Chapter 1

Prologue

Overview: In this first chapter we present an introduction/overview of material that is related to the propagation of laser beams through random media like the atmosphere. The intent here is to provide the reader with a broad view of the subject without the distraction of mathematical detail that is required in other chapters of the text. The wavelengths of interest throughout the text are the visible and infrared (IR) portions of the electromagnetic spectrum, although some results can readily be applied to other wavelengths like millimeter waves and, under some conditions, microwaves.

We begin by briefly introducing some of the standard optical wave models like the plane wave, spherical wave, and lowest-order Gaussian-beam wave. Next, we describe the origin of certain atmospheric effects (including meteorological phenomena) associated with propagating optical waves. Some of the traditional application areas are discussed for laser beam propagation—*free space optical communications* (FSO), *laser radar, imaging*, and *remote sensing*—followed by a short historical summary of developmental programs for laser satellite communication systems (*lasersatcom*) in the United States, Europe, and Japan. In the last section of this chapter we present an overview of the material contained in the remaining chapters, delineating the primary topics to be treated in each individual chapter.

1.1 Introduction

The first working *LASER*, an acronym standing for *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation, was introduced in 1960 and from that point in time the scientific community concentrated a great deal of attention on its possible applications. In particular, it was suggested that lasers be used to extend radio-frequency (RF) atmospheric communication and radar techniques to the optical-frequency band. Other areas of interest for laser applications include weaponry, ranging, remote sensing, target designation, adaptive optics, and medical uses, among others. However, all systems that utilize optical (visible) or infrared (IR) waves must take into account general propagation effects associated with the medium in which it propagates in addition to effects associated with the wave itself. The propagation medium in many cases is the turbulent atmosphere for which small index-of-refraction fluctuations along the propagation path cause a variety of deleterious effects on the wave.

Random fluctuations in the refractive index of the atmosphere are directly associated with microscopic temperature fluctuations caused by turbulent motion of the air due to winds and convection. Although these refractive-index fluctuations are only a few parts in 10^6, a propagating optical wave passes through a large number of refractive-index inhomogeneities, so their cumulative effect on the optical wave is quite profound. For example, refractive-index fluctuations cause the twinkling of stars and limit the “seeing” ability of astronomers to resolve small objects to within a few seconds of arc. This latter atmospheric effect motivates the use of adaptive optics techniques and the placement of large telescopes in space, such as the famous Hubble telescope.

Early investigations concerning the propagation of electromagnetic radiation and other waves through random media involved the propagation of starlight through the atmosphere, propagation of sound waves through the atmosphere and ocean, propagation of microwaves through planetary atmospheres, and propagation of radio waves through the ionosphere and interplanetary space. Thus, some of the theoretical work concerning the propagation of an optical wave in a turbulent medium was done prior to the introduction of the laser. The propagation of laser light, which is simply one form of electromagnetic radiation, is a subtopic of much of this early research. Both Chernov and Tatarskii published monographs before 1960 on the propagation of optical plane waves and spherical waves through turbulence; these monographs were subsequently translated into English in 1960 and 1961, respectively [1,2]. Additional background on optical wave propagation in random media, along with many early references, can also be found in Lawrence and Strohbehn [3], Prokhorov et al. [4], Fante [5,6], Uscinski [7], Strohbehn [8], Ishimaru [9], Zuev [10], Rytov et al. [11], Tatarskii et al. [12], Sasiela [13], Andrews et al. [14], and Wheelon [15,16].

1.2 Historical Background of Light

Until about the middle of the seventeenth century, the general belief of the scientific community [including Newton (1642–1727)] was that light consisted of a stream of corpuscles. These "corpuscles" emitted by light sources traveled in straight lines, could penetrate transparent materials, and were reflected from the surfaces of opaque objects. Laws of refraction were established by Snell (1591–1626), diffraction was discovered by Grimaldi (1618–1663), and double refraction was discovered by Bartholinus (1625–1698). However, discoveries like diffraction were particularly puzzling to explain on the basis of the corpuscular theory. For example, it was difficult under the corpuscular theory to explain why shadows reach a limiting sharpness as the size of the source becomes small, and why fringes appear on the light side of the shadow of a sharp edge.

Huygens (1629–1695) showed in 1670 that the laws of reflection and refraction could be explained on the basis of a wave theory, although he thought light waves were longitudinal (in the direction of propagation) rather than transversal (perpendicular to the direction of propagation). It is interesting that even though the idea that light might involve a wave motion of some kind arose in the middle of the seventeenth century, a wave theory of light was not widely accepted by the scientific community until the end of the eighteenth century, mostly because of Newton's support of the corpuscular theory and his long-lasting influence.

In the early 1800s, the interference experiments of Young (1773–1829), Fresnel (1788–1827), and others finally put the corpuscular theory to rest. Young's experiments enabled him to measure the wavelength of light waves and Fresnel showed that the rectilinear propagation of light as well as the diffraction effects observed by Grimaldi and others could be accounted for by the behavior of waves of short wavelength.

The speed of light was directly measured in 1850 and found to be $c = 3 \times 10^8$ m/s, confirming the estimates made many years earlier first by Romer (1644–1710) and latter by Bradley (1693–1762). Knowledge of the speed of light was important for Maxwell's (1831–1879) theory of electromagnetic waves published in 1873. Hertz (1857–1894) discovered the photoelectric effect in 1887 and became the first to verify Maxwell's theory by producing short wavelength radiation (microwaves) that possessed all the properties of waves. However, it took the quantum theory of Planck (1858–1947), as interpreted by Einstein (1879–1955) in 1905, to explain the photoelectric effect and to introduce the notion that wave energy of light is concentrated in small packets called *photons.*

1.2.1 Electromagnetic spectrum

Although the quantum theory played an important role in our understanding the general nature of light, it is widely accepted that the phenomenon of light propagation is best explained by the electromagnetic wave theory of classical mechanics. Because of the vast difference in wavelengths of various electromagnetic waves, the electromagnetic spectrum is divided into a number of wavebands as illustrated in Fig. 1.1. The standard units of measurement for the various wavelengths include the kilometer (km), meter (m), centimeter (cm), millimeter (mm), nanometer (nm), micrometer (μm), angstrom (Å), and X-unit (XU), where:

$$\boxed{\begin{aligned} 1\,\text{nm} &= 10^{-9}\,\text{m},\\ 1\,\mu\text{m} &= 10^{-6}\,\text{m},\\ 1\,\text{Å} &= 10^{-10}\,\text{m} = 10^{-4}\,\mu\text{m}, \text{ and}\\ 1\,\text{XU} &= 10^{-13}\,\text{m} = 10^{-7}\,\mu\text{m} = 10^{-3}\,\text{Å}. \end{aligned}}$$

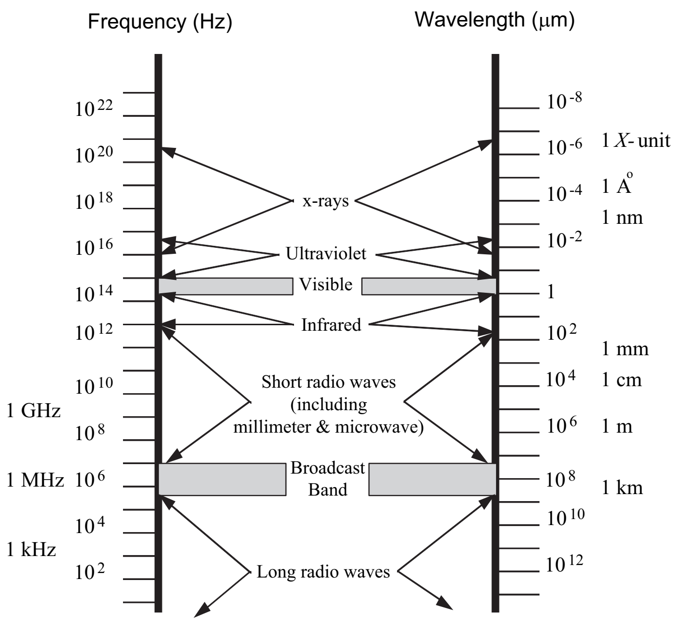


Figure 1.1 Electromagnetic spectrum.

The range of *radio frequency* (RF) *waves* extends from about 20 km down to approximately 1 to 2 mm. Included in this range are the standard *broadcast bands* of radio waves (180 to 560 m for AM and 2.78 to 3.4 m for FM) and the various *microwave bands* between 2 mm and 16 cm. At wavelengths shorter than 2 mm are the *millimeter waveband* and *infrared* (IR) *bands* (classified as far-IR, mid-IR, and near-IR), the latter of which extend to the visible spectrum. Because the human eye responds to wavelengths only between 0.4 and 0.7 μm, this range of wavelengths is known as the *visible band.* At wavelengths shorter than the visible band, we find the *ultraviolet* bands (roughly 100 to 3900 Å) and *x-rays* (roughly 0.1 to 200 Å). *Gamma rays* have even shorter wavelengths measured in X-units.

Useful lasers are devices that generate coherent radiation at wavelengths in the infrared, visible, and ultraviolet regions of the electromagnetic spectrum. They operate on the same basic principle originally developed for *masers*, which stands for microwave amplification by stimulated emission of radiation. The first maser device was developed in 1954 at Columbia University by Townes, followed by a similar device developed in the former Soviet Union by Basov and Prokhorov. The extension of microwave maser concepts to optical wavelengths, which led to the term *laser*, was discussed in 1958 in a now famous paper by Townes and Schawlow [17]. The first experimentally successful laser device was a flashlamp-pumped ruby laser at 0.694 μm operated by Maiman at the Hughes Research Laboratory in 1960. That same year a helium-neon (He-Ne) gas discharge laser was successfully operated by a group at Bell Laboratories. This first He-Ne laser was operated initially at 1.15 μm but was extended the next year to the familiar 0.633-μm wavelength.

An enormous number of laser devices have emerged since 1960, with literally thousands of different discrete wavelengths available. However, the number of commercially important and useful practical lasers is much smaller, but still numerous. A summary of some commonly used laser wavelengths is given below [18]:

- HCN far-IR laser (311, 337, 545, 676, and 744 μm)
- H_2O far-IR laser (28, 48, and 120 μm)
- CO_2 laser (9.6 to 10.6 μm)
- CO laser (5.1 to 6.5 μm)
- HF chemical laser (2.7 to 3.0 μm)
- Nd:YAG laser (1.06 μm)
- He-Ne laser (0.633 and 1.15 μm)
- GaAs semiconductor laser (0.870 μm)
- Ruby laser (0.694 μm)
- Rhodamine 6G dye laser (0.560 to 0.640 μm)
- Argon-ion laser (0.488 to 0.515 μm)
- Pulsed N_2 discharge laser (0.337 μm)
- Pulsed H_2 discharge laser (0.160 μm)

1.3 Optical Wave Models

There are several basic geometries used to describe various optical/IR wave models. Among these are the following, where propagation is assumed to be along the z-axis:

- *Plane wave*—an unbounded wave with constant amplitude A_0 and constant phase φ_0, described in the plane of the transmitter ($z = 0$) by

$$U_0(x, y, 0) = A_0 e^{i\varphi_0}. \tag{1}$$

  The plane wave model is used in describing the properties of starlight and other exo-atmospheric sources at a ground-based receiver.
- *Spherical wave*—an unbounded wave associated with a point source, described in the plane of the transmitter ($z = 0$) by

$$U_0(x, y, 0) = \lim_{R\to 0} \frac{e^{ikR}}{4\pi R}, \tag{2}$$

  where $R = |\mathbf{R}| = \sqrt{x^2 + y^2 + z^2}$. The spherical wave model is sometimes used for a small-aperture source or a source with a large divergence angle.
- *Beam wave*—a wave of finite extent with focusing capabilities. The Gaussian-beam wave has an amplitude and phase profile described in the plane of the exit aperture of the transmitter ($z = 0$) by

$$U_0(x, y, 0) = a_0 \exp\left[-\frac{x^2 + y^2}{W_0^2} - \frac{ik}{2F_0}(x^2 + y^2)\right], \tag{3}$$

  where a_0 is the on-axis amplitude, W_0 is the beam spot radius (defined by the $1/e$ point of the field amplitude), and F_0 is its phase front radius of curvature. This model is most often used in beam wave analyses.

A number of fundamental phenomena concerning optical/IR wave propagation in a random medium are important to the systems engineer. Among these are the following:

- diffraction
- atmospheric attenuation
- atmospheric turbulence
- thermal blooming

Except for thermal blooming, which is a nonlinear effect, the other phenomena are considered linear. Only linear phenomena will be discussed in this text and, of those, diffraction and atmospheric turbulence concern us most.

1.3.1 Diffraction

Diffraction is a natural wave phenomenon of all light waves—it causes beam spreading of the wave as it propagates, which reduces the amount of energy within any given spot size inside the beam diameter. In addition, the phase front radius of curvature of the propagating optical wave is also constantly increasing. A laser beam is subject to further spreading when atmospheric turbulence is present.

The amount of beam spreading due to pure diffraction depends on the wavelength λ of the optical wave, shape of the phase front (i.e., spherical, uniform, etc.), and size of the emitting aperture. In our treatment we consider primarily the Gaussian-beam wave, or its limiting case of a uniform amplitude plane wave or spherical wave. The notion of "beam spot size" has an unambiguous physical meaning only for the simple Gaussian beam for which the irradiance (intensity) has a Gaussian profile and produces a single spot in the observation plane. The beam spot size along the propagation path has its minimum value at the *beam waist*, and the amount of beam spreading at large distances from the waist can be estimated by the beam divergence angle (see Fig. 1.2)

$$\theta_B \cong \frac{\lambda}{\pi W_B}, \qquad z \gg \frac{\pi W_B^2}{\lambda}, \tag{4}$$

where W_B is the beam radius at the waist. In Chap. 4 we will develop more complete relations for diffractive beam spreading.

1.4 Atmospheric Effects

It is a common experience to notice the changing view of distant objects or a city skyline from day to day as atmospheric conditions vary. These varying conditions are caused by factors like rain, snow, sleet, fog, haze, pollution, etc., that can greatly limit our ability to view distant objects. These same factors also affect the transmission of electromagnetic radiation through the atmosphere, particularly optical waves.

The three primary atmospheric phenomena that affect optical wave propagation are *absorption, scattering*, and *refractive-index fluctuations* (i.e., *optical turbulence*). Absorption and scattering by the constituent gases and particulates of the atmosphere are wavelength dependent and give rise primarily to attenuation of an optical wave. Index of refraction fluctuations lead to *irradiance fluctuations,*

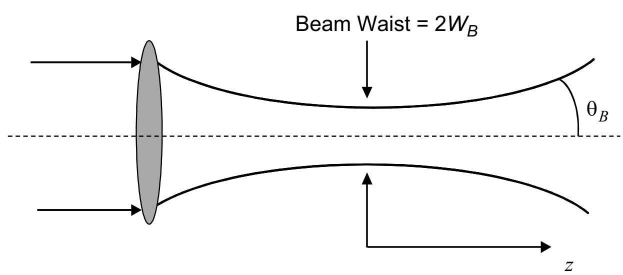


Figure 1.2 Far-field divergence angle.

beam spreading, and *loss of spatial coherence* of the optical wave, among other effects. Unfortunately, these detrimental effects have far-reaching consequences on astronomical imaging, free-space optical communications, remote sensing, laser radar, and other applications that require the transmission of optical waves through the atmosphere.

1.4.1 Atmospheric structure with altitude

The atmosphere is a gaseous envelope that surrounds the Earth and extends to several hundred kilometers above the surface. Over 98% of the atmosphere by volume is comprised of the elements nitrogen and oxygen. The major constituents of the atmosphere are water vapor, carbon dioxide, nitrous oxide, carbon monoxide, and ozone. Based mostly on temperature variations, the Earth's atmosphere is divided into four primary layers (see Fig. 1.3):

- *Troposphere*—extends up to 11 km and contains roughly 75% of the Earth's atmospheric mass. Maximum air temperature occurs near the surface of the Earth, but decreases with altitude to $-55°C$. The *tropopause* is an isothermal layer extending 9 km above the troposphere where air temperature remains constant at $-55°C$. The tropopause and troposphere together are known as the *lower atmosphere.*
- *Stratosphere*—layer above the tropopause, which extends from 20 km up to 48 km altitude. The air temperature is roughly constant in the very lowest

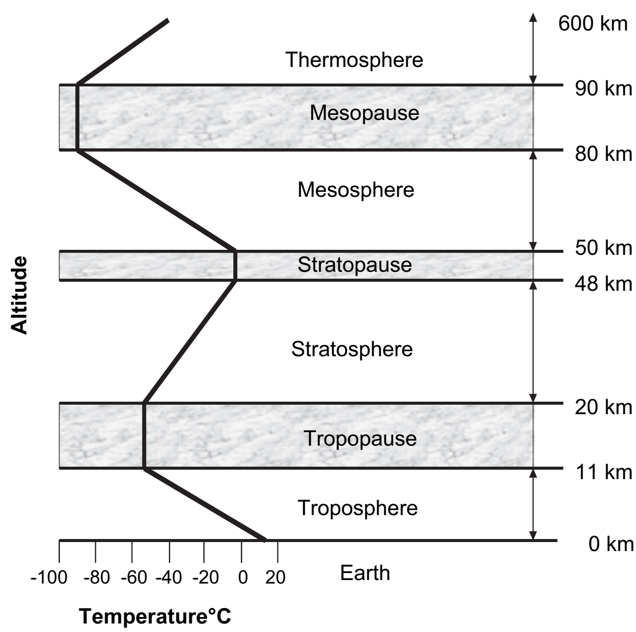


Figure 1.3 Diagram depicting various atmospheric layers and air temperature.

part of the stratosphere but then increases with altitude because the ozone gas in this layer absorbs ultraviolet sunlight, thereby creating heat energy. The ozone layer, which protects life from harmful ultraviolet radiation, is concentrated between 10 and 50 km. Separating the stratosphere from the mesosphere is the *stratopause*, another isothermal layer at approximately $-3°C$.

- *Mesosphere*— extends from the stratopause to roughly 80 km. Temperature here generally decreases at a constant rate down to $-90°C$, which is the coldest temperature in the atmosphere. The *mesopause* is the third isothermal layer, separating the mesosphere and the thermosphere. The regions of the stratosphere and the mesosphere, along with the stratopause and mesopause, constitute what is commonly called the *middle atmosphere.*
- *Thermosphere*—extends from the mesopause to roughly 600 km. Air temperature in the thermosphere increases quite strongly above 90 km due to the Sun's energy. Most of the *ionosphere* and the *exosphere* are included in the thermosphere. The ionosphere starts around 70 or 80 km up to an indefinite height ($\sim$1000 km) and is so named because it is sufficiently ionized by solar ultraviolet radiation that the concentration of free electrons in this layer affects the propagation of radio waves.

1.4.2 Absorption and scattering

The Earth's atmosphere is an absorbing medium. *Absorption* occurs when a photon of radiation is absorbed by a gaseous molecule of the atmosphere that converts the photon into the molecule's kinetic energy. Hence, absorption is a mechanism by which the atmosphere is heated. Atmospheric absorption is a strong function of wavelength. For example, absorption by O_2 and O_3 essentially eliminates propagation of radiation at wavelengths below 0.2 μm, but there is very little absorption at the visible wavelengths (0.4 to 0.7 μm).

Scattering of electromagnetic waves in the visible and IR wavelengths occurs when the radiation propagates through certain air molecules and particles. Light scattering is strongly wavelength dependent, but there is no loss of energy like in absorption. The physical size of the scatterers determines the type of scattering.

- *Rayleigh scattering*—(named after Lord Rayleigh) caused by air molecules and haze that are small in comparison with the wavelength λ of the radiation (see Fig. 1.4). Rayleigh scattering, also called *molecular scattering*, applies only to very clear atmosphere. The scattering coefficient is proportional to λ^{-4}, a relation known as the *Rayleigh law.* For these small air molecules, scattering is negligible at wavelengths greater than roughly 3 μm. At wavelengths below 1 μm, Rayleigh scattering produces the blue color of the sky as a consequence that blue light is scattered much more than other visible wavelengths.

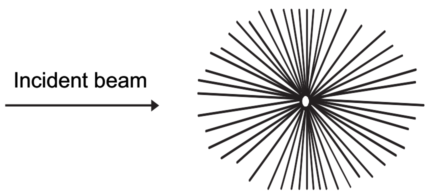


Figure 1.4 Rayleigh scattering.

- *Mie scattering*—(named after Gustav Mie) scattering by particles comparable in size to the radiation wavelength (also called *aerosol scattering*). Unlike Rayleigh scattering, scattering by particles comparable in size to or greater than the radiation wavelength is concentrated in the forward direction (see Fig. 1.5). Scattering losses decrease rapidly with increasing wavelength, eventually approaching the Rayleigh scattering case. Mie scattering is the reason why sunsets appear red.

A term that is sometimes used to describe atmospheric "visibility" is the *visual range*, which corresponds to the range at which radiation at 0.55 μm is attenuated to 0.02 times its transmitted level. Rayleigh scattering by molecules implies a visual range of approximately 340 km (or 213 miles) [19].

Absorption and scattering are often grouped together under the topic of *extinction*, defined as the reduction or attenuation in the amount of radiation passing through the atmosphere. The *transmittance* (also called *atmospheric transmission*) of laser radiation that has propagated a distance L is related to extinction as described by Beer's law, which can be written as [19,20]

$$\tau = \exp[-\alpha(\lambda)L], \quad [\text{unitless}] \tag{5}$$

where $\alpha(\lambda)$ is the *extinction coefficient* and the product $\alpha(\lambda)L$ is called the *optical depth.* The extinction coefficient is composed of two parts:

$$\alpha(\lambda) = A_a + S_a, \quad [\mathrm{m}^{-1}] \tag{6}$$

where A_a is the absorption coefficient and S_a is the scattering coefficient.

Absorption and scattering are deterministic effects that are fairly well known. Software packages like LOWTRAN, FASCODE, MODTRAN, HITRAN, and PCLNWIN are commonly used by both government and private industry to predict transmittance (attenuation) effects as a function of wavelength λ, based on a variety of conditions—meteorological range, latitude (tropical, mid, artic),

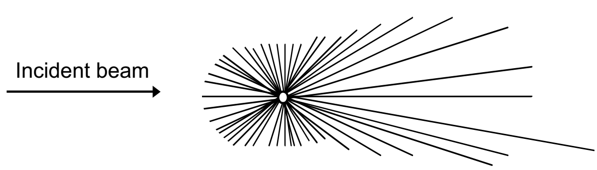


Figure 1.5 Mie scattering.

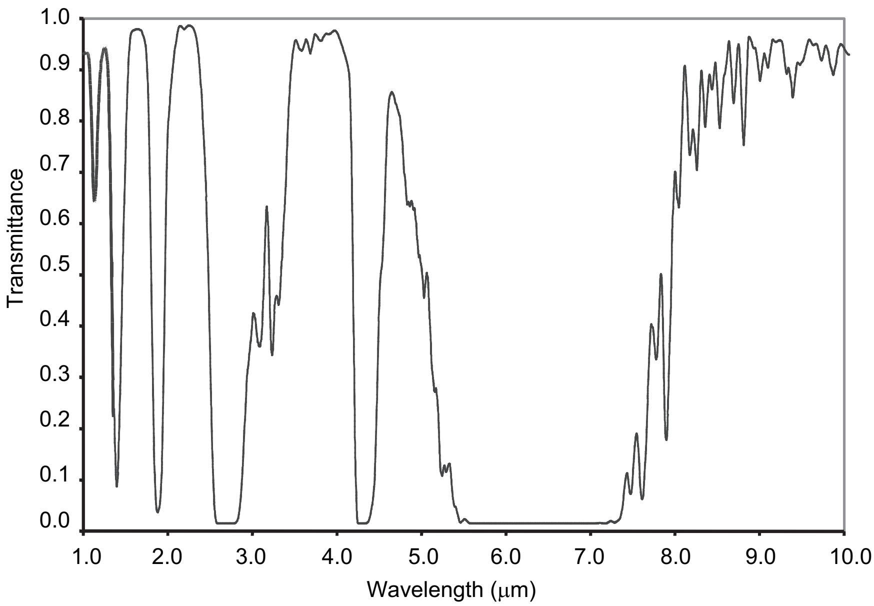


Figure 1.6 Typical atmospheric transmittance for a horizontal 1-km path. Height above ground is 3 m with no rain or clouds.

altitude, etc.[1] A typical output from MODTRAN for rural aerosols with meteorological range of 23 km is shown in Fig. 1.6 as a function of wavelength over 1 to 10 μm.

1.4.3 Meteorological phenomena

Meteorological optics involves the interplay of light with the atmosphere, leading to some of the most colorful aspects of atmospheric optics [21,22]. In particular, the process of scattering sunlight causes several colorful and fascinating phenomena like rainbows and ice-crystal halos. Some of the phenomena are quite rare but others very common. Below, we briefly describe some of the familiar effects.

- *Blue sky:* The blue color of the sky is caused by the scattering of sunlight off air particles (molecules) that are small in comparison with the radiation wavelength.
- *Rainbow:* The colorful rainbows that often appear after a rainstorm are caused by internal reflection and refraction of sunlight by water droplets in the atmosphere. Because of the dispersion of light within the water droplet, the colors associated with various wavelengths are separated in the backscattered image.

[1]These and other software packages are available from the Ontar Corporation, 9 Village Way, North Andover, MA 01845-2000. Also, see http://www.ontar.com.

- *Red sunset:* Sunsets appear red because sunlight near the horizon must pass through a greater thickness of air than when the sun is overhead. Shorter wavelength sunlight is therefore scattered more out of the sunlight by the additional aerosols and particulate matter, leaving only the longer red wavelength to get through to the observer.
- *Green flash:* A “green flash” is a rare phenomenon seen at sunrise and sunset when some part of the sun suddenly changes color from red or orange to green or blue. At sunset, it occurs just before the last part of the sun disappears from view and is caused by dispersion. As the sun sets, the last image to be viewed is the shortest wavelength color, blue or violet. Due to Rayleigh scattering of the blue light from the image and extinction of the violet light, the last image observed is generally closer to the color green.
- *Green ray:* A “green ray” is a very rare kind of green flash in which a beam of green light is seen shooting up from the horizon where the sun has just set.
- *Halo:* A variety of halo phenomena occur around the sun in cold climates as a result of ice crystals in the air. The familiar 22° halo around the sun or moon occurs because of refraction in tiny hexagonal ice crystals in the air. The order of colors is reversed from that of diffraction (i.e., the inner circle is red).
- *Corona:* A “corona” is a smaller circle of light (on the order of 10°) distinct from the 22° halo that can sometimes be seen around the sun or moon if there are thin clouds composed of water droplets or ice crystals of nearly uniform size. It is caused by diffraction of light by small particles, often appearing in alternating blue-green and red circles.
- *Glory:* The term “glory” refers to a phenomenon seen from an aircraft. It involves a rainbow band around the shadow of your aircraft seen on a cloud below. It is another phenomenon of diffraction, with smaller droplets causing larger glories through Mie scattering.

1.4.4 Optical turbulence

Atmospheric turbulence, generated by a temperature differential between the Earth’s surface and the atmosphere, causes effects on optical waves that have been of great interest to scientists for many years. During daytime, the Earth is hotter than the air, causing the air nearest the ground to be hotter than that above. This negative temperature gradient causes light rays parallel to the Earth to bend upward. If the negative temperature gradient is sufficiently strong, it can result in an inverted image known as a *mirage* (another meteorological phenomenon). Temperature gradients are positive during nighttime hours, resulting in downward bending of light rays. This downward bending of light rays through refraction enables one to see objects (like stars) slightly below the horizon, a phenomenon called *looming.* In fact, just before the sun disappears from view at sunset, its actual position is about a diameter below the horizon.

Wave front distortions in the optical wave induced by atmospheric turbulence result in a *spreading of the beam* (beyond that due to pure diffraction), random variations of the position of the beam centroid called *beam wander*, and a random redistribution of the beam energy within a cross section of the beam leading to *irradiance fluctuations.* Perhaps the most well-known effect of atmospheric turbulence is the *twinkling* of stars, which is an irregular change in brightness of the image. In addition, the atmospheric turbulence that limits astronomical seeing gradually destroys the *spatial coherence* of a laser beam as it propagates through the atmosphere. This loss of spatial coherence limits the extent to which laser beams may be collimated or focused, resulting in significant power level reductions in optical communication and radar systems. Also, heterodyne detection optical receivers are very sensitive to the loss of spatial coherence because this limits the effective aperture size of such a detection system.

Wind blowing over an aerodynamically rough region of the Earth's surface in the presence of a temperature gradient creates fluctuations in the atmosphere's refractive index known as *optical turbulence.* The behavior of a subportion of optical turbulence may be described in a statistical manner, and this forms the basis of most propagation theories. Consequently, the propagation of an optical/IR wave through optical turbulence can also be described by statistical quantities. Inherent in the methods of analysis, theoretical studies concerning optical/IR wave propagation through optical turbulence are typically classified into one of two general categories—*weak fluctuations* or *strong fluctuations.* Weak fluctuation theory is usually based on the *Rytov perturbation approximation* (see Chap. 5), which yields relatively simple mathematical models for a number of basic statistical quantities involving the wave field. Many of the theoretical results presented in this text are based on the Rytov method, but this imposes a strict limitation on the assumed magnitude of the irradiance fluctuations. Strong fluctuation theory has evolved from several different approaches, such as the *parabolic equation method* and the *extended Huygens-Fresnel principle.* Both methods are briefly reviewed in Chaps. 5 and 7, but for other techniques the reader is referred to the references.

1.5 Application Areas

In this section we briefly review some application areas involving the propagation of optical/IR waves through a random medium. Our focus here concerns horizontal-path free space optical (FSO) communication systems, laser satellite communication systems (*laser satcom*) [22,24], and laser radar systems [25]. Atmospheric effects that pertain to FSO, laser satcom systems, and laser radar systems are discussed in Chaps. 11, 12, and 13, respectively. Interesting overviews of early optical communication systems are given in Refs. [26] and [27].

1.5.1 Free space optics

Optical wireless communications, better known as *Free Space Optics*, has become a very important application area because of the increasing need for larger bandwidths and high-data-rate transfer of information that is available at optical wavelengths. Although early interests concentrated largely on higher and higher data rates afforded by optical systems over radio frequency (RF) systems, the greatest benefits of laser communication may be: (*i*) less mass, power, and volume as compared with RF systems, (*ii*) the intrinsic narrow-beam/high-gain nature of laser beams, and (*iii*) no regulatory restrictions for using frequencies and bandwidths.

Free space optics is a line-of-sight technology that uses lasers to provide optical bandwidth connections. Currently, FSO is capable of up to 2.5 gigabits per second (Gbps) of data, voice, and video communications through the air, and allowing optical connectivity without requiring fiber-optic cable. Only 5 percent of the major companies in the United States are connected to fiber-optic infrastructure (backbone), yet 75 percent are within one mile of fiber (known as the "Last Mile Problem"). As bandwidth demands increase and businesses turn to high-speed LANs (local area network), it becomes more frustrating to be connected to the outside world through lower-speed connections (wire- and copper-based technologies) such as DSL (digital subscriber line), cable modems, or T1s (transmission system 1). Small FSO networks have already been set up in Denver, Dallas, Los Angeles, and Seattle. In Europe, some regional fiber-optic carriers are marketing FSO to companies seeking a quick access to high-speed connections.

Commercially available FSO equipment provides data rates much greater than those of digital subscriber lines or coaxial cables, from 10 Mbps to 1.25 Gbps, more than enough for most high-end broadband services and applications. Furthermore, state-of-the-art laser diodes already on the market can be turned on and off at speeds that could transmit information at even higher rates—as much as 9.6 Gbps. Although this equipment has not yet been adapted for FSO use, such a system would feature optical pulses lasting a mere 100 picosecond (100 trillionths of a second) each.

Typical laser wavelengths considered for FSO systems are 850 and 1550 nm. Low-power infrared lasers, which operate in an unlicensed electromagnetic-frequency band, either are or can be made to, operate in an eye-safe manner. However, the lasers' limited power restricts the range of applicability. Depending on weather conditions, FSO links along horizontal near-ground paths can extend from a few hundred meters to one or more kilometers—far enough to get broadband traffic from a backbone to many end users and back. Because bad weather (thick fog, mainly) can severely curtail the reach of these line-of-sight devices, each optical transceiver node, or link head, can be set up to communicate with several nearby nodes in a network arrangement. This "mesh topology" can ensure that vast amounts of data will be relayed reliably from sensor sites to central control centers and users.

Susceptibility to fog has slowed the commercial deployment of near-ground FSO systems. It turns out that fog (and, to a much lesser degree, rain and snow) considerably limits the maximum range of an FSO link. Because fog causes significant loss of received optical power, a practical FSO link must be designed with some specified "link margin," i.e., an excess of optical power that can be engaged to overcome foggy conditions when required. Under ideal clear-sky conditions, the absolute reliability of a laser communication link through the atmosphere is still physically limited by absorption of atmospheric constituents and the constantly present atmospheric turbulence.

For a given link margin, it becomes meaningful to speak of another metric—the link availability, which is based on the fraction of the total operating time that the link fails as a result of fog or other physical interruption. Link-availability objectives vary with the application. When FSO technology is used for private enterprise networking (e.g., to connect two offices situated in separate buildings), 99.9 percent uptime may be acceptable. This value corresponds to a downtime of about nine hours a year. In contrast, public carrier-class service, which is provided to a carrier's prime business customers, demands a link availability of 99.999 percent (the so-called five-nine benchmark in the telecommunications business), which translates into only five minutes of allowable downtime a year. Fiber-optic systems regularly operate at the five-nines-service level.

FSO technology started in the 1960s, but deleterious atmospheric effects on optical waves together with the invention of optical fibers in the early seventies caused a decline in its immediate use. However, FSO systems can provide high-speed connections between buildings, between a building and the optical fiber network, aircraft-to-aircraft, or between ground and a satellite. Moreover, a FSO system can often be installed in a matter of days or even hours in some cases, whereas it can take weeks or months to install an optical fiber connection. Now, because of the growing demand for access to high-data-rate connections all over the world and the inherent limitations of optical fiber networks in certain environments, there is renewed interest in FSO.

1.5.2 Laser satellite communication systems

The first artificial satellite, called Sputnik-1, was launched on October 4, 1957 by the former Soviet Union. In 1958, President Eisenhower broadcast a Christmas message using the world's first communications satellite (Explorer I), and the first commercial satellite (Telstar-1) was launched by AT&T on July 10, 1962. Since that time, worldwide communications have been completely revolutionized through the use of satellites. For example, telephone calls to many countries can now be dialed directly because of satellites and many of the television channels that we watch are distributed by satellites. Future space-to-space crosslinks between satellites will permit information transfer to even the most remote sites on Earth without the need for expensive ground relay stations.

The development of laser satellite communications, or *laser satcom*, is carried out mainly by the National Aeronautics and Space Administration (NASA) in the United States, by the European Space Agency (ESA) in Europe, and by the National Space Development Agency (NASDA) in Japan. Interest in the possibility of laser satcom, along with government-sponsored developmental programs, dates back to the early sixties. The first programs concerned the development of a coherent CO_2 system by NASA and a Nd:YAG direct detection system by the

Air Force. In the seventies, the Air Force sponsored a program known as the *Space Flight Test System* (SFTS) to develop and build a space laser communication payload that would communicate with an Air Force ground station at White Sands, New Mexico. Because of funding cuts, the program was changed to an aircraft-to-ground station experiment and renamed the *Airborne Flight Test System* (AFTS). Experiments flown in an EC-135 test aircraft in the late seventies under this program led to the first successful incremental flight demonstration in 1981 of transferring 1 Gbps of data from an aircraft to a ground station. The success of the AFTS program led to several other developmental programs during the eighties and nineties. The first orbital partial success took place in 1986 with the Strategic Defense Initiative Organization's (SDIO) Nd:YAG laser radar experiment using hardware originally designed for a space-to-ground and space-to-aircraft lasercom experiment. In late 1992, a successful Earth-to-space transmission demonstration took place from two separate ground sites to the Galileo spacecraft. Other Department of Defense (DoD) funded programs during the eighties and nineties time frame include the *Laser Crosslink Subsystem* (LCS) for space-to-space laser communication crosslink for a geosynchronous satellite system, the *Boost Surveillance and Tracking System* (BSTS) laser cross-link, and the *Follow-on Early Warning System* (FEWS) laser crosslink. Unfortunately, most of these developmental programs were terminated due to funding cutbacks.

Space laser communications is once again being seriously considered as a viable and reliable means of transferring data between satellites, from satellites to terminals on the Earth's surface, or from satellites to aircraft. In particular, NASA in conjunction with the Jet Propulsion Laboratory (JPL) is developing optical ground-to-space links. The *Ground/Orbiter Lasercomm Demonstation* (GOLD) in 1995–96 was the first ground-to-space two-way optical communication experiment. It took place between the Japanese ETS-VI test satellite and the JPL optical ground station in California. Successful uplink and downlink connections were achieved more than 50 percent of the time. They also demonstrated the advantages of multibeam transmission over a single beam for an uplink channel. Another recent NASA/JPL project is the *Optical Communications Demonstrator* (OCD)—a laboratory prototype terminal that is being developed for future NASA missions to enable high-data-rate transmissions from planets and high-Earth orbit satellites to ground [28]. NASA/JPL performed a 46-km horizontal optical link demonstration between two mountaintops in the summer of 2000, using a multibeam beacon comprised of eight laser beams that was launched from a 60-cm telescope. The multibeam beacon signal received by the OCD showed a reduction in scintillation by a factor of four, essentially eliminating beacon fades sensed by the OCD.

In addition to the work being done on laser satcom in the United States, the European Space Agency (ESA) and its Japanese equivalent have been developing experimental systems. Ongoing hardware development efforts include the *Space Intersatellite Link Experiment* (SILEX) sponsored by the ESA. The SILEX program involves the transmission of information from a low Earth orbit (LEO) satellite to one in geosynchronous orbit (GEO). The Japanese program, entitled the *Laser Communication Experiment* (LCE), will eventually lead to a satellite-to-satellite data link similar to that of the SILEX experiment. Also, NASDA is working on satellite-to-ground and satellite-to-satellite communications systems. In particular, NASDA is planning a lasercom experiment with a downlink bit rate of 2.5 Gbps between the International Space Station (ISS) and several ground stations.

Progress in technology development over the past 40 years has finally led to reliable laser sources that can maintain consistent performance under modulation. This was followed by successful advancements in aquisition, pointing and tracking mechanics, and control, which over the years have been perceived as laser satcom's most challenging problems. The vast majority of laser satcom systems currently under development are direct detection systems. Aggressive development of high-data-rate direct detection systems is currently underway in the United States, Europe, and Japan. Coherent detection systems are being developed to a much lesser degree, but may offer a viable alternative for certain applications [29–31].

It is anticipated that the future will see great advancements in the area of laser satcom systems. There are many commercial as well as governmental application areas that can benefit from the laser satcom technology. In general, applications will include relays from LEO satellites to GEO satellites, LEO to ground, GEO to ground, LEO and GEO to aircraft, and aircraft-to-aircraft links. Space-to-space crosslinks are important for the rapid transfer of data from sensor spacecraft to any location around the world. High-data-rate space-to-ground links then permit the collected information to reach a ground station or a high-flying aircraft quickly. In addition, satellite-to-submarine links are feasible as well as large Earth-orbiting receivers capable of high-data-rate transfer of information from deep space mission spacecraft.

Some common types of laser satellite communication channels are cited below with a brief description of primary atmospheric effects:

- *Satellite-ground:* Laser communications to the ground from a satellite are disrupted by the atmospheric turbulence near the ground, but for most of the path the beam passes primarily through free space. Because of this, the beam is very broad by the time it encounters the atmospheric layer. The primary concerns for downlink propagation paths are *scintillations* and *angle-of-arrival fluctuations*.
- *Ground-satellite:* A transmitted laser beam from the ground to a satellite is disrupted by atmospheric turbulence near the ground and, thus, near the transmitter. Because most of the propagation path lies beyond the atmospheric layer, there is a long propagation path in free space that is dominated by free-space diffraction. The primary concerns for an uplink path are *scintillations* and *beam wander*, the latter related to *beam pointing.*
- *Aircraft-satellite and satellite-aircraft:* These two communication paths are similar to the ground-satellite and satellite-ground paths described above. Although the aircraft is above much of the natural atmospheric ground-induced turbulence, aircraft *boundary layer effects* due to platform speed may need to be addressed.

1.5.3 Laser radar systems

RADAR, an acronym for *RA*dio *D*etection *A*nd *R*anging, came into being during the mid thirties. Its principle application was the detection, ranging, and tracking of aircraft. Since that time, radar has become a necessary tool in modern warfare, commercial aircraft traffic control, communications satellite location, and law enforcement applications, among others. With the invention of the laser in 1960, the radar techniques were soon carried over to the optical portion of the electromagnetic spectrum.

Laser radars constitute a direct extension of conventional radar techniques (microwave frequencies) to very short optical wavelengths (including ultraviolet, visible, near-IR, mid-IR, and far-IR). The first optical radar systems were called *LIDAR*, an acronym standing for *LI*ght *D*etection *A*nd *R*anging. This term was later changed to *LADAR* to distinguish it from lidar systems that used noncoherent light. Ladar is an acronym standing for *LA*ser *D*etection *A*nd *R*anging, analogous to that for radar. Laser radars operate on the same basic principles as microwave radars. Because they operate at much shorter wavelengths, laser radars have certain advantages over conventional radars such as higher accuracy and more precise resolution.

All radar waves are of two types—continuous wave (CW) and pulsed. Pulsed radars that sense Doppler frequencies are further called *pulse Doppler radars.* The (temporal) pulse width is often denoted by the symbol τ, and the number of pulses transmitted per second is the *pulse repetition frequency* (PRF) f_R. The reciprocal of the PRF defines the *pulse repetition interval* (PRI), which provides a measure of the period T between the start of one pulse and the start of the next pulse. The *duty cycle* τ/T represents the fraction of time that the radar is actually transmitting. If P denotes *peak power* in the transmitted pulse, the *average power* is defined by $P_{\text{ave}} = P\tau/T$.

The classical theory of pulsed radar performance was developed by Marcum and Swerling [32] for microwave radars. Extension of the classical theory to the optical regime requires some modification to account for the shorter wavelengths in the IR, visible, and ultraviolet (UV) bands. However, as a consequence of shorter wavelengths, laser radars are more susceptible to atmospheric effects like scattering, absorption, and optical turbulence than are microwave radars. This generally restricts the usefulness of laser radars to shorter distances in the lower atmosphere, but this is offset by new capabilities of laser radars over microwave radars such as [25]:

- tactical range and velocity imaging systems
- autonomous missile guidance
- precise aircraft navigation and guidance
- precision fire control
- remote atmospheric sensing

Modern laser radar systems combine the capabilities of radar and optical systems to permit simultaneous measurement of range, reflectivity, velocity, temperature, azimuth, and elevation angle. This target information can be used in a variety of applications to allow *target acquisition, tracking, classification*, and *imaging*. The *velocity* measurement of a laser radar from a moving object is usually disrupted by phase fluctuations induced on the laser signal by the turbulence. Fortunately, the Doppler shift of the signal due to the moving target is ordinarily much larger than the frequency shift due to the turbulence moving through the propagation path. However, the *range* measurement of a pulsed laser radar can easily be corrupted by pulse lengthening due to beam wander, multipath propagation paths, and signal loss due to scintillations.

1.5.4 Other application areas

Below we briefly describe some additional areas of application.

- *Imaging:* Problems associated with imaging through the atmosphere are similar to those associated with beam propagation through the atmosphere. For example, the "dancing" of an image in the focal plane of an imaging system is mathematically similar to the wander of a beam focused at the object by the same optical system.

Among other methods, adaptive optics systems are widely used today to provide turbulence-compensation techniques to improve image quality [33–35]. Such systems can provide a means of sensing atmospherically induced abberations of an optical signal and correct for them in real time by mechanical means.

- *Remote Sensing:* Atmospheric remote sensing concerns the use of an optical wave or laser beam to sense information remotely about the atmosphere or a distant target, including:
  - the detection of the concentration of water vapor in the atmosphere
  - the range-resolved distribution of aerosols and particulates in the atmosphere, including ozone
  - Doppler wind measurements
- *Radio Astronomy:* Long-wavelength radio signals from stars can be corrupted by the interstellar medium in space. The medium has an extremely low density but for the long-wavelength signals and the extremely long propagation paths, the medium causes frequency shifts and scintillations that alter the observations.
- *Space Radio Communications:* Radio communications to spacecraft can be disrupted by the solar wind. This is a wind of charged particles streaming from the sun. The radio waves propagating from a fast-moving spacecraft will pass through the randomly distributed wind and cause random fluctuations on the signal. Radio communications can also be corrupted by fluctuations in the ionospheric layer surrounding the Earth.
- *Random Gravity Waves:* A novel application of propagation theory involves the transmission of electromagnetic waves through an interstellar space characterized by random gravitational fields. Random refractive index fluctuations in this case are directly related to the random gravitational potential.

1.6 A Brief Review of Communication Systems

Communication theory is basically the transmission and reception of information [36,37]. Both FSO and laser radar rely on basic communication principles. Communication systems include common devices like telephone, radio, and television, but also more complicated devices such as those that guide aircraft and spacecraft and those used in laser radar and satellite communication systems. The three basic subsystems of a *communication system*, shown in Fig. 1.7, are listed below:

- *Transmitter*—typically composed of an encoder and modulator. The transmitter prepares the information to be sent, which may be an electrical signal or optical/IR wave. Only visible and IR waves are considered in this text.
- *Channel*—the transmission medium between the transmitter and receiver. The channel includes effects of additive noise, interference, propagation, and distortion, and is the limiting factor in the performance of any well-designed communication system. The channel may include the ionosphere, troposphere, free space, or simply a transmission line. For communication systems of interest to us, the channel is some portion of the atmosphere.
- *Receiver*—typically composed of a demodulator and decoder. The purpose of a receiver is to recover the information sent; thus, it basically reverses the transmitter operations.

A necessary requirement in the design of any communication system is the *bandwidth*, which is a measure of how rapidly the information-bearing portions of the signal can change. Another important parameter in the theory and design of a communication system is the ratio of the average signal power to the average noise power, commonly called the *signal-to-noise ratio* (SNR). All communication systems can be judged on the basis of bandwidth, SNR, and economic (cost) factors.

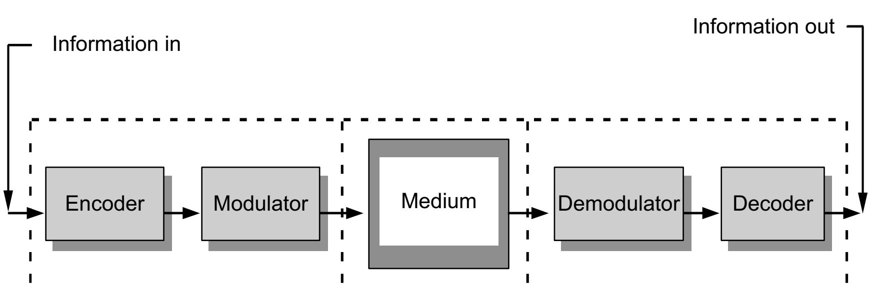


Figure 1.7 A typical communication system.

1.6.1 Direct detection systems

The modulation formats for optical communication systems are quite similar to conventional RF techniques. Thus, like RF systems, techniques for detecting the received signal are numerous, but are broadly separated into two major categories—*direct* (or *incoherent*) *detection* and *coherent detection.*

- *Direct detection:* In direct detection the information is transmitted at baseband and directly demodulated at the receiver back into the transmitted signal (see Fig. 1.8).

A direct detection system has the following characteristics:

- responds only to the instantaneous power of the collected field
- receiving lens focuses the optical signal onto a photodetecting surface
- photodetector converts the focused optical field into an electrical signal for processing

The modulation format for transmitted signal is generally *intensity modulation.* Noise sources present throughout the receiver include:

- background radiation (sun, blackbody, etc.)
- detector noise or shot noise
- circuit and electronic noise after photodetection

If the receiver aperture in the presence of atmospheric turbulence is smaller than the correlation width of the irradiance fluctuations of the received signal, the system behaves essentially like a "point receiver." In this case, turbulence-induced signal fluctuations can be quite deleterious to system performance.

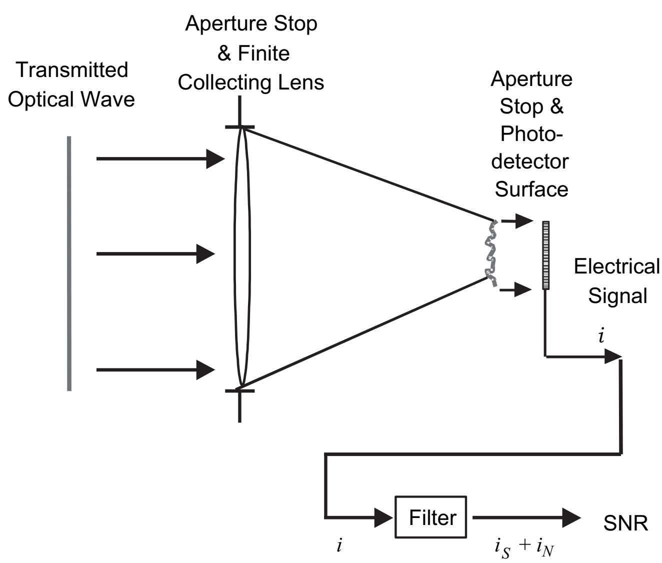


Figure 1.8 Direct detection system.

Increasing the aperture diameter beyond the irradiance correlation width not only increases the average signal level, but decreases the fluctuation level in the received signal (*aperture averaging* effect).

1.6.2 Coherent detection system

- *Coherent detection*: A coherent detector imparts the message onto a carrier signal and uses a local oscillator at the receiver to downconvert the carrier to baseband (homodyne) or to an intermediate frequency (IF) carrier (heterodyne). A typical coherent detection system is shown in Fig. 1.9.

A coherent detector has the following characteristics:

- detects both the amplitude and phase
- involves the addition of the LO signal with the incoming signal before photodetection
- the mixing process is to convert a weak signal to IF in the RF region for improved detection and processing

Also, the modulation format of a coherent detector can include:

- amplitude modulation
- frequency modulation
- phase modulation
- polarization modulation

In coherent detection the noise sources are similar to those for direct detection, but the primary noise source is local oscillator (LO) shot noise, which generally dominates all other noise sources. In the presence of atmospheric turbulence, increasing the receiver aperture size in a heterodyne detection receiver causes a

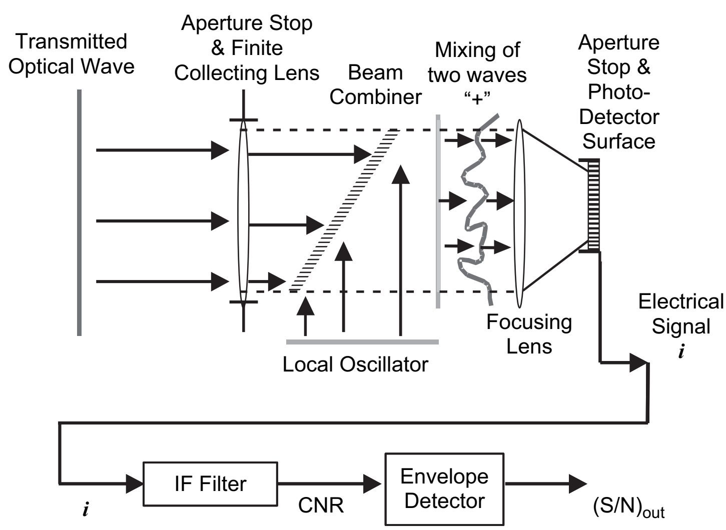


Figure 1.9 Coherent detection system.

decrease in the irradiance fluctuations of the received signal, similar to that of a direct detection system. Unfortunately, the corresponding phase fluctuations limit the effective aperture diameter to essentially that of the *atmospheric coherence width* r_0 (see Chaps. 6 and 14).

1.6.3 Channel models

The transmission medium, or channel, is the limiting factor in the performance of a communication system. In our discussions the channel under consideration is a random medium that may be classified as one of three types.

- *Extended Medium Model*: If the random medium exists everywhere along the propagation path between the transmitter and receiver, it is referred to as an extended medium model (see Fig. 1.10). Propagation environments along most horizontal paths in the atmosphere are of this type. In Fig. 1.11, we illustrate the effect of an extended medium on the irradiance cross section of a beam that has propagated 1500 m.
- *Random Phase Screen Model*: If the random medium is confined to a thin “slab” between the transmitter and receiver, it is referred to as a random phase screen [see Fig. 1.12(*a*)]. For mathematical simplification, the phase screen model has been used for studying scintillation phenomena over many years in such areas as:
    - satellite radio communications through the ionosphere
    - reflection of electromagnetic waves from a rough sea surface
    - laboratory experiments.

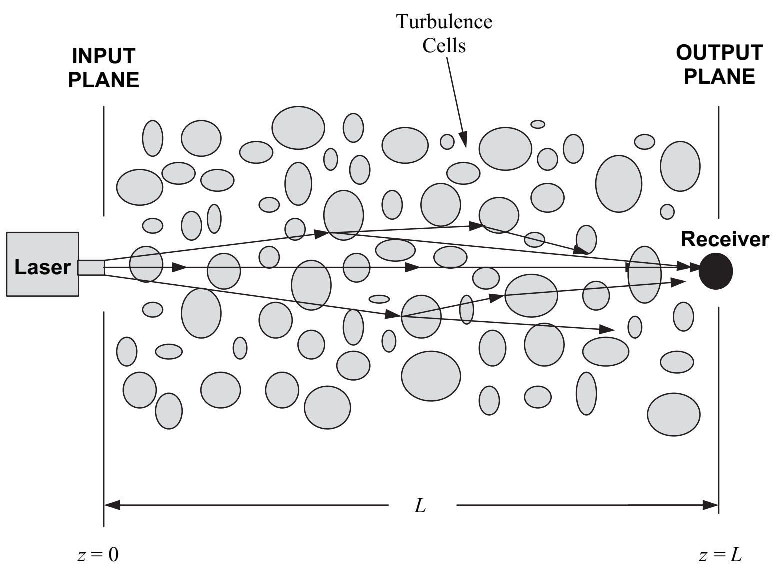


Figure 1.10 Propagation geometry for an extended medium.

(*a*) (*b*)

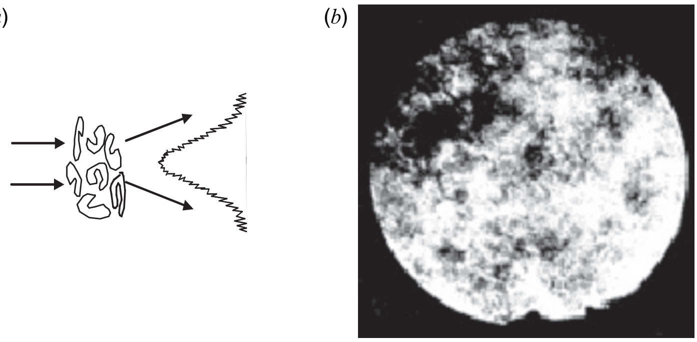


Figure 1.11 (*a*) After passing through a random refractive medium, a laser beam will develop intensity scintillations across its profile. (*b*) Photograph of an intensity beam cross section after propagating 1500 m at a height of 1.5 m above the ground through extended turbulence.

- *Multiple Phase Screen Model*: In some cases there may exist two or more random turbulence layers or "slabs" located between the transmitter and receiver [see Fig. 1.12(*b*)], and these are referred to as a multiple phase screen model.

In Fig. 1.13 we illustrate the irradiance cross section of a beam at various distances behind a random phase screen. The bottom figure corresponds to weak irradiance fluctuations directly behind the phase screen, the middle figure corresponds to moderate irradiance fluctuations in the focusing regime, and the top figure corresponds to the saturation regime of irradiance fluctuations.

1.7 Summary and Overview of the Book

When an optical wave propagates through the atmosphere of the Earth, it experiences distortions caused by small temperature variations related to the sun's heating of the atmosphere and the turbulent motion of the air due to winds and convection. The most well-known manifestation of this phenomenon is the twinkling of stars, observed long before the invention of the laser. Interest in twinkling of stars and quivering of the image of an astronomical object at the focus of a telescope began in the early 1950s. Before that (1941), investigations had begun on the scattering of sound waves by turbulence. Scientific interest in these research areas continues today.

Atmospheric effects on an optical wave can be broadly classified as linear or nonlinear. Linear theory can generally be used when the output power of the laser source is low. But, nonlinear effects such as thermal blooming may arise when the output power is high. Here we assume the output power of the laser source is sufficiently low that linear theory may be used.

The chapter organization of the book consists of three distinct parts: Part I is *Basic Theory* and extends over Chaps. 1–10, Part II is *Applications* and covers Chaps. 11–14, and Part III is called *Related Topics* and extends from Chap. 15 through Chap. 18.

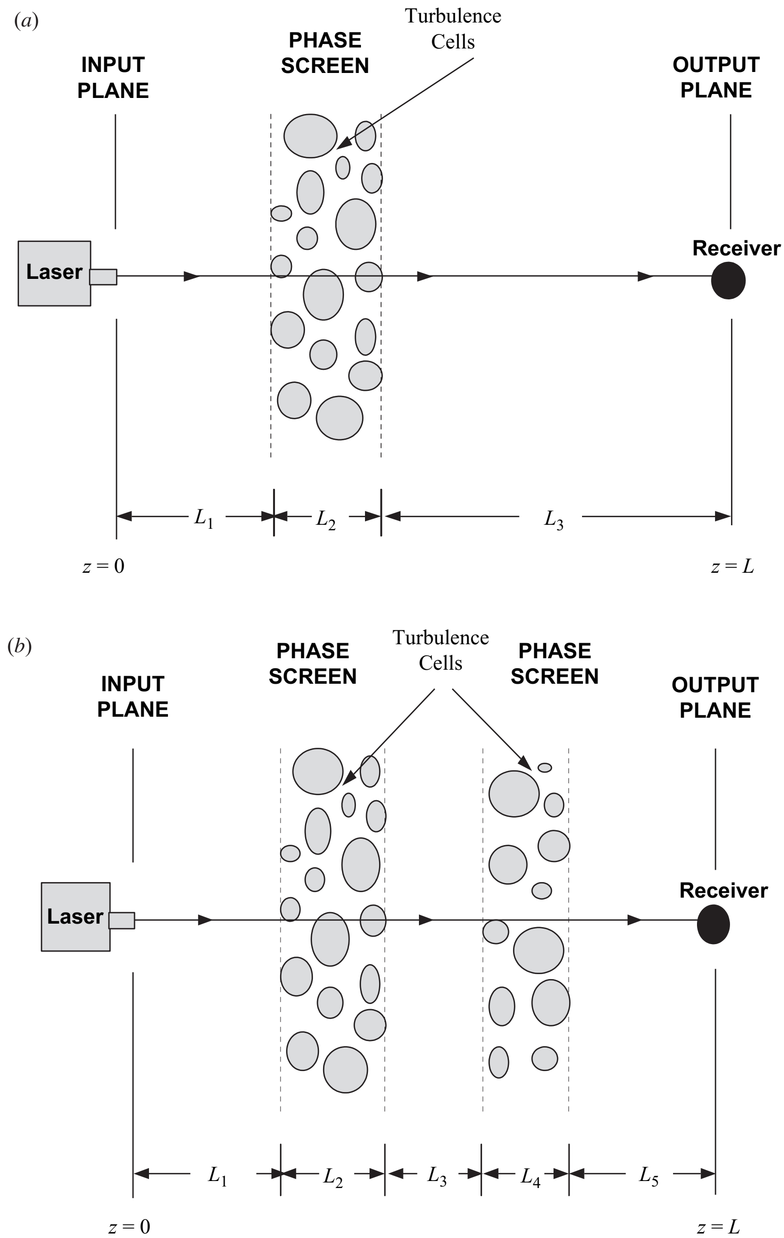


Figure 1.12 Propagation geometry for (*a*) a single phase screen and (*b*) a double phase screen.

Part I: Basic Theory

Chapters 1 through 3 contain background material on optical wave propagation. In particular, Chaps. 2 and 3 present background necessary to understand the statistical behavior of the random medium through which the optical/IR wave is

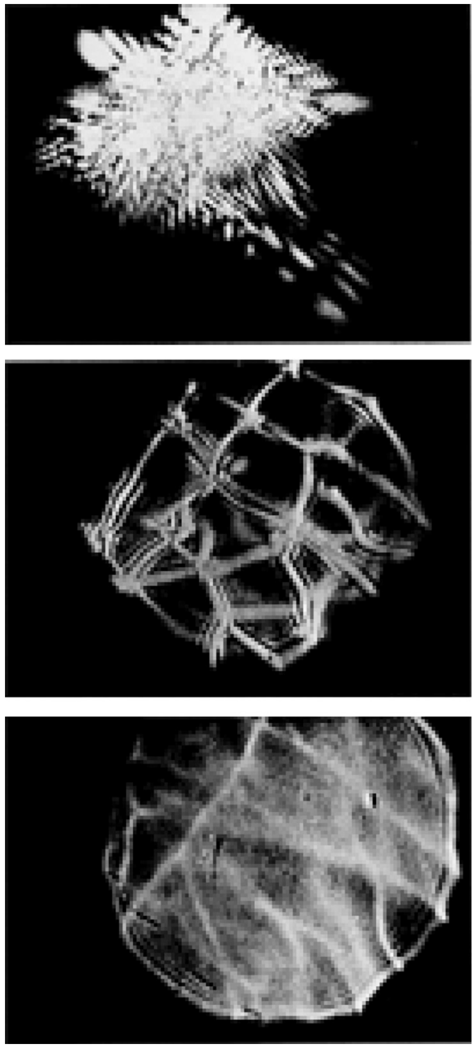


Figure 1.13 Irradiance cross section of beam after passing through a random phase screen, immediately beyond (bottom), further beyond (middle), and far beyond (top).

propagated. Chapter 2 contains a review of the general ideas concerning *random processes and random fields.* Time and spatial domain descriptions of a random process include correlation, covariance, and structure functions. The corresponding frequency or wave number domain description, obtained through Fourier analysis, is provided by the power spectral density. Also discussed is the significance of stationarity in the time domain, or statistical homogeneity and isotropy in the spatial domain. The Riemann-Stieltjes integral representation of a random function is presented as an analog of the Fourier representation of a deterministic signal. In Chap. 3, we begin with a review of the classical *Kolmogorov theory of turbulence* developed specifically for velocity fluctuations.

This review includes the notions of inner scale, outer scale, inertial range, and dissipation range. Key concepts are then extended to temperature fluctuations and finally to index-of-refraction fluctuations, the latter commonly referred to as optical turbulence. Here we discuss the role of the refractive-index structure constant C_n^2 in characterizing the strength of optical turbulence. Models of the spatial power spectrum of refractive-index fluctuations regularly used in theoretical studies include the Kolmogorov $-11/3$ power law spectrum for the inertial range and some that incorporate inner scale/outer scale parameters to extend the validity of the model outside the inertial range.

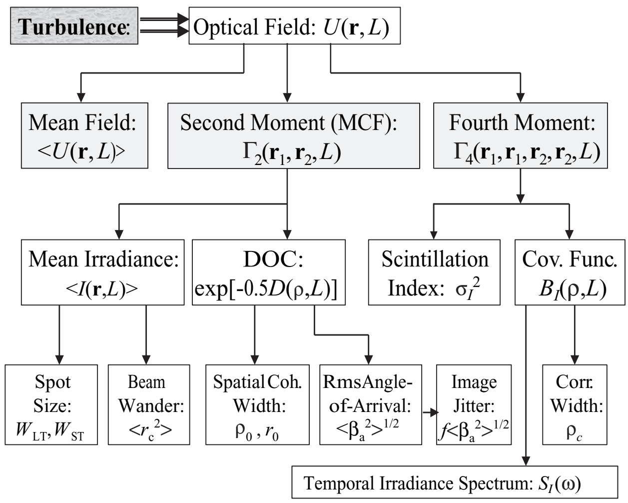
In Chap. 4, we concentrate on the *diffractive properties* of the optical wave model, emphasizing those associated with a simple *Gaussian-beam wave* (TEM_{00}). Significant here is the identification of two pairs of nondimensional beam parameters that characterize the Gaussian beam—one pair describing the beam in the plane of the transmitter and the other pair describing the beam in the plane of the receiver. Each pair forms the real and imaginary parts of a complex quantity directly related to the on-axis complex amplitude of the beam wave, and the two complex quantities are related through a simple inversion mapping. Geometrical interpretations involving each pair of beam parameters are explored in some detail, and higher-order Hermite-Gaussian and Laguerre-Gaussian beam modes are briefly discussed. Last, we introduce the *ABCD* ray-matrix method of analyzing a Gaussian-beam wave propagating through a system of optical elements between the input and output planes. This technique permits the use of a single 2×2 *ABCD* matrix to characterize the entire propagation path.

The well-known *Born* and *Rytov perturbation theories* are introduced in Chap. 5 for wave propagation in a random medium under the assumption of weak irradiance fluctuations. Here we develop important spectral representations for the first-order and second-order Rytov approximations from which all statistical quantities can be deduced in the weak fluctuation regime. The adaptation of the Rytov theory to wave propagation through optical elements characterized by *ABCD* matrices is also presented as well as an embellishment of the Rytov theory to regimes of moderate-to-strong irradiance fluctuations. In addition, we briefly examine the *parabolic equation method* and the *extended Huygens-Fresnel principle*, both applicable under strong fluctuations.

Chapters 6 through 9 provide the development of most of the theory that is used throughout the rest of the text. Hence, to aid the reader in the organization of the material in these chapters, we have provided the flowchart shown below in Table 1.1 that illustrates how various statistical quantities of interest are related to the second-order and fourth-order field moments of the propagating wave.

In Chaps. 6 through 9, we use the spectral representations arising from the Rytov method and extended Huygens-Fresnel principle to develop line-of-sight propagation of an optical wave along a horizontal path. The horizontal path concept is one in which the index-of-refraction structure parameter can generally be treated as constant. In Chaps. 6 and 7, the *mutual coherence function* (MCF) is identified as the general *second-order moment* of the optical/IR field from which the *mean irradiance* and turbulence-induced beam spreading can be deduced.

Table 1.1 Flowchart of Optical Turbulence Effects on the Optical Field



The MCF is also used to describe the loss of spatial coherence of an initially coherent wave. Tractable expressions for the wave structure function and spatial coherence radius are derived for the Kolmogorov power law spectrum, and comparable expressions for other spectrum models are presented in tabular form in Appendix III. Image degradation effects, such as image blurring and image dancing, are briefly discussed and related to equivalent beam degradation effects. Beam wander is examined in terms of the variance of the random displacement of the short-term beam spot size. The combination of short-term spot size and beam wander variance give rise to the long-term spot size. Chapter 6 is restricted to conditions of weak irradiance fluctuations but Chap. 7 examines the MCF and related topics under strong fluctuations. Specializations of the *fourth-order moment* of the field treated in Chaps. 8 and 9 leads to the *covariance function* and *scintillation index*, the latter quantity important in the analysis of channel fading. A tractable expression for the scintillation index of a Gaussian-beam wave is developed for the Kolmogorov spectrum, and similar expressions based on other spectrum models are placed in tables in Appendix III. Use of the frozen-turbulence hypothesis permits the development of the temporal covariance function and the related temporal irradiance spectrum. Also included in Chap. 8 is a short treatment of phase fluctuations, which features the phase variance, phase structure function, and the covariance function. We limit results in Chap. 8 to weak irradiance fluctuations and introduce a theory of scintillation in Chap. 9 that extends results from weak fluctuations into the saturation regime.

The use of *ABCD ray matrices* discussed in Chap. 4 for free-space propagation of an optical wave through a system of cascaded optical elements is reintroduced in Chap. 10 for the case when the system operates in the presence of atmospheric turbulence. Attention is confined to optical systems displaying circular symmetry, but the formulation is general enough to permit placement of the random medium at various locations along the path. Examples featuring only one optical element are presented for calculating the reduction in scintillation known as *aperture averaging* that is achieved with the use of large receiver apertures. Separate treatment is given for plane waves, spherical waves, and Gaussian-beam waves, and results are valid under all conditions of irradiance fluctuations. Extension of the results to systems with N optical elements between source and receiver is briefly discussed.

Part II: Applications

FSO *communication systems* are studied in Chap. 11 in connection with direct detection receivers. In particular, we illustrate the effect of aperture averaging as a means of reducing the fade probability through a reduction in scintillation. The use of spatial diversity techniques is discussed and additional fade statistics, including the mean fade time and bit error rate, are developed for consideration of both detector noise and atmospheric turbulence effects. The analysis is extended in Chap. 12 to slant paths involving *laser satellite/aircraft communications.* Our treatment includes the cases of uplink and downlink propagation paths between a ground/airborne transmitter/receiver and a satellite transmitter/receiver. Several models of C_n^2 as a function of altitude are introduced, but the Hufnagle-Valley model is the one selected for our calculations. We concentrate largely on fade statistics associated with both uplink and downlink channels of a satellite in geosynchronous orbit. In particular, we examine the fractional fade time, expected number of fades, and the mean fade time expected if a fade should occur. In addition, we present expressions for the spatial coherence radius, angle-of-arrival fluctuations, isoplanatic angle, and root-mean-square (rms) beam wander.

The *ABCD* method of Chap. 10 is extended to *double-pass problems* associated with *laser radar* applications in Chap. 13 where we discuss the enhanced backscatter effects associated with an optical wave propagating twice through the same random inhomogeneities in opposite directions. Expressions are developed for the mean irradiance, spatial coherence radius, and scintillation index for both bistatic and monostatic laser radar configurations. A brief treatment of *imaging systems* is presented in Chap. 14. Here we introduce performance measures such as Fried's atmospheric coherence width and the Strehl ratio. The use of Zernike ploynomials in developing various spatial filters for use in adaptive optics is also discussed.

Part III: Related Topics

In Chap. 15, we extend the development of Chaps. 6 and 8 to the notion of a thin *random phase screen*, modeled as a limiting case of extended turbulence confined to a thin slab between the transmitter and receiver. Derived statistics for the phase screen model in the case of a Gaussian beam are shown to depend critically upon the location of the phase screen between transmitter and receiver. The use of a thin phase screen to model a diffuser placed at the transmitter aperture of a FSO communication system to produce a *partially coherent beam* is introduced in Chap. 16. Such a technique is shown to reduce bit error rates over that of a coherent beam under suitable conditions. The thin phase screen model is also used to model a rough target in a laser radar system.

In Chap. 17 we examine other beam shapes such as higher-order *Hermite Gaussian beams* and *Laguerre-Gaussian beams* propagating through optical turbulence. The analysis here is limited to beam spreading. We also examine an *annular beam* but discuss its scintillation characteristics in addition to beam spreading. Last, in Chap. 18 we briefly look at the propagation characteristics of a short pulse.

Because exact analytic results often involve higher-order transcendental functions of mathematics, we include a brief introduction in Appendix I to some of the special functions that appear in our analysis. In addition, a short table of relevant integrals is given in Appendix II for easy reference. Tables of derived formulas for the wave structure function, spatial coherence radius, and scintillation index are provided in Appendix III for several power spectrum models of refractive-index fluctuations.

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NOTE: The following *field guide* is a handy reference summary of much of the material contained within this textbook.

L. C. Andrews, *Field Guide to Atmospheric Optics* (SPIE Press, Bellingham, 2004).