ORIGINS OF OFF-AXIS LIGHT IN AN OPTICAL COMMUNICATIONS SYSTEM

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1. Introduction

The purpose of this technical memorandum is to outline the various phenomena that give rise to off-axis components of light in a collimated optical communications system. This system consists of three main sections: the light source; the optical system consisting of lenses, reflectors, and modulators; and the media through which the signal is propagated. The only propagating medium to be considered will be the earth's atmosphere, and the only light sources to be considered will be lasers. The off-axis light is assumed to be sensed by a detector located somewhere outside of the volume occupied by the incident beam and optical system and will be capable of being directed toward any part of the optical communications system. Figure 1 is a schematic depicting the system and defining the nomenclature to be used.

There are two main types of off-axis light: that for which the scattered light has the same wavelength as the incident light (excluding the effects of Doppler shift), and that for which the wavelength of the off-axis light is different than the incident light. The first category is far more important than the second considering the intensities involved.

Scattering without wavelength conversion can be further divided into two categories: independent and dependent scattering.

Dependent scattering implies that a signal reaching the off-axis

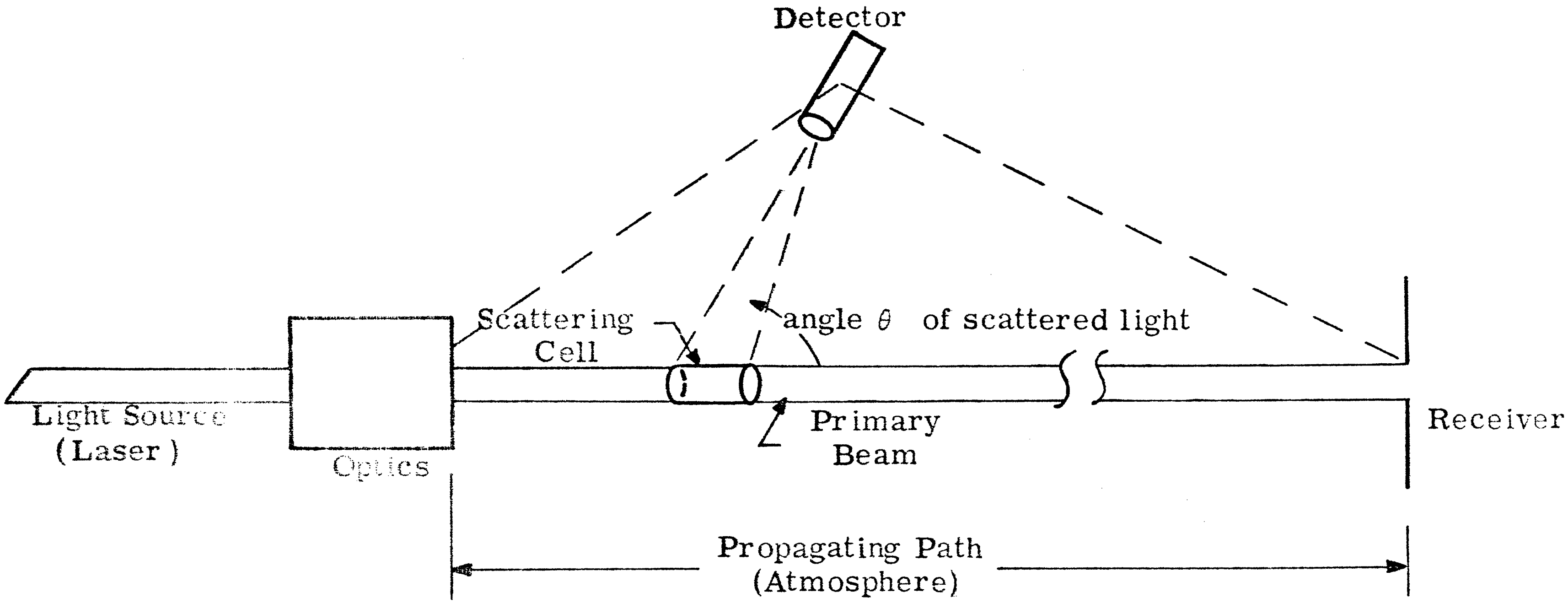

Fig. 1. Schematic of optical communications system

detector has undergone multiple scattering. This problem is discussed in the literature as radiative transfer. Under dependent scattering the primary beam will have undergone total extinction for any practical path length. An example of dependent scattering is a dense cloud. The particles giving rise to dependent scattering may be considered either nonabsorbing, for example, water droplets, or highly absorbing, e.g., fly ash. In either case the communication system can often be considered totally blocked. Radiative transfer will not be considered further in this memo.

Once a criterion has been established for the amount of attenuation of the primary beam that can be tolerated before the optical communication system becomes inoperable, it might be desirable to determine if dependent scattering is a factor. The experimental criterion is a twofold increase in the density of the scattering medium, producing a twofold increase in the intensity of the scattered light if the scattering mechanisms are independent. This can be related to the extinction coefficient γ

where

$$I(x) = I_0 e^{-\gamma x} \tag{1}$$

A value of γ can be determined so that for particular atmosphere values less than this determined value indicate single scattering and values greater than this determined value indicate double or multiple scattering. Since γ is a function of absorption as well as scattering, care must be exercised in applying a value determined for one wavelength and atmospheric conditions to another situation.

The case of practical interest, independent scattering, assumes that any light intercepted by the off-axis detector has suffered only a single incidence of scattering. Phenomena that are employed to explain the intensity and angular distribution of scattered light include diffraction, reflection and refraction. Processes that give rise to absorption are of interest only in that they force limits on the selection of the wavelength of the light source and the types of atmospheres for which a particular light source is suited. Reference 1 is a discussion of absorption at various laser wavelengths and contains high resolution absorption spectra of the atmosphere over a wide range of wavelengths. Since absorption is a function of the chemical composition of the atmosphere, absorption at a particular wavelength could be a strong function of the atmospheric pollutants and water vapor concentration.

Although materials have been made to lase at wavelengths from the near ultraviolet to the far infrared, the majority of the laser lines of interest lie in the red and infrared regions. A few important laser lines are indicated in Table I for devices presently developed to the point where use in an optical communications system would be feasible from the standpoint of the power and coherence of the light source. Fortunately, many suitable lasers operate in atmospheric windows. A knowledge of the fine structure of the absorption spectra is also necessary in order to select an optimum laser material and operating temperature. (Some laser lines are relatively strong functions of the operating temperature of the lasing medium, i.e., ruby. See Ref. 1.)

Table I. Wavelengths of laser lines suitable for an optical communications system

Wavelength in microns	Type of laser
10.6	CO_2 gas
5.3	CO_2 gas doubled
3.31	HeNe gas
1.15	HeNe gas
1.06	Nd^{+++} crystal or glass
0.6943	Ruby crystal
0.6328	HeNe gas

Note: Consideration has been given to the laser technology as well as scattering and absorption phenomena

In general the angular distribution and intensity of light scattered in the atmosphere is a function of the wavelength of the source, the composition of the atmosphere, the size, shape and composition of the particulate material suspended in the atmosphere, and the local weather conditions. Off-axis components generated in the optical system and light source are caused by defects, the effects of which can generally be minimized. No discussion of scattered light would be complete without reference to the rarely encountered atmospheric phenomena such as mirages, halos, glories, etc. Reference 2 has a fairly complete discussion of these phenomena.

A number of phenomena give rise to light emissions whose wavelength distribution and coherence are quite different from those of the incident beam. High power lasers are capable of causing breakdown of the medium through which they are traveling, producing a great deal of scattered light of the incident wavelength as well as other wavelengths (Ref. 3). Other nonlinear effect include Raman and Brillouin scattering. All of these phenomena give rise to scattered energy of such low intensity when the lasers listed in Table I are employed that they will be considered a negligible part of the scattered light in the optical communication system discussed in this technical memo.

2. Light Sources

It will be assumed that all practical light sources will be lasers operating at one of the wide ranges of wavelengths available. The symmetrical divergence of a laser is a function of the type of laser (noble gas, ion, crystal, glass, liquid and solid state), its geometry, type of cavity and bore (diameter and length), and its power (single or multimode). For a single mode noble gas laser the beam divergence can be made essentially diffraction-limited by the laser apertures. As a worse case one can consider a solid state laser with an angle of divergence of 30 deg. The output of all lasers can be considered monochromatic thereby eliminating the effect of chromatic aberration which might produce off-axis components. It can also be assumed that the light is plane polarized.

Asymmetrical divergence from a laser is due to inhomogeneities in the lasing medium such as striations which may either be frozen in during the manufacturing process or be caused by transient thermal gradients.

Lasing media produce a fluorescence or spontaneous emission of relatively wideband, incoherent, highly divergent light along with the laser light. Interaction of this light with the modulators could give rise to a detectable off-axis signal.

In general, undesirable components of the light generated at the source can be eliminated by the proper construction of the laser and optical system and by the judicious choice of lasers. Due to the short path length through the lasing medium, the quality controls exercised on the manufacture of the lasers and the mechanical design, scattered light from the laser appearing outside the optical system should be negligible.

3. Optics

3.1 Surface Scattering

Scattering of light from the surface of lenses and other optical elements can produce strong off-axis components. Scattered light is generated by reflections from the air-glass interface, microscopic imperfections in the surfaces and macroscopic dust particles, which are unavoidable, at least on the surface exposed to the atmosphere. Independent of the wavelength of the light the front surface of an optical system will always be visible in scattered laser light as long as the surface is visible by natural light at the detector. The light scattered in the forward direction from the front surface is primarily due to diffraction from odd-shaped, opaque particles whose sizes are many orders of magnitude larger than the wavelength of light.

A bare glass-air interface will reflect approximately 10 percent of the incident light; this light can find its way out of the optical system as off-axis components after multiple reflections from the lens surfaces or lens mounts. Since the light source is monochromatic, interference type antireflection coatings can be applied, which will reduce the reflected light to essentially zero.

Microscopic imperfections in the surface of either glass refracting elements or reflecting type elements can result in off-axis components that can be made very low in intensity by proper fabrication. These imperfections can lead to eventual destruction of the elements or an increase in the size of the imperfections when irradiated by a high power laser. Reference 4 discusses the effects of reflector quality on scattered light.

3.2 Bulk Effects

In most solids and liquids the size of the molecules and their spacing is small compared with the wavelength of light. Therefore, these materials can be considered homogeneous to light and do not produce scattering. However, both microscopic and macroscopic bubbles and particles are generally imbedded in the glass used for conventional imaging. They cause negligible loss in contrast and efficiency when the glasses are used as intended but give rise to large diffraction intensities when used with coherent light. Equations derived for scattering by a particle suspended in the atmosphere can be applied here if the proper indices of refraction are used. In addition, particles that normally would be too large to remain suspended in the atmosphere must also be considered.

Crystal and liquid materials are largely free of scattering particles, but they still are subject to gross imperfections such as striations and thermal gradients which can cause scattering.

All materials used in optics are subject to fluorescence under irradiation by a high intensity laser beam. Especially sensitive are the rare earth glasses. Fluorescence is more apt to occur with short wavelength lasers, and the light generated will be of very low intensity. The time scale of the fluorescence is much longer than the time scale used in most practical, high speed modulating schemes.

Within recent years materials, especially glasses that are largely free of the imperfections mentioned above have been developed for use with coherent light systems.

Proper design of optical systems should result in the elimination of all scattered light generated in the optical system other than scattering from the lens-atmosphere interface.

4. Aerosols

The earth's atmosphere supports a great variety of natural and man-made particulate materials whose diameters are larger than the wavelength of light in addition to the molecules of gas which are much smaller than the wavelength of light. For both scattering and absorption the most important component of the atmosphere is water in the vapor and in droplet form. Figure 2, adapted from Ref. 5, indicates the relative extinction due to scattering and absorption in a typical atmosphere as a function of wavelength. Figure 3, adapted from Ref. 4, diagrams the concentration of particles as a function of diameter for several important situations. More detailed tables of atmospheric constituents can be found in Ref. 6 and 7. Particles larger than 30 microns are generally too massive to remain suspended in the atmosphere permanently but their transient presence can cause strong scattering intensities to the point of total extinction of the beam.

As a first approximation, it is generally assumed that the scattering particles are spherical, nonabsorbing, independent scatterers. Maxwell's equations with the proper boundary conditions can be applied to this problem and the scattered radiation calculated. References 8 and 9 describe this and apply limiting conditions to their general solutions to obtain solutions for near and far field, conducting and nonconducting materials, and large and small particles (relative to the wavelength of light). Both Refs. 8 and 9 also consider special shapes such as cylinders

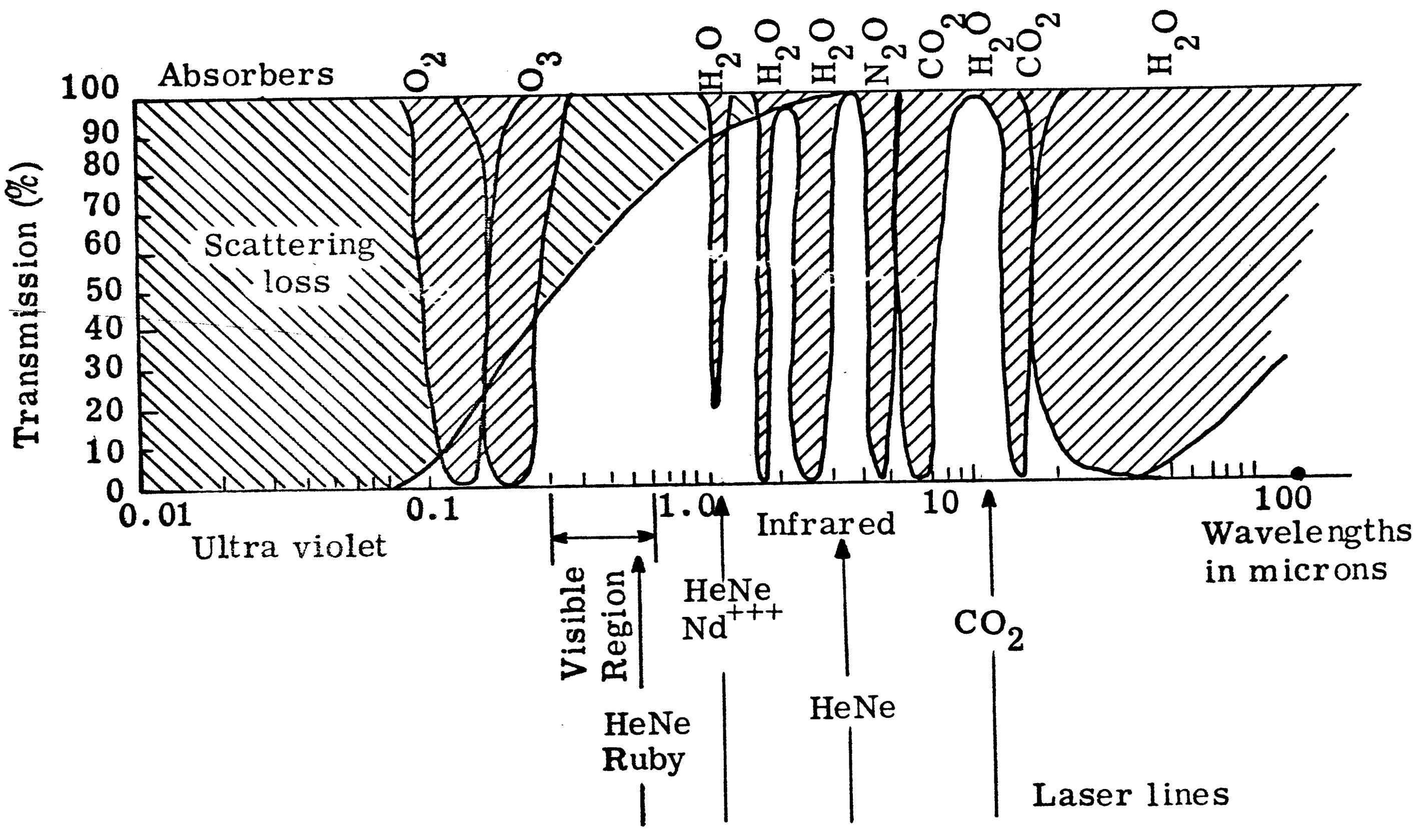

Fig. 2. Relative importance of scattering and absorbing mechanisms in the atmosphere as a function of wavelength

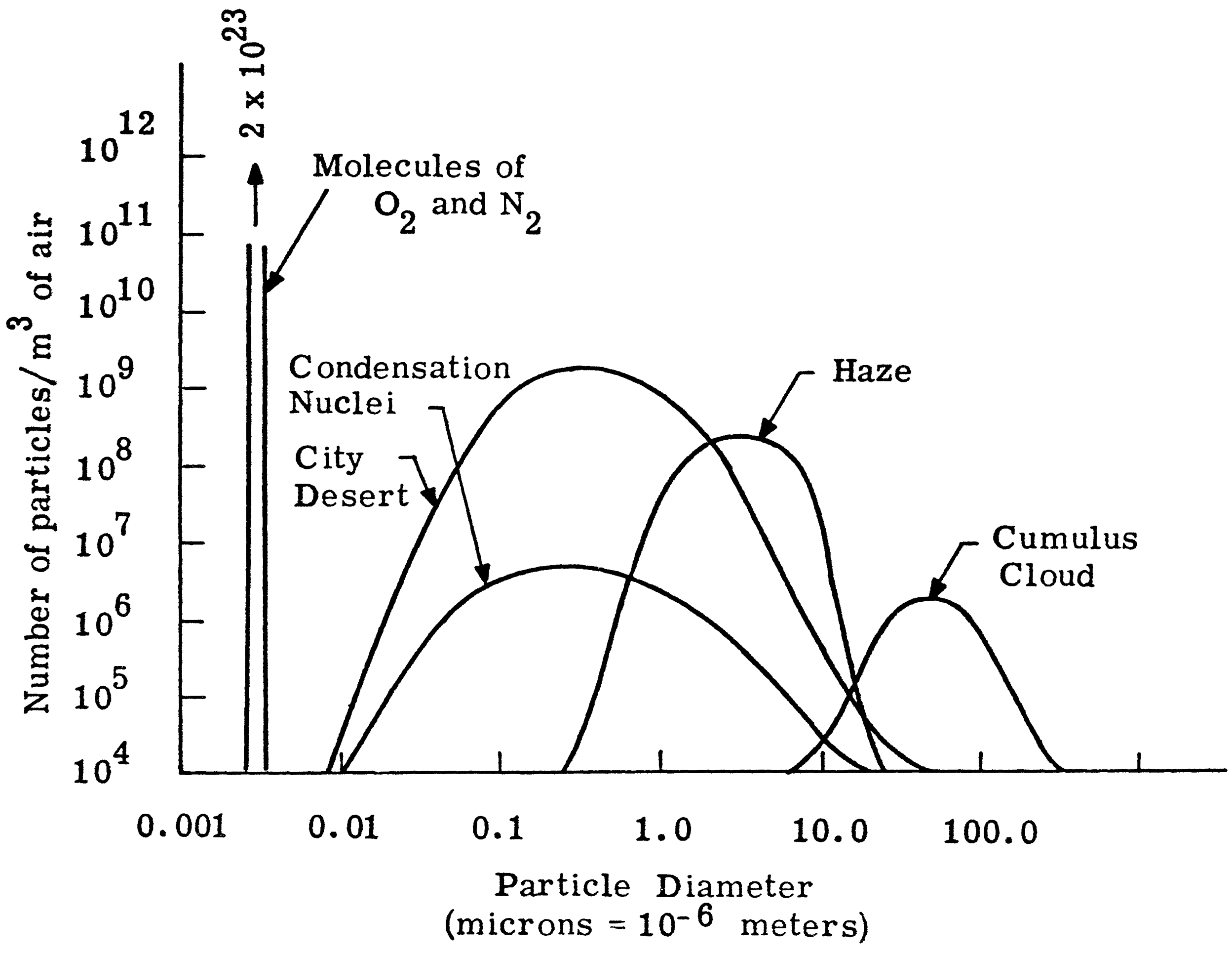

Fig. 3. Atmospheric particle size distributions

(applicable to ice crystals) and special materials such as metals (index of refraction approaching ∞) and absorbing particles (complex index of refraction). The scattered light can be calculated for each type of particle in the atmosphere and the total intensity of the scattered light determined from the sum of the scattering of the various types of particles and their individual concentrations.

Since 1945 a large body of theory has evolved dealing with the scattering of polarized incoherent light by spherical particles with indices of refraction from 0.6 to infinity, including complex values, and of diameter ranging from much less than the wavelength of light to 200 times the wavelength of light. This size range covers all wavelength-diameter combinations for feasible lasers and atmospheric particles.

Reference 8 (p. 568) is the theoretical basis of most tables of Mie scattering functions derived using this approach (Refs. 10-14). A short outline of the derivation will suffice for this memo. A spherical particle of diameter α (normalized to the wavelength of light; $\alpha = \frac{\pi d}{\lambda}$ where d is the diameter of the particle and λ is the wavelength of the incident light) and index of refraction m relative to the surrounding medium is illuminated with a collimated plane polarized monochromatic light source. Figure 4 is a diagram of the spherical coordinate system whose origin is the center of the scattering particle. The proper boundary conditions are applied to Maxwell's equations and the solution expressed in terms of spherical harmonics. The assumption is made that the

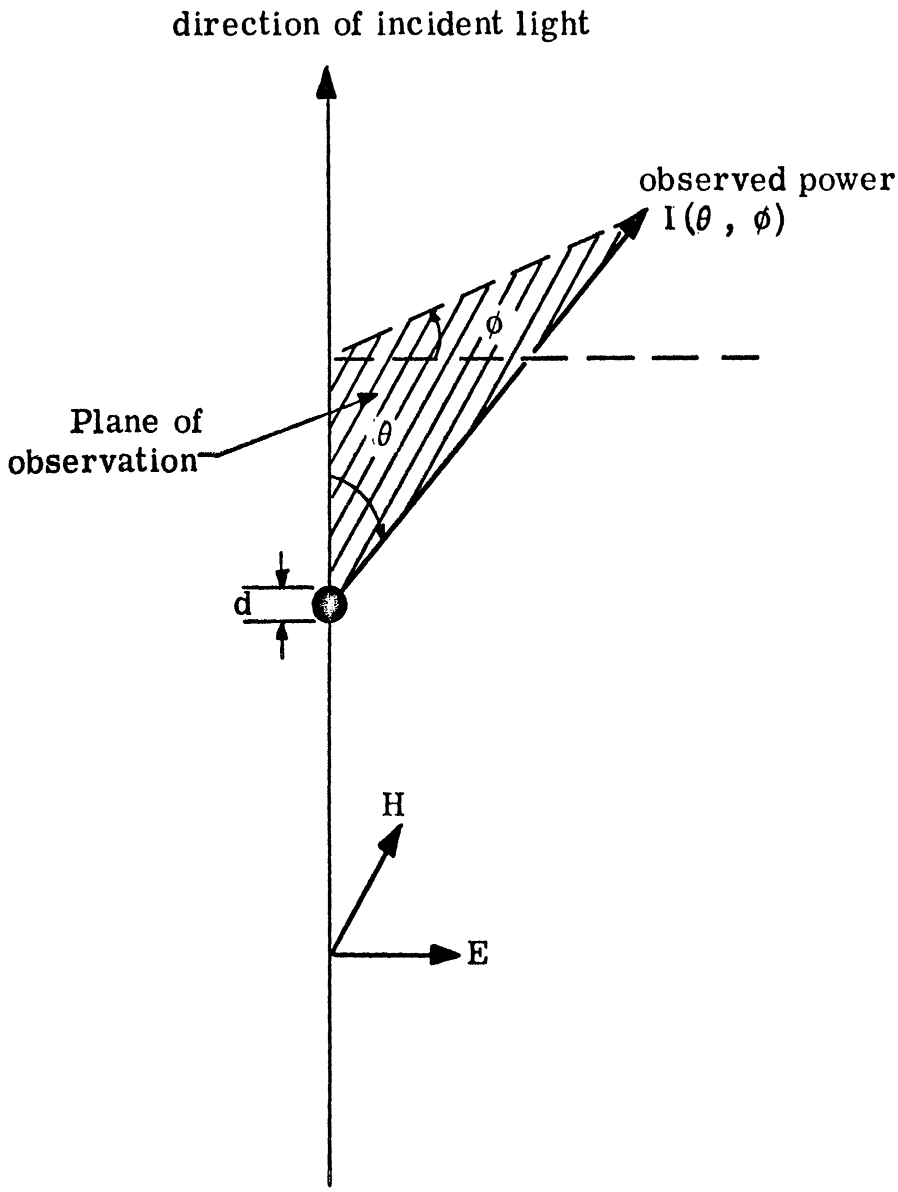

Fig. 4. Coordinate system for scattering geometry

scattered light is observed at $r >> \lambda$ and outside of the incident beam. When summing the intensities generated by each scatterer in the volume being observed, the components due to individual scatterers are assumed incoherent. Independent scattering is, of course, also assumed.

The assumption that the components of scattered laser (i.e., coherent) light can be integrated incoherently is valid because any sample of scattered light reaching a realizable detector originating from a finite volume of the incident beam will be caused by a very large number of scatterers with a random velocity distribution many wavelengths of light distant from one another. The Doppler shifts produced by the random motion of the scatterers and the distance between them will tend to destroy any coherence.

Estimations of the intensity of scattered light due to aerosol particles other than water are difficult for a number of reasons. The nature of these particles varies erratically with time and location. The distribution curves for particle diameter versus concentration are not necessarily narrow enough to assume that the great majority of the particles have the average diameter indicated by the distribution curve so that the average diameter and the concentration at that diameter do not result in an accurate calculation of scattered light. The distribution of the index of refraction and the particle shape as well as the particle diameter would have to be known as a function of concentration before complete and accurate calculations of the intensity of scattered light could be performed.

The introduction sections of Refs. 10 through 13 contain sufficient information to apply their respective tables to calculating the intensity of scattered light for a variety of situations. Some tables (Ref. 13) compute scattering intensities directly for tabulated values of α, m, and θ. Others list coefficients of the spherical harmonic expansion for values of α and m (Ref. 14). Very large values and values less than one for m are considered in Ref. 12. Complex indices are discussed in Section 14 of Ref. 9.

One special case of scattering in the atmosphere should be noted. An optical communications link operating over a body of salt water will suffer scattering from a wider range of water droplet diameters and a higher concentration of moisture than over an overland path. Although the quantity of airborne dust is somewhat less at sea, one must also take into account the amount of scattering due to microscopic salt crystals present above a body of salt water especially when the relative humidity drops below 75 percent. Droplets of water with salt content also have a slightly higher index of refraction. The mechanisms for creation of scatters near the surface of salt water bodies is discussed in Refs. 7 and 15. The concentration of scatters is similar to the concentration of haze from Fig. 3, and the diameters range from 4 to 20 microns.

5. Limiting Cases

Due to the great complexity of the general case of scattering from a sphere of radius a and index of refraction m (possibly complex), it would be desirable to look at the limiting case of scattering for m and a approaching zero or one and infinity. For purposes of establishing limiting cases consider the phase shift of a light wave traveling along the diameter of a spherical particle with real index of refraction

$$d(m-1)\,\frac{2\pi}{\lambda} = 2\alpha(m-1)$$

where α is the radius of the nonabsorbing sphere normalized to the wavelength of the incident light. Figure 5 charts the regions where the various limiting cases hold. In some regions both m and α are limited, two regions overlap, and the resulting expressions are more tractable. The definitions of the regions are given in Table II.

Details of the various regions listed can be found in Ref. 9. Not all of them are applicable to real particles which exist in the atmosphere. While this discussion has assumed spherical particles with real indices of refraction (i.e., nonabsorbing), the above limiting cases can often allow estimation of nonspherical shapes and complex indices of refraction. There are no known atmospheric particles whose indices of refraction are less than one.

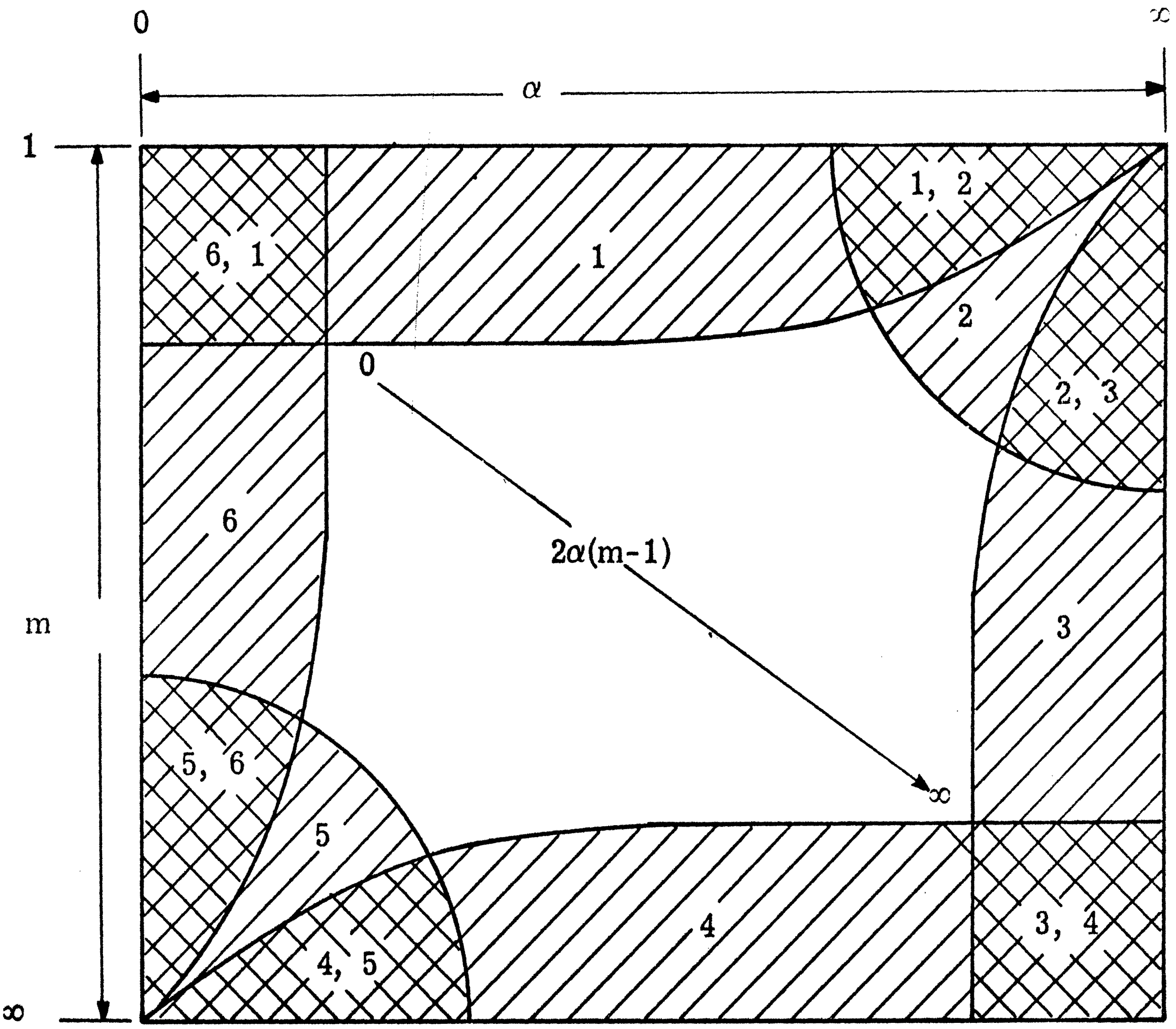

Fig. 5.. Survey of limiting cases in the m-α domain

Table II. Definitions of the regions

Regions	α	m	$2\alpha(m-1)$	Definitions
6, 1	s	s	s	
1	a	s	s	Rayleigh - Gans
1, 2	l	s	s	
2	l	s	a	Anomalous diffraction
2, 3	l	s	l	
3	l	a	a	large spheres
3, 4	l	l	l	
4	a	l	l	total reflector
4, 5	s	l	l	
5	s	l	a	optical resonance
5, 6	s	l	s	
6	s	a	s	Rayleigh scattering

a = arbitrary

s = small

l = large

5.1 Rayleigh Scattering

If we assume that the diameter of the scattering particle is small compared with the wavelength of the incident light, the dependence of the scattered intensity on the shape and angle θ, defined in Fig. 4, of the scatterer is removed. The intensity of the scattered light is strongly dependent on the inverse of the wavelength of the incident light (λ^{-4}) and weakly dependent on the composition. Air molecules will then scatter strongly in the ultraviolet and blue parts of the spectrum because of the high concentration of particles in the proper size range. The Rayleigh scattering from air molecules in the infrared range is negligible. However, microscopic water particles in the one micron range present in the atmosphere will act as Rayleigh scatterers to infrared light. Figure 3 indicates that the concentration of one micron particles in the atmosphere is approximately fifteen orders of magnitude less than the concentration of air molecules. Therefore, the total intensity due to Rayleigh scattering should be negligible in the infrared region.

The equations for Rayleigh scattering (Ref. 16) is as follows:

$$I = \frac{9\pi^2}{R^2} \left(\frac{m^2-1}{m^2+1} \right)^2 \frac{V^2}{\lambda^4} \left(\sin^2\psi \right) N(1+\cos^2\theta)$$

where

m = relative index of refraction of the scatter

v = volume of scatter = $\frac{\pi d^2}{4}$ in meter ^{2}

d = diameter of individual scatter

N = concentration of particles in meters $^{-3}$

ψ, θ = angles indicated in Fig. 4

λ = wavelength of incident light in meters

R = distance from scattering volume ($R >>$ dimensions of scattering cell of Fig. 1)

I = intensity of scattered light per unit volume of scattering cell

Since the calculation and measurement of the actual intensity of the scattered light is so difficult and the usual parameter of interest is the total amount of light lost from the incident beam from all mechanisms, the concept of scattering coefficient σ (km^{-1}) is introduced. The transmission T of a sample of atmosphere is defined as I/I_o, where I_o is the initial intensity of the incident beam and I is the intensity measured after the beam has traversed the sample of atmosphere of length x (km). If we assume independent scattering and negligible absorption Eq. 1 becomes

$$T = e^{-\sigma x} \qquad (2)$$

For Rayleigh scattering

$$\sigma = \frac{4\pi^2}{\lambda^4} \frac{(n^2 - n_o^2)^2}{(n^2 + 2n_o^2)^2} NV^2$$

$$= \frac{\pi^4}{6} \frac{d^6 NM}{\lambda^4} = 1.08 \frac{d^6 NM}{\lambda^4} \tag{3}$$

where n = the index of refraction of the scatterer

n_o = the index of refraction of the medium in which the scatterer is suspended

$M = \left(\frac{n^2 - n_o^2}{n^2 + 2n_o^2}\right)^2$

N = the concentration of scatterers in number/meter^3

V = the volume of an individual scatterer in meters^3

λ = the wavelength of the incident light

This relation remains reasonably accurate if $\frac{2\sqrt{A}}{\pi}$ or $NA^3 << \lambda$. Figure 6 shows some typical values of scattering coefficient as a function of wavelength. The importance of water droplets is indicated and the theoretical values of Rayleigh scattering for air are included for comparison.

Sample calculations show that σ for water droplets $1\,\mu$ in

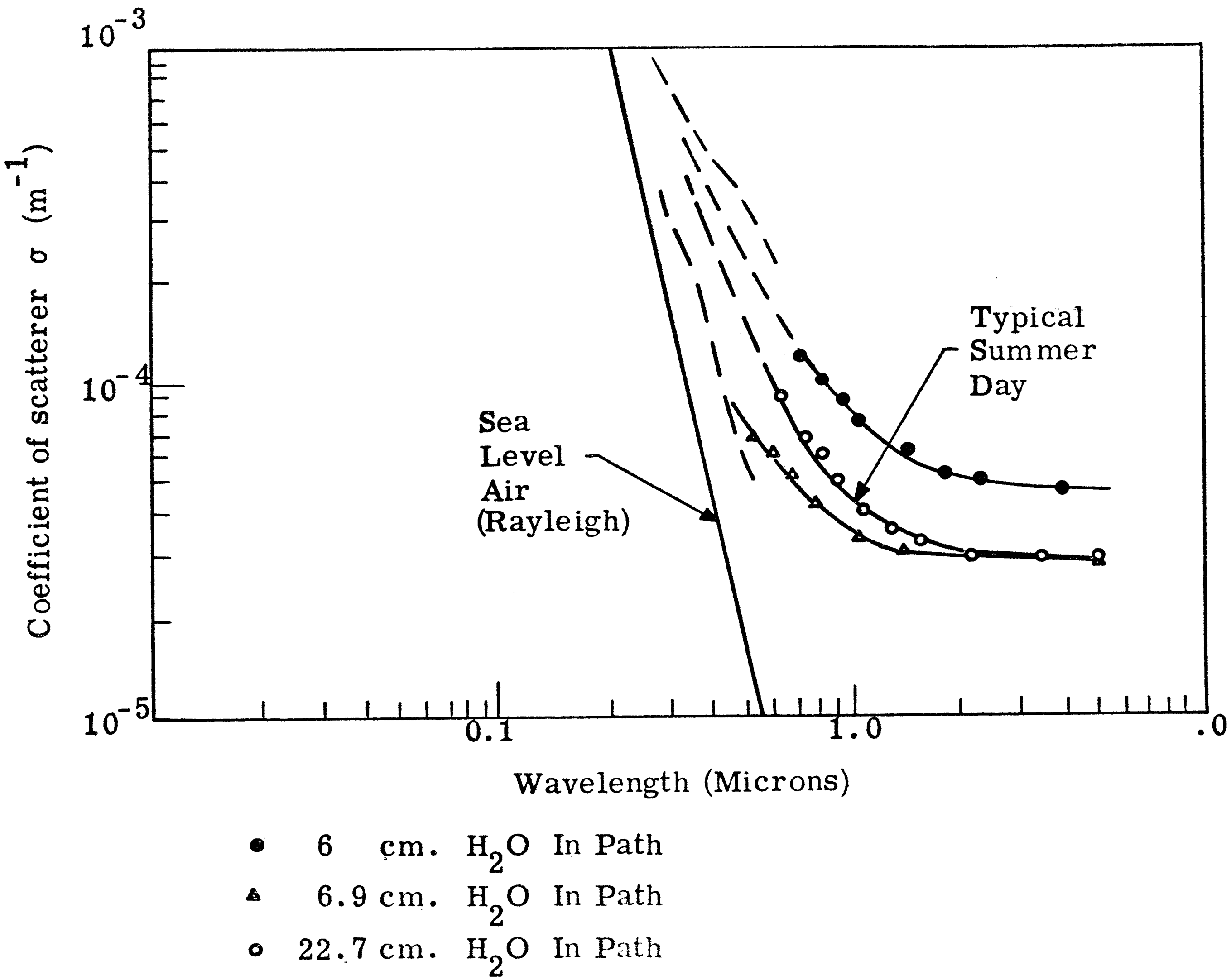

Fig. 6 . Coefficient of scatter measured over 16.25 km sea level path

diameter (barely visible haze) at 0.6328 and 10.6 μ is

$$\sigma_{0.6328} = 2.79 \times 10^{-6}/\text{m}$$

$$\sigma_{10.6} = 2.13 \times 10^{-11}/\text{m}$$

The index of refraction in water is

1.3312 for 0.6348 μ

1.25 for 10.6 μ

The value of $\sigma_{0.6328}$ for Rayleigh scattering is several orders of magnitude below the experimentally determined value (3×10^{-5}/m) indicating that other scattering mechanisms are more prominent. Experimental values for $\sigma_{10.6}$ for the Rayleigh scattering are not available.

5.2 Optical Resonance

For large values of m (on the order of 9 and larger) and small α (typically 1 or less) a resonance phenomenon occurs and the particle acts as if it were a spherical cavity. For this situation the intensity of the scattered light reaches a peak of typically an order of magnitude greater for selected real particles. The resonance peak is limited by the fact that most particles in the atmosphere whose indices of refraction are high also have a complex index and a non-spherical shape. Inhomogeneity of the particle will also affect the Q of the spherical cavity and tend to reduce the resonance peak. As particles in the proper range of m and α exist in the atmosphere this phenomenon could be of some importance. However, the concentration of suitable scatterers in a typical atmosphere would probably be too small to produce a reasonable level of intensity of scattered light of a given wavelength. This phenomenon might prove useful if scattering in an artificial situation is to be optimized. Reference 9 Section 10.5 discusses the details.

6. Weather Independent Scattering

6.1 Atmospheric Turbulence

It was pointed out above that the atmosphere is not homogeneous to light on a microscopic scale thus giving rise to scattering from air molecules (Rayleigh scattering) and aerosols. In addition, a real atmosphere is not homogeneous on a macroscopic scale generating scattered light by entirely different phenomena. Variations in the index of refraction of the atmosphere due to thermal gradients and winds cause refraction of the incident beam (or parts of it) away from its straight-line path as well as partial reflection of the incident beam off the interfaces between cells of different indices of refraction. The statistics of atmospheric turbulence are discussed in Refs. 17 and 18.

Deflection of the incident beam is usually restricted to less than 0.5 degrees and the major effect of this phenomenon is to cause distortion of the wavefront (Ref. 19). The time scale for these deflections is less than 500 Hz.

Partial reflections from weather cell interfaces have been used to detect clear air turbulence as described in Ref. 20. Weather cells vary greatly in size, ranging from one centimeter in diameter to many kilometers. Differences in index of refraction between the cells and the surrounding medium generally increase with increasing cell size. Large cells tend to be stable compared to the length of time necessary for a practical data transmission. Small cells move quickly through the beam resulting in reflected light variations at rates less than 500 Hz. Therefore, the fastest time scale associated with atmospheric turbulence is many orders of magnitude less than the time scales of practical modulating schemes.

The usual method of reducing noise resulting from atmospheric turbulence in an optical radar or communication system consists of making the incident beam diameter larger than the small quickly varying atmospheric turbulence cells. Statistically, then, at least part of the beam will be received undistorted at all times. However, this also means that the probability of finding a component of scattered light in a given volume of incident beam is greater.

6.2 Moisture

Probably the single most important component of the atmosphere as far as extinction of light is concerned is water in the form of vapor, liquid or solid. Water is responsible for refraction, reflection and absorption of the incident beam depending on the wavelength of the light and the form of the moisture. Figure 3 shows some of the larger regions of absorption in the atmosphere and Fig. 4 shows the size versus concentration distribution for hazes and clouds. References 6, 21 and 22 contain more detailed information on the distribution of moisture in the atmosphere.

1. Vapor

Even in dry, clear weather (i.e., no fog, rain, etc.) there is some water vapor in the atmosphere. The diameter of the water molecules themselves and their mean-free path are such that scattering is of the Rayleigh type. Since the concentration of water vapor in the atmosphere is generally many orders of magnitude less than the oxygen and nitrogen molecules that constitute essentially all of the theoretically dry atmosphere, the effect of the presence of water vapor on the intensity of scattered light is negligible.

2. Liquid

As weather conditions dictate individual water molecules begin to coalesce forming progressively larger particles. References 6, 21 and 22 contain information on the statistics of water droplet size as a function of weather conditions. However, even clear air, which appears dry to the naked eye, supports water droplets up to one micron in diameter. The general theory of aerosols can be applied to the water droplets with a great deal of success since the index of refraction as a function of wavelength is well known and the assumption that the scattering particle is spherical is valid for particles that remain suspended in the atmosphere.

Droplets whose diameters are on the order of 0.1 microns (called Aitken particles) are generally not responsible for visible haze. For a laser operating in the infrared range (i.e., 10.6 microns) scattering by Aitken particles can be described by the Rayleigh approximation. Droplets whose diameters are on the order of approximately one micron are generally called Mie scatterers, and the theory described in Section 4 of this technical memo can be used to predict the intensity of scattered light quite accurately once the distribution of the Mie scatterers in the atmosphere is known.

Particles whose diameters are approximately 10 microns (fog) or larger generally result in dependent scattering and total extinction of the incident beam. The diameter of cloud droplets is approximately 30 microns, and particles larger than this can usually be considered precipitation. The approximation that the droplets are spherical becomes less accurate as the drops of precipitation increase in size, and the scattering is no longer isotropic. In addition to scattering, droplets, whose diameters are larger than 10 wavelengths, are capable of producing high intensity off-axis components due to refraction and internal reflection (i.e., rainbow effect). See Table III for a summary of scattering mechanisms due to water droplets.

3. Solid

Under certain conditions microscopic ice crystals (roughly cylindrical in shape) can form in the atmosphere producing scattered light whose intensity distribution is not accurately predicted by the Mie theory. Reference 9 considers this problem and identifies the scattering mechanisms, but there are no quantitative descriptions available.

Operation of an optical communications system through most

Table III. Survey of Size Criteria for Water Drops (Ref. 9)

	Range of α	Range of Diameters for Red Light	Quantities Sensitive to Changes in Size	Range of Diameter for 10.6 μ
Small drops (Rayleigh scattering)	0-0.5	0-0.1 μ	The ratio of any quantity quadratic in V (scattered intensity, extinction) to any quantity linear in V (refractive index of composite medium, excess density of composite medium over solvent). V = volume of drop.	0-2.0μ
3-term region	0.5-1	0.1μ-0.2μ	Angle of maximum polarization, or degree of polarization at 90°, or color of scattered light at any angle, or ratio of scattered intensities at 45° and 135° (dissymmetry).	2-4 μ
Region of complicated patterns	1-10	0.2μ-2μ	Dependence of extinction on wavelength; width of main scattering lobe between half-intensity angles; angles of any distinguishable maxima or minima in the scattering diagram; higher-order Tyndall spectra.	4-40μ

Table III continued

Anomalous diffraction	10-50	2μ-10μ	Angular positions of minima and maxima in the diffraction pattern.	40- 200 μ
Big drops (ordinary diffraction)	50-∞	10μ-∞	Diameters of diffraction rings, or angles between them; position of rainbow maximum and angles between the adjoining maxima; diameters of glory rings; colors of all these phenomena if the light source is white.	200μ - ∞

forms of solid precipitation is not feasible, and since the scattering mechanisms are quite complex, there has been little impetus to study the situation. The same restriction applies to rain.

In any particular weather situation in which water particles in the atmosphere are a factor in producing scattered light, the distribution of particle diameters follows a Gaussian-shaped curve as demonstrated in Fig. 3. For an accurate calculation of the total scattered energy at any particular detector position, one must integrate over the intensity due to each type of scatterer weighted by its concentration. However, a good approximation can often be obtained if one only considers the mean diameter for a particular type of scatterer (i.e., water droplets or dust particles) and uses as a weighting function for the total concentration of that type of scatterer the concentration at the mean diameter. The distribution curves for water droplets as a function of weather conditions are quite narrow and this approximation is accurate.

The narrowness of the distribution function is due to the fact that the size of water particles in the atmosphere is governed by the state of the atmosphere. A given set of weather parameters produces a determined size of water particle whose variance is relatively small and only weakly a function of the weather conditions.

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