The Principles of Astronomical Telescope Design

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The Principles of Astronomical Telescope Design

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This book is dedicated to those who have provided help and encouragement in my thirty-year pursuit of astronomical telescope knowledge

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Preface of English Edition

Progress in astronomy has been fueled by the construction of many large classical and modern telescopes. Today, astronomical telescopes image celestial sources not only across the wide electromagnetic spectrum from 10 m radio waves to 100 zm (10^{-19} m) gamma rays, but also through other spectra in gravitational waves, cosmic rays, and dark matter. Electromagnetic and other waves or particles cover a very wide energy density range. Very high energy cosmic rays have energy a billion times greater than that accelerated at Fermilab and some light dark matter particles have tiny energies beyond the detection limit of the finest existing quantum devices. Now astronomical telescopes are very large, very expensive, and very sophisticated. They are colossal in size, extremely demanding in technology, and terribly high in cost. Because of the technology, scale of construction, and the desire of scientists to plumb the depths of the Universe, astronomy today epitomizes the oft-used expression "Big Science."

Over the past 400 years, the size, the wave or particle types, and the spectral coverage of astronomical telescopes have increased substantially. Currently, large optical telescopes have apertures as large as 10 m (78 m^2). It is important to note that the total optical collecting area around the world in the past 20 years has more than tripled. At radio wavelengths, the largest collecting area of a single telescope is still dominated by the 300-m Arecibo telescope (roughly 70,000 m^2) although a 500-hundred-meter-diameter Aperture Spherical radio Telescope (FAST) is under construction in China. For interferometers, the Very Large Array (VLA, roughly 13,000 m^2) located in New Mexico (USA) is currently dominant. By comparison, the Atacama Large Millimeter Array (ALMA), presently being constructed in northern Chile, will have a collecting area of roughly 6,000 m^2. In gravitational wave detection, the Laser Interferometer Gravitational wave Observatory (LIGO) has two very long laser interferometer arms, each 4 km long (much longer if multi-reflection is taken into account). The sensitivity acquired by this instrument is as high as 10^{-21}. For cosmic ray detection, one site of the Pierre Auger Observatory has 30 fluorescence detectors and 1,600 water Cherenkov detecting stations over a surface area of 6,000 km^2 on earth. In the search for dark matter particles, thousands of detectors are located inside ice layer between 1,400 and 2,400 m underground at the South Pole. Detectors are also located at other underground or underwater locations all over the world. Some of these detectors are working at extremely low temperatures of 20–40 mK.

At the current time, plans are underway to construct optical telescopes with apertures up to 42 m, radio telescope arrays up to a square kilometer aperture area, and space telescopes of diameters up to 6.5 m. Extremely sensitive gravitational wave detectors, large cosmic ray telescopes, and the most sensitive dark matter telescopes are also under construction. Larger aperture area, lower detector temperature, and sophisticated technology greatly improve the sensitivity of telescopes. This means more detecting power for fainter and far away objects and increasing clarity of star images. However, it is not just the size and accuracy of a telescope that matters; the gain in efficiency that results from performing many functions simultaneously and the ability to measure spectra and to monitor rapid variation are also important figures of merit.

Interferometry was pioneered by radio interferometers. A resolution of 50 milliarcsecs was routinely obtained by the VLA. Long baseline interferometry at millimeter wavelengths, using the Very Long Baseline Array (VLBA), can achieve a thousand times better angular resolution than that of the VLA. In the optical field, an important breakthrough has been achieved in optical interferometers. Another important achievement is the development of active and adaptive optics (AO). Active and adaptive optics holds promise to transform a whole new generation of optical telescopes which have large aperture size as well as diffraction limited image capability, improving the angular resolution of ground-based telescopes. In nonelectromagnetic wave detections, extremely low temperature, vibration isolation, adaptive compensation for interference, superconductor transition edge sensors, and SQUID quantum detectors are widely used for improving instrument sensitivity and accuracy. All of these are pushing technologies in many fields to their limiting boundaries. In general, modern telescope projects are very different from any other comparable commercial projects as they heavily involve extensive scientific research and state of the art innovative technical development.

To write a book on these exciting and multi-field telescope techniques is a real challenge. The author's intention is to introduce the basic principles, essential theories, and fundamental techniques related to different astronomical telescopes in a step-by-step manner. From the book, the reader can immediately get into the frontier of these exciting fields. The book pays particular attention to relevant technologies such as: active and adaptive optics; artificial guide star; speckle, Michelson, Fizeau, intensity, and amplitude interferometers; aperture synthesis; holographic surface measurement; infrared signal modulation; optical truss; broadband planar antenna; stealth surface design; laser interferometer; Cherenkov fluorescence detector; wide field of view retro-reflector; wavefront, curvature, and phasing sensors; X-ray and gamma ray imaging; actuators; metrology systems; and many more. The principles behind these technologies are also presented in a manner tempered by practical applications. Telescope component design is also discussed in relevant chapters. Because many component design principles can be applied to a particular telescope design, readers should reference all relevant chapters and sections when a telescope design project is undertaken.

The early version of this book started as lecture notes for postgraduate students in 1986 in Nanjing, China. The notes had a wide circulation among the postgraduate students. In 2003, the Chinese version of this book was published. The book was well received by the Chinese astronomical community, especially by postgraduate students. With a wide circulation of the Chinese version, requests were received from English speaking students for an English language version. The translation of this book started in 2005. The basic arrangement of the book remains unchanged. The book is intended to target postgraduate students, engineers, and scientists in astronomy, optics, particle physics, instrumentation, space science, and other related fields. The book provides explanations of instruments, how they are designed, and what the restrictions are. This book is intended to form a bridge between the telescope practical engineering and the most advanced physics theories. During the translation of this English version, many experts and friends provided great help both with technical contents and the English language. Among these reviewers, Dr. Albert Greve of IRAM reviewed all chapters of this book. In the language aspect, Ms. Penelope Ward patiently reviewed the entire book. Without this help, the book translation project would not have succeeded.

Charlottesville, Virginia *Jingquan Cheng*
December 2008

Preface of Chinese Edition

Astronomical telescopes as important tools in the exploration of the universe are based on scientific theory and technology developments. This book provides a systematic discussion on these design principles behind various astronomical telescopes. The development of astronomical telescopes usually reflects the highest technology achievements of the times. Therefore, this book pays more attention to these telescope-related technologies. Some of these relevant technologies are applied not only in astronomy, but also in other fields, such as telecommunication, aerospace, remote sensing, military, high energy physics, atmospheric sciences, and so on. Special technologies used in astronomy include active and adaptive optics, artificial laser guide star, speckle, Michelson, Fizeau, intensity and amplitude interferometers, holographic surface measurement, infrared signal modulation, optical truss, broadband planar antenna, stealth surface design, and many more. Widely used techniques include optical mirror manufacture, mirror supporting, air and hydrostatic bearings, Stewart platform, encoders and actuators, system simulation, vibration control, homologous structural design, laser ranger, laser lateral positioning, wide field retro-reflectors, carbon fiber reinforced composites, tilt-meters, accelerometers, precision surface manufacturing, X-ray and gamma ray imaging, lightning protection, three-dimensional surface measurement, etc. This book also provides discussions on wind, temperature, and earthquake-induced effects on telescope performance. The telescope foundation design is also discussed.

The writing of this monograph has taken 16 years of time. The author had prepared multiple versions of manuscripts in order to best explain these complicated telescope-related theories and principles. The notes soon expanded as fresh information was gained through design and research practice. This book reflects the author's experiences and knowledge in the astronomical telescope field. This book is intended to be used by scientists, engineers, and students in astronomy, optics, communications, aerospace, remote sensing, structure, military, high energy physics, atmospheric science, mechanics, metrology, and other related fields.

During preparation of this book, many scientists, engineers, and friends provided advice and help. These include Yang Ji, Jiang Shi-yang, Ye Bian-xie, Wang She-guan, Ai Gong-xiang, Cui Xiang-qun, Zhao Gong, Cai Xian-de, Cheng Jing-yun, Fan Zhang-yun, Huang Ke-liang, Liang Ming. Among these, Prof. Jiang She-yang had reviewed all chapters of this book. Many publishers and science organizations also kindly granted permission to the author for use of the many figures in this book. The publication of this book was supported partly by Beijing Astronomy Observatory, China.

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Star-Forming Region LH 95 in the Large Magellanic Cloud (NASA, ESA, Hubble Heritage team, and G. Gouliermis) (©STScI).

Chapter 1
Fundamentals of Optical Telescopes

This chapter provides a general overview of optical telescope history, astronomical requirements, optical aberrations, optical telescope system design, and modern optical theory. In this chapter, important optical concepts such as angular resolution, light collecting power, field of view, telescope efficiency, atmospheric seeing, geometrical aberrations, wavefront error, ray tracing, merit function, optical and modulation transfer function, point spread function, Strehl ratio, and imaging spatial frequency are introduced. The concept discussions are arranged in a systematic way so that readers can learn step-by-step. The chapter provides many important formulas of optical system design and evaluation. Emphases are placed on both the traditional geometric aberrational theory and the modern optical theory. At the end of the chapter, image properties of a segmented mirror system are also discussed in detail.

1.1 A Brief History of Optical Telescopes

Visible light is the only part of the electromagnetic radiation that can produce a response in human eyes. The wavelengths of visible light range between 390 and 750 nm. This region is also known as the optical or visible (VIS) region. The human eye is a complex organ composed of a light collector and detector. The eye is very sensitive. If one injects seven photons of 500 nm wavelength into a human eye within a time interval of 100 ms, the eye will produce a response (Schnapf and Baylor, 1987). The rod cells in the human eye play an important role for the sensitivity under a dark environment. A single photon may produce a response from a rod cell. Cone cells are less sensitive. However, as a light collector, the collecting area of the eye is very limited. The maximum iris opening (pupil) is only about 6 mm in diameter. It can only collect a very small part of light within a cone angle from a radiation source. The separation between light-sensitive cells in the eye is 2.5 μm. The angular resolution of the eye is about

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1 arcmin. To detect very faint sources or to separate two closely located celestial sources, one has to use optical telescopes.

The invention of the optical telescope is surrounded by controversy. One story puts it in a shop of a Dutch lens maker, Hans Lippershey, in October of 1608. As the story goes, two children were playing with his lenses, put two together, peered through them at a distant church tower and saw it wonderfully magnified. This was the first known optical telescope. In July of 1609, Galileo Galilei developed the first astronomical optical telescope. With his simple telescope, he made important early discoveries in astronomy. His telescope is formed by the combination of a concave and a convex lens, today known as the Galileo telescope system [Figure 1.1(a)]. The front convex lens is called an objective because it is close to the object being viewed and the rear concave lens is called an eyepiece because it is closest to the observer's eye. Binoculars based on Galileo telescope design, known as opera glasses, were also invented in the same period.

In 1611, Johannes Kepler invented another type of longer telescope comprising two convex lenses [Figure 1.1(b)], known as the Kepler telescope system. The Kepler telescope forms an upside down image, but with a slightly larger field of view.

Telescopes for personal use with the eye, including binoculars, are called afocal optical systems because rays of light from a distant object that are parallel when they enter the objective are also parallel when they exit the eyepiece. For afocal telescopes, an important parameter is angular magnification. The angular

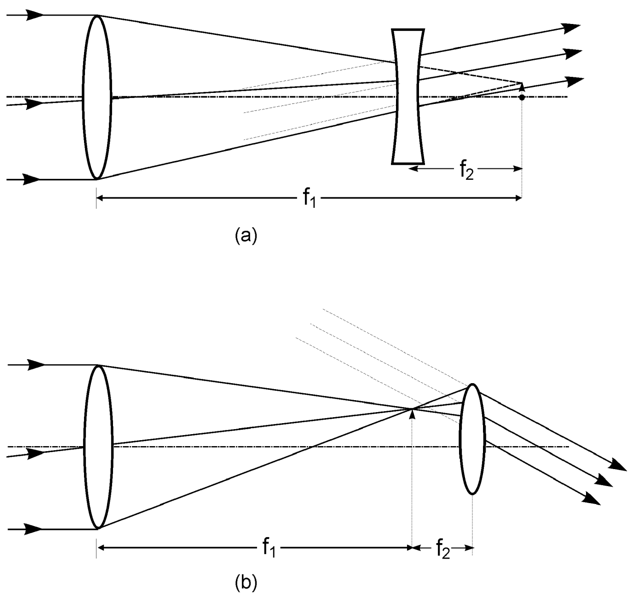

Fig. 1.1. (**a**) Galileo telescope and (**b**) Kepler telescope.

magnification or magnification factor is the ratio between the angle subtended by the output image and the angle subtended by the input object. Kepler telescopes usually have larger magnification than Galileo ones.

Large telescopes are often used to form a direct image, for example, an image on a detector. For these large telescopes, another parameter, resolution, is used instead of the magnification. Resolution is the ability to separate two closely located objects. Angular resolution is discussed in Section 1.2.1. However, the magnification concept is still used for the secondary mirror of modern telescopes.

Earlier telescopes were made of simple glass lenses, and the chromatic aberration caused by the change in refractive index with wavelength was a serious problem. To reduce chromatic aberrations, Christiaan Huygens proposed using lenses with smaller curvature. This, however, resulted in long tube lengths for early refractive telescopes. A telescope built in 1655 had an objective lens of 5 cm diameter and a tube length of 3.6 m. Johannes Hevelius built an even longer telescope with a tube length of 46 m.

In 1664, James Gregory proposed a spherical error-free reflecting optical telescope with conic section mirrors, known as the Gregorian telescope. However, the elliptical concave secondary mirror used in this system was difficult to make at that time. The system was never built by Gregory. Isaac Newton was the first to construct a usable reflecting telescope. In January of 1670, he produced a much simpler optical system with a parabolic mirror and an inclined small flat mirror, today known as a Newtonian telescope. Meanwhile, a French optician N. Cassegrain came up with a third configuration for a reflecting telescope, called the Cassegrain telescope. Instead of the concave secondary mirror of a Gregorian telescope, the Cassegrain system uses a convex hyperboloid. Reflecting telescopes are free from chromatic aberration and can have a short tube length. The fabrication of a reflecting telescope was still difficult in the early days. Mirror material stiffness and tighter surface requirements were the main problems.

In 1672, Newton claimed that there was no way to eliminate the chromatic aberration of a refracting optical telescope. However, achromatic lenses were invented 86 years later by John Dollond in 1758. The first use of achromatic lenses in astronomical telescopes was in 1761. Achromatic lenses bring two colors (e.g., red and blue) into focus in the same plane. The telescope performance improved and the tube length of refracting telescopes was reduced about ten times. This accelerated the development of large refracting telescopes. If three colors (e.g., red, green, and blue) are brought into focus in the same plane, the lenses are called apochromatic ones.

Binoculars of the Kepler system have an inverted image. In 1854, a double prism Z-shaped configuration to erect the image was invented by Ignazio Porro. Binoculars using roof prisms appeared as early as the 1880s. These are the two optical designs most commonly used in binoculars today.

In 1888, a 91.44 cm refracting telescope was built east of San Jose, California at Lick Observatory. In 1895, the Yerkes Astronomical Observatory produced a refracting telescope of 1 m diameter, the largest refracting telescope in the world.

At the same time, progress was also being made in constructing large reflecting telescopes. In the 1840s, Lord Ross produced a 1.8 m reflecting optical telescope. In 1856, the first optical telescope with a coated silver surface mirror was produced. In 1917, the 2.54 m Hooker reflecting telescope was built at Mount Wilson Observatory. In 1934, a new method of vacuum aluminum coating was invented. The reflectivity was improved significantly by this aluminum coating. In 1948, the giant 5 m Hale optical telescope was built at Palomar Observatory, 130 km southeast of the Hooker telescope.

At the beginning of the 20th century, two special types of astronomical telescopes were developed; astrometric and solar telescopes. Astrometric telescopes require high positional accuracy, while solar ones require reduction of the Sun's heat. Today, astrometric telescopes are merged with normal optical telescopes, while solar telescopes still remain a special type of telescope. At the same time, efforts were made to increase the field of view of telescopes. In 1931, a wide field so-called catadioptric telescope involving reflecting and refracting components known as a Schmidt telescope was invented. The field of view of a Schmidt telescope can be 6×6 square degrees.

Beginning in the 1960s, there were continuous developments in optical telescope technology. In 1969, the USSR built the 6 m Bolshoi Teleskop Azimultalnyi also known as the Big Telescope Alt-azimuthal (BTA). It used, for the first time in a large optical telescope, an altitude-azimuth mount. Compared to equatorial mounts, altitude-azimuth mounts have a more direct load path for transferring the weight of telescope to the ground. One area where this is particularly important is in the difference between declination axis bearings on equatorial telescopes, which must support the weight of the telescope over a range of orientations, and elevation axis bearings on altitude-azimuth mounts, which have a fixed orientation. The new mounting makes optical telescopes with even larger diameters possible. In 1979, the 4.5 m Multiple Mirror Telescope (MMT) was built in the U.S. This telescope combined six 1.8 m sub-telescopes in one structure. Although the MMT was modified in 1998 into a single mirror 6.5 m telescope, the original version nevertheless had a great impact on modern telescope design.

In 1990, the Hubble Space Telescope (HST) was launched into space. This was the first major space telescope in astronomy. In the HST, 24 actuators were on the mirror back, intended for deforming the mirror to improve imaging performance. This was an attempt to control a telescope actively even in space. The first working active optics system was built in 1989 on the ESO New Technology Telescope (NTT) in Chile. In 1992, the 10 m Keck I segmented mirror telescope (SMT) was built. The primary mirror of this telescope is composed of 36 hexagonal segments of 1.8 m size. This represents a milestone in modern telescope design.

In 1997, the 10 m Hobby-Eberly Telescope (HET) was built with a segmented spherical mirror and a fixed altitude mounting. In 1998, the second Keck II telescope was completed.

In 1999, the Subaru 8.2 m and the northern Gemini 8 m telescopes were built. The Very Large Telescope (VLT) with four 8.2 m telescopes was built in 2000, and the southern Gemini telescope was completed in 2002. These seven telescopes are large single mirror ones.

The 10 m Gran Telescope Canarias (GTC) in Spain and the 10 m South African Large Telescope (SALT) were built in 2003 and 2005, respectively. The Chinese 4 m Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST), a reflecting Schmidt telescope with a field of view of 5×5 square degrees, was built in 2008. It involves both segmented mirror and active optics technologies. The giant Large Binocular Telescope (LBT) had its first light for both mirrors in 2008. This is a MMT-style Fizeau interferometer instrument with two large 8.4 m sub-telescopes.

Now the 22 m Giant Magellan Telescope (GMT), the 30 m Thirty Meter Telescope (TMT), and the 42 m European Extremely Large Telescope (E-ELT) are under serious design study. These are a new generation of modern astronomical optical telescopes.

With the development of modern computer and control systems, active optics control soon expanded into the higher frequency region, which became adaptive optics. Adaptive optics, using natural guide stars, was developed in the 1970s and 1980s by the military, but was first used in astronomy in 1989 at the European Southern Observatory. However, natural guide stars have limited sky coverage. The use of laser guide stars was proposed by Foy and Labeyrie (1985) in 1985 and was realized by the military first before 1990. It expands the sky coverage of the adaptive optics. Even so, the field of view with laser guide stars is still limited. At the turn of the century, multi-laser guide stars, atmospheric tomography, and multi-conjugated adaptive optics brought a new revolution in ground-based optical telescope design.

The development of optical interferometers is parallel to the development of telescopes. In 1868 Hippolyte Fizeau proposed for the first time an interferometric method with two separated apertures for measuring the diameter of a star. In 1891, Albert Michelson realized this technique which is now called a Michelson interferometer. A Michelson interferometer with a real and a mirror imaging telescope from the sea surface was first realized in radio wavelength in 1945 by Pawsey et al. (1946). Aperture synthesis in radio wavelengths was realized afterwards.

In 1956, Hanbury-Brown and Twiss realized an optical intensity interferometer. In 1970, Antoine Labeyrie produced a high-resolution optical speckle interferometer. An optical Michelson interferometer was also realized by Labeyrie in 1976. In 1995, a Fizeau interference image from separated optical telescopes was obtained by the Cambridge Optical Aperture Synthesis Telescope (COAST).

The development of optical telescopes provides astronomers with larger and larger light collecting area and higher and higher angular resolution. At the same time, it pushes the design of optical systems, mounting structures, sensors, actuators, control systems, and receiver systems to their present limits, producing design revolutions in many related fields.

1.2 General Astronomical Requirements

In optical telescope design, three basic requirements are high angular resolution, large light collecting power, and large field of view. When an image is formed by an optical telescope, the first question one would ask is: Is the source a single star or made up of closely spaced stars? To resolve closely spaced stars, high angular resolution is necessary. The second question one would ask is: Is a telescope able to detect very faint stars? The photons collected by a telescope from a star are proportional in number to the area of the telescope aperture, while the photon number from the star per unit area on the earth is inversely proportional to the square of the distance to the star. To detect a very faint or a very distant star, a large aperture, high telescope efficiency, and good clear site are required. Together these define the light collecting power of the telescope. The third question one would ask is: How many stars can one record inside the image field? For this question, a large field of view is required. This section will discuss all these related topics.

1.2.1 Angular Resolution

The angular resolution of an optical telescope is its ability to resolve two closely located point objects. Three factors influence the angular resolution of a telescope. These are diffraction of the aperture, aberrations of the optical system, and atmospheric turbulence.

In Gaussian optics, light from a single point object will arrive at a single point in the image space. The form of Gaussian optics known as paraxial or first-order optics is the first approximation of a practical optical system. In Gaussian optics, the sine of an angle is replaced by the angle itself. There is no aberration in a Gaussian system.

The term of aberration in optics describes the geometrical difference between a practical image and the corresponding Gaussian image. If the third order aberrations (first few terms of the aberration) are included, the second approximation of a practical optical system is referred to as classical optics where only third power terms of the aberrations are considered.

Geometrical optics is the third approximation for a practical optical system, where all the aberration terms are included. Geometrical optics does not fully describe a practical optical system which is influenced by the wave features of light.

One important property of light is interference. By including the wave effect, the fourth approximation of a practical optical system is referred to as physical optics. Physical optics includes diffraction, interference, and aberrations in a practical optical system. For optical telescope design, this stage of approximation is generally adequate.

The next stage in optics will be quantum optics where light is studied as quantized photons.

The aberrations and wavefront errors of an optical system are discussed in latter sections. In this section the aperture diffraction and atmospheric turbulence are discussed.

In physical optics, light also acts like a wave. Therefore, the actual image of a point source even without aberrations is not a sharp Gaussian image but a diffraction pattern. The size of this pattern determines the angular resolution of the optical system. The pattern is a function of the size and shape of the main mirror (aperture), due to the effects of Fraunhofer diffraction. It has many names depending on the conditions and the parameters being used, such as Fraunhofer pattern, diffraction pattern, far field pattern, radiation pattern, point spread function, intensity pattern, and, in some case, Airy disk. Some of these refer to the complex amplitude and phase, others to the amplitude squared (intensity).

If the Fraunhofer diffraction of an aperture field, S, is considered, then any small area ds on the aperture will have a contribution of light radiation in a direction of P (Figure 1.2). $F(x,y)$ is a complex field function in the aperture. The radiation contribution of an element $ds = dxdy$ in a direction of P will be $F(x,y)\,dxdy$, but with an added phase of $(2\pi/\lambda)(lx+my)$, where (l,m,n) are the direction cosines of the direction P and λ the wavelength of light. An aperture, as entrance pupil, is an opening through which light or radiation is admitted. It is usually a projection of the primary mirror which determines the cone angle of a bundle of rays that come to a focus in the image plane.

The radiation amplitude in the direction (l,m) is the integral of the contributions of each small area (Graham Smith and Thompson, 1988):

$$A(l,m) = C \iint_{Aperture} F(x,y) \exp\left[-\frac{2\pi \cdot j}{\lambda}(lx+my)\right] \cdot dxdy \tag{1.1}$$

where $j^2 = -1$ and C a constant with the unit of $[\text{length}]^{-2}$. The phase term in the equation for each small area includes two parts. One is the phase of the aperture

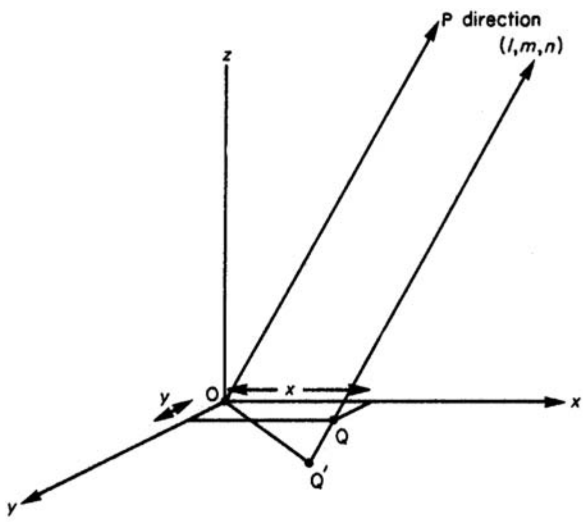

Fig. 1.2. Radiation contribution to a direction by a small area on an aperture field (Graham Smith and Thompson, 1988).

function itself of $F(x,y)$ and the other is the phase due to a path length of $QQ' = lx+my$. Mathematically, this equation represents approximately the Fourier transform of the aperture function $F(x,y)$, where x/λ and y/λ are dimensional variables. Therefore, the Fraunhofer diffraction pattern is the Fourier transform of the aperture field.

For a rectangular aperture with sides a and b, placed symmetrically about the origin and being uniformly illuminated, we have $F(x,y) = F_0$. By separating the variables:

$$A(l,m) = C \cdot F_0 ab \frac{\sin(\pi \cdot la/\lambda)}{\pi \cdot la/\lambda} \frac{\sin(\pi \cdot mb/\lambda)}{\pi \cdot mb/\lambda} \tag{1.2}$$

This is the diffraction pattern for a rectangular aperture without aberration.

For a uniformly illuminated circular aperture of a radius a, the above equation becomes:

$$A(w,\phi) = C \cdot F_0 \int_0^a \int_0^{2\pi} \exp\left[-\frac{2\pi j}{\lambda} rw\cos(\theta - \phi)\right] \cdot rdrd\theta \tag{1.3}$$

where (r, θ) is the polar coordinates in the aperture plane and (w, ϕ) in the image plane. It is equal to:

$$A(w,\phi) = C \cdot F_0 \frac{2J_1(2\pi aw/\lambda)}{2\pi aw/\lambda} = A(0,0)\frac{2J_1(2\pi aw/\lambda)}{2\pi aw/\lambda} \tag{1.4}$$

where $A(0,0) = C \cdot F_0$ is the amplitude of the radiation field at the origin, $J_1(x)$ the first-order Bessel function, $r\cos\theta = x$, $r\sin\theta = y$, $w\cos\phi = l$, $w\sin\phi = m$, and $w = (l^2 + m^2)^{1/2}$ the sine of the angle of the radiation direction measured from the z-axis. The intensity (power, energy) distribution of the diffraction pattern is:

$$I(w,\phi) = A^2(0,0)\left[\frac{2J_1(2\pi aw/\lambda)}{2\pi aw/\lambda}\right]^2 \tag{1.5}$$

This equation shows that the diffraction pattern of a circular aperture is axially symmetric with bright and dark rings. This pattern is called the Airy disk. The cross sections of amplitude and intensity patterns of an Airy disk are shown in Figure 1.3. The radius of the first zero (dark ring) of an Airy disk is at $1.22\lambda/d$, where d is the aperture diameter.

Generally, the intensity distribution of the diffraction pattern is called the point spread function (PSF) of an aperture field. The diffraction pattern of a

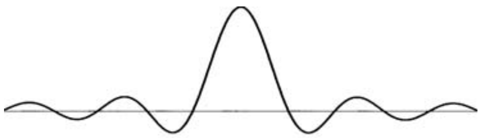

Fig. 1.3. The cross sections of the field pattern (a) and the intensity diffraction pattern (b) of a circular aperture.

dual-reflector telescope is slightly different due to the presence of a central blockage. For circular aperture and circular blockage, the amplitude pattern is:

$$A(w,\phi) = A(0,0)\left[\frac{2J_1(2\pi aw/\lambda)}{2\pi aw/\lambda} - \beta^2\frac{2J_1(2\pi\beta aw/\lambda)}{2\pi\beta aw/\lambda}\right] \tag{1.6}$$

where β is the blockage ratio. The blockage ratio is the relative radius of the secondary mirror blockage on the aperture plane. The intensity pattern is:

$$I(w,\phi) = A^2(0,0)\left[\frac{2J_1(2\pi aw/\lambda)}{2\pi aw/\lambda} - \beta^2\frac{2J_1(2\pi\beta aw/\lambda)}{2\pi a\beta w/\lambda}\right]^2 \tag{1.7}$$

This equation shows that the radius of first dark ring becomes smaller due to central blockage. Tables 1.1 and 1.2 give the radius of the first dark ring and the energy distribution in different rings of the diffraction pattern for the wavelength of 550 nm when central blockage is considered.

Table 1.1. The radius of the first dark ring in the intensity diffraction pattern of a circular aperture with different central blockage and at a wavelength of 550 nm

Central blockage ratio	0.0	0.1	0.2	0.3	0.4	0.5
Diameter of first dark ring (in arcsec)	13.8/d	13.6/d	13.2/d	12.6/d	11.9/d	11.3/d

Note: The unit of the aperture diameter d is in centimeter.

Table 1.2. The energy distribution in the intensity diffraction pattern of a circular aperture with different central blockage and at a wavelength of 550 nm

Central blockage ratio	0.0	0.1	0.2	0.3	0.4	0.5
Central spot	83.78%	81.84%	76.38%	68.24%	58.43%	47.86%
First ring	7.21%	8.74%	13.65%	21.71%	30.08%	34.99%
Second ring	2.77%	1.90%	0.72%	0.47%	1.75%	7.29%
Third ring	1.47%	2.41%	3.98%	2.52%	0.39%	0.17%

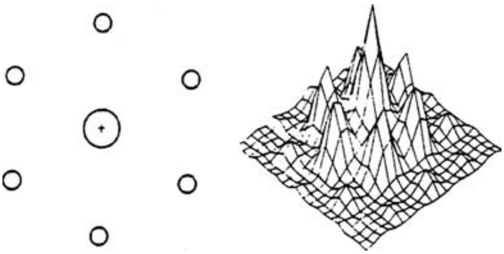

Fig. 1.4. An array of apertures in an interferometer and the resulting diffraction pattern.

Using the same method, the diffraction patterns for an unfilled aperture field can be derived. Figure 1.4 shows an array of apertures in an interferometer and its radiation pattern or its point spread function.

It is the intensity diffraction pattern that determines the angular resolution of an optical telescope. The angular resolution is defined as the minimum angle between two distinguishable objects in image space. In modern optics, the resolution is expressed as a cut-off spatial frequency of the aperture field (Section 1.4). The cut-off spatial frequency of an aperture is represented by the wavelength to diameter ratio.

Without the concept of spatial frequency, one requires empirical criteria for the separation of two stellar images with the same brightness. Three criteria were used in classical optics: the Rayleigh, the Sparrow, and the Dawes criteria.

The Rayleigh criterion is widely used. In 1879, Rayleigh suggested that if two star images of the same brightness are so close that the first dark ring of one pattern is at the center of another, then two images are resolved [Figure 1.5(a)]. In this case, the brightness in the middle of two images is about 0.735 of the maximum for the combined image.

The Sparrow criterion is less strict. From this criterion, if two images get so close that the faint middle point just disappears, then two stars are resolved. If two stars become even closer, there will be only one peak in the image [Figure 1.5(c)]. The Dawes criterion was derived after a long period of studies. It is in between the Rayleigh and Sparrow criteria. In Dawes criterion, there is

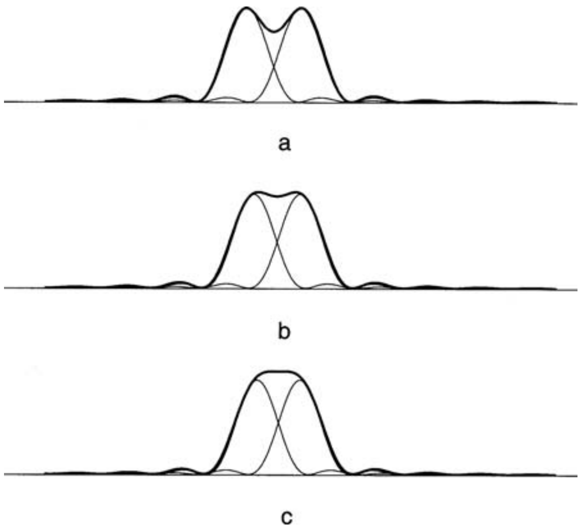

Fig. 1.5. Three resolution criteria: (**a**) Rayleigh, (**b**) Dawes, and (**c**) Sparrow.

just a tiny faint spot between two bright peaks which a human eye can just detect [Figure 1.5(b)]. These criteria are close to the cutoff spatial frequency in modern optical theory.

These three empirical criteria can also be applied to stars of different brightness. Figure 1.6 is the intensity diffraction pattern of two stars that meet the Rayleigh criterion, for which the magnitude ratio is 1.5. In this case, a faint spot

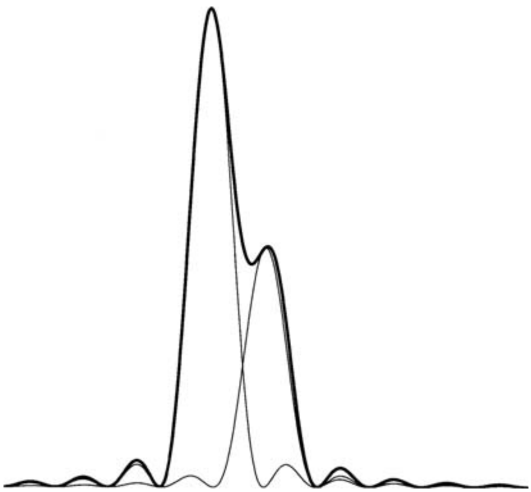

Fig. 1.6. Brightness distribution in case of the Rayleigh criterion when the stellar magnitude ratio is 1.5.

exists between two bright peaks. For a circular aperture, these three criteria are expressed as:

$$q_r = 1.22\frac{\lambda}{D}\text{(Rayleigh)} \tag{1.8}$$

$$q_d = 1.02\frac{\lambda}{D} \quad \text{(Dawes)} \tag{1.9}$$

$$q_s = 0.95\frac{\lambda}{D} \quad \text{(Sparrow)} \tag{1.10}$$

The angular resolution for apertures with blockage is better since the radius of the first dark ring is reduced.

The cut-off spatial frequency and Rayleigh criterion represent the diffraction limited resolution. The diffraction limit can be achieved by space telescopes, small ground-based telescopes, and ground-based telescopes with adaptive optics or interferometers. Another way to achieve diffraction-limited resolution when observing through the atmosphere is to use super-resolution (SR) techniques, most of which employ computer processing. One of these is to process many shifted short exposure frames of the same image. One type of image shift is caused by atmospheric turbulence, which is called the seeing effect. The seeing moves the image slightly and randomly in image plane. Another super-resolution technique moves the image in the longitude direction, called longitudinal super-resolution. In this technique, both in- and out- of focus images are collected as the out of focus image provides more spatial frequency information. Using template images of two point sources of different separations is also a super-resolution technique. Extrapolating in frequency domain by an assumed analytic function is another super-resolution technique.

However, super-resolution is largely a matter of data processing techniques. The ultimate image intensity distribution of a telescope is still set by the corresponding spatial frequency distribution of the aperture field.

Using the Rayleigh criterion, angular resolutions for different aperture sizes can be calculated. The 5 m Hale telescope of the Palomar Observatory should have an angular resolution of $\omega = 0.028$ arcsec at $\lambda = 550$ nm. In fact, this telescope has an angular resolution of about $\omega = 1$ arcsec. This resolution is not diffraction limited but is seeing limited because of the atmospheric turbulence.

The main origin of the atmospheric turbulence is wind. Wind has a wide frequency band and different wind frequencies will excite different scales of the turbulence. Within a single scale of the turbulence, the temperature is the same but the temperature is different when the scales are different. Temperature variations cause changes in the refractive index of the atmosphere, resulting in gradients of refractive index. The spatial scale of the wind frequency variation ranges from a few millimeters to a few hundred meters. Therefore, random differential or anomalous refraction occurs when stellar light passes through a turbulent atmosphere.