# Atmospheric Propagation Effects Relevant to Optical Communications

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*A number of atmospheric phenomena affect the propagation of light. This article reviews the effects of clear-air turbulence as well as atmospheric turbidity on optical communications. Among the phenomena considered are astronomical and random refraction, scintillation, beam broadening, spatial coherence, angle of arrival, aperture averaging, absorption and scattering, and the effect of opaque clouds. An extensive reference list is also provided for further study. Useful information on the atmospheric propagation of light in relation to optical deep-space communications to an earth-based receiving station is available, however, further data must be generated before such a link can be designed with committed performance.*

## I. Introduction

There is considerable interest in the development of optical communication systems for space applications. Use of optical frequencies will result in very high gain antennas as well as potentially enormous channel capacities. The interaction of electromagnetic waves with the atmosphere at optical frequencies is stronger than that at microwave frequencies. Hence, it is important to show that laser communication systems are capable of operating within the atmosphere with predictable statistics for availability and reliability.

There are several phenomena that affect the manner of light propagation through the atmosphere. A laser beam propagating through the atmosphere can quickly lose its energy due to molecular scattering, molecular absorption, and particulate scattering. Refractive turbulence may also contribute to energy loss; however, it mainly degrades the beam quality, both by distorting the phase front and by randomly modulating the signal power. The presence of opaque clouds may occlude the signal completely, rendering the line-of-sight communication link useless. The problems described above are quite distinct from each other, and the difficulties presented by each of these obstacles need to be studied and understood independently.

The next section will identify and describe various ingredients of an atmospheric model that must be studied in some detail before a coherent view of optical communications through the atmosphere can be developed. Sections III and IV describe the optical consequences of the model atmosphere for the propagation of laser beams. The focus will be on those results that are especially relevant to optical communications.

Also suggested will be methods and strategies to minimize the adverse effects of the atmosphere on optical communication links. Section V then concludes the discussion by putting the future of optical communications research in perspective.

## II. Description of the Atmosphere

The atmosphere is a dynamic system of considerable complexity. It is obvious that the entire set of phenomena that characterizes the atmosphere and its interaction with laser radiation needs to be understood before useful optical systems can be designed for operation in the atmosphere. Various components of the atmosphere will be considered in the subsections that follow.

The atmosphere is usually divided into a number of layers based on its mean temperature profile. From the ground to an altitude of 10 to 12 km, the mean temperature decreases steadily. This lowest layer is called the troposphere. For the next layer, which is called the stratosphere, the temperature increases with altitude. Unlike the troposphere, the air in this layer is very stable, and turbulent mixing is inhibited in the stratosphere due to the inverted temperature profile. Low turbulence and the absence of rainfall account for the long residence time of aerosols and other particulate matter in the stratosphere. Figure 1 shows the mean temperature of the atmosphere as a function of altitude at a 45-degree north latitude during July [1].

### A. Chemical Composition

Table 1 gives a list of dry clear-air chemical components of the atmosphere near sea level [2]. The water vapor content of the atmosphere in the troposphere is highly variable and ranges from 1 to 3 percent in concentration. A number of minor constituents, all influencing turbidity at optical frequencies, are also found in the atmosphere in varying concentrations. Some of these constituents are aerosols, oxides of carbon, compounds of sulfur and nitrogen, hydrocarbons, and ozone.

### B. Turbidity

For the present discussion, turbidity is defined to consist of all particulate matter which absorbs and scatters light. For the study of optical beam propagation, atmospheric turbidity can be roughly divided into two classes. The first includes gas molecules, aerosols, light fog and haze, and thin cirrus clouds. The attenuation or extinction loss of light energy from the laser beam for this category is generally due to Rayleigh and Mie scattering. The direct beam retains a fair percentage of its energy even after traveling through the entire atmosphere. The second class of turbidity consists of opaque clouds and of dense fog and haze. Scattering losses for this case are very high; most of the beam energy appears as diffused light. For optical communications, the strategies to overcome the problems posed by the two categories are quite different and will be discussed later.

### C. Astronomical Refraction

The index of refraction, which depends on the density of the atmosphere, decreases with height above ground. Light arriving at the top of the atmosphere on a slant path bends downward, which causes the observed zenith distance of the transmitter to be different from the true zenith. The angular distance between the true and the apparent zenith angle of the object, referred to as the terrestrial refraction angle, can be obtained by applying Fermat's principle to the atmospheric profile. Garfinkel [3] has prepared a computer program to compute the magnitude of the refraction angle for any atmospheric profile, including the *U.S. Standard Atmosphere* [4] for all apparent zenith angles. For a grazing ray at sea level, the terrestrial refraction angle can be as large as 10 mrad [5].

The refractivity, $N$, of the atmosphere for optical wavelengths can be approximated by the relation [5]

$$N \approx 79 \times 10^6 (n-1)P/T \tag{1}$$

where $n$ is the refractive index of the atmosphere, $P$ is the atmospheric pressure in millibars, and $T$ is temperature in kelvins. For a detailed analysis of optical refractive index and more accurate formulas, see [6]–[8]. $N$ is about 290 at sea level [5]; it varies about 10 percent with wavelength over the visible range and by 0.5 percent with humidity [9].

### D. Random Refraction

The average profile of the atmosphere, which follows from the meteorological conditions, determines the regular or mean refraction of light beams. Random or stochastic refraction is due to the motion of inhomogeneities in the air. It is this type of refraction that causes the light rays to wander in time and degrades their spatial as well as temporal coherence. Stochastic refraction may impose some special requirements on the pointing and tracking mechanisms of optical systems. It may also restrict the rate of data transmission on optical channels.

Systematic astronomical observations of the refraction angle have led to the discovery of several types of random oscillations. For most practical purposes, they can be put in two classes: (1) oscillations with frequencies of 1 Hz or less; and (2) rapid oscillations with frequencies of 10 Hz or higher. High-frequency oscillations will be discussed in detail in the following section.

Slow oscillations arise due to general shifts of weather patterns and air masses in time. Such oscillations cause the image

to drift slowly with amplitudes attaining several arc seconds [9]. Beckmann [10] and Hodara [11] have observed random refraction along horizontal paths, noting a slow drift of laser beams over paths of 5 to 15 km at a rate of several microradians per hour. Another study estimates that inhomogeneities in the atmosphere have a scale length of 10 to 40 km and that the fluctuations of the beam direction are as high as 75 $\mu$rad [9]. Lese [12], using a 0.9-m telescope, has measured angular deviations with a mean value of 3 $\mu$rad for zenith angles of less than a radian for the entire atmosphere.

## E. Clear-Air Turbulence

Refractive turbulence of the atmosphere is caused by rapid, small-scale spatial and temporal fluctuations in temperature (on the order of 0.1 to 1.0 K). While the deviations of the refractive index from their average values are very small (a few parts per million), the cumulative effect of such inhomogeneities over large distances of practical interest can be quite significant.

Turbulence results from disordered mixing of air in the atmosphere. A flow becomes turbulent when the Reynolds number, $Re = vL/\mu$, for a flow process exceeds a critical value. Here, $v$ is a characteristic flow velocity, $L$ is some scale size of the flow process, and $\mu$ is the kinetic viscosity of the fluid. For $L = 2 - 10$ m, $v = 1 - 5$ m/s, and $\mu = 15 \times 10^{-6}$ m$^2$/s, the Reynolds number is on the order of $10^6$. Such large Reynolds numbers, which are typical of the atmosphere, usually correspond to fully developed turbulent flow.

The kinetic energy of turbulence is usually introduced by wind shear or convection from solar heating at scale sizes of the inhomogeneities in the atmosphere, $L \geqslant L_0$, where $L_0$ is called the outer scale. The kinetic energy of large-scale motions characterized by the outer scale is transferred to increasingly small-scale inhomogeneities by turbulent means. When the Reynolds number, which depends on the scale size of motions, becomes small enough, the mechanism for dissipation of energy becomes predominantly viscous rather than turbulent. This transition takes place for a scale size $l_0$, which will be called the inner scale of the turbulent flow. Typically, $l_0 \sim 1 - 10$ mm and $L_0 \sim 10 - 100$ m in the troposphere; close to the earth's surface, $L_0$ can be approximated by the height from the ground.

The flow for scale sizes L, where $l_0 \leqslant L \leqslant L_0$, is then strongly turbulent, with velocity gradients occurring in all possible directions randomly in time and space. For the present purposes, we may view the atmosphere to be composed of vortices or blobs of homogeneous fluid of sizes between $l_0$ and $L_0$, which have dissimilar temperatures and pressures from their neighboring vortices, and which are mixing chaotically. It is necessary to use stochastic methods to explain and interpret atmospheric turbulence.

Modern understanding of atmospheric turbulence is based on the Kolmogorov–Obukhov theory. The range of applicability of their theory, referred to as the inertial range, is between the scale sizes $l_0$ and $L_0$. Tatarski based his work on their theory to obtain results relevant to the propagation of electromagnetic waves through the turbulent atmosphere. The refractive index $n(r)$ of the atmosphere can be expressed as

$$n(r) = E[n(r)] + n_1(r) \tag{2}$$

where $E[\cdot]$ represents ensemble averaging, $n_1$ is the refractive index fluctuation with $E[n_1(r)] = 0$, and $E[n(r)] \simeq 1$ for the atmosphere. The characteristics of the fluctuation may be expressed by a structure function which obeys the Kolmogorov–Obukhov 2/3 law:

$$D_n(r) = E[|n_1(r+r_1) - n_1(r_1)|^2] = C_n^2 r^{-2/3} \tag{3}$$

where the structure constant $C_n$ represents the strength of turbulence. Typically the values of $C_n$ range from $10^{-9}$ for weak turbulence to $10^{-7}$ for strong turbulence. For a more complete account of turbulence spectrum, the refractive structure constant and its relation to the temperature structure constant, see [13] - [16].

Extensive experimental data available today confirm the validity of theoretical results fairly well for the atmospheric layers of altitudes higher than 50 m. For heights lower than 50 m during daytime, the shape of the structure constant is better approximated by $C_n(z) \sim r^{-4/3}$ [9].

For heights greater than 3 km above sea level, the Hufnagel model provides a good approximation for the refractive index structure constant [17] - [22]. According to the model, $C_n^2(z)$ may be expressed as

$$C_n^2(z) = 2.72 \times 10^{-16} \left\{ 3V^2 \left(\frac{z}{10}\right)^{10} \exp[-z] + \exp\left[-\frac{z}{1.5}\right] \right\} (m^{-2/3}) \tag{4}$$

where $V$ is the wind speed in meters per second and $z$ is the altitude in kilometers. Measurements by Barletti et al. [23] and Vernin et al. [24] show that for $z \geqslant 4$ km, the data are nearly independent of the site location and agree quite well

with the Hufnagel model. The data also indicate little variation in the value of the structure constant with seasons.

## III. Effects of Turbulence on Optical Beams

Most studies, after Tatarski, employ the hypothesis of "frozen" turbulence to model optical propagation through the atmosphere. The approximation consists of assuming that the temporal variations at any point result from a uniform, cross-beam motion of the atmosphere as a whole due to prevailing winds. The changes in the internal structure of the atmosphere due to evolution of turbulence in time are neglected.

Several mathematical techniques, including diagrammatic methods [25]-[31], coherence theory [32]-[34], Markov approximation [13], [35]-[37], and others [38], [39], have been used to solve the wave equation for the propagation of light in order to study the effects of turbulence. Most of these techniques are equivalent and yield comparable results, which will be reviewed in the following paragraphs.

### A. Scintillation

Stellar scintillation is a well-known phenomenon. Turbulence causes fluctuations in the intensity of a light wave by redistributing its power spatially in time. The strength of scintillation can be measured in terms of the variance of the beam amplitude or its irradiance at a point. Theoretical investigations have led to the prediction that the log-amplitude, $\chi = \ln[A/A_0]$, where $A$ is the amplitude and $A_0$ is a normalization factor, has a Gaussian distribution. Also Gaussian is the distribution for the log-intensity or the log-irradiance. Other methods point to a Rice–Nakagami distribution for the amplitude $A$ [40]-[42]. For small variances in $\chi$, the difference between the two is small. However, the solutions are valid when the variance of $\chi$, $\sigma_\chi^2 \leqslant 0.5$; i.e., the solutions hold for weak turbulence only. The restriction is quite stringent: for horizontal paths near the ground, where the turbulence is strong, the limit may be reached over path lengths of about 1 km. Since $C_n^2$ decreases rapidly with height above the ground, the problem of optical propagation through the whole atmosphere may still remain amenable to weak turbulence methods for zenith angles of less than a radian. Experimental data seem to favor the log-normal distribution for the amplitude and the irradiance in the weak turbulence region. Theoretical results for strong turbulence are scarce and quite controversial [26]-[31], [33], [34], [37], [39], [43]-[61].

For weak turbulence, the variance in log irradiance, which is the usual parameter that is measured experimentally, can be simply related to the calculated log amplitude by

$$\sigma_{\ln I}^2 = 4\sigma_\chi^2 \tag{5}$$

It can be shown from Tatarski's work that

$$\sigma_{\ln I}^2 \simeq 2.24 k^{7/6} (\sec\theta)^{11/6} \int_0^Z C_n^2(z) z^{5/6}\, dz \tag{6}$$

where $\theta \leqslant 1$ rad is the zenith angle, $k = 2\pi/\lambda$ is the optical wave number, and $Z$ is the altitude of the source. For larger angles this result may not be very useful as scintillation effects move into the strong turbulence regime. Equation (6) above is insensitive to small values of $z$ due to the $z^{5/6}$ factor in the integrand, and most of the intensity fluctuation effects come from higher altitudes. This justifies the use of the Hufnagel model, which Yura and McKinley [62] have employed to obtain the following result for log-irradiance variance:

$$\sigma_{\ln I}^2 \simeq \left[7.41 \times 10^{-2} \left(\frac{V}{27}\right)^2 + 4.45 \times 10^{-3}\right] \lambda^{-7/6} (\sec\theta)^{11/6} \tag{7}$$

where $\lambda$ is the wavelength in micrometers and $V$ is wind speed in meters per second. Wind speeds at higher altitudes seem to be quite stable diurnally as well as seasonally and do not differ much from site to site. For Maryland, the wind speed appears to be normally distributed with a mean value of 27 m/s and a standard deviation of 9 m/s.

The wavelength dependence of scintillation is apparent from observations of stars near the horizon, where the turbulence is strong. The wavelengths at small elevation angles are decorrelated enough that the stars seem to scintillate with different colors at different times. The effect is much smaller for stars higher in the sky. Quantitative studies of this effect show that the correlation of intensity fluctuations drops to about 0.6 for wavelengths differing by 50 percent [5].

### B. Beam Broadening

Consider a Gaussian beam of size $W_0$ and beam-axis intensity $I_0$ at the transmitter. Its intensity at distance $z$ in free space is given by [63] as

$$I(z,\rho) = I_0 \left(\frac{W_0}{W_f}\right)^2 \exp\left[-\frac{2\rho^2}{W_f^2}\right] \tag{8}$$

where $\rho$ is the transverse distance from the beam and $W_f$, the beam size at $z$ for a collimated beam, is

$$W_f^2 = W_0^2 + \left(\frac{2z}{kW_0}\right)^2 \tag{9}$$

For large distances $z$, the beamwidth $W_t$ in the turbulent medium is given by

$$W_t^2 = W_f^2 + 4.38 C_n^2 l_0^{-1/3} z^3 \tag{10}$$

and the average intensity, $E[I]$ on the beam axis is

$$E[I] = \frac{W_0^2 I_0}{W_t^2} \tag{11}$$

where it is assumed that the beam propagates without loss of power, i.e., the backscattering and absorption are negligible for clear air. A more complete description of both short- and long-term behavior of beam spreading can be found in [59] and [64].

## C. Spatial Coherence

Loss of spatial coherence across a light beam is another important effect of clear-air turbulence. Refractive-index inhomogeneities of relatively larger scale sizes produce random phase fluctuations which degrade coherence of the propagating wavefront. Kon and Tatarski [65], Schmeltzer [66], and Ishimaru [67] have studied the problem in detail and have obtained expressions for the structure function of the phase fluctuations, $D_s(\rho_1, \rho_2)$, which is defined to be

$$D_s(\rho_1, \rho_2) = E[|s(\rho_1) - s(\rho_2)|^2] \tag{12}$$

where $\rho_1$ and $\rho_2$ are position vectors in the plane of observation across the beam and $s(\cdot)$ is the phase at that point. For weak turbulence, [9] gives a simple result for the phase structure function

$$D_s(0,\rho) = 2.91 b_1 C_n^2 k^2 z \rho^{5/3} \tag{13}$$

where the value of $b_1$, a constant, ranges from 1.0 for a plane wave to 0.375 for a spherical wave.

The correlation in phase between two points $\rho_1$ and $\rho_2$ on the wavefront degrades with the distance $\rho = |\rho_1 - \rho_2|$. For a plane or a spherical wave, the degree of coherence can be expressed as

$$\gamma(z,\rho) = \exp\left[-\left(\frac{\rho}{\rho_0}\right)^{5/3}\right] \tag{14}$$

where $\rho_0$ is the phase coherence radius and is given by

$$\rho_0 = (b_2 C_n^2 k^2 z^2)^{-3/5} \tag{15}$$

where $b_2$ = 1.45 (0.55) for a plane (spherical) wave. When $\rho \geqslant \rho_0$, the random phase angle difference is larger than $\pi$, and the wavefront is assumed to have lost its spatial coherence.

## D. Angle of Arrival

Fluctuations in the angle of arrival of a signal at the receiver aperture are a consequence of random phase distortions due to turbulence. The phase difference $\Delta s$ across a receiver aperture of diameter $d$ can be approximated by

$$\Delta s \simeq kd \sin\alpha \simeq kd\alpha \tag{16}$$

where $\alpha$ is the random angle of arrival. The variance of the angle of arrival can be written as

$$E[\alpha^2] = \sigma_\alpha^2 = \frac{E[(\Delta s)^2]}{k^2 d^2} = \frac{D_s(0,d)}{k^2 d^2} \tag{17}$$

Using Eq. (13), the variance in angle of arrival can be computed for the weak turbulence case.

## E. Aperture Averaging

The scintillation statistics discussed above are true for a point observer. If the receiver has a non-zero aperture diameter, the observed effect of scintillation will be the spatially averaged value of $\sigma_{\ln I}^2$ over the entire collecting surface. The strength of received intensity fluctuations is found to decrease with increasing aperture size. This effect, known as aperture smoothing, has been observed experimentally [68], [69]. For weak turbulence, the smoothing effect continues to be pronounced until the diameter of the aperture becomes as large as the Fresnel zone, i.e., $(\lambda z)^{1/2}$, after which it saturates. In the case of strong turbulence, the critical diameter is on the order of the transverse spatial coherence parameter of the incoming beam, which is usually much smaller than the Fresnel zone.

## F. Other Effects

Refractive turbulence may also produce depolarization of light and temporal stretching of optical pulses. Calculations by Strohbehn and Clifford [70] show that average power in the depolarized component is about 160 dB smaller than that of the incident beam. Attempts to measure depolarization with an accuracy of 45 dB have yielded a negative result [71]. Indeed,

most theoretical studies of clear-air turbulence neglect the polarization term in the wave equation to simplify calculations.

Light pulses arrive at the receiver with variable path delays as they travel through spatially different parts of the turbulent atmosphere [72] - [77]. Calculations show that temporal stretching of pulses is typically about 0.01 picosecond for the entire height of the atmosphere.

We find that the magnitude of both of these effects is negligibly small, and consequently their effects on optical communications can be ignored. It must be noted, however, that the effects can be much stronger when scattering due to turbid constituents of the atmosphere is considered. This aspect of the problem will be discussed in a later section.

### G. Optical Communications in Turbulence

For communications from an exoatmospheric laser source in deep space to an earth-bound receiver (downlink), the Fresnel zone size of the beam in the atmosphere will be much larger than the scale size $L$ of the inhomogeneities. The main effects of turbulence on the signal for this configuration will be beam spreading, scintillation, and loss of spatial coherence. For earth–space optical communications (uplinks), with the optical transmitter residing inside the atmosphere, the Fresnel zone size will be much smaller than $L$, making beam wander and fluctuations in the angle of arrival the principal factors contributing to signal degradation.

Scintillation produces both temporal and spatial intensity fluctuations at the receiving aperture, resulting in power surges and fades. The typical duration of scintillation-induced temporal fades is on the order of a few milliseconds [78]. The probability of fade events for given fade levels, as well as the duration of such fades, is described in [62] and [78]. It is shown there that fade values of 10 dB or larger are observed 12 percent of the time for worst-case turbulence (1 percent of the time for weak turbulence). A brute force approach may be used to overcome fades produced by temporal scintillation. Yura and McKinley [62] provide a worst-case scintillation fade analysis. With this approach, a link margin of 10 dB will be necessary for the system to work properly 99 percent of the time. However, the situation in reality is not this bad for ground receivers [79], [80]. The results given above refer to a point receiver, whereas actual receivers have a non-zero size. Aperture averaging reduces the probability of fades. Yura and McKinley [80] have obtained an engineering approximation for the magnitude of this effect on ground-based receivers. The factor $A$ by which the irradiance variance is reduced due to aperture averaging is given by

$$A \simeq \left[1 + 1.1\,(D^2/\lambda h_0 \sec\theta)^{7/6}\right]^{-1} \tag{18}$$

where $D$ is the aperture diameter, $\theta$ is the zenith angle, $\lambda$ is the laser wavelength, and $h_0 \sim 10$ km is the scale height of the atmosphere. For $\lambda = 1\ \mu$m, $D = 1$ m, and a scale height of the atmosphere $h_0 = 10.3$ km, the aperture averaging factor $A$ becomes $4.3 \times 10^{-3}$. It should be noted here that the advantage of aperture averaging is not available for uplink applications, as the phase coherence radius in this case is much larger than the probable receiving aperture on a spacecraft.

A number of phase compensation techniques to remove turbulence-induced tilt have been discussed in the literature [81] - [88]. A rigorous calculation of tilt correction on axial beam intensity is provided in [89] - [91]. Dunphy and Kerr [86] have obtained a simplified approximate expression for this effect. For path length in turbulence, $z \leqslant kd^2$, where $d$ is the transmitter aperture diameter, they find

$$E[I] = \left(\frac{d_e}{16z}\right)^2 \left\{(kd_e)^{-2} + \left[1 - C\left(\frac{d_e}{r_0}\right)^{-1/3} (kr_0)^{-2}\right]\right\}^{-1} \tag{19}$$

where the effective diameter $d_e = d$ for a uniformly illuminated circular beam cross-section, but for a Gaussian profile $d_e$ is set equal to $2d$. $C = 0$ if there is no tilt correction, and $C = 1.18$ when tilt correction is included. Also, $r_0 = 2.098\,\rho_0$ is Fried's spatial coherence diameter. Furthermore, the above result is true when $d_e/r_0 > 2$. The largest improvement in the received intensity occurs when $2 \leqslant d/r_0 \leqslant 5$. Whereas theoretical calculations predict an improvement of about 5 dB, measured data show that the improvement can be as high as 8 dB [86].

## IV. Turbidity Effects on Beam Propagation

Atmospheric constituents in the form of gases and particulates absorb and scatter light. Thus, the design of successful optical systems has to contend with atmospheric turbidity and must account for the diminished direct-beam energy as light travels through the atmosphere.

### A. Absorption and Scattering

The only notable effect of molecular absorption is to take away some of the energy from the laser beam [92]. The beam irradiance $I$ as the light travels a distance $Z$ through the atmosphere can be written as

$$I = I_0 \exp\left[-\int_0^Z \gamma_a(z)\,dz\right] \tag{20}$$

where $I_0$ is the irradiance at $z = 0$, and $\gamma_a(z)$ is the absorption coefficient at position $z$. The argument of the exponential in the above equation is known as optical depth or optical thickness.

Light is absorbed when the quantum state of a molecule, characterized by its electronic, vibrational, or rotational energy, is excited from a lower to a higher state. The absorption cross section has a Lorentzian shape [93] that peaks at the molecular transition energy. For each transition line, one needs to know the peak frequency, the width, and its total absorption cross section. The widths of these lines are typically on the order of $10^{-5}$ nm. However, Doppler and pressure broadening, which result from the thermal motion of molecules and molecular collisions, respectively, lead to much larger Gaussian-shaped absorption lines. Therefore, to obtain the total absorption coefficient at a particular frequency, one must calculate the line shape factor, including temperature and pressure effects as well.

There are a number of texts on spectroscopy and catalogs of line parameters. The High Resolution Transmittance (HITRAN) program, one of the most complete compilations of such data, was developed at the Air Force Geophysics Laboratory (AFGL). The compilation gives various line parameters for almost 350,000 lines over a spectral region from the ultraviolet to millimeter waves [94] - [100].

For typical optical calculations, however, the source and receiver bandwidths will be much larger than the resolution provided by the HITRAN database. Another database, called the Low Resolution Transmission (LOWTRAN) program, which is suitable for optical communication needs, has also been developed by AFGL. The LOWTRAN codes calculate molecular absorption from 0.25 to 28.5 $\mu$m [101] - [106]. They also calculate extinction due to molecular and aerosol scattering. These codes have been used extensively, and a number of comments on their use have been published [107] - [114]. A typical LOWTRAN calculated plot, shown in Fig. 2, is presented in [114] for space-to-ground light transmission under hazy conditions. Note that it includes the effects of molecular and aerosol scattering in addition to molecular absorption.

Since the size of air molecules is much smaller than optical wavelengths, the scattering of light by molecules falls into the Rayleigh regime. The main effect on a beam of light, as in the case of molecular absorption, is extinction of the beam. A relation similar to Eq. (20) above can be defined by replacing the absorption coefficient by the Rayleigh scattering coefficient, $\gamma_{sr}(z)$. The argument of the exponential now gives the optical depth of the atmospheric path due to molecular scattering. The scattering coefficient for a gas with refractive index $n$ is given by [115]

$$\gamma_{sr} = \frac{8\pi^3 (n^2 - 1)^2}{3N_m \lambda^4} \frac{6 + 3\delta}{6 - 7\delta} \tag{21}$$

where $N_m$ is the number of molecules of the gas per unit volume, $\lambda$ is the optical wavelength, and $\delta$ is the depolarization factor of the scattered radiation. According to recent measurements, $\delta = 0.035$ [116]. By adding contributions from the constituent gases in the air, the total molecular scattering coefficient for a given atmospheric profile can be computed. Tabulated values for various vertical paths are provided by Elterman [117] - [118]. As mentioned earlier, molecular scattering effects have been included in the LOWTRAN computer codes.

Scattering by aerosols, light fog and haze, and thin clouds generally falls into the Mie category. The size of the scatterers in this case is between 0.01 to 10.0 $\mu$m, comparable to the optical wavelengths under consideration. A relation analogous to Eq. (20) defines the Mie scattering extinction coefficient, $\gamma_{sm}$, and the relevant optical depth. The calculation of the Mie scattering coefficient is not a simple task. The size, concentration, and shape of Mie particles in the atmosphere are not well defined and vary with time and height. A good sampling of numerous techniques used to determine Mie scattering coefficients is given in [119] - [155]. Tables for the scattering coefficient and the angular scattering function for various atmospheric particles are given in [156] - [164]. Some typical profiles of this type of scattering are also included in the LOWTRAN computer codes.

## B. Opaque Clouds

As a rule of thumb, if the disk of the sun or moon can be seen, the clouds are considered thin, and their effect on light beams can be adequately explained in terms of Mie scattering as discussed above. Opaque clouds are a different matter altogether. Vertical attenuation of over 100 dB has been observed for cumulus clouds [165]. Calculated extinctions of over 1000 dB for realistic dense fog or clouds in the atmosphere are possible. The only viable strategy for optical system designers is to avoid such severe atmospheric conditions by employing spatial and temporal diversity.

## C. Cloud Cover Studies

Satellite monitoring of the skies to build up a reasonable database to draw appropriate statistical conclusions about the suitability of a site seems promising, but for the present, imaging and direct visual observations dominate. The length of time for which GOES, GMS, and NOAA satellites have collected data is no more than a few years (1983–present). This duration is too short to obtain reliable, long-term cloud cover statistics.

Single-object monitoring can be very precise but must include many stars over the sky to be fully relevant. So far this method has not been used extensively. The expense of setting up such stations indiscriminately would alone be prohibitive.

A number of databases giving coarse information on cloud cover and visibility exist. Surface Airways Observations is one such database and is available from National Climatic Data Center in Asheville, North Carolina [166]. It provides information on cloud cover, visibility, and other parameters for over 1000 sites in the United States with a temporal resolution of 3 hours for the last 40 years. Data of this type are being used by the Air Force Geophysics Laboratory (AFGL) and other institutions to develop cloud cover models and computer programs with which to understand and design optical communication systems that would work under ambient weather conditions.

AFGL is also helping to set up whole sky imaging (WSI) stations. The WSI cameras use a fisheye lens to image the sky dome with a resolution of 512 × 512 pixels. There will be six such stations initially dispersed over the continental United States. This type of database can be quite useful for the work at hand but as yet is unavailable.

Almost all data and statistics currently available on cloud cover are not readily amenable to the study of optical propagation through the atmosphere. However, the available weather data may be used as a guide to develop computer models for the simulation of real-time dynamic cloud behavior. An early model for cloud cover was developed by scientists at SRI International. Work at AFGL, which is based on the SRI model, has produced considerably sophisticated computer programs suitable for modeling light propagation through the atmosphere. These models may be used to compute cloud-free line of sight (CFLOS) or cloud-free arc (CFARC) probabilities for any site. It is also possible to compute joint CFLOS and CFARC probabilities for two or more sites. These statistics, needless to say, are of great importance to the development of an optical space network (OSN).

## D. Optical Communications in a Turbid Atmosphere

In the absence of opaque clouds, the only significant effect of the atmospheric scattering and absorption is described by Bouguer's law:

$$I = I_0 \exp\left[ - \int_0^Z \gamma_t(z) dz \right] \tag{22}$$

where $\gamma_t(z)$ is the sum of all absorption and scattering coefficients due to gas molecules, aerosols, and other particulate matter at position $z$, and $Z$ is the propagation distance through the atmosphere. The law assumes that the extinction loss of beam power is independent of beam intensity, and that the absorbing and scattering events occur independently. The magnitude of the exponent in Eq. (22) is defined as the optical depth or thickness, $\tau$, of the atmosphere, i.e.,

$$\tau = \int_0^Z \gamma_t(z) dz \tag{23}$$

Experiments with artificial fog and smoke and with diluted milk solution [9] show that the law holds well for optical thickness $\tau \leqslant 12$.

It is possible to describe the attenuation coefficient over horizontal paths in terms of meterological range, $R_v$, commonly called "visibility" [167] - [169]. The approximate relationship is given by

$$\gamma_t(\nu, z) = \gamma_t = \frac{3.912}{R_v} \tag{24}$$

where we have disregarded the dependence of the attenuation coefficient on laser frequency and position, and $R_v$ is measured in kilometers. Further approximate results may then be used to obtain the optical depth of the entire atmosphere along vertical paths. For example, it may be assumed that the scale height of the atmosphere is about 10 to 20 km along near-zenith paths; this assumption may then be used to obtain total attenuation loss. It may be necessary to devise direct measurement methods to obtain more accurate determinations of optical depths along vertical paths.

The presence of thick clouds, in general, will have a catastrophic effect on the availability of an optical communication link. Although scattered laser light will be available for communication, the system has to be designed to have (1) a wide field of view to collect enough power, which greatly increases the background noise; and (2) a low data rate to avoid intersymbol interference due to pulse spreading. Also, polarization coding of the signal cannot be used as the scattered light is depolarized. An optical communication system designed to employ the scattered beam through thick clouds, then quickly loses its advantages over conventional radio frequency systems.

The only reasonable strategy is to develop the OSN such that it avoids opaque clouds by employing diversity techniques. It will be necessary to identify sites for the installation of optical receiver and transmitter stations where the clouds have a low probability of occurrence. Several such sites with uncorrelated weather patterns may need to be operated simultaneously to obtain desired link availability.

Some of the possible configurations of an OSN which uses spatial diversity to get around the problem of opaque clouds is discussed in JPL IOM 331.6-88-491.[1] In [170], a first-order theoretical weather model is given for the estimation of the link budget for extinction loss through the atmosphere.

## V. Conclusion

Various aspects of the light propagation problem through the atmosphere have been discussed in this article. Loss of beam energy due to absorption and scattering, degradation of beam quality due to scintillation and reduced spatial coherence from refractive turbulence, and link unavailability due to opaque clouds are some of the factors that cannot be overlooked while designing an optical communication system.

A number of optical communication systems and techniques have been investigated to demonstrate optical communication links over horizontal as well as vertical paths through the lower atmosphere [171] - [178]. These include the Airborne Flight Test System (AFTS) developed by McDonnell Douglas, demonstrating a 1000-Mbit/s laser communication air-to-ground system [179]; a Laser Airborne Communications Experiment demonstrating a 50-km air-to-air and air-to-ground optical communication link using a 100-mW laser operating at 0.904 $\mu$m developed by GTE [180]; and SLCAIR demonstrations for submarine laser communications [181]. Detailed reviews of optical communications techniques and design procedures and considerations for atmospheric links can be found in [182] - [184].

Considerable information regarding the atmosphere and its effects on the propagation of light is available. To this end, an extensive reference list has been compiled. The work on optical communications through the atmosphere, however, is not yet complete. Further experiments and statistical studies will be necessary before reliable estimates on link availability and link budgets for optical communications through the atmosphere can be predicted with confidence.

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**Table 1. Composition of "clean" dry air near sea level[1]**

| Component | Percent by Volume | Content, ppm |
|---|---|---|
| Nitrogen | 78.09 | 780900 |
| Oxygen | 20.94 | 209400 |
| Argon | 0.93 | 9300 |
| Carbon dioxide | 0.0318 | 318 |
| Neon | 0.0018 | 18 |
| Helium | 0.00052 | 5.2 |
| Krypton | 0.0001 | 1 |
| Xenon | 0.000008 | 0.08 |
| Nitrous oxide | 0.000025 | 0.25 |
| Hydrogen | 0.00005 | 0.5 |
| Methane | 0.00015 | 1.5 |
| Nitrogen dioxide | 0.0000001 | 0.001 |
| Ozone | 0.000002 | 0.02 |
| Sulfur dioxide | 0.00000002 | 0.0002 |
| Carbon monoxide | 0.00001 | 0.1 |
| Ammonia | 0.000001 | 0.01 |

[1]The concentrations of some of these gases may differ with time and place, and the data for some are open to question. Single values for concentrations, instead of ranges of concentrations, are given above to indicate order of magnitude, not specific and universally accepted concentrations.

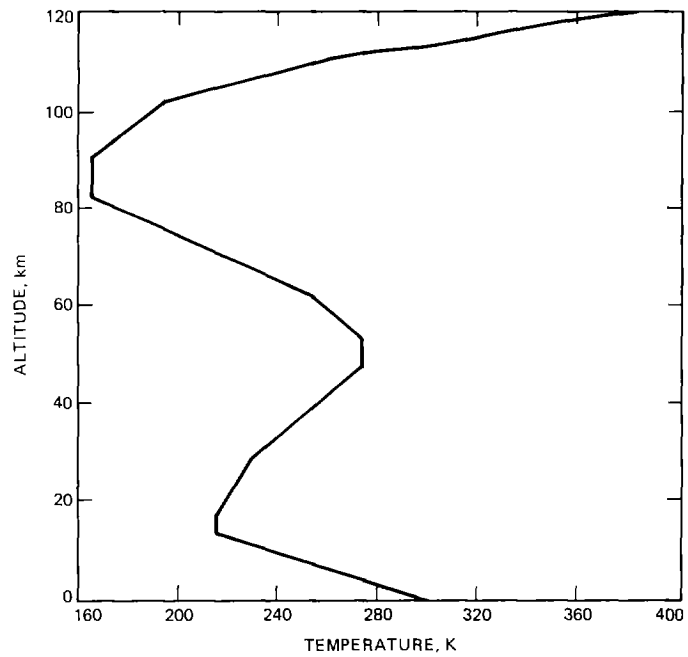


**Fig. 1. Mean temperature as a function of altitude at 45 degree north latitude during July**

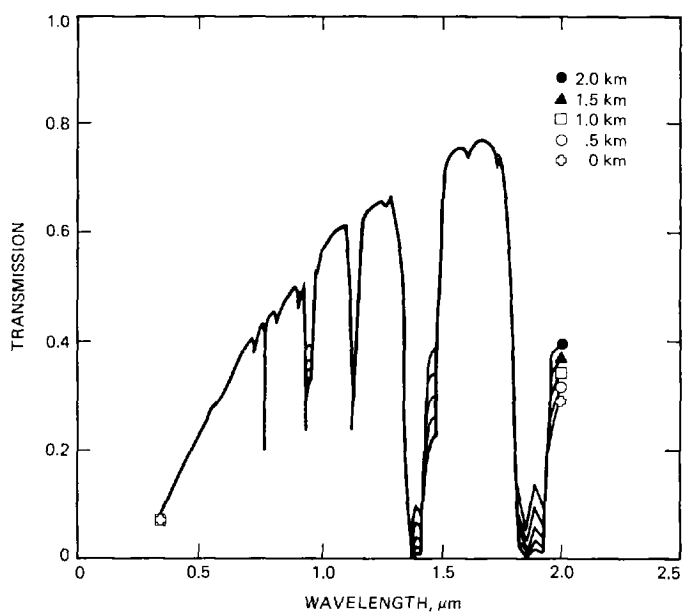


**Fig. 2. LOWTRAN6 calculation of space-to-ground transmission as a function of wavelength in the presence of mid-latitude winter haze. The curves correspond to transmitter altitude.**