_r}$($\varepsilon_r$:relative permittivity, μ_r:relative permeability)

・ The distance between crests inside the material is now λ/n.

・dispersion: the angular divergence of light of different wavelengths

dispersive power=$\frac{1}{V} = (n_F - n_C)/(n_D - 1)$(F:486nm(blue), D:589nm(yellow), C:656nm(red))

3.2.1 Basic optical properties

・optical path=nd (n:refractive index, d:distance that light travels)

・Fermat's principle : the path taken by a light ray in going from one point to another through any set of media is such as to render its optical path equal, in the first approximation, to other paths closely adjacent to the actual one.

・paraxial optics : approximation in which angles are sufficiently small

→ $\sin\theta = \theta$ to first order

$\theta = 10°$ → Error$\approx 0.5\%$ $\theta = 30°$ → Error$< 5\%$

・systems with large focal ratios (f/D) meet the paraxial approximation.

3.2.1 Basic optical properties

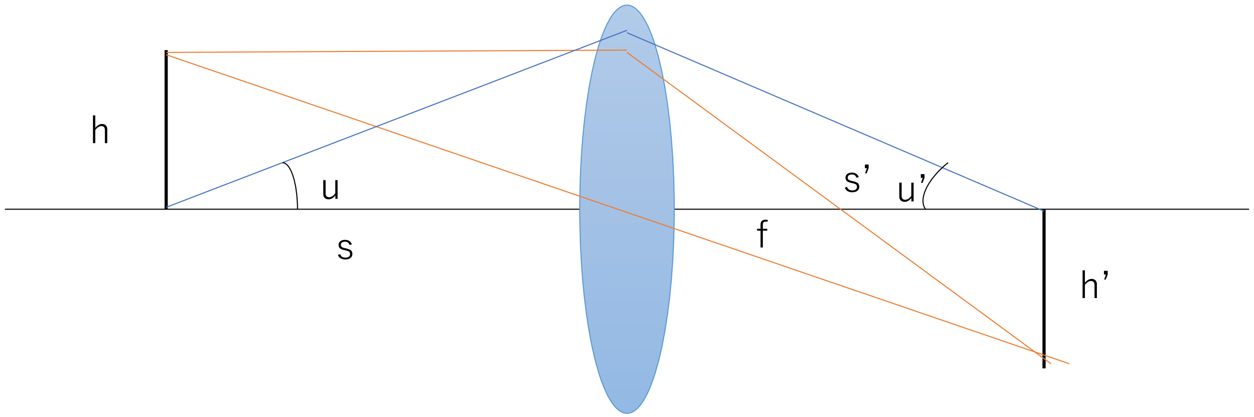
- the thin lens equation in air or vacuum : $\frac{1}{f} = \frac{1}{s} + \frac{1}{s\prime},\ m = -\frac{s'}{s} = \frac{h'}{h},\ f/number = \frac{f}{D}$

  (f:the focal length, s,s':the object & image disatance, h,h':the object & image heights, m:the lateral or transverse magnification, D:the clear aperture diameter of the lens)
- the spherical mirror equation : $\frac{1}{f} = \frac{1}{s} + \frac{1}{s\prime} = \frac{2}{R},\ m = -\frac{s'}{s} = \frac{h'}{h}$

  (R:the radius of curvature of the mirror)
- optical power and the lensmaker's formula : $P = \frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n-1)}{nR_1R_2}\right]$

  (P:the power of the lens(diopter[1/m]), R_1, R_2:the radius of curvature of the front & back surface, t:the central thickness of the lens)
  - thick lenses or two thin lenses separated by a distance d

    →$P = P_1 + P_2 - (\frac{n}{d})P_1P_2$


h
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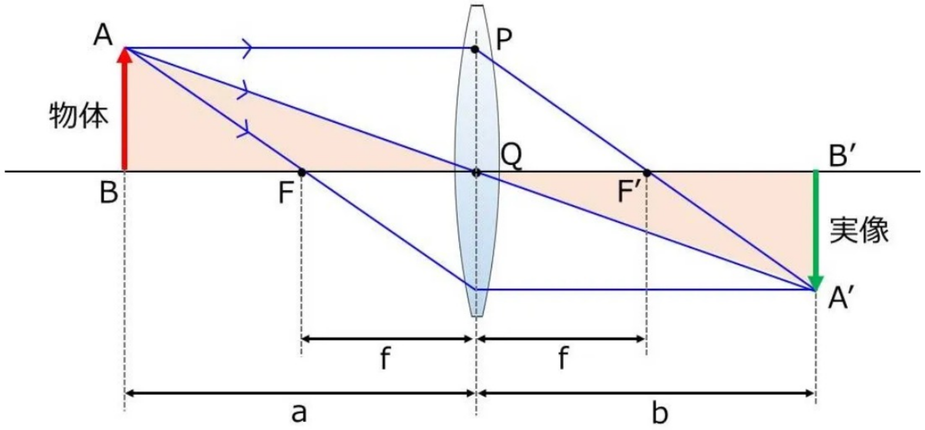

図2.正レンズで実像が作られる場合のレンズの公式の導出(1)

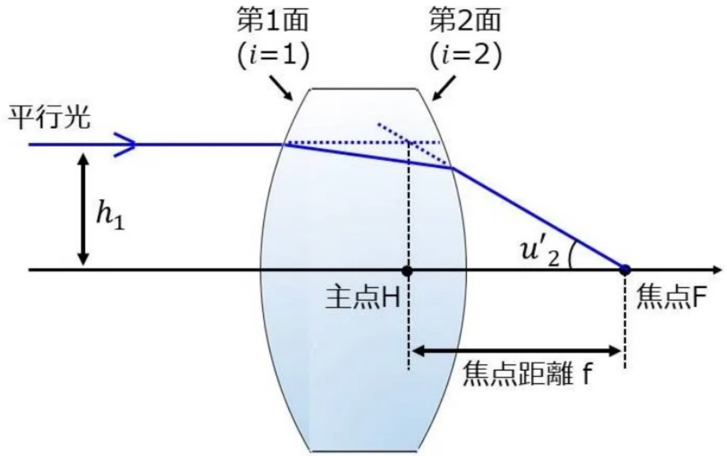

図2.レンズメーカーの公式(単レンズの焦点距離)の導出

3.2.1 Basic optical properties

- Newton's equation : $x'x = f^2$

  (x=s-f, x'=s'-f)

  most useful for calculating the amount of re-focus required

- angular magnification : $M = \frac{\tan u'}{\tan u} = \frac{s}{s'} = \frac{h}{h'}$

  (u,u':the angle of incident & refracted ray respect to the optical axis)

  defined in terms of the slope angles of the rays

- the lagrange invariant : $nh\tan u = n'h'\tan u'$

  (n,n':the refractive indices in object and image space)

  The quantity $(nh\tan u)$ is constant in a system with refracting or reflective surfaces.

3.2.2 The astronomical (lens) telescope

- Kepler's telescope
  - If the eyepiece is moved along the axis such that the real image formed by the objective lens coincides with the focal point of the eyepiece , then the emergent rays are parallel and the final image is at infinity
  - the telescope is afocal and the image is inverted.
- Galileo's telescope
  - the eyepiece lens : concave
  - the lenses are separated by the difference of their focal lengths
  - the system is afocal but the image in a Galilean telescope is upright
    →more convenient for terrestrial use.

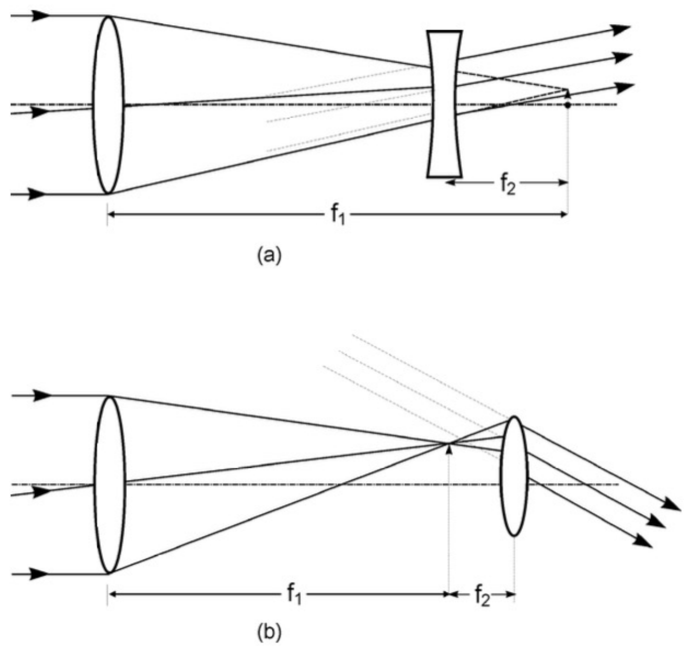

Fig. 1.1. (**a**) Galileo telescope and (**b**) Kepler telescope.

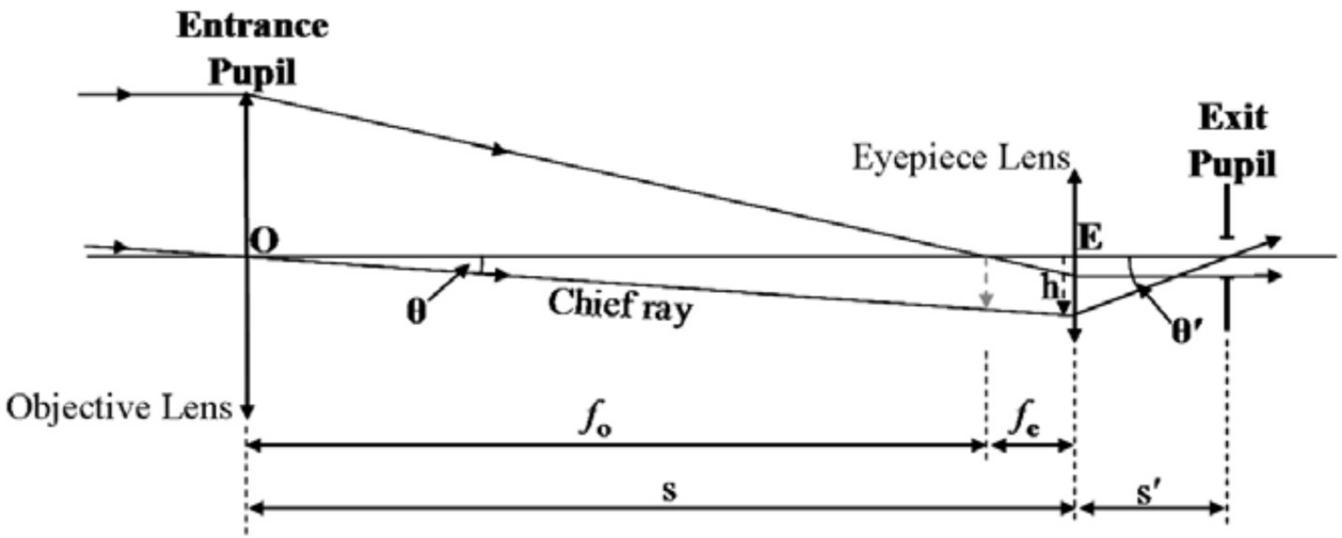

Figure 3.3. The principle of the astronomical telescope. The objective lens and the eyepiece lens are represented by vertical lines with double-ended arrows.

3.2.2 The astronomical (lens) telescope

・The objective lens defines the aperture or “stop'' and it is said to form the “entrance pupil'' for the system.

→ the objective lens itself is a relatively nearby object for the eyepiece lens and an image of the entrance pupil is formed behind lens E (the “exit'' pupil)

・chief ray: passed through the center of both the entrance and exit pupils.

・the magnifying power: $M = \theta'/\theta$

・$h = s\tan\theta = s'\tan\theta'$, $s = f_o + f_e$, $f_e = -s'$ ⇨ $M = -f_o/f_e$

・ $M = D_o/D_e$

(D_o, D_e: the diameter of the objective lens & the exit pupil)

・the advent of CCD imaging

→most astronomical telescopes do not employ an eyepiece, but form images directly onto the detector pixels in the telescope's focal plane.

3.2.2 The astronomical (lens) telescope

・longitudinal chromatic aberration
The horizontal distance along the optical axis between the different focal positions
・lateral chromatic aberration
The vertical difference in image height

・ the classical method for correcting chromatic aberration is to use two lenses of different materials in contact to make an achromatic doublet

→$P_D = P'_D + P''_D = (n'_D - 1)K' + (n''_D - 1)K''$

(D:yellow line of Na, the prime:the crown glass, the double prime:the flint glass, $K = \frac{1}{R_1} - \frac{1}{R_2}$)

$P_F = P_C \Rightarrow \frac{K'}{K''} = -\frac{n''_F - n''_C}{n'_F - n'_C}$ the negative sign out front implies that one lens must be concave

$\frac{P'_D}{P''_D} = -\frac{V'}{V''}$ these are the dispersion constants for the two glasses

$P'_D = P_D[V'/(V' - V'')]$, $P''_D = -P_D[V''/(V' - V'')]$

3.2.2 The astronomical (lens) telescope

・select the required focal length $f_D (= 1/P_D)$

・select the best pair of glasses from the glass table on the basis of their dispersion constants V' and V''

・calculate the powers of each lens

・derive K' and K'' where P'_D and P''_D are defined

・find the radii from the definition of K

・ To facilitate cementing of the convex and concave lenses, the second radius of the first lens should match the first radius of the second lens

→ $R''_1 = R'_2$

・ it is convenient to use the same radius on the entrance face of the convex lens

→ $R'_2 = -R'_1$

・ R''_2: adjusted to give the required power P''_D

3.2.2 The astronomical (lens) telescope

・ Keeping the more curved crown glass element towards the incoming light reduces spherical aberration

・ Colors outside the corrected range can still cause a halo of color around a point source, referred to as the ``secondary'' spectrum.

・ the sheer size and weight of large achromatic doublets reaching 1 m in diameter

→switched to mirrors

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