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ATMOSPHERIC TRANSMISSION HANDBOOK:

A SURVEY OF ELECTROMAGNETIC WAVE TRANSMISSION IN THE EARTH'S ATMOSPHERE OVER THE FREQUENCY (WAVELENGTH) RANGE 3kHz (100km) 3,000 THz(0.1μm)

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16. Abstract

This handbook presents material on electromagnetic wave transmission in the earth's atmosphere with emphasis on earth-to-space paths up to January 1970. This type of information is needed in such varied fields as air pollution, astronomy, communications, earth resources, geodesy, meteorology, and navigation.

Part I presents basic background information dealing with transmission fundamentals, the properties of electromagnetic waves, the electromagnetic spectrum, and the earth's atmosphere.

Part II is a guide to information on the transmission properties of the earth's atmosphere to electromagnetic radiation. A major feature of Part II is the listing of tables of contents of several books and major articles on atmospheric transmission.

Part III contains selected transmission information on the following observable quantities: refraction, absorption, and scattering.

Part IV is a bibliography to be published in a separate volume entitled <u>Atmospheric Transmission Bibliography 1960-1969: A KWIC Index of Electromagnetic Wave Transmission in the Earth's Atmosphere Over the Frequency (Wavelength) Range 3 kHz (100 km) - 3,000 THz (0.1 μm)</u>. The bibliography covers the frequency regions: radio, microwave, infrared, visible, and ultraviolet. There is a listing of citations by local accession number, a key-word-in-context (KWIC) index or permuted title index, and an author index.

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PREFACE

This survey is the result of a request of A. M. Greg Andrus, John J. Kelleher*, Jules Lehmann, and Theodore George of the National Aeronautics and Space Administration Headquarters. It was compiled while the author was with the former NASA Electronics Research Center in Cambridge, Massachusetts.

The basic task was to locate and collect information on the electromagnetic properties of the earth's atmosphere as they relate to earth-to-space propagation paths. This information was to be presented in handbook form for ready reference. The present document are an attempt to fulfill this requirement and in addition point to hundreds of other sources of pertinent information.

I wish to acknowledge the suggestions, comments and encouragement of George G. Haroules** and Alfred C. Holland*** of the Electronics Research Center in the formulation and preparation of this handbook. I would also like to thank Judith Hubbard of Shrewsbury High School, Shrewsbury, Massachusetts, for her proofreading efforts.

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PART I. ATMOSPHERIC TRANSMISSION FUNDAMENTALS

1.0 OVERVIEW

1.1 SUMMARY

This handbook presents material on electromagnetic wave transmission in the earth's atmosphere with emphasis on earth-to-space paths up to January 1970. This type of information is needed in such varied fields as air pollution, astronomy, communications, earth resources, geodesy, meteorology, and navigation.

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1.2 TRANSMISSION PRINCIPLES

1.2.1 <u>Introduction</u>

A good review of radio wave propagation as it relates to space communications is found in Krassner and Michaels, (ref. 1). The problem of space communication has recently been reviewed on several NASA contracts by Hughes (ref. 2) and Bell Telephone Laboratories (ref. 3). In most cases it is the inverse of transmission or attenuation which is considered. In physics, attenuation is any process in which the flux density (or power, amplitude, intensity, illuminance, etc.) of a "parallel beam" of energy decreases with increasing distance from the energy source. Attenuation is always due to the action of the transmitting medium itself (mainly by absorption and scattering). It should not be applied to the divergence of the flux due to distance alone, as described by the inverse-square law (Sections 2.7, 2.8).

The space rate of attenuation of electromagnetic radiation is customarily described by Bouguer's law (Section 1.2.2) although this law has been questioned by Rozenberg (ref. 4). In meteorological optics the attenuation of light is customarily termed extinction (ref. 5).

1.2.2 Bouguer's Law of Transmission

Bouguer's law (or Beer's law, sometimes called Lambert's law of absorption) is a relationship describing the rate of decrease of flux density of a plane-parallel beam of monochromatic radiation as it penetrates a medium which both scatters and absorbs at that wavelength. This law may be expressed:

$$dI_\lambda = -\alpha_\lambda I_\lambda \, dx \qquad (1\text{-}1)$$

or

$$I_\lambda = I_{\lambda o} \exp \, (-\alpha_\lambda \, x) \qquad (1\text{-}2)$$

where I_λ is the flux density of the radiation and α_λ is the attenuation coefficient (or extinction coefficient) of the medium at wavelength λ; $I_{\lambda o}$ is the flux density at the source, and x is the distance from the source (See Fig. 1-1).

This law was first established experimentally by Bouguer in 1960. At a later date, Beer applied it to transmission of light through a turbid liquid. The law was rediscovered by Lambert.

Rozenberg (ref. 4) has recently discussed the limitations of Bouguer's law to atmospheric optics. (See Section 10.8).

1.2.3 Units for Expressing Transmission

Various units used to describe transmission (or attenuation) of electromagnetic waves are presented below. An excellent derivation of these basic quantities is presented in Kraus (ref. 6).

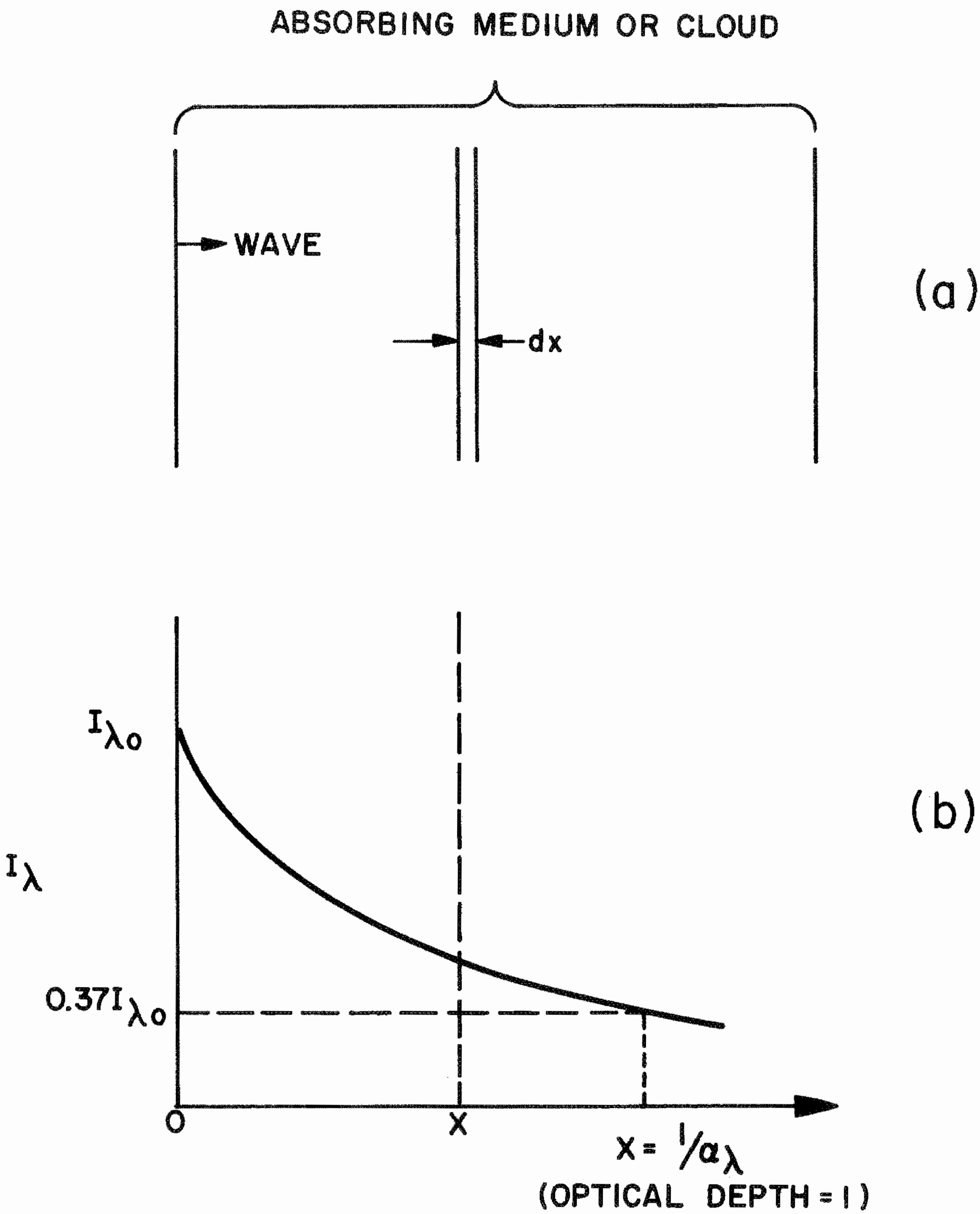

Figure 1-1.- Absorbing medium (a) and attenuation of a wave in it (b), (After Kraus, ref. 7).

Define the following symbols:

I = observed flux density ($W\ m^{-2}\ Hz^{-1}$),

I_o = flux density at the source ($W\ m^{-2}\ Hz^{-1}$),

τ = optical depth or Nepers Attenuation, (dimensionless).

Then the fractional attenuation, γ, is defined by:

$$\gamma = I/I_o = \exp(-\tau) \quad \text{or} \quad I = I_o \exp(-\tau). \qquad (1\text{-}3)$$

It follows that for an optical depth of unity the flux density is reduced to 1/e (36.8%) of its initial value (Fig. 1-1). This is the same as saying that in an optical depth of unity the flux density has been decreased by 1 neper. Thus, from Eq. (1-3) the optical depth (or attenuation in nepers) is given by

$$\tau = \ln(I_o/I) = 2.3 \log(I_o/I). \qquad (1\text{-}4)$$

In decibels the attenuation is given by

$$\text{Decibel Attenuation} = 10 \log(I_o/I). \qquad (1\text{-}5)$$

From Eq. (1-5) and Eq. (1-4) it follows that

$$\text{Decibel Attenuation} = 4.3\ \tau. \qquad (1\text{-}6)$$

A number of values of fractional absorption, percent absorption, fractional transmission, percent transmission, optical depth, and decibels attenuation are given in Table 1-1.

For example, an absorbing cloud that attenuates the flux density to 1 percent of its incident value produces 20 decibel (dB) attenuation, or has an optical depth of 4.6.

TABLE 1-1.- VALUES OF VARIOUS UNITS OF TRANSMISSION.

Fractional Attenuation	Percent Attenuation	Fractional Transmission	Percent Transmission	Optical Depth, or Nepers Attenuation	Decibels (dB) Attenuation
γ	100γ	$1-\gamma$	$100\ (1-\gamma)$	$\mathrm{Ln}\ 1/\gamma$	4.343τ
1	100	0	0	0	0
$1/e = 0.368$	36.8	0.632	63.2	1	4.343
$1/e^2 = 0.135$	13.53	0.865	86.5	2	8.686
0.1	10	0.9	90	2.303	10
0.01	1	0.99	99	4.605	20
0.001	0.1	0.999	99.9	6.908	30
0.0001	0.01	0.9999	99.99	9.210	40
0.00001	0.001	0.99999	99.999	11.513	50

1.3 CONCLUSIONS

It seems appropriate to include a brief summary at this point. Several works which are especially helpful in summarizing present knowledge in various frequency regions will be mentioned.

Radio Region (3 MHz - 3 THz; 100 m - 100 μm)

The main cause of electromagnetic wave transmission irregularities is absorption by ionospheric electrons and polarization rotation caused by the earth's magnetic field. Key sources are Lawrence, Little, and Chivers, 1964, ref. 7; Millman, 1967, ref. 8, and various chapters in Valley, 1965, ref. 9 (outlined in Section 6.4.2).

The main causes of electromagnetic wave transmission irregularities in the microwave-millimeter wave region (3 GHz - 3 THz; 10 cm - 100 μm) are resonant absorption by atmospheric oxygen and water vapor, and scattering by atmospheric hydrometeors. Key sources are Kerr, 1951, ref. 10; Atlas, et al. 1965, ref. 11; Hogg, 1968, ref. 12; Lukes, 1968, ref. 13; and Fowler and LaGrone, 1969, ref. 14.

Optical Region (3 THz - 3,000 THz; 100 μm - 0.1 μm)

The main causes of atmospheric degradation of electromagnetic waves in the optical region are absorption and scattering by molecular constituents and scattering by aerosols such as smoke, fog, and haze particles. Molecular absorption is treated in Howard, Garing, and Walter, 1965, ref. 15; and Lukes, 1968, ref. 13. A discussion of attenuation by scattering is contained in Elterman and Toolin, 1965, ref. 16; and Lukes, 1968, ref. 13.

2.0 CHARACTERISTICS OF ELECTROMAGNETIC WAVES

2.1 SUMMARY

A wave is an oscillatory motion of any kind, the most familiar being waves on the surface of water. Sound waves, another common example, are vibrations of the air or of various material substances. Both wave types involve mechanical motion. Electromagnetic waves are electric and magnetic field variations.

All waves are characterized by the property called *propagation*. The vibrations at a particular point in space excite similar vibrations at neighboring points, and thus the wave travels or *propagates*. The particular substance or space in which it exists is the *propagation medium*.

It was demonstrated by Heinrich Hertz in 1887 that electromagnetic energy in the form of radio waves can be transmitted into space. He postulated that when energy is delivered to an antenna, two fields are induced therein: an induction field and a radiation field. The induction field, being a product of the energy stored in the system, exists only in close proximity to the radiator. The radiation field is derived from electric flux lines established by charges moving in the system and prevails out through free space.

The radiation field consists of two components, in-phase in time, but 90° out-of-phase in orientation: the electric (E) field and the magnetic (H) field. The two components support each other.

The time variation of the E field is equivalent to a hypothetical current flow which produces the H field, and the variation of the H field induces a voltage differential which is indeed the E field. Figure 2-1 illustrates the instantaneous relations of the E and H fields. Phase and amplitude vary coherently with time according to the frequency of the propagated wave. The wavelength interval λ, indicated in Figure 2-1, is related to frequency in free space, as follows:

$$\lambda = \frac{c}{f} \tag{2-1}$$

where

λ = wavelength, m,

c = 2.9979×10^8 m/sec, phase velocity of light in a vacuum,

f = frequency, Hz.

These concepts are discussed in more detail below.

2.2 WAVE VELOCITY

Electromagnetic waves travel in free space* at approximately 186,000 statute miles per second. In other propagation media their speed may be less, but ordinarily it is very high compared with the speeds of things observable without special instruments.

*Free Space is a term much used in discussion of electromagnetic waves. It implies not only empty space (a vacuum) but also remoteness from any material substances from which waves may be reflected.

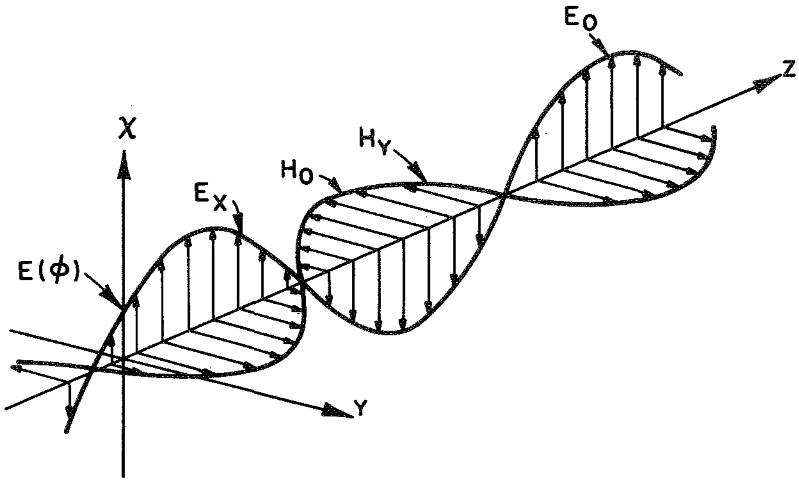

Figure 2-1.- Spatial relationships of a plane electromagnetic wave in free space

In the gases of the earth's normal atmosphere, in fact, the speed is only slightly less than in empty space (vacuum), and for practical purposes the difference is negligible except over very long paths. Even then it is ordinarily permissible to use the free-space velocity figure for calculating how long it will take a radio wave to travel from one point to another in the atmosphere.

An important exception to this statement occurs when waves at certain radio frequencies travel in the ionosphere, a layer of charged particles (ions) lying above the earth between the heights of about 40 and 200 miles. At very low radio frequencies, radio waves cannot penetrate the ionosphere; they are reflected from it. At very high frequencies, waves pass through the ionosphere unimpeded at the same speed they would have in empty space. But in a critical intermediate frequency region, depending on ionospheric conditions (which vary considerably from day to night and with the season and other factors), the wave velocity in the ionosphere may be different than it is in vacuum.

The speed of electromagnetic propagation in a vacuum is of fundamental importance. This value, commonly called the "speed of light" in vacuum, is designated by the symbol c. The value of c is 186,283 statue miles per second, or 299,793 kilometers per second, rounded off for most purposes to 186,000 miles per second or 3×10^8 meters per second.

The velocity of propagation is the rate of flow of electromagnetic radiation, and is sometimes defined for various situations as follows:

(a) Phase Velocity: Of a traveling plane wave at a single frequency, the velocity of an equiphase surface along the wave normal. Also called phase speed, wave speed, and wave velocity.

(b) Group Velocity: The velocity of propagation of electromagnetic radiant energy in a nondispersive or normally dispersive medium. For a complex waveform, group velocity refers to the velocity of propagation of the beats between the component frequencies of the waveform.

(c) Signal Velocity: The velocity of propagation of a signal. In a nondispersive or normally dispersive medium, signal and group velocity are the same. For pure CW (continuous wave) systems, utilizing no modulation, phase velocity is applicable.

2.3 FREQUENCY AND WAVELENGTH

The oscillations of waves are periodic, or repetitious. They are characterized by a *frequency*, the rate at which the periodic motion repreats itself, as observed at a particular point in the propagation medium. Complex waves may contain more than one frequency. The frequency is expressed in *cycles per second*, a cycle being one full period of the wave. In the International System the cycle per second is called a hertz (abbreviation, Hz).

Chapter 3 briefly describes the wide range of frequencies and wavelengths contained in the electromagnetic spectrum. A single-frequency wave motion has the form of a sinusoid.

The wavelength of an electromagnetic wave is the spatial separation of two successive "oscillations", which is equal to the distance that the wave travels during one sinusoidal cycle of oscillation. Therefore, if the wave velocity is v meters per second and the frequency is f cycles per second, the wavelength in meters is

$$\lambda = \frac{v}{f} \qquad (2\text{-}2)$$

As has been noted, v may have different values in different propagation media. When the value in free space (vacuum), c, is used in Eq. 2-2, the resulting value of λ is the *free-space wavelength*, sometimes denoted by λ_o, (Eq. 2-1).

2.4 SPACE-TIME RELATIONSHIP*

An electromagnetic wave has two components, an electric field and a magnetic field. Each component varies sinusoidally in time at a fixed point of space, with time period $T = 1/f$ seconds, where f is the frequency in Hz. Also at a fixed instant of time there is a sinusoidal variation in space along the direction of propagation, with spatial period (wavelength) $\lambda = v/f$ meters, where v is the velocity of propagation in meters per second (Eq. 2-2). In terms of a cartesian coordinate system (rectangular coordinates x, y, z), if the electric field E of the wave is represented by vectors parallel to the x-axis and the wave is propagating in free space in a direction parallel to the y-axis, as shown in Fig. 2-1, the space-time relationships for a *plane wave* are expressed by the following equations:

$$E_x(z,t) = E_o \sin\left(2\pi\, ft - \frac{2\pi z}{\lambda} + \phi\right) \qquad (2\text{-}3)$$

$$H_y(z,t) = H_o \sin\left(2\pi\, ft - \frac{2\pi z}{\lambda} + \phi\right) \qquad (2\text{-}4)$$

The notation $E_x(z,t)$ indicates that E_x is a vector parallel to the x-axis and has a magnitude that depends on the values of the variables z and t. The parameter E_o is the maximum value, called the *amplitude* of the wave, that $E_x(z,t)$ attains when $|\sin(2\pi\, ft - 2\pi\, z/\lambda + \phi)| = 1$, which in turn will occur periodically at time intervals of $T = 1/2f$ at a fixed point and at z-intervals of $\lambda/2$ (half-cycle and half-wavelength intervals). The parameter ϕ is the initial phase angle of the wave; that is, at $t = 0$ and $z = 0$, $E_x(z,t)$ has the value $E_o \sin\phi$. Similar statements apply to $H_y(z,t)$. Figure 2-1 portrays these relationships schematically.

As shown, both the electric and magnetic components of the wave are "in phase" in space, that is, their maxima and minima occur for the same values of z. They are also in phase in time, at a fixed value of z. However, they are both directed at right angles to each other and to the direction of propagation, a relationship that they always bear to each other in free-space propagation. The designation *plane wave* means that the pattern shown, although described as existing only along the z-axis, actually exists everywhere in space, the wave vectors at any point (x,y,z) being exactly like those at the point $(0,0,z)$. At a fixed value of z there is no variation of the field in the

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*After L. V. Blake, ref. 1.

x and y- directions, that is, in an xy-plane at the point z; hence the name *plane wave*. (Not all electromagnetic waves are plane. A plane wave is an idealization never perfectly realized, but in practice waves may often be considered plane, with small error and with great simplification of mathematical description).

The motion of the wave may be visualized by imagining that the entire set of field vectors, not only those shown but also those at all other values of x and y, is moving in unison in the positive z-direction at velocity $c = 3 \times 10^8$ meters per second. An observer at a fixed point would see a sinusoidal time variation of both E and H. On the other hand, if he could somehow (magically) "freeze" the motion and take measurements of E and H along the z-axis, he would observe the pattern in Fig. 2-1.

2.5 POLARIZATION*

The plane wave shown in Fig. 2-1 is *linearly polarized*; that is, the electric vector has a particular direction in space for all values of z, in this case the x-axis direction. The wave is therefore said to be polarized in the x-direction. In actual space above the earth, if the electric vector is vertical or lies in a vertical plane, the wave is said to be vertically polarized; if the E-vector lies in a horizontal plane, the wave is said to be horizontally polarized. (It is conventional to describe polarization in terms of the E-vector).

The initial polarization of a radio wave is determined by the antenna that launches the waves into space. The polarization desired, therefore, is one of the factors entering into antenna design. In some applications a particular polarization is preferable; in others it makes little or no difference.

Electromagnetic waves are not always linearly polarized. In *circular polarization* the electric vector of a wave is rotating about the z-axis (direction of propagation) so that the wave advances with a screw motion, making one full rotation for each wavelength it advances. Extending the analogy with a screw thread further, the rotation may be clockwise or counterclockwise, corresponding to right-hand-circular and left-hand-circular polarizations. A circularly polarized wave results when two linearly polarized waves are combined, that is, if they are simultaneously launched in the same direction from the same antenna, provided that the two linear polarizations are at right angles to each other and their phase angles (the angle ϕ in Eqs. 2-3 and 2-4) differ by 90 degrees or $\pi/2$ radians. The right-hand

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*After L. V. Blake, ref. 1.

or left-hand rotation depends on whether the phase difference is plus or minus. For true circular polarization it is necessary also that the two linearly polarized components be of equal amplitude. If they are of different amplitudes, *elliptical polarization* results.

The polarization is *random* when there is no fixed polarization or pattern of polarization-variation that is repetitive along the *z*-axis, an effect present in light waves emitted from an incandescent source (e.g., the sun or an electric light bulb). It is seldom observed in man-made radio emissions, but these waves would result if two independently random sources of radio noise (used in radio and radar military countermeasures, or "jamming") are connected to right-angle-polarized elements of a single antenna.

Linear polarization is by far the most commonly employed. Circular polarization is employed fairly often at the very high frequencies.

2.6 RAYS AND WAVEFRONTS*

Because the detailed structure of an electromagnetic wave is invisible, its nature can be determined only by indirect methods. Diagrams such as Fig. 2-1 are not truly pictorial; they are purely schematic, man-conceived schemes of representing certain aspects of the waves, namely, the magnitude variations of the E and H components. Another such scheme utilizes the concept of rays and wavefronts as an aid in illustrating the effect of variations in the propagation medium (including discontinuities) on the propagation of waves.

A *ray* is a line drawn along the direction of propagation of a wave. The *z*-axis in Fig. 2-1 is an example of a ray. Any line drawn parallel to the *z*-axis in this diagram is also a ray, since the wave is plane and has the same direction anywhere. Therefore, if the wave is plane, there is no point in drawing more than one ray, for they are all alike.

A *wavefront* is a surface of constant phase of the wave. As mentioned in connection with Fig. 2-1, such surfaces are planes perpendicular to the direction of propagation when the wave is plane. As also mentioned, not all waves are plane. In fact, in the vicinity of the source from which waves are emanating (an antenna, for example), rather complicated wavefronts may exist. Of particular importance, and only slightly more complicated than a plane wave, is the spherical wave. Any "point" source of waves

*After L. V. Blake, ref. 1.

in free space will generate a spherical wave, as is readily deduced from the fact that if a certain part of the wave travels outward from a point, at the same speed in all directions, it will, after traveling a distance R, define the surface of a sphere of radius R, with its center at the point of origin of the waves.

In free space, at a sufficient distance from a source of electromagnetic waves for the size of the source to be very small compared to the distance, the wavefronts will be spherical, that is, the source may be considered equivalent to a point source. The system of rays and wavefronts generated by a point source is shown in Fig. 2-2.

It is apparent that the wavefronts here are spherical (appearing as circles in this two-dimensional drawing) and that all the rays are diverging from the common center or source. But if a small portion of a spherical wave, at a great distance from its source, is considered, this small portion will be approximately plane. For example, consider a cubic region of space, shown dotted in Fig. 2-2 near the mid-portion of the arc denoted wavefront D. This is a spherical wavefront. Within the dotted region, however, the small portion of the wavefront can hardly be distinguished from the plane surface of the cube to which it is tangent. Moreover, all the ray lines inside this cube are approximately parallel.

If the wavefront is one mile from the source, for example, and if the cube edge-dimension is 100 feet, the wavefront will deviate from perfect planeness (coincidence with the cube face) by only about 3 inches. For most practical purposes the wavefront in this 100-foot region may be regarded as plane. At a distance of 10 miles, the deviation in 100 feet would be only 0.3 inch.

2.7 SPHERICAL WAVES AND THE INVERSE-SQUARE LAW*

One of the fundamental laws of physics is the Law of Conservation of Energy. An electromagnetic wave represents a flow of energy in the direction of propagation. The rate at which energy flows through a unit area of surface in space (energy per unit time per unit of area) is called the *power density* of the wave, usually expressed in watts per square meter. The principle of energy conservation can be applied to a uniform spherical wave in the following terms, with reference to Fig. 2-2. If the source radiates power at a constant rate

*After L. V. Blake, ref. 1.

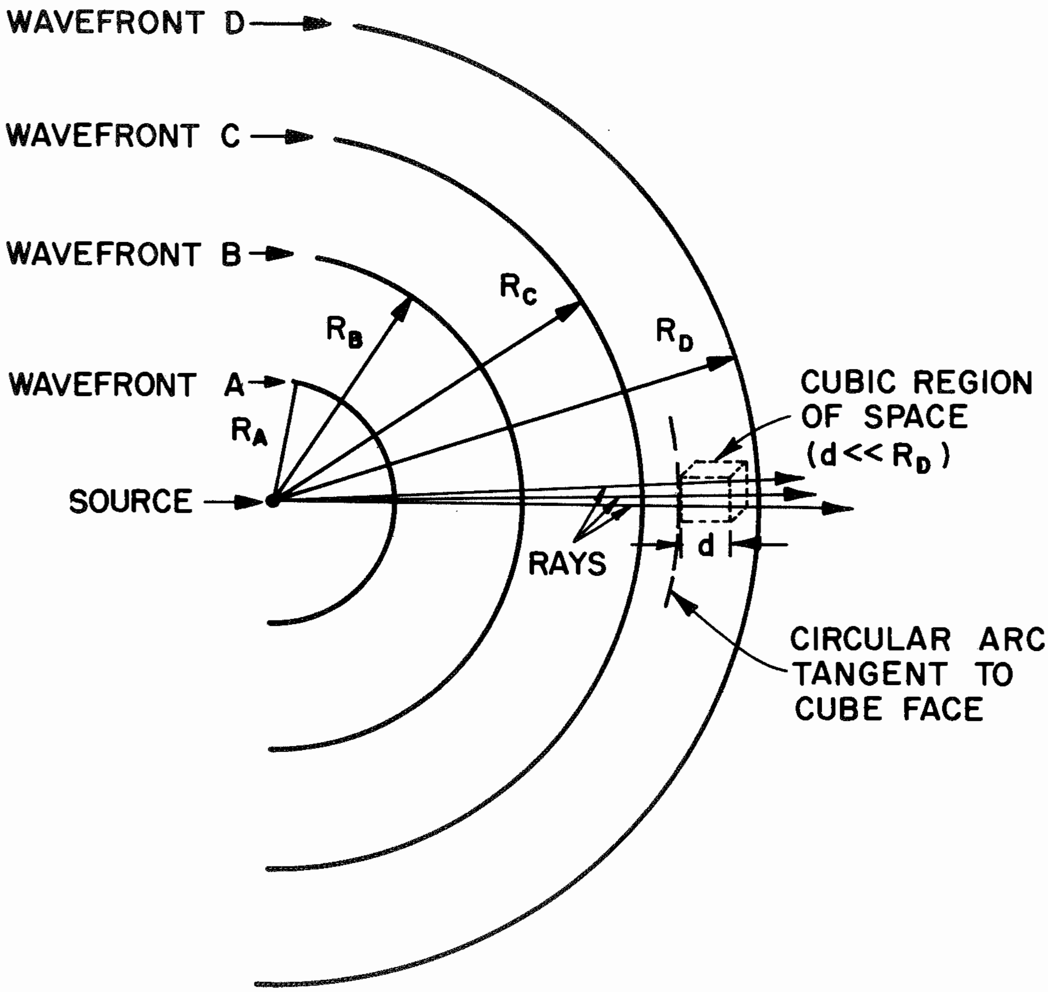

Figure 2-2.- Point-source wavefronts and rays in free space (After Blake, ref. 1)

uniformly in all directions, the total power flowing through any spherical surface centered at the source will be uniformly distributed over the surface and must equal the total power radiated. Such a source is called an isotropic radiator, or *isotrope*.

In Figure 2-2, wavefront B, for example, constitutes a spherical surface. Although only a portion of it is shown, the complete sphere may be visualized as surrounding the source. If wavefront B is at a distance R_B meters from the source, the total surface area of this sphere is, from elementary geometry, $4\pi R_B{}^2$ square meters. If the source is radiating a total power P_t watts, since this total power is by hypothesis distributed uniformly over the spherical surface at distance R_B, the power density $\mathcal{P}_B$ must be

$$\mathcal{P}_B = \frac{P_t}{4\pi R_B^2} \text{ watts per square meter.} \qquad (2\text{-}5)$$

By similar reasoning the power density at the greater distance of wavefront C will be

$$\mathcal{P}_c = \frac{P_t}{4\pi R_c^2} \text{ watts per square meter.} \qquad (2\text{-}6)$$

This value is obviously smaller than the power density at wavefront B, since R_c is greater than R_B. Thus the power density decreases as the distance from the source increases.

What is the law of this decrease? It may be found by dividing Eq. 2-5 by Eq. 2-6:

$$\frac{\mathcal{P}_B}{\mathcal{P}_c} = \left(\frac{R_c}{R_B}\right)^2 , \qquad (2\text{-}7)$$

which shows that the power density is inversely proportional to the square of the distance from the source. This is the celebrated *inverse-square law* of radiation, observed experimentally for all forms of electromagnetic waves in free space or in limited regions whose characteristics approximate the uniformity of free space.

In deriving this result it has been assumed that the source radiates isotropically - uniformly in all directions. This assumption was made because it simplifies the reasoning, but actually it is not a necessary assumption. The same result is obtained if the source radiates nonuniformly, that is, if it radiates power preferentially in certain directions, as occurs in practice with directional antennas. It is always necessary, however, to assume that the velocity of electromagnetic propagation is the same in all outward directions from the source, which is certainly true in free space. (This assumption is necessary in order that the wavefronts may be spherical, i.e., that the distance to the wavefront from the source at any instant may be equal in all directions, corresponding to the geometrical definition of a sphere).

A propagation medium that satisfies this assumption is called isotropic, meaning that the propagation velocity is the same regardless of the direction of propagation. The *inverse-square law*, therefore, is the result both of the spherical spreading of the wavefronts in an isotropic *propagation medium* and of the law of conservation of energy. This very important result has many applications in antenna theory, as well as in wave-propagation theory.

2.8 FIELD INTENSITY AND POWER DENSITY*

The power density of the field is related to the values of the electric and magnetic intensities in the same way that power in an electric circuit is related to voltage and current; it is the product of the two. (This assumes the free-space relationship of the field vectors depicted in Fig. 2-1). The product of the instantaneous values gives the instantaneous power, but this quantity is usually of little interest. The average power density over an rf cycle is ordinarily desired, and, just as in computing a-c power in circuits, it is obtained by multiplying the *effective* values of E and H, equal to $1/\sqrt{2}$ times the amplitudes, or $0.707E_o = 0.707H_o$. Hence

$$P = (0.707E_o) \times (0.707H_o) = 0.5E_oH_o \ , \qquad (2\text{-}8)$$

where E_o and H_o are the amplitudes as in Eqs. 2-3 and 2-4. E_o is expressed in volts per meter, H_o is ampere-turns per meter to give P in watts per square meter.

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*After L. V. Blake, ref. 1.

Just as voltage and current in circuits are related through the resistance by Ohm's law, the electric and magnetic intensities are related by the characteristic wave impedance of space. In a lossless propagation medium this impedance is equal to the square root of the ratio of its magnetic permeability μ to its electric permittivity ε:

$$Z_P = \sqrt{\mu/\varepsilon} \quad \text{ohms.} \tag{2-9}$$

In a vacuum μ has the value 1.26×10^{-6} henrys per meter, and ε is 8.85×10^{-12} farad per meter. (These values are customarily denoted μ_o and ε_o). Consequently, Z_s is about 377 ohms (actually 120π ohms) in free space, a value also applicable in air. Hence in these media

$$P = \frac{E^2}{377} = 377\ H^2 \text{ watts per square meter} \tag{2-10}$$

where E and H are effective (rms) values, equal to $0.707E_o$ and $0.707H_o$, in volts per meter and ampere-turns per meter, respectively. This also means that

$$H = \frac{E}{377} \text{ ampere-turns per meter} \tag{2-11}$$

for any wave propagating in free space or air; that is, E and H are related through this expression, and specifying one of them is equivalent to specifying both. Ordinarily, therefore, only the electric intensity is specified.

If Eq. 2-10 is applied to the inverse-square law, the result is

$$\frac{E_B}{E_C} = \frac{R_C}{R_B} \tag{2-12}$$

which states that the electric intensity is inversely proportional to the first power of the distance from the source (subject to the same stipulations that apply to the inverse-square law in its original form).

Equations 2-7 and 2-12 are different ways of showing how the electromagnetic wave is attenuated with increasing distance from the source. Equation 2-7 expresses the attenuation in terms of the power-density ratio, Equation 2-12 in terms of the electric-density ratio.

2.9 DISPERSION

The dispersion is the variation of phase velocity with frequency. Dispersion results when a process, such as diffraction, refraction, or scattering, varied according to frequency.

3.0 THE ELECTROMAGNETIC SPECTRUM

3.1 SUMMARY

The electromagnetic spectrum is the entire range of wavelengths or frequencies of electromagnetic radiation. This chapter discusses various aspects of the electromagnetic spectrum.

The notation used to describe the electromagnetic spectrum of interest is discussed. Two detailed frequency spectrum charts are presented and several related charts are cited. Some fundamentals and information of frequency management are outlined.

3.2 ELECTROMAGNETIC SPECTRUM NOTATION

A breakdown of the electromagnetic frequency spectrum of interest in this handbook is presented in Table 3-1. In Table 3-1 the following multiples of units for frequency are used: $k = 10^3$; $M = 10^6$; $G = 10^9$; and $T = 10^{12}$. The notation in the VLF-EHF frequency region is after Booker and Little (ref. 1).

3.3 FREQUENCY SPECTRUM CHARTS

Figure 3-1 presents a chart describing the frequency spectrum from 4×10^{-4} Hz to 6×10^{22} Hz (7.5×10^{11} m to 5×10^{-9} µm). The chart is reproduced with the permission of North American Rockwell. This frequency spectrum chart consists mostly of the electromagnetic spectrum, but to create a stimulating comparison, mechanical and sonic frequencies are also included on the lower portion of the scale. The chart is adequately described by the remarks contained thereon.

TABLE 3-1.- BREAKDOWN OF THE ELECTROMAGNETIC SPECTRUM UNDER CONSIDERATION

REGION NOTATION	FREQUENCY RANGE	WAVELENGTH RANGE
Very Low Frequencies (VLF)	3 kHz - 30 kHz	100 km - 10 km
Low Frequencies (LF)	30 kHz - 300 kHz	10 km - 1 km
Medium Frequencies (MF)	300 kHz - 3 MHz	1 km - 100 m
High Frequencies (HF)	3 MHz - 30 MHz	100 m - 10 m
Very High Frequencies (VHF)	30 MHz - 300 MHz	10 m - 1 m
Ultra High Frequencies (UHF)	300 MHz - 3 GHz	1 m - 10 cm
Super High Frequencies (SHF)	3 GHz - 30 GHz	10 cm - 1 cm
Extremely High Frequencies (EHF)	30 GHz - 300 GHz	1 cm - 1 mm
Terahertz Radio	300 GHz - 3 THz	1 mm - 100 μm
Infrared (IR)	3 THz - 400 THz	100 μm - 0.75 μm
Visible	400 THz - 800 THz	0.75 μm - 0.38 μm
Near Ultraviolet (NUV)	800 THz - 1,000 THz	0.38 μm - 0.3 μm
Middle Ultraviolet (MUV)	1,000 THz - 1,500 THz	0.3 μm - 0.2 μm
Far Ultraviolet (FUV)	1,500 THz - 3,000 THz	0.2 μm - 0.1 μm

Figure 3-2 presents a frequency spectrum chart which is an expansion of a portion of the frequency spectrum chart in Figure 3-1. Figure 3-2 is used with the permission of the Joint Technical Advisory Committee (ref. 2) and North American Rockwell.

The chart is divided into two sections: (1) man's use of electromagnetic energy, and (2) natural phenomena with a subsection titled side effects, showing the interaction between the two.

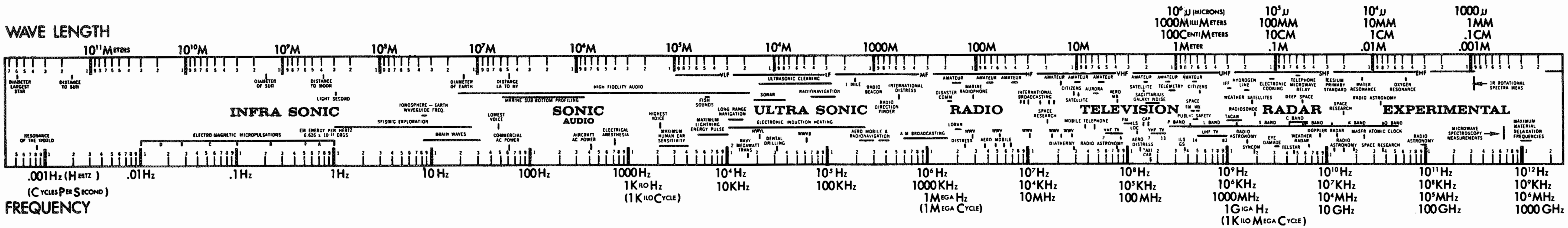
The presentation of the spectrum in these two categories is an attempt to suggest a simple means for showing man's use and natural phenomena in simple terms of a common denominator: frequency. Although extreme care was taken to place activities in their proper frequency relationship, this chart should not be used as a basis for technical reference.

The first section, man's use is made up of (1) frequency allocations, and (2) a listing of miscellaneous items of general applications. In (1) the Office of Telecommunications Management allocates these frequencies for federal government use, and the Federal Communications Commission for all other uses. These are current allocations for usage in the United States.

Man's unintended use, broadband interference, is also placed in the miscellaneous section. This notation indicates the frequency ranges at which there is generation of spurious or unwanted electromagnetic energy resulting from man's use of electric and electronic products. These frequencies would include the radiated and conducted signals.

The incidences of such side effects which have been entered on the chart indicate frequencies at which experiments have been performed and do not imply evidence of a unique frequency effect or the intensity and duration of exposure necessary to induce the effect.

A number of charts have been prepared by various organizations which consider various aspects of the electromagnetic spectrum. These are listed in Table 3-2. These types of charts are useful for obtaining order of magnitude numbers for many physical parameters.



The effects of frequency resonance explain many phenomena in nature. At resonance the amplitude of oscillation is a maximum regardless of whether the type of wave energy be mechanical, acoustical, or electrical (radio). Even the earth has a natural resonant frequency. The records of the 1960 Chilean earthquake show that the earth vibrated like a bell at the very low frequency of 0.0008 cycles per second for one month. This is one complete cycle in 20 minutes.

Electromagnetic radiation over a wide frequency range reaches the earth from cosmic space. Some of these wavelengths have astronomical dimensions on the order of 18,600,000 miles or about one-fifth the distance to the sun. One hypothesis for such oscillations is that streams of charged particles, or protons, emanating from the Sun, interact with the Earth's magnetic field, distorting the lines of force thereby inducing a phenomena which generates the long wavelength oscillations.

This Frequency Spectrum Chart consists mostly of the electromagnetic spectrum, but to create a stimulating comparison, mechanical and sonic frequencies are also included on the lower portion of the scale. The sonic spectrum is divided according to the normal frequency range of the human ear 20 to 20,000 cps. Infrasonic is the range below, and ultrasonic the range above the sonic. The upper frequency limits for ultrasonic waves approaches the relaxation frequencies of metals, around 10^{12} cps, beyond which materials can no longer respond to the input of mechanical wave energy.

Early commercial use of radio began in this part of the spectrum providing maritime communications and navigational aids. Later came commercial broadcasting and long-distance communication. Broadcasting to great distances beyond the horizon of the earth is made possible by reflecting radio waves off the ionosphere, an ionized, gaseous layer enveloping the earth. The National Bureau of Standards operates radio stations (WWV, WWVB, WWVL), giving precise frequency and time signals. These signals are controlled by extremely stable atomic frequency primary standards.

As electromagnetic (EM) waves increase in frequency they begin to penetrate the ionosphere at about 30 mcs, escaping into outer space as through a window. Without the ionosphere to reflect wave energy transmission, commercial broadcasting in this area is limited to "line of sight" broadcasts such as TV. However, this penetration of the ionosphere by the EM waves makes possible our space communications, radio astronomy, tracking of satellites, etc. Much of radio astronomy centers around the hydrogen line at 21 cm (1420 mc) which is the natural radio frequency emitted by atomic hydrogen in interstellar space.

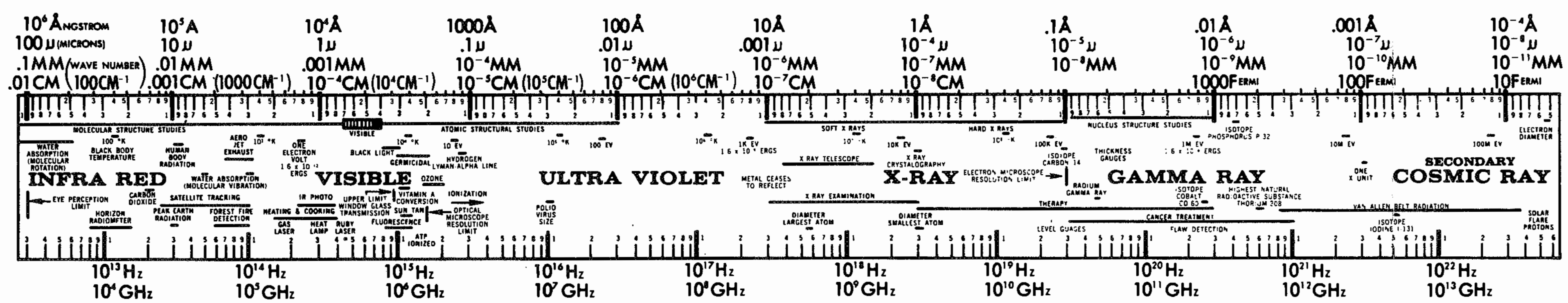
The "window" into space for the EM waves ceases as the frequency increases to the water resonance absorption frequency which is near the 1 cm wavelength. The upper limit for producing radio frequency energy by electrical circuits is reached in the Experimental region because of the physical limitations in making circuit elements small enough. To meet the higher frequency requirements the internal structures of atoms and molecules are being used. The Atomic Clock is an example of the use of atomic frequency. The oscillation of the nitrogen-atom in the NH_3 molecule of the clock provides one of the most stable frequencies known.

The frequencies shown on this chart vary from 5×10^{-4} to 6×10^{22} cycles per second and the wavelengths vary in length from the diameter of an electron to the diameter of our largest star, this dimension being equal to four times the distance to our sun. To show this tremendous range, advantage is taken of the compressibility offered by the logarithmic scale.

The wavelength or frequency of electromagnetic radiation is determined by the amount of energy carried by that radiation. As the energy content increases the frequency increases, while the corresponding wavelength decreases. Gamma rays are examples of high-energy radiation while radio waves may be considered to have low energy radiation.

North American Rockwell is actively engaged in projects which probe into unknowns over the full range of the Frequency Spectrum. Sonic wave destruction of structures, cooling by radiation, pyrotechnic laser development, radiation absorption, and frequency effects on humans are just a few of the fascinating studies in which the company is interested and which can be linked to this spectrum.

A 24-foot-long model of this Frequency Spectrum has been presented to the California Museum of Science and Industry at Los Angeles, California, as a permanent exhibit by the Aerospace Electrical Society, North American Rockwell, and by Luther Monell of NR, who designed and constructed the exhibit.



Our whole universe has been put together in an orderly and harmonious arrangement. There are interrelationships existing between the elements of our universe that follow strict and well defined patterns. The phenomena of resonance and oscillation keeps these harmonious patterns consistent with the laws of matter and energy. A scientific appreciation of this fact may be obtained by starting with a systematic study of the known frequency spectrum which may be considered a common denominator to all science. The Frequency Spectrum Chart is a brainstorming tool to stimulate learning and research, or it can be used as a guide for a more comprehensive understanding of all science studies.

Common properties exist in all radiations, oscillations, and vibrations. After a careful study of the electromagnetic frequencies, it is fascinating to note how seemingly unrelated phenomena possess a close relationship. Radio waves are the same as radiant heat, light, X-rays, and gamma rays. The only difference between them is the frequency which they vibrate, the means of production, and the different ways in which they reveal themselves. Electromagnetic radiation phenomena are placed on the Frequency Spectrum Chart according to their position in the scales of increasing frequency and decreasing wavelength. In addition, to provide a stimulating comparison on this chart, mechanical and sonic frequencies overlap the electromagnetic frequencies in the low frequency portion of this chart.

In this part of the spectrum the energy of radiation is not produced by electric circuit elements in the usual sense. In the infrared region the EM energy is generated by rotational and vibrational oscillations within the molecular and atomic structures. In the visible region the transition of energized or "excited" electrons to lower energy levels results in the emission of photons whose frequencies excite the naked eye as visible light. This one octave visible band is another "window" into space.

The increased energy of the electromagnetic waves in this region excites the valence (bonding) electrons in the molecules causing chemical reactions to take place. At wavelengths below 2000 Angstroms, the ultraviolet rays actually drive electrons out of the molecules resulting in their ionization. All EM waves above approximately 10 electron volts are very energetic ionizing waves and can be harmful to life if not properly controlled. Mutations can result from irradiation. Our atmosphere above us protects us from the ionizing rays from the sun by absorbing them.

X-rays are produced when highly accelerated electrons (from a hot cathode) bombard an anode metal such as tungsten, which is at a very high electrical potential. The impact of the charged particles causes the electrons in the inner orbit of the anode atoms to be ejected. X-rays are produced when electrons from the outer orbits of the atom fall into the vacated inner orbits. The higher the anode voltage, the "harder" the X-rays become and the greater their penetrating power. X-rays have the same fundamental nature as gamma rays, differing only in the means of production.

Gamma rays are produced during the disintegration occurring in radio-active materials. They are also produced when an extremely high-energy particle, measured in millions of electron volts (MEV), penetrates a nucleus of an atom and a rapid transition of nucleons takes place from one nuclear energy level to another. Secondary cosmic rays are considered high-energy gamma rays and are produced when very high energy particles (usually positive charged atomic nuclei) arrive from outer cosmic space and bombard our atmosphere atoms and molecules.

PUBLICATION 529-M NEW 4-69 (FORMERLY NA-64-302 C)

Figure 3-1.- Frequency Spectrum Chart

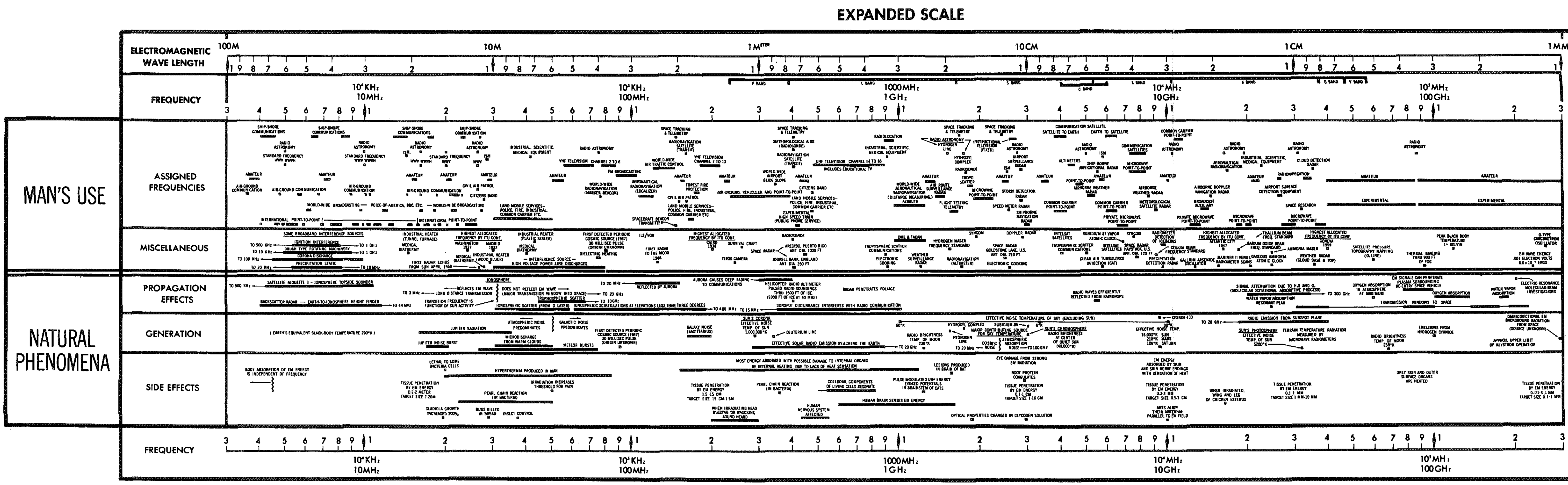


Figure 3-2.- Frequency Spectrum Chart

TABLE 3-2.- CHARTS CONTAINING INFORMATION ON THE VARIOUS ASPECTS OF THE ELECTROMAGNETIC SPECTRUM

TITLE	TYPE	SOURCE
(1) Aerospace Environment	Miscellaneous geophysical and astronomical data, (39"x31").	Air Force Cambridge Research Laboratories Bedford, MA 01730 ATTN: N.J. Oliver
(2) Frequency Spectra	Part of a wall chart series, Space Science Charts, 1 cps - 10^{23} cps, #GC131A, (20"x16").	Public Relations Library Douglas Corporate Office 3000 Ocean Park Blvd. Santa Monica, CA. 90406
(3) Frequency Spectrum	10^{-3} Hz - 10^{22} Hz NA-64-302C, (See Figure 3-1), (21"10 1/2").	North American Rockwell Los Angeles Division International Airport Los Angeles, CA. 90009
(4) Frequency Spectrum Chart	In JTAC (1968), ref. 2, 10^{-3} Hz - 10^{22} Hz, (A portion is found in Figure 3-2), (39"x15").	Institute of Electrical and Electronic Engineers, Inc. 345 E. 47 Street New York, NY 10017
(5) Infrared Detection	0.5 - 25 μm, (30"x16").	Santa Barbara Research Center Goleta, CA. 93017
(6) Radiation and the Atmosphere	SRI Journal, No. 2, 1963, 3 MHz - 30,000 THz, (32"x11"), ($3)	Stanford Research Institute Menlo Park, CA. 94025
(7) The Electromagnetic Spectrum	10 KHz - 100 GHz, (22"x15").($1.00)	The Electronic Engineer Chestnut and 56th Streets Philadelphia, PA. 19139
(8) The Electromagnetic Spectrum	30 cps - 10^{24} cps, Chart MB-1937, (41"x29").($3.50).	Westinghouse Electric Corp. Printing Division Trafford, PA. 15085
(9) The Electromagnetic Spectrum	Detailed, expanded Scale, 3 KHz - 300 GHz in 20 feet (32"x32"), Feb. 1969 Chart No. SPP-F-1000	Department of Transportation Federal Aviation Administration Frequency Management Division Spectrum Plans & Programs Br. Washington, DC 20590

3.4 ELECTROMAGNETIC FREQUENCY MANAGEMENT

The electromagnetic frequency spectrum is, from the point of view of administration and utilization, a natural resource. Interference among radiations of various users can impare or disable effective use. It is a unique resource in that it is not depleted or depreciated by use. However, its value at any time may be drastically reduced by overuse or misuse (ref. 3).

Radio frequency allocation and assignment have been outlined in Siling (ref. 4). Ref. 2 presents the most recent study of the overall problem of frequency management. The Federal Communications Commission (FCC) regulates the electromagnetic frequency spectrum for the civilian United States. The FCC has many documents describing the rules and tariffs (refs. 5, 6). Present frequency allocations in the United States are outlined in (ref. 7) and are shown graphically in Chart Number 7 in Table 3-2.

International frequency allocation is accomplished through an agency of the United Nations, the International Telecommunication Union (ITU). The ITU periodically holds Administrative Radio Conferences which revise the Table of Allocations through negotiations based on needs expressed by the Governments of ITU member countries.

4.0 GUIDE TO ATMOSPHERIC DATA

4.1 SUMMARY

The purpose of this chapter is to indicate where atmospheric data relevant to electromagnetic wave propagation problems can be located.

The atmosphere is the envelope of air surrounding the earth. The atmosphere may be subdivided vertically into a number of atmospheric shells, but the most common basic subdivision is that which recognizes a troposphere from the surface to about 10 km, a stratosphere from about 10 km to about 80 km, and an ionosphere above 80 km. Each of these regions is often subdivided (refs. 1,2).

For convenience in study and description, the earth's lower atmosphere is usually divided into two regions: the troposphere and the stratosphere. The troposphere extends from the earth's surface up to an altitude of, very roughly, 10 km, but it may vary from as low as 7 km at high latitudes to as high as 18 km at the equator. Throughout the troposphere the mean temperature decreases approximately linearly with altitude, from a surface value near 290° K to one of about 220° K at the tropopause, i.e., the upper altitude limit of the linear temperature profile. The mean temperature tends to remain more or less invariant with altitude up to about 30 km (stratosphere). Subsequently the temperature increases with height, and continues to do so up to some 50 km where it reaches a maximum called the thermopause.

Throughout the troposphere and stratosphere the mean absolute pressure, P, decreases approximately exponentially with height; it has decreased to about one-quarter of its ground level value at the tropopause. The average water vapor content, ζ, also falls off very rapidly from that at ground level, becoming very small above the troposphere.

Good approximations to these exponential decays are given by:

$$P/P_o = \exp\ (-h/a) \tag{4-1}$$

where a = 7 km, and

$$\zeta/\zeta_o = \exp\ (-h/b) \tag{4-2}$$

where b = 2 km, and h is the height in km. (Section 10.3).

The relative concentration of the major gas constituents, except for uncondenced water, remain essentially constant up to an altitude of about 20 km. Immediately above this general region, the relative concentration of molecular oxygen begins to decrease somewhat, and ozone appears (see Fig. 4-1).

It will be appreciated that the foregoing statements are, of necessity, qualitative in nature. There are variations in absolute partial water vapor pressure and temperature with time, location, and altitude. Over short distance and time scales such variations can be large and intense. Also, much of the lower atmosphere often contains atmospheric hydrometeors (cloud, fog, rain, etc.). The occurrence, concentration, and extent of these latter atmospheric constituents can usually be described only in very approximate and/or statistical terms. All of these variations influence electromagnetic wave propagation in the earth's lower atmosphere - sometimes in an abrupt and marked manner.

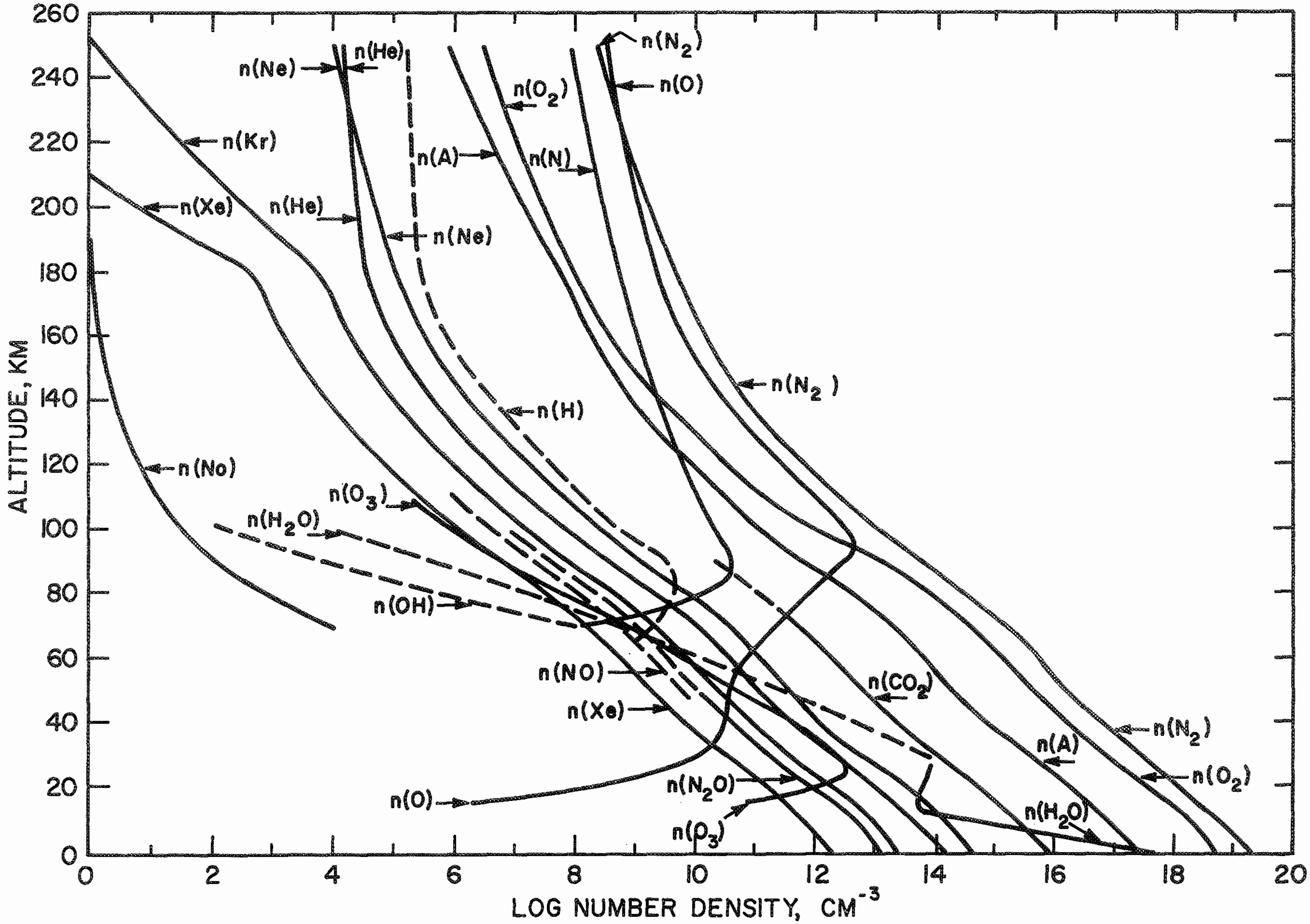


Figure 4-1.- Distribution of atmospheric constituents with height (ref. 3)

The upper atmosphere is discussed in books dealing with ionospheric physics and the like. Several of these texts are outlined in the following sections.

This guide, while not exhaustive, is representative of the type of information available on the earth's atmosphere. There is special emphasis on global distribution of atmospheric properties and on hydrometeors, in particular.

4.2 TYPES OF ATMOSPHERIC DATA

The physics of the earth's atmosphere is conveniently divided into tropospheric and ionospheric physics. General information on tropospheric physics is found in Bean and Dutton, 1964, (ref. 4), (outlined in Section 6.4.4), and Portman et al. 1965, (ref. 5), (outlined in Section 4.4.2). Information on ionospheric physics is contained in Davies, 1965, (ref. 6), (outlined in Section 6.4.3); Jones, 1965, (ref. 7), (outlined in Section 4.4.3); Cormier, et al. 1965, (ref. 8), (outlined in Section 4.4.5); and Davies, 1969, (ref. 9), (outlined in Section 6.4.24).

The mean properties of the earth's atmosphere have been studied and presented in various model atmospheres. General descriptions of model atmospheres have been presented by Allen, 1965, (ref. 2) and Fairbridge, 1967, (ref. 10). Specific information on the most recent model atmospheres is given in Cole, et al. 1965, (ref. 11), (outlined in Section 4.4.12) and in ref. 12.

The Range Commanders Council (ref. 71) have prepared reference atmospheres for many missile ranges both within and without the continental United States. Information on these reference atmospheres can be obtained by writing to the address given in ref. 71.

The types of atmospheric data are temperature, density, pressure, water vapor, winds, composition, hydrometeors, and aerosols. Since many of these properties have rather large spatial and temporal variations, many types of atlases are developed to aid in systems design and evaluation. Thus the Handbook of Geophysics and Space Environments, edited by S. L. Valley, 1965, (ref. 13), (outlined in Section 6.4.2) will be referred to heavily in this chapter. Section 4.7 treats global data.

Table 4-1 lists the types of atmospheric data and in the second column presents some representative sources containing information on the variation of the data with space and time.

TABLE 4-1.- TYPES AND SOURCES OF REPRESENTATIVE ATMOSPHERIC PHYSICAL DATA

Data	Sources
Temperature	Gringorten, Kantor, et al. 1965, ref. 14, (Outlined in Section 4.4.7).
Density	Gringorten, Kantor, et al. 1965, ref. 14, (Outlined in Section 4.4.7).
Pressure	Gringorten, Kantor, et al. 1965, ref. 14, (Outlined in Section 4.4.7).
Water Vapor (Moisture)	Gringorten, Kantor, et al. 1965, ref. 14, (Outlined in Section 4.4.7). Gringorten, Salmela, et al. 1965, ref. 15,
Winds	Gringorten, Lenhard, et al. 1965, ref. 16, (Outlined in Section 4.4.9).
Composition	Stergis, et al. 1965, ref. 17.
Hydrometeors Atmospheric)	Cole, et al. 1965, ref. 18, (Outlined in Section 4.4.10).
Aerosols	Cole, et al. 1965, ref. 18, (Outlined in Section 4.4.10). Lodge, 1962, ref. 19.

4.3 BIBLIOGRAPHIES AND REVIEWS

Table 4-2 lists several bibliographies and reviews on the earth's atmosphere and related topics. Items 1, 4, and 6 are particularly pertinent. Bibliographies dealing with electromagnetic wave effects are given in Sections 6.2 and 7.2. Reviews are treated in Sections 6.3 and 7.3.

TABLE 4-2.- BIBLIOGRAPHIES AND REVIEWS DEALING WITH THE EARTH'S ATMOSPHERE.

Title	Source
1. Meteorology and Atmospheric Physics	AGU, 1960, ref. 20.
2. Precipitation	Huff, 1960, ref. 21.
3. Satellite Meteorology	Fritz, 1960, ref. 22.
4. Meteorology and Atmospheric Physics	AGU, 1963, ref. 23.
5. Precipitation	Hershfield, 1963, ref. 24.
6. Meteorological Satellites	Fritz, 1963, ref. 25.
7. Meteorology and Atmospheric Physics	AGU, 1967, ref. 26.
8. Precipitation	Hershfield and Schleusener, 1967, ref. 27.
9. Meteorological Satellite Achievement	Widger, 1967, ref. 28.
10. A Selective Bibliography in Meteorology	AMS, 1967, ref. 29.
11. Clear Air Turbulence: A Bibliography	Bulford, 1968, ref. 30.
12. Weather, Astronomy, and Meteorology	GPO, 1967, ref. 31.
13. An Annotated Bibliography of Dynamic Cloud Modeling	Murray, 1968, ref. 32.
14. An Annotated Bibliography on Cloudiness in the U.S.S.R.	Stepanova, 1967, ref. 33.
15. Bibliography on Precipitation Statistics and Related Subjects	Thompson, 1968, ref. 34.

4.4 BOOKS

4.4.1 Introduction

To locate books dealing with various phases of meteorology consult ref. 29. Several books of a handbook nature dealing with the earth's atmosphere are outlined below.

4.4.2 The Lower Atmosphere, Chapter 5, System Engineering Handbook (ref. 5).

4.4.3 The Upper Atmosphere, Chapter 6, <u>System Engineering Handbook</u>, (ref. 7).

4.4.4 Atmospheric Structure and Composition, Chapter 3, Tentative, Optics of the Atmosphere: Scattering, Absorption, Refraction, (ref. 35).

4.4.5 Ionospheric Physics, Chapter 12, Handbook of Geophysics and Space Environments, (ref. 8).

4.4.6 Atmospheric Composition, Section 6.1.4, Handbook of Military Infrared Technology, (ref. 36).

Section | Page in original

4.4.7 Atmospheric Temperature, Density, Pressure, and Moisture, Chapter 3, Handbook of Geophysics and Space Environments, (ref. 14).

4.4.8 Properties of the Atmosphere, Section 6.1, Handbook of Military Infrared Technology, (ref. 36).

4.4.9 Winds, Chapter 4, Handbook of Geophysics and Space Environments, (ref. 16).

4.4.10 Precipitation, Clouds, and Aerosols, Chapter 5, Handbook of Geophysics and Space Environments, (ref. 18).

4.4.11 Background, Chapter 5, Handbook of Military Infrared Technology, (ref. 36).

The table of contents of this chapter is found in Section 7.4.19 of this handbook. Note particularly Section 5.6 of the chapter which discusses cloud meteorology.

4.4.12 Model Atmospheres, Chapter 2, Handbook of Geophysics and Space Environments, (ref. 11).

4.5 PERIODICALS

Various periodicals which treat meteorology are listed in Table 4-3.

TABLE 4-3.- PERIODICALS WHICH TREAT THE EARTH'S ATMOSPHERE.

Title	Publisher
Meteorological and Geoastrophysical Abstracts (monthly).	American Meteorological Society 45 Beacon Street Boston, MA 02108 (617) 227-2425
Journal of the Atmospheric Sciences (bimonthly).	
Journal of Applied Meteorology (bimonthly).	
Weatherwise (bimonthly).	
Bulletin of the American Meteorological Society (monthly).	
Meteorological Monographs (irregular)	
Weekly Weather and Crop Bulletin.	Environmental Data Service Environmental Science Services Administration Gramax Building 8060 13th Street Silver Springs, MD 20910 (301) 495-2410
Hourly Precipitation Data (monthly and annual, by states).	
Local Climatological Data (monthly and annual, for principal cities or airports).	
Climatological Data (monthly and annual, by states).	
Climatological Data, National Summary (monthly and annual).	
Monthly Climatic Data for the World	
Decennial Census (climatological).	

4.6 INFORMATION CENTERS

There are a number of places where information on the earth's atmosphere can be located. Table 4-4 lists several.

TABLE 4-4.- SEVERAL CENTERS WHERE INFORMATION OF THE EARTH'S ATMOSPHERE MAY BE LOCATED.

Title	Location
Interdepartmental Committee for Atmospheric Sciences (ICAS)	Capt. S. W. Betts Executive Secretary Room 5896 Department of Commerce Washington, DC 20230
National Weather Records Center, (NWRC)	U.S. Department of Commerce Environmental Science Services Administration Environmental Data Service National Weather Records Center Asheville, NC 28801 (ref. 37)
National Center for Atmospheric Research, (NCAR)	Boulder, CO 80301 (ref. 38).
Environmental Technical Applications Center	Air Weather Service U.S. Air Force Building 159 Navy Yard Annex Washington, DC 20333
American Meteorological Society, (AMS)	45 Beacon Street Boston, MA 02108 (617) 227-2425

4.7 GLOBAL DATA

This section gives many sources of global atmospheric data. This is presented in Table 4-5.

TABLE 4-5.- SOME SOURCES OF GLOBAL ATMOSPHERIC DATA

Type of Data	Sources
Aerosols	Cole, et al. 1965, ref. 18.
Clouds and Cloud Cover	Arking, 1964, ref. 39.
	Blackmer, et al. 1968, ref. 40.
	Quayle, et al. 1968, ref. 41.
	Sherr, et al. 1968, ref. 42.
	Fean, 1961, ref. 43.
	Bunker and Chaffee, 1969, ref. 44.
	Atlas, 1966, ref. 45.
	Young, 1967, ref. 46.
	Kauth and Penquite, 1967, ref. 47.
	Kauth, 1965, ref. 48.
	Edson and Daye, 1968, ref. 49.
	Murray, 1968, ref. 32.
	Sadler, 1969, ref. 50.
	Stephanova, 1967, ref. 33.
	Cole, et al. 1965, ref. 18.
	Brown, 1969, ref. 57.
Climate	NAVY, 1955, ref. 51; 1956, ref. 52; 1958, ref. 53; 1959, ref. 54.
	USWB, 1959, ref. 55.
	Thompson, 1968, ref. 34.
	Rumney, 1968, ref. 56.
Precipitation	Cole, et al. 1965, ref. 18.
	Grantham and Kantor, 1967, ref. 58.
	Essenwanger, 1960, ref. 59.
	Hershfield, et al. 1961, ref. 60.

TABLE 4-5.- Continued

Type of Data	Sources
Precipitation	Thompson, 1968, ref. 34. M.O. 1958, ref. 61. Schirmer and Manig, 1965, ref. 62.
Temperature	M.O. 1958, ref. 61. Gringorten, et al. 1965, ref. 14.
Thunderstorms	Blackmer, 1963, ref. 63. Cole, et al. 1965, ref. 18. WMO, 1953, ref. 64. WMO, 1956, ref. 65.
Water Vapor (Moisture)	Gringorten, et al. 1966, ref. 15. Kuznetsova, 1967, ref. 66. M.O. 1958, ref. 61. Pershina, 1968, ref. 67.
Winds	Gringorten, et al. 1965, ref. 14. Bulford, 1968, ref. 30.
General Tables	Letestu, 1966, ref. 68. Nicholson, 1969, ref. 69. Conway, et al. 1963, ref. 70.

4.8 COMPUTATIONAL AIDS

There are a large number of computation aids in the field of meteorology and more are becoming available. Several of these are discussed in Sections 5.7, 6.7, and 7.7 of this handbook.

PART II. ATMOSPHERIC TRANSMISSION SOURCEBOOK

5.0 INFORMATION RETRIEVAL

5.1 INTRODUCTION

This chapter considers information retrieval in a general way. Chapters 6 and 7 discuss specific sources of information in the radio and optical regions respectively.

The transfer of knowledge to a user is illustrated in Fig. 5-1, where section numbers are shown in the appropriate boxes. Since, in some cases the user will also be a contributor of knowledge, this is indicated by arrows in both directions. In addition, the various means of communication interact with each other.

A classic guide to the literature of mathematics and physics by Parke (ref. 1) is recommended. The basic principles of study and of literature search are described in some detail. A book describing the more recent aspects of technical information has been written by Dyke (ref. 2), where he describes the use and management of technical information.

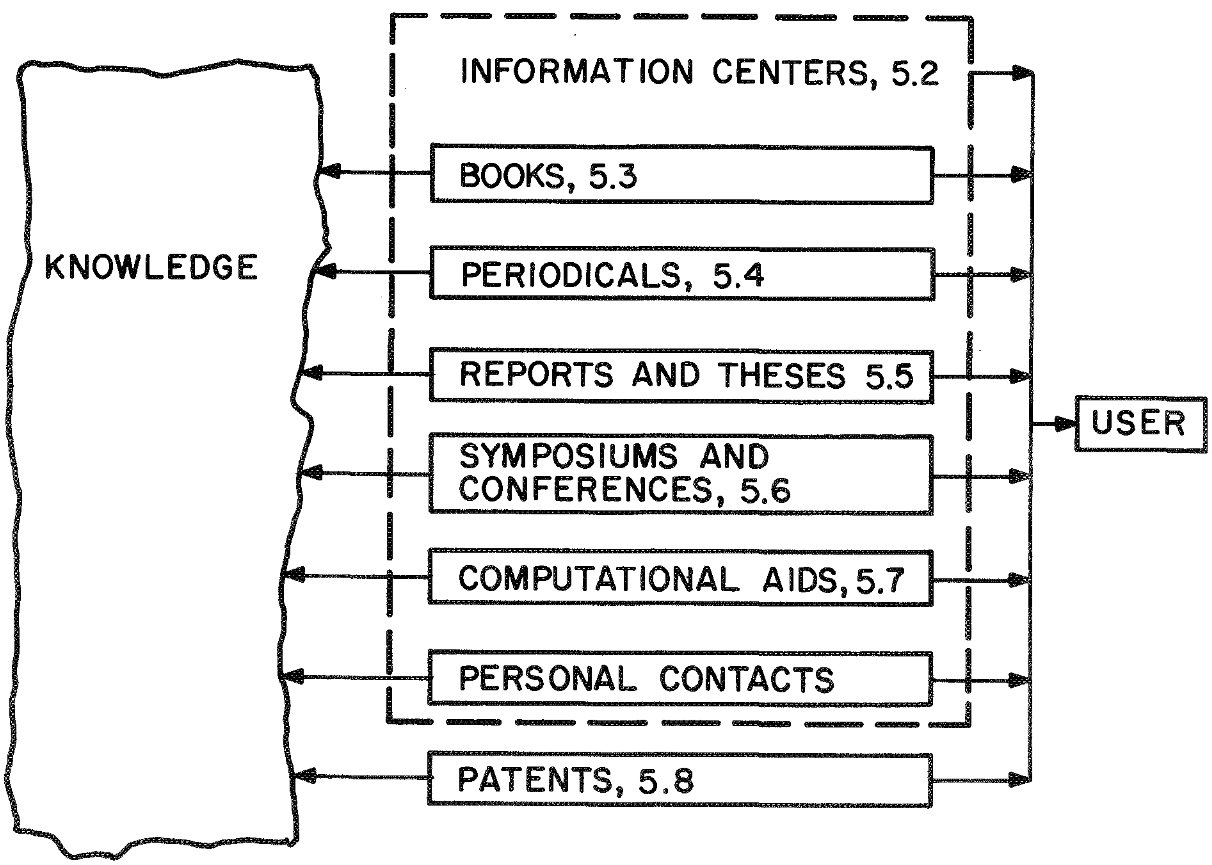


Figure 5-1.- A schematic diagram of the transfer of technical knowledge

5.2 INFORMATION CENTERS

Information centers include libraries, document storage and retrieval centers, special libraries, and referral centers.

A few document storage and distribution centers are listed in Table 5-1. Sources of information in various fields can be located in refs. 3-8.

Information centers dealing primarily with atmospheric effects on wave propagation do not exist at present. However, many existing agencies have information services which can obtain useful information on this subject. For example, the Air Force Cambridge Research Laboratories (AFCRL) provides advice and consultation in response to requests for technical information on subjects covered in the Handbook of Geophysics and Space Environments (Table of contents in Section 6.4.2). Specific and definable problems in these areas should be directed by government agencies and their contractors to the Evaluations Division, Deputy for Technical Plans and Operations, AFCRL, L. G. Hanscom Field, Bedford, MA. 01371.

Table 5-2 lists information centers which do consider electromagnetic wave propagation in the earth's atmosphere.

5.3 BOOKS

Books are a primary source of digested organized information. The subject or author index to Books in Print (refs. 9, 10) is invaluable in the location of books on specific subjects. Of course, browsing the shelves of a good library under the appropriate subject classifications can be a very quick source of relevant information.

There are several types of books useful in the study of atmospheric effects on electromagnetic wave propagation. These include dictionaries, encyclopedias, handbooks, textbooks, treatises, and monographs. More recently, conference proceedings are becoming more useful as reference works as they are published soon after a conference is completed. (These are considered in Section 5.6).

Table 5-3 lists reference books of a general nature alphabetically by title. Each of these works has information on atmospheric effects on electromagnetic wave propagation.

TABLE 5-1.- COMMON SOURCES OF TECHNICAL INFORMATION WITH THEIR ACCESSION NUMBER SYMBOL OR ABBREVIATED TITLE

SYMBOL	SOURCE
AXX-XXXXX	International Aerospace Abstracts (IAA) Published semimonthly by American Institute of Aeronatuics and Astronautics, 750 Third Avenue, New York, NY 10017 (#after the symbol indicates that a microfiche copy is available), (see Ref. 28).
AD XXX-XXX ATI	Defense Documentation Center (DDC), Cameron Station, Alexandria, VA 22314 Channels and Forms for DDC Users to Order Copies of Technical Reports - 1 July 1968. For Hard Copies, as follows.

DDC Catalogue Number Range	NO CHARGE Send DDC Form 1 To DDC	SERVICE CHARGE Send CFSTI Order To CFSTI
AD-1 -199 999	X	
200 000 - 299 999	X	
AD-300 000 Series		
300 000 - 361 514	X	
361 515 - 395 999		X
396 000 - 396 999	X	
397 000 - 399 999		X
AD-400 000 Series		
400 000 - 464 929	X	
464 930 - 489 999		X
490 000 - 492 999	X	
493 000 - 499 999		X
AD-600 000 Series		X
AD-800 000 Series		X
DDC number Unknown		X
Pre-AD (TIP & ATI)	X	

TABLE 5-1.- Continued

SYMBOL	SOURCE
CC or ISI	Current Contents - in such fields as: Engineering and Technology; Physical Sciences; A Service of the Institute for Scientific Information, 325 Chestnut St., Philadelphia, PA. 19106.
CFSTI or PB XXX-XXX	Clearinghouse for Federal Scientific and Technical Information (CFSTI), National Bureau of Standards, Springfield, VA 22151.
NXX-XXXXX	Scientific and Technical Aerospace Reports (see Ref. 28). Published semimonthly by: NASA Scientific and Technical Information Facility, P.O.Box 33, College Park, MD 20740. (# symbol indicates that a microfiche copy is available).
Sm. Inst.	Publications Distribution Section, Editorial and Publications Division, Smithsonian Institution, Washington, DC 20560.
Supt. Docs. TIP (see AD)	Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.
Univ. Microfilms	University Microfilms, 300 N. Zebb Road, Ann Arbor, MI 48106.
	Commissioner of Patents, Washington, DC 20231, ($0.50 for each patent).
X00-00000	Unclassified report in the NASA Information System available to United States Government Agencies and United States Government Contractors only

TABLE 5-2.- INFORMATION CENTERS WHICH CONSIDER ELECTROMAGNETIC WAVE PROPAGATION IN THE EARTH'S ATMOSPHERE

TITLE	ADDRESS
Evaluations Division and the Environmental Consultation Service	Air Force Cambridge Research Laboratories, L. G. Hanscom Field Bedford, MA 01730 (617) 274-6100
U.S. Army Electronics Command	Technical Information Division Fort Monmouth, NJ 07703 (201) 535-2160
Institute for Telecommunication Science and the Wave Propagation Laboratory	Environmental Science Services Administration Research Laboratories Boulder, CO 80302 (303) 447-1000
RECON Central	Air Force Avionics Laboratory Reconnaissance Division Reconnaissance Applications Branch Wright Patterson Air Force Base, OH 45433
The Center for Remote Sensing Information and Analysis	Willow Run Laboratories Institute of Science and Technology The University of Michigan P.O. Box 618 Ann Arbor, MI 48107
Infrared Information and Analysis Center (IRIA)	Willow Run Laboratories (see above).

TABLE 5-3.- SELECTED GENERAL BOOKS TREATING THE PROPAGATION OF ELECTROMAGNETIC WAVES IN THE EARTH'S ATMOSPHERE

TITLE	REFERENCE
Aerospace Glossary	Heflin, 1959, ref. 11
Air Force Dictionary	Heflin, 1956, ref. 12
Astrophysical Quantities	Allen, 1963, ref. 13
Compendium of Meteorology	Malone, 1959, ref. 14
Dictionary of Technical Terms for Aerospace Use	Allen, 1965, ref. 15
Encyclopedic Dictionary of Physics (7 volumes)	Thewlis, 1962, ref. 16
Encyclopedia of Atmospheric Sciences and Astrogeology	Fairbridge, 1967, ref. 17
Frequency Allocations 10 kc/s - 90 Gc/s	RCA, 1956, ref. 18
Glossary of Meteorology	Huschke, 1959, ref. 19
Handbook of Geophysics and Space Environments	Valley, 1965, ref. 20
International Dictionary of Geophysics	Runcorn, 1967, ref. 21
Smithsonian Meteorological Tables	List, 1963, ref. 22
Smithsonian Physical Tables	Forsythe, 1964, ref. 23
Sourcebook on the Space Sciences	Glasstone, 1965, ref. 24
The Encyclopedia of Electronics	Susskind, 1962, ref. 25
The Encyclopedia of Physics	Besancon, 1966, ref. 26
The Meteorological Glossary	McIntosh, 1963, ref. 27

5.4 PERIODICALS

The various periodicals which treat atmospheric transmission will be considered in Chapters 6 and 7. However, several services useful in locating information in the periodical literature are listed in Table 5-4.

TABLE 5-4.- SELECTED ABSTRACTING SERVICES WHICH COVER PERIODICAL LITERATURE

TITLE	PUBLISHER
International Aerospace Abstracts (IAA). (See Ref. 28).	American Institute for Aeronautics and Astronautics (AIAA) 750 Third Avenue New York, NY 10017
Electrical and Electronics Abstracts Science Abstracts, Series B.	The Institution of Electrical Engineers (IEE) Savoy Place London- WC2, England The Institute of Electrical and Electronics Engineers, Inc. (IEEE) 345 E. 47 Street New York, NY 10017
Engineering Abstracts	Engineering Index, Inc. 345 E. 47 Street New York, NY 10017
Meterological and Geoastrophysical Abstracts	American Meteorological Society (AMS) 45 Beacon Street Boston, MA 02108
Physics Abstracts, Science Abstracts Series A	IEE, IEEE, (See Above).
Pandex Current Index to Scientific and Technical Literature	CCM Information Sciences, Inc. 866 Third Ave. New York, NY 10022

To keep one abreast of the current literature in any field there are current surveillance services provided by professional societies and private companies. Several are listed in Table 5-5.

TABLE 5-5.- SELECTED CURRENT SURVEILLANCE SERVICES

TITLE	PUBLISHER
Current Contents - Physical Sciences	Institute for Scientific Information 325 Chestnut Street Philadelphia, PA 19016
Engineering Index Card Service and Monthly Bulletin	Engineering Index, Inc. 345 E. 47 Street New York, NY 10017
Current Papers Series	Institute of Electrical and Electronics Engineers, Inc. 345 E. 47 Street New York, NY 10017

5.5 REPORTS AND THESES

Information services for reports and theses are listed in Table 5-6.

TABLE 5-6.- INFORMATION SERVICES FOR REPORTS AND THESES

TITLE	PUBLISHER
Dissertation Abstracts	University Microfilms A Xerox Company 300 N. Zeeb Road Ann Arbor, MI 48106
Scientific and Technical Aerospace Reports (STAR) (See ref. 28).	NASA Scientific and Technical Information Facility (STIF) P.O. Box 33 College Park, MD 20740
Technical Abstract Bulletin (TAB)	Defense Documentation Center (DDC) Cameron Station Alexandria, VA 22314
U.S. Government Research and Development Reports (USGRDR)	Clearinghouse for Federal Scientific and Technical Information (CFSTI) National Bureau of Standards Springfield, VA 22151

5.6 SYMPOSIUMS AND CONFERENCES

Conference proceedings provide an excellent source of up-to-date information on the state-of-the-art in many fields. The American Institute of Aeronautics and Astronautics (AIAA) includes the tables of contents of many conferences in their International Aerospace Abstracts (IAA) published under a contract from the NASA (see Table 5-3). Table 5-7 lists many of the pertinent conferences and the accession number of the table of contents (see Table 5-1 for an explanation of the accession numbers). The IAA can also be searched to locate earlier conferences. A directory of published proceedings is also available (ref. 29).

To find out about future conferences the Technical Meetings Index of the Technical Meetings Information Service (TMIS)* should be consulted. Many useful meetings are abstracted in the Bulletin of the American Meteorological Society.

Three particular international agencies known to the author have some very special reports. These agencies are given in Table 5-7 under Items 10, 11, and 14. The U.S. Committees of these agencies prepare brief reports with excellent bibliographies in such fields as radio propagation, ionospheric propagation, radiation transfer, meteorological satellites, precipitation, atmospheric optics, etc. These are very worthwhile beginning places in literature searches.

5.7 COMPUTATIONAL AIDS

5.7.1 Nomographs and Slide Rules

A nomograph or nomogram is a graph that enables one by the aid of a straightedge to read off the value of a dependent variable when the values of two or more independent variables are given. An example of a nomograph is given in Section 8.7.

Graphical methods in research and engineering problems have been considered by Levens (ref. 30), Burrows (ref. 31), and Heacock (ref. 32). Nomography has been presented by Kuong (ref. 33) and Slaby (ref. 34). Recently Richards (ref. 35) discussed how to construct nomograms without equations.

Slide rules are actually a different mode of presentation for a nomograph. Various types of special rules are available.

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*79 Drumlin Road, Newton Centre, MA 02159

TABLE 5-7.- SELECTED CONFERENCES AND SYMPOSIUM TREATING THE TRANSMISSION OF ELECTROMAGNETIC RADIATION IN THE EARTH'S ATMOSPHERE.

CONFERENCE TITLE	DATE	LOCATION	TABLE of CONTENTS
1. Space Progress, Space Programs in the Next Decade, 8th International Technical and Scientific Conference on Space	Apr. 1-3, 1968	Rome, Italy	A68-37218
2. 5th Space Congress, Canaveral Council of Technical Societies	Mar. 11-14, 1968	Cocoa Beach, FL, USA	A68-37736
3. 10th Plenary Meeting, Committee on Space Research (COSPAR)	Jul. 24-29, 1967	London, England	A68-29401
4. 8th International Conference on Communications, Institute of Electrical and Electronics Engineers (EEE)	1968	Philadelphia, PA, USA	A68-35556
5. 9th International Conference on Communications, Institute of Electrical and Electronics Engineers (IEEE)	June 9-11, 1969	Boulder, CO, USA	______
6. International Colloquim on Atmospheric Turbulence and Radio Wave Propagation	June 15-22, 1965	Moscow, USSR	A68-17267
7. Laser Range Instrumentation Seminar-in-Depth, Optical Instrumentation Engineers	Oct. 16-17, 1967	El Paso, TX, USA	A68-29038
8. Propagation Factors in Space Communications, The Advisory Group for Aerospace Research and Development (AGARD) of the North Atlantic Treaty Organization (NATO)	Sept. 21-25, 1965	Rome, Italy	Section 6.4.8 A68-23069

TABLE 5-7.- Continued

CONFERENCE TITLE	DATE	LOCATION	TABLE OF CONTENTS
9. International Symposium of Dynamics of Large-Scale Atmospheric Processes	June 23-30, 1965	Moscow, USSR	A68-40003
10. Plenary Assemblies of the International Radio Consultative Committee (CCIR)	XIth, 1966	Oslo, Norway	Volume 2, A68-13041
11. General Assemblies of the International Union of Geodesy and Geophysics (IUGG) (Trans. Am. Geophys. Un., Vols. 41, 44, 48, Nos. 2)	12th, 1960 13th, 1963 14th, 1967	Helsinki, Finland Berkeley, CA USA Washington, DC, USA	U.S. Reports AGU, 1960 AGU, 1963 AGU, 1967
12. NATO Advanced Study Institute Winds and Turbance in the Stratosphere, Mesosphere, and Ionoshpere	Sept. 18 Oct. 1, 1966	Lindau, West Germany	A68-30667
13. International Symposium on Noctilucent Clouds	Mar. 15-18, 1966	Tallen, Estonian, USSR	A68-29634
14. General Assemblies of the International Scientific Radio Union (URSI)	XIIIth, 1960 XIVth, 1963 XVth, 1966	London, England Tokyo, Japan Munich, Germany	U.S. Reports (A67-28388; A68-28428).
15. 12th Conference on Radar Meteorology	Oct. 17-20, 1968	Norman, OK, USA	A68-18122
16. 13th Radar Meteorology Conference	Aug. 20-23, 1968	Montreal, Canada	A68-41001

TABLE 5-7.- Continued

CONFERENCE TITLE	DATE	LOCATION	TABLE of CONTENTS
17. 3rd Conference on Aerospace Meteorology	May 6-9, 1968	New Orleans, LA, USA	A68-35067
18. Conference on Lidar Probing of the Atmosphere	Apr. 16-17, 1968	Boulder, CO, USA	Goyer, 1968*
19. Conference on Tropospheric Wave Propagation	Sept. 30 - Oct. 2, 1968	London, England	A68-43674 IEE, 1968
20. Symposium on Electromagnetic Sensing of the Earth from Satellites	Nov. 22-24, 1965	Brooklyn, NY, USA	Zirkind, 1967**
21. Symposium on the Application of Atmospheric Studies to Satellite Transmissions	Sept. 3-5, 1969	Boston, MA, USA	
22. Effects of Atmospheric Water on Electromagnetic Wave Propagation NATO Advanced Study Institute	Aug. 29 - Sept. 6, 1969	London, Ontario, Canada	

*Bull. American Meteorological Society, Vol. 49, pp. 936-937; 1968.

**Published by Polytechnic Press, Brooklyn, NY

TABLE 5-8.- COMPUTATIONAL DEVICES OF A GENERAL NATURE

TITLE	DESCRIPTION	SOURCE
Special-Purpose Slide Rule Kit	Basic material to make your own special slide rule (either circular or straight)	TAC Products Corporation P.O. Box 25 Beverly, MA 01915
Custom Slide Rules		see above
Gerber Variable Scale	A mechanical device which utilizes a spring whose coils are always equally spaced	The Gerber Scientific Instrument Company P.O. Box 305 Hartford, CN 06101
Gerber Graphanalogue	Used for nonlinear scales	see above
Gerber Derivimeter	A mechanical desk computer designed to read the slope (derivative) directly from a curve.	see above
Radiation Slide Rules	An aid to solving Planck's law	see Table 7-4.
Planimeters	Mechanical instrument for accurately measuring plane areas of any form.	Various drafting supply companies

Computational devices of a general nature are listed in Table 5-8. A large number of technical aids for design are now offered by many companies. Additional aids are discussed in Sections 6.7 and 7.7.

5.7.2 Tables and Charts

A table is an arrangement of words, facts, or figures in some systematic order for ease of reference and comparison. Long tables may fill several volumes, e.g. the "International Critical Tables", 7 volumes. A short table may require a line or two.

Table 5-9 lists several directories or indexes of tables along with a few recent compilations of tables that could not have appeared in the directories.

A chart is a sheet giving information in an ordered form. Charts dealing with the electromagnetic spectrum are listed in Table 3-2. Two examples are given in Figs. 3-1 and 3-2.

TABLE 5-9.- REPRESENTATIVE TABLES AND INDEXES

TITLE	SOURCE
An Index of Mathematical Tables	Fletcher, Miller, Rosenhead, and Comrie (ref. 36)
Tables of Higher Functions	Jahnke, Emde, and Lösch (ref. 37)
Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables	Abramowitz and Stegun (ref. 38)
Mathematical Handbook for Scientists and Engineers	Korn and Korn (ref. 39)
CRC Handbook of Tables for Probability and Statistics	Beyer (ref. 40)
Guide to Tables in Mathematical Statistics	Greenwood and Hartley (ref. 41)
Handbook of Statistical Tables	Owen (ref. 42)

5.7.3 Computers

A computer is defined here as an automatic electric and/or electronic machine for performing calculations. These machines range from desk top size to room size. Where available, the computer has to a large extent obviated the frequent use of slide rules and tables. The computer and associated equipment can create the tables, graphs, nomographs, etc. that may be required.

There are several ways in which computer programs can be located. One is the COmputer Software Management Information Center (COSMIC) located at Barrow Hall at the University of Georgia at Athens. The computer manufacturers also have program information.

Recently an International Journal of Numerical Methods in Engineering was started by Wiley-Interscience. This type of publication can aid in making more efficient use of computers.

5.8 PATENTS

Patents are an extremely useful source of technical information on instrumentation and techniques. Newman (ref. 43) describes how the U. S. Patent Office can be used as an information source.

The journal Applied Optics has a section on patents in each issue.

Printed copies of United States Patents may be ordered from the Commissioner of Patents, Washington, D.C. 20231 ($0.50 each).

6.0 INFORMATION SOURCES FOR THE RADIO REGION

6.1 INTRODUCTION

An informative frequency spectrum chart between the frequencies of 30 kHz (100 m) and 300 GHz (1 mm) is presented and described in Chapter 3 (Fig. 3-2). This chart is an expanded section of the frequency spectrum chart presented in Fig. 3-1. These charts provide an overview of the frequency spectrum so necessary in program planning and in brainstorming sessions.

Section 6.2 presents information on bibliographies dealing with the propagation of radio waves. Section 6.3 discusses various reviews of radio wave and microwave propagation in the earth's atmosphere. Section 6.4 deals with books, and in particular, presents the table of contents of many books and book chapters. Section 6.4.23 is the single exception, as it is a report. Section 6.5 considers periodicals and, in particular, lists several periodicals which usually contain articles on atmospheric effects on radio waves. Section 6.6 mentions information centers and Section 6.7 covers computational aids.

6.2 BIBLIOGRAPHIES

Table 6-1 presents bibliographies on the propagation of radiowaves in the earth's atmosphere and Table 6-2 presents bibliographies in the microwave region.

6.3 REVIEWS

Review documents on radio wave and microwave propagation in the earth's atmosphere are presented in Tables 6-3 and 6-4, respectively.

6.4 BOOKS

(continued on page 66)

TABLE 6-1.- SELECTED BIBLIOGRAPHIES ON THE PROPAGATION OF RADIO WAVES IN THE EARTH'S ATMOSPHERE

TITLE	REFERENCES	REMARKS
Bibliography on Ionospheric Propagation of Radio Waves	Nupen, 1960 ref. 1	1404 references with abstracts; subject, author and geographical indexes
Bibliography on Meteoric Radio Wave Propagation	Nupen, 1961 ref. 2	368 references with abstracts; subject, author geographical, and chronological indexes
Bibliography on Auroral Radio Wave Propagation	Nupen, 1962 ref. 3	297 references with abstracts; subject, author, geographical, and chronological indexes
Bibliography on Atmospheric Aspects of Radio Astronomy	Nupen, 1963 ref. 4	1013 references with abstracts; subject, author, geographical, and chronological indexes
Bibliography on Tropospheric Propagation of Radio Waves	Nupen, 1965 ref. 5	1110 references with abstracts; subject, author, and geographical indexes

TABLE 6-2.- SELECTED BIBLIOGRAPHIES ON THE PROPAGATION OF MICROWAVES IN THE EARTH'S ATMOSPHERE

TITLE	REFERENCES	REMARKS
Survey of Attenuation by the Earth's Atmosphere at Millimeter Wavelengths	Hunt, 1960, ref. 6	25 references; 41 graphs of theoretical and experimental attenuation curves
Survey of the Literature on Millimeter and Submillimeter Waves	Lurye, 1960, ref. 7	40 references on propagation with explanatory text
Atmospheric Absorption of 10-400 kmcps Radiation: Summary and Bibliography to 1961	Rosenblum, 1961, ref. 8	84 references without titles; summary of theoretical and experimental work
Bibliography on Atmospheric Aspects of Radio Astronomy	Nupen, 1963, ref. 4	1013 references with abstracts; subject, geographicak, author and chronological indexes
Scattering and Attenuation by Precipatation Particles	Boudreau and Stone, 1965 ref. 9	494 references, subject outline and index
Bibliography on Tropospheric Propagation of Radio Waves	Nupen, 1965, ref. 5	1110 references with abstracts; subject outline and index; geographical, and author indexes

TABLE 6-3.- SELECTED REVIEWS ON THE PROPAGATION OF RADIO WAVES IN THE EARTH'S ATMOSPHERE WITH EMPHASIS ON EARTH-TO-SPACE PROPAGATION PATHS.

TITLE	REFERENCE
A Survey of Ionospheric Effects on Earth-Space Radio Propagation	Lawrence, Little, and Chivers, 1964, ref. 10, etc.
Radio Wave Propagation	Krassner and Michaels, 1964, ref. 11
Report of the United States of America National Committee to the XIV General Assembly of the International Scientific Radio Union (URSI)	URSI, 1964, ref. 12
Atmospheric Effects on Radio Wave Propagation	Millman, 1965, ref. 13
Report of the USA to the XVth General Assembly of URSI	URSI, 1966, ref. 14
A survey of Tropospheric, Ionospheric, and Extraterrestrial Effects on Radio Propagation Between the Earth and Space Vehicles (6.4.9)	Millman, 1967, ref. 15
Study of Meter, Decimeter, Centimeter, and Submillimeter Radiowave Propagation	Vvedenskiy, Kolosox, and Sokolov, 1967, ref. 16
Propagation in the Ionosphere (6.4.5)	Evans, 1968, ref. 17

TABLE 6-4.- SELECTED REVIEWS ON THE PROPAGATION OF MICROWAVES IN THE EARTH'S ATMOSPHERE WITH EMPHASIS ON EARTH-TO-SPACE PROPAGATION PATHS

TITLE	REFERENCE
Factors for Systems Considerations of Earth Satellites	Siewers, et al., 1960, ref. 18.
The Radio Spectrum from 10 Gc to 300 Gc in Aerospace Communications (6.4.23)	Evans, Bachynski, and Wacker, 1962, ref. 19.
Propagation of Radar Waves	Skolnik, 1962, ref. 20.
Propagation of Radio Waves	Harvey, 1963, ref. 21.
Advances in Radar Meteorology	Atlas, 1964, ref. 22.
Survey of Propagation Effects (6.4.11)	Barton, 1964, ref. 23.
Tropospheric Propagation Affecting Space Communications	Hogg, 1964, ref. 24.
Radio-Wave Propagation	Krassner and Michaels, 1964, ref. 11.
Tropospheric Propagation	Rice and Herbstreit, 1964, ref. 25.
Report of the United States of America National Committee to the XIV General Assembly of URSI	URSI, 1964, ref. 12.
Earth-to-Space Communications at Millimeter Wavelengths	Altshuler, 1965, ref. 26.
Some Aspects of Electromagnetic Wave Propagation	Atlas, et al., 1964, ref. 27.
Communications in Space	Haviland and House, 1965, ref. 28.
Atmospheric Effects on Radio Wave Propagation (6.4.12)	Millman, 1965, ref. 13

(continued on page 65)

TABLE 6-4.- Continued

TITLE	REFERENCE
Report of the United States of America National Committee to the XV General Assembly of URSI	URSI, 1966, ref. 14.
Influence of the Non-Ionized Regions of the Atmosphere on the Propagation of Waves, Earth-Space Propagation	CCIR, 1967, ref. 29.
Factors Affecting the Selection of Frequencies for Telecommunications with and Between Spacecraft	CCIR, 1967, ref. 30.
A Survey of Tropospheric, Ionospheric, and Extraterrestrial Effects on Radio Propagation Between the Earth and Space Vehicles*	Millman, 1967, ref. 15.
Study of Meter, Decimeter, Centimeter, and Submillimeter Radiowave Propagation	Vvedenskiy, Kolosov and Sokolov, 1967, ref. 16.
Millimeter Communication Propagation	Raytheon, 1965, 1967, refs. 31, 32.
Propagation	Heisler and Hewitt, 1966, ref. 33.
Advanced Deep Space Communication System Study	Hughes, 1967, ref. 34.
Investigation in and Research of Aerospace Related Microwave Technology	University of Penn., 1967, ref. 35.
Signal Attenuation Due to Neutral Oxygen and Water Vapour, Rain, and Clouds	Benoit, 1968, ref. 36.
Deep Space Communication and Navigation Study	BTL, 1968, ref. 37.
Millimeter-Wave Communication Through the Atmosphere	Hogg, 1968, ref. 38.
Propagation in the Neutral Atmosphere	Rogers, 1968, ref. 39.

(continued on page 67)

6.4 continued

6.4.1 INTRODUCTION

A list of books containing information on the propagation of radiowaves and microwaves in the earth's atmosphere is found in Table 6-5. In Table 6-5 the titles are arranged alphabetically. If any part of the contents of these books is listed in this handbook, the number of the section where it appears can be found in column 3 of the Table. Although the main emphasis of this guide is on earth-to-space paths, some ground-to-ground material is included in Table 6-5. Table 5-3 should be consulted for a selected list of general books treating the propagation of radio waves in the earth's atmosphere.

In the listing of the tables of contents in Sections 6.4.2 - 6.4.24, section headings and pages are those of the original document.

6.4.2 HANDBOOK OF GEOPHYSICS AND SPACE ENVIORNMENT, (Valley, 1965, ref. 40)

This handbook is a comprehensive collection of data, formulas, definitions, and theories about the earth's environment. This information was obtained by many experts: Air Force Scientists of other government organizations, industrial and university contractors, and private individuals.

(continued on page 70)

TABLE 6-5.- SELECTED BOOKS DISCUSSING THE PROPAGATION OF RADIO WAVES AND MICROWAVES IN THE EARTH'S ATMOSPHERE

TITLE	REFERENCE	TABLE OF CONTENTS
Communication Systems Engineering Handbook	Hamsher, 1967, ref. 52	---
Documents of the XIth Plenary Assembly of the International Radio Consultative Committee	CCIR, 1967, ref. 53	---
Electromagnetic Sensing of the Earth From Satellites	Zirkind, 1967, ref. 54	---
Handbook of Geophysics and Space Environments	Valley, 1965, ref. 40	6.4.2, 6.4.6
Handbook of Telemetry and Remote Control	Gruenberg, 1967, ref. 55	---
Interference Notebook	Heisler and Hewitt, 1966, ref. 33	6.4.20
Introduction to Radar Systems	Skolnik, 1962, ref. 20	6.4.13
Introduction to Space Communication Systems	Krassner and Michaels, 1964, ref. 11	6.4.14
Ionospheric Radio Waves	Davies, 1969, ref. 51	6.4.24
Ionospheric Radio Wave Propagation	Davies, 1965 ref. 41	6.4.3
Landolt-Bornstein, Numerical Data and Functional Relationships in Science and Technology, New Series	Siedentopf, et al., 1965, ref. 46	6.4.10
Meteorological and Astronomical Influence on Radio Wave Propagation	Landmark, 1963, ref. 47	6.4.15, 6.4.16

(continued on page 69)

TABLE 6-5.- Continued

TITLE	REFERENCE	TABLE OF CONTENTS
Microwave Engineering	Harvey, 1963, ref. 21	---
Modern Radar Analysis, Evaluation, and System Design	Berkowitz, 1965, ref. 56	6.4.12
Proceedings of the Tropospheric Wave Propagation Conference	IEE, 1968, ref. 57	---
Propagation Factors in Space Communications	Blackband, 1967, ref. 45	6.4.8, 6.4.9
Propagation of Radio Waves at Frequencies Below 300 kc/s	Blackband, 1964, ref. 58	---
Progress in Radio Science	Beaty, et al., 1967, ref. 59	---
Propagation of Short Radio Waves	Kerr, 1951, ref. 44	6.4.7
Radar Astronomy	Evans and Hagfors, 1968, ref. 43	6.4.5
Radar Handbook	Skolnik, ref. 60	---
Radar Meteorology	Battan, 1959, ref. 61	---
Radar Systems Analysis	Barton, 1964, ref. 23	6.4.11
Radio Astronomical and Satellite Studies of the Atmosphere	Aarons, 1963, (59) ref. 62	---
Radio Meteorology	Bean and Dutton, 1966, ref. 42.	6.4.4, 6.4.17, 6.4.18
Radio Wave Propagation	Burrows and Atwood, 1949, ref. 48	6.4.19

(continued on page 70)

TABLE 6-5.- Continued

TITLE	REFERENCE	TABLE OF CONTENTS
Radio Wave Propagation in the Ionosphere	Kelso, 1964, ref. 63	---
Reference Data for Radio Engineers	Westman, 1968, ref. 49	6.4.21
Spread-F and Its Effects Upon Radiowave Propagation and Communication	Newman, 1966, ref. 64	---
Systems Engineering Handbook	Machol, 1965, ref. 65	---
Transmission Loss Predictions for Tropospheric Communication Circuits	Rice, et al., 1966 ref. 66	---
Ultra High Frequency Propagation	Reed and Russell, 1953, ref. 50	6.4.22
VLF Radio Engineering	Watt, 1967, ref. 67	---
Wave Propagation in a Turbulent Medium	Tatarski, 1961, ref. 68.	---

The handbook was written by scientists of the Air Force Cambridge Research Laboratories (AFCRL) to serve a broad spectrum of users: the planner, designer, developer, and operator of aerospace systems; the scientist who will find the tables and figures a convenient reference is his own field; the specialist who needs reliable environmental data in another discipline; and scientific-minded people who need a summary of space-age environmental research.

Chapter 5. Precipitation, Clouds, and Aerosols*

Chapter 6. Atmospheric Composition

Chapter 7. Atmospheric Optics (Section 7.4.2 of this Handbook)

Chapter 8. Atmospheric Electricity

Chapter 9. Some Aspects of Electromagnetic Wave Propagation**

Chapter 10. Transmission and Detection of Infrared Radiation (Section 7.4.18 of this Handbook)

Chapter 11. The Geomagnetic Field

Chapter 12. Ionospheric Physics

Chapter 13. Airglow and Aruorae

Chapter 14. Meteoritic Phenomena

Chapter 15. The Sun

Chapter 16. Solar Electronagnetic Radiation

Chapter 17. Corpuscular Radiation

Chapter 18. Interplanetary Space and the Solar Atmosphere

Chapter 19. The Lunar Environment

Chapter 20. Planetary Environments

Chapter 21. Astrophysics and Astronomy

Chapter 22. Radio Astronomy***

Appendix A Units, Constants and Conversion Factors

Appendix B Blackbody Radiation

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* Revised by Cole, et. al., 1969, (ref. 77).

** Revised by Falcone and Dyer, 1970, (ref. 76).

*** Revised in Guidice, 1967, (ref. 69).

6.4.3 Ionospheric Radio Propagation, (Davies, 1965, ref. 41)

6.4.4 Radio Meteorology, (Bean and Dutton, 1968, ref. 42)

Chapters 3 and 7 of Radio Meteorology are further outlined in Sections 6.4.17 and 6.4.18, respectively.

6.4.5 Radio wave propagation through the earth's neutral atmosphere and ionosphere, Chapter 2, Radar Astronomy, (Evans and Hagfors, 1968, ref. 43).

6.4.5 (Continued)

6.4.6 Some Aspects of Electromagnetic Wave Propagation, Chapter 9, Handbook of Geophysics and Space Environments, (Atlas et al., 1968, ref. 27)

6.4.6 (Continued)

6.4.7 Propagation of Short Radio Waves, (Kerr, 1951, ref. 44).

6.4.7 (Continued)

6.4.7 (Continued)

6.4.8 Propagation Factors in Space Communications, (Blackband, 1967, ref. 45).

6.4.8 (Continued)

6.4.8 (Continued)

6.4.8 (Continued)

6.4.8 (Continued)

Page in original

SUPPLEMENT-TRANSLATIONS

6.4.9 General Survey of Propagation Factors, Chapter 1-1, Propagation Factors in Space Communications, (Millman, 1967, ref. 15)

This book is outlined in Section 6.4.8.

6.4.9 (Continued)

6.4.10 Influence of the Earth's Atmosphere, Section 1.5, <u>Landolt-Bornstein</u>, New Series, (Siedentopf, et al. 1965, ref. 46)

6.4.10 (Continued)

6.4.11 Survey of Propagation Effects, Chapter 15, Radar System Analysis, (Barton, 1964, ref. 23).

6.4.11 (Continued)

6.4.12 Atmospheric Effects on Radio Wave Propagation, Part V, Section 1, Modern Radar Analysis, Evaluation, and System Design, (Millman, 1965, ref. 13).

6.4.12 (Continued)

6.4.12 (Continued)

6.4.13 Propagation of Radar Waves, Chapter 11, <u>Introduction to Radar Systems</u>, (Skolnik, 1962, ref. 20)

6.4.14 Radio-wave Propagation, Chapter 4, Introduction to Space Communication Systems, (Krassner and Michaels, 1964, ref. 11)

6.4.14 (Continued)

6.4.15 The Propagation of Radio Signals at the Lower Frequencies, Chapter 10, <u>Meteorological and Astronomical Influences on Radio Propagation</u>, (Landmark, 1963, ref. 47)

In this survey article an account is given of the main features of the propagation of radio signals in the following frequency bands:

Low Frequency	LF	300 KHz - 30 KHz
Very Low Frequency	VLF	30 KHz - 3 KHz
Extremely Low Frequency	ELF	3 KHz

6.4.16 Propagation of Decameter Waves (HF Band), Chapter 11, Meteorological and Astronomical Influences on Radio Propagation, (Landmark, 1963, ref. 47)

6.4.16 (Continued)

6.4.17 Tropospheric Refraction, Chapter 3, Radio Meteorology, (Bean and Dutton, 1965, ref. 42)

6.4.17 (Continued)

6.4.18 Attenuation of Radio Waves, Chapter 7, Radio Meteorology, (Bean and Dutton, 1965, ref. 42)

6.4.18 (Continued)

6.4.19 Dielectric Constant, Absorption, and Scattering, Chapter 5, Radio Wave Propagation, (Burrows and Atwood, 1949, ref. 48)

6.4.19 (Continued)

6.4.20 Propagation, Section VI, Interference Notebook, (Heisler and Hewitt, 1966, ref. 33)

6.4.20 (Continued)

6.4.20 (Continued)

6.4.20 (Continued)

6.4.20 (Continued)

6.4.21 Electromagnetic-Wave Propagation, Chapter 26, Reference Data for Radio Engineers, (Westman, 1968, ref. 49)

6.4.21 (Continued)

6.4.21 (Continued)

6.4.22 Ultra High Frequency Propagation, (Reed and Russell, 1953, ref. 50)

6.4.22 (Continued)

6.4.23 The Radio Spectrum from 10 GC to 300 GC in Aerospace Communications, Vol. IV, (Evans, Bachynski, and Wacker, 1962, ref. 19)

PART I - Absorption of Electromagnetic Waves in the Atmosphere of The Earth and Other Planets

6.4.23 (Continued)

6.4.23 (Continued)

6.4.24 Ionospheric Radio Waves, Davies, (ref. 51)

6.4.24 (Continued)

6.4.25 Selected portions from Electromagnetic Scattering, (Kerker, 1963, ref. 75), (See Section 7.4.40).

PART III Microwave and Radiowave Scattering in the Atmosphere

6.5 PERIODICALS

Table 6-6 lists selected periodicals which usually contain information on atmospheric effects on radio wave propagation.

TABLE 6-6.- SELECTED PERIODICALS WHICH TREAT ATMOSPHERIC EFFECTS ON RADIO WAVE AND MICROWAVE PROPAGATION

Title	Publisher
IEEE Transactions on Antennas and Propagation	Institute of Electrical and Electronics Engineers, (IEEE), New York,
J. Geophysical Research	American Geophysical Union (AGU), Washington.
Proc. IEE	Institute of Electrical Engineers (IEE), London.
Proc. IEEE	IEEE
Radio Science	AGU

6.6 INFORMATION CENTERS

Information centers are discussed in Section 5.2. Table 5-2 lists several centers which deal specifically with electromagnetic wave propagation in the earth's atmosphere.

6.7 COMPUTATIONAL AIDS

Computational aids are discussed in general in Section 5.7. Table 6-7 presents some computational devices for use in problems dealing with radio waves.

7.0 INFORMATION SOURCES FOR THE OPTICAL REGION

7.1 INTRODUCTION

Section 7.2 presents information on bibliographies dealing with the propagation of optical waves in the earth's atmosphere.

Section 7.3 discusses various reviews of optical wave propagation in the earth's atmosphere.

TABLE 6-7.- COMPUTATION AIDS IN THE RADIO REGION

TITLE	DESCRIPTION	SOURCE
1. Inverse Square Law Slide Rule	Part of the Antenna and Propagation Computer	Andrews P.O. Box 807 Chicago, IL 60642 ($2.00)
2. Radar Range Equation Solution	--	W.C. Morchin (Nov 1966) The Electronic Engineer, pp. 92-93
3. Amphenol/RF Calculator Radio Transmission Line Calculator (Smith Chart) and Circular Slide Rule	--	Amphenol RF Div. 33 E. Franklin St. Danbury, CN 06810 ($3.00)
4. Antenna Handbook	Various graphs on Antenna Design	Washington Aluminum Co., Inc., Technical Division Knecht Avenue and Penn. R.R. Baltimore, MD 21229
5. SHF Transmission Lines and Antennas	Contains 104 nomograms covering the most frequently encountered problems of transmission line elements and antenna devices for microwave frequencies	Rodinov, 1969, ref. 70

TABLE 6-7.- Continued

TITLE	DESCRIPTION	SOURCE
6. Complete Microwave Scattering and Extinction Properties of Polydispersed Cloud and Rain Elements	--	Deirmendjian, 1963, ref. 71
7. Data on the Complex Index of Refraction of Water	--	Lukes, 1968, ref. 72
8. Ionospheric Properties	Ionospheric Predictions are issued monthly as an aid in determining the best sky-wave frequencies over any transmission path, at any time of day, for average conditions for the month. Issued three months in advance, each issue provides tables of numerical coefficients that define the functions describing the predicted worldwide distribution of foF2 and M(3000) F2 and maps for each even hour of universal time of MUF (Zero) F2 and MUF (4000) F2	ITS, ref. 73

Section 7.4 deals with books and in particular presents the table of contents of many books and book chapters.

Section 7.5 considers periodicals and in particular lists several periodicals which usually contain articles on atmospheric effects on optical waves or spectroscopy at these frequencies.

Section 7.6 deals with information centers and section 7.7 covers computational aids useful in the optical frequency region.

7.2 BIBLIOGRAPHIES

Table 7-1 presents bibliographies on the propagation of optical waves in the earth's atmosphere.

TABLE 7-1.- BIBLIOGRAPHIES ON THE PROPAGATION OF OPTICAL WAVES IN THE EARTH'S ATMOSPHERE WITH EMPHASIS ON EARTH-TO-SPACE PROPAGATION

TITLE	REFERENCE
Research in Atmospheric Optics and Radiation	Sekera, 1960, ref. 1
Atmospheric Radiation and Optics	Kaplan and Sekera, 1963, ref. 2
Bibliography on Meteorological Satellites	Kiss, 1963, ref. 3
Optical Scintillation; A Survey of the Literature	Meyer-Arendt and Emmanual, 1965, ref. 4
A Literature Survey on the Atmospheric Effects on the Propagation of 1.06 Micron Laser Radiation	Roy and Emmons, 1965, ref. 5
Permuted Bibliography on Laser Literature	Ashburn and Ashburn, 1967, ref. 6
Atmospheric Optics and Radiation Transfer	Howard and Garing, 1967, ref. 7
Laser Abstracts	Lowrey-Cockcroft Abstracts, Evanston, IL

7.3 REVIEWS

Table 7-2 lists reviews of various aspects of optical wave propagation in the earth's atmosphere with emphasis on earth-to-space propagation paths.

7.4 BOOKS

TABLE 7-2.- SELECTED REVIEWS ON THE PROPAGATION OF OPTICAL WAVES IN THE EARTH'S ATMOSPHERE WITH EMPHASIS ON EARTH-TO-SPACE PROPAGATION PATHS

TITLE	REFERENCE
Vision Through the Atmosphere*	Middleton, 1952, 1957, refs. 8, 9.
The Transmission of the Atmosphere in the Infrared	Howard, 1959, ref. 10
The Transmission of the Atmosphere in the Infrared - a Review	Howard and Garing, 1962, ref. 11
Infrared	King, et al., 1963, ref. 12
Scattered Radiation in the Atmosphere	Bullrich, 1964, ref. 13
Atmospheric Optics (7.4.2)	Elterman and Toolin, 1965, ref. 14
Transmission and Detection of Infrared Radiation (7.4.18)	Howard, Garing and Walter, 1965, ref. 15
Atmospheric Phenomena (7.4.23)	Plass & Yates, 1965, ref. 16
The Effect of the Atmosphere on Solar Radiation Reaching the Ground (7.4.5)	Robinson, 1966, ref. 17
Atmospheric Optics and Radiation Transfer	Howard and Garing, 1967, ref. 7
Transmission of Infrared Radiation Through the Earth's Atmosphere (7.4.30)	Hudson, 1969, ref. 18
Optics of the Atmosphere: Scattering, Absorption, Refraction (7.4.10;11;12;13,14,15)	McCartney, ref. 19
Penetrability of Haze, Fog, Clouds, and Precipitation by Radiant Energy over the Spectral Range 0.1 Micron to 10 Centimeters (7.4.39)	Lukes, ref. 56

TABLE 7-3.- SELECTED BOOKS DISCUSSING THE PROPAGATION OF OPTICAL WAVES IN THE EARTH'S ATMOSPHERE

TITLE	REFERENCE	TABLE OF CONTENTS
Applied Optics and Optical Engineering	Kingslake, 1967, ref. 38	7.4.3
Astrophysical Quantities	Allen, 1963, ref. 29	7.4.24
Atmospheric Radiation I Theoretical Basis	Goody, 1964, ref. 39	---
Compendium of Meteorology	Malone, 1959, ref. 23	7.4.9
Elements of Infrared Technology: Generation, Transmission, and Detection	Kruse, et al. 1962, ref. 32	7.4.27
Fundamentals of Infrared Technology	Holter, et al. 1962, ref. 28	7.4.23
Handbook of Geophysics and Space Environments	Valley, 1965, ref. 40	6.4.2; 7.4.2;
Handbook of Military Infrared Technology	Wolfe, ref. 41	7.4.19; 20
Handbuch der Physik	Middleton, 1957, ref. 9	7.4.8
Infrared Physics and Engineering	Jamieson, et al. 1963, ref. 27	7.4.21; 22
Infrared Radiation	Hackforth, 1960, ref. 42	---
Infrared Radiation: A Handbook for Applications	Bramson, ref. 33	7.4.28
Infrared Systems Engineering	Hudson, 1969, ref. 18	7.4.30
Introduction to Theoretical Meteorology	Hess, 1959, ref. 43	---

(continued on page 119)

7.4.1 Introduction

Table 7-3 lists the title of books which contain information on optical wave propagation in the earth's atmosphere. The titles are listed alphabetically and the section number of the table of contents, if given in this handbook, are given in column 3.

In the listing of the tables of contents in Sections 7.4.2 - 7.4.40 the section headings and pages are those of the original document.

7.4.2 Atmospheric Optics, Chapter 7, Handbook of Geophysics and Space Environments (Elterman and Toolin, 1965, ref. 20)

(continued on page 120)

TABLE 7-3.- Continued

TITLE	REFERENCE	TABLE OF CONTENTS
Landolt-Bornstein	Siedentopf, et al., 1965, ref. 25	7.4.17
Laser Communication Systems	Pratt, ref. 35	7.4.31
Light Scattering by Small Particles	Van de Hulst, 1957, ref. 44	---
Optical and Photographic Reconnaissance Systems	Jensen, 1968, ref. 34	7.4.29
Optical Instability of the Earth's Atmosphere	Kucherov, 1965, ref. 45	---
Optics of the Atmosphere: Scattering, Absorption, and Refraction	McCartney, 1970, ref. 19	7.4.10; 11; 12; 13; 14; 15
Proceedings of the Symposium on Electromagnetic Sensing of the Earth from Satellites	Zirkind, 1967, ref. 46	---
Radiation in the Atmosphere	Kondratyev, 1969, ref. 36	7.4.32;33;34;35
Radiative Heat Exchange in the Atmosphere	Kondratyev, 1965, ref. 47	---
Smithsonian Meteorological Tables	List, 1963, ref. 30	7.4.25
Smithsonian Physical Tables	Forsythe, 1964, ref. 48	---
Solar Radiation	Robinson, 1966, ref. 22	7.4.4; 5; 6
System Engineering Handbook	Machol, 1965, ref. 49	4.4.2; 3
The Earth as a Planet	Kuiper, 1954, ref. 50	---

(continued on page 120)

TABLE 7-3.- Continued

TITLE	REFERENCE	TABLE OF CONTENTS
Ultraviolet Radiation	Koller, 1965, ref. 31	7.4.26
Visibility in the Atmosphere	Gavrilov, 1966, ref. 51	(A67-40600, See Table 5-1)
Vision Through the Atmosphere	Middleton, 1952, ref. 8	7.4.7
Visibility	Duntley, et al. ref. 37	7.4.36

7.4.2 (Continued)

7.4.3 Atmospheric Effects, Chapter 4, Volume I, <u>Applied Optics and Optical Engineering</u>, (Stewart and Hopfield, 1967, ref. 21)

7.4.4 Solar Radiation, (Robinson, 1966, ref. 22)

7.4.5 The Effect of the Atmosphere on Solar Radiation Reaching the Earth, Chapter 3, Solar Radiation, (Robinson, 1966, ref. 22)

7.4.6 Direct and Scattered Radiation Reaching the Earth, as Influenced by Atmospheric, Geographical and Astronomical Factors, Chapter 4, Solar Radiation, (Robinson, 1966, ref. 22)

7.4.6 (Continued)

7.4.7 Vision Through the Atmosphere, (Middleton, 152, ref. 8)

7.4.7 (Continued)

7.4.8 Vision Through the Atmosphere, Handbuch der Physik, XLVIII, (Middleton, 1957, ref. 9)

7.4.8 (Continued)

7.4.8 (Continued)

7.4.8 (Continued)

7.4.9 Selected Titles from the <u>Compendium of Meteorology</u>, (Malone, 1959, ref. 23)

7.4.9 (Continued)

7.4.10 Optics of the Atmosphere: Scattering, Absorption, Refraction (McCartney, 1970, ref. 19)

7.4.11 Rayleigh Scattering by Molecules, Chapter 4, Optics of the Atmosphere: Scattering, Absorption, Refraction, (McCartney, 1970, ref. 19)

Section

4.1 The Elemental Scatterer

4.2 Radiation from a Molecular Dipole

4.3 Angular Scattering Function

4.4 Total Scattering Function

4.5 Numerical Values of Scattering Coefficients

4.6 Corrections for Temperature, Pressure, and Altitude

4.7 Experimental Verifications of Rayleigh Theory

4.8 Rayleigh Scattering in the Atmosphere

7.4.12 Mie Scattering by Particles, Chapter 5, Optics of the Atmosphere: Scattering, Absorption, Refraction, (McCartney, 1970, ref. 19)

Section

5.1 Basic Considerations

5.2 Angular Scattering Function

5.3 Mie Coefficient and Total Scattering Function

5.4 Numerical Values of Scattering Coefficients

5.5 Effects of Meteorological Conditions

5.6 Experimental Verifications of the Mie Theory

5.7 Mie Scattering in the Atmosphere

5.8 Atmospheric Contrast and Visual Range

7.4.13 Absorption and Emission by Gases, Chapter 6, Optics of the Atmosphere: Scattering, Absorption, Refraction (McCartney, 1970, ref. 19)

Section

6.1 An Overall View of the Processes

6.2 Molecular Energy Levels and Transitions

6.3 Spectra of Simultaneous Transitions

6.4 Parameters of Line and Band Absorptions

6.5 Absorption Data for the Atmospheric Gases

6.6 Radiative Transfer of Energy

6.7 Elements of the Earth's Heat Balance

7.4.14 Theory and Effects of Refraction, Chapter 7, Optics of the Atmosphere: Scattering, Absorption, Refraction (McCartney, 1970, ref. 19)

7.4.15 Atmospheric Radiance, Transmittance, and Visibility, Chapter 8, Optics of the Atmosphere: Scattering, Absorption, Refraction (McCartney, 1970, ref. 19)

7.4.16 Solar Electromagnetic Radiation, Chapter 16, Handbook of Geophysics and Space Environments, (Gast, et al. 1965, ref. 24)

7.4.16 (Continued)

7.4.17 Influence of the Earth's Atmosphere, Section 1.5, Landolt-Börnstein, New Series, (Siedentopf, et al. 1957, ref. 25).

The contents of this section are found in Section 6.4.10 of this handbook. While some of the text is in German most of the paper has partial English text.

7.4.18 Transmission and Detection of Infrared Radiation, Chapter 10, Handbook of Geophysics and Space Environments (Howard, Garing, and Walter, 1965, ref. 15).

7.4.19 Backgrounds, Chapter 5, Handbook of Military Infrared Technology, (Kauth, 1965, ref. 26).

7.4.19 (Continued)

7.4.20 Atmospheric Phenomena, Chapter 6, Handbook of Military Infrared Technology, (Plass and Yates, 1965, ref. 16).

7.4.20 (Continued)

7.4.20 (Continued)

7.4.21 Transmission of Infrared Radiation Through the Atmosphere, Chapter 3, Infrared Physics and Engineering, (Jamieson, et al. 1963, ref. 27).

7.4.21 (Continued)

7.4.22 Backgrounds and Targets, Chapter 4, Infrared Physics and Engineering, (Jamieson, et al. 1963, ref. 27).

7.4.23 Atmospheric Phenomena, Chapter 4, Fundamentals of Infrared Technology, (Holter, et al. 1962, ref. 28).

7.4.24 Selected data from Astrophysical Quantities, (Allen, 1963, ref. 29).

7.4.24 (Continued)

7.4.25 Radiation and Visibility Tables, Section X, Smithsonian Meteorological Tables, (List, 1966, ref. 30).

7.4.25 (Continued)

7.4.25 (Continued)

7.4.26 Solar Radiation, Chapter 4, Ultraviolet Radiation, (Koller, 1965, ref. 31).

7.4.26 (Continued)

7.4.27 Optical Properties of the Atmosphere, Chapter 5, Elements of Infrared Technology: Generation, Transmission, and Detection, (Kruse, McGlauchlin and McQuistan, 1962, ref.32).

7.4.28 Atmospheric Transmission, Part 9, Infrared Radiation; A Handbook for Applications, (Bramson, 1968, ref. 33).

7.4.29 Atmospheric Optics, Chapter 5, Optical and Photographic Reconnaissance Systems, (Jensen, 1968, ref. 34).

7.4.29 (Continued)

7.4.30 Transmission of Infrared Radiation Through the Earth's Atmosphere, Chapter 4, Infrared System Engineering, (Hudson, ref. 18).

7.4.31 Atmospheric Propagation, Chapter 7, Laser Communications Systems, (Pratt, ref. 35).

7.4.32 Radiation in the Atmosphere, (Kondratyev, 1969, ref. 36).

7.4.32 (Continued)

7.4.33 Radiation Absorption in the Atmosphere, Chapter 3, Radiation in the Atmosphere, (Kondratyev, 1969, ref. 36), Section 7.4.32.

7.4.34 Scattering of Radiation in the Atmosphere, Chapter 4, Radiation in the Atmosphere, (Kondratyev, ref. 36), Section 7.4.32.

7.4.35 Direct Solar Radiation, Chapter 5 in Radiation in the Atmosphere, (Kondratyev, 1969, ref. 36), Section 7.4.32.

7.4.35 (Continued)

7.4.36 Visibility, (S. Q. Duntley, et al. 1964, ref. 37)

7.4.37 Experimental Studies of Optical Properties of the Surface Layer of the Atmosphere, (Barteneva, et al. 1967, ref. 61).

7.4.38 Atmospheric absorption and laser radiation, (Long, 1966, ref. 62).

7.4.38 (Continued)

Note: There are hundreds of atmospheric transmission spectra for horizontal paths given.

7.4.39 Penetrability of haze, fog, clouds and precipitation by radiant energy over the spectral range 0.1 micron to 10 centimeters, Lukes, 1968, ref. 56.

7.4.39 (Continued)

7.4.40 Selected Portions from Electromagnetic Scattering (Kerker, 1963, ref. 63).

7.4.40 (Continued)

7.5 PERIODICALS

Howard and Garing (ref. 7), in their report on atmospheric optics and radiation transfer, noted that of the 400 American papers reviewed for the report, 53% were published in three optics journals (Applied Optics, Journal of the Optical Society of America, Journal of Quantitative Spectroscopy and Radiative Transfer), 23% in four leading geophysics journals (Journal of Geophysical Research, Journal of the Atmospheric Sciences, Planetary Space Science, and the Astrophysical Journal), and the remainder scattered among 24 other journals.

7.6 INFORMATION CENTERS

Information centers are discussed in Section 5.3. Table 5-2 lists several centers which deal specifically with electromagnetic wave propagation in the earth's atmosphere.

7.7 COMPUTATIONAL AIDS

Computational aids are discussed in general in Section 5.7. Table 7-4 lists some sources of computational aids for use in the optical frequency region.

TABLE 7-4.- COMPUTATIONAL DEVICES FOR USE IN THE OPTICAL FREQUENCY REGION

TITLE	DESCRIPTION	SOURCE
1. Aids for Radiation Calculations (Planck's Law)	Describes in detail: (1) Radiation Slide Rules (2) Charts & Nomographs (3) Tables of Blackbody Functions	Hudson 1969, ref. 18 Wolfe 1965, ref. 41
2. Tables of Light Scattering, Part I	Tables of Angular Functions	Shifrin and Zelmanovich, 1966, ref. 52
3. Tables of Light Scattering, Part II	Tables of the Scattering Matrix and of the components of the Scattered Electric Field	Shifrin and Zelmanovich, 1968, ref. 53
4. Tables of Light Scattering, Part III	Coefficients of Extinction, Scattering, and Light Pressure	Zelmanovich and Shifrin, 1968, ref. 54
5. Tables of Mie Scattering Cross Sections and Amplitudes	--	Deirmendjian, 1963 ref. 55
6. Data on Complex Index of Refraction of Water	--	Lukes, 1968, ref. 56
7. Units, Constants, and Conversion Factors	--	Valley, 1965, ref. 40 Wolfe, 1965, ref. 41
8. Atmospheric Attenuation Model	A series of tabulations for a turbid atmosphere for 22 wavelengths from 0.27 to 40μm (1,111-75 THz)	Elterman and Toolin, 1965, ref. 20

TABLE 7-4.- Continued

TITLE	DESCRIPTION	SOURCE
9. Tables of Corrections for Refraction During Observation of Objects in the Earth's Atmosphere	--	Kolchinskii, Kurianova, and Scmelkina, 1969, ref. 57
10. New Tables of Mie Scattering Functions for Spherical Particles	6 vols.	Penndorf, 1956, ref. 58
11. Tables Related to Radiation Emerging from a Planetary Atmosphere with Rayleigh Scattering	--	Coulson, Dave and Sekera, 1960, ref. 59
12. Tables Related to Light Scattering in a Turbid Atmosphere	3 volumes; Results of computations of the intensity and the degree of polarization of sky radiation and radiation scattered by a unit volume of air containing natural aerosols.	deBary, Braun, and Bullrich, 1965, ref. 60
13. Nomograms for the Visual Range		p. 273 of Middleton, 1957, ref. 9

PART III. ATMOSPHERIC TRANSMISSION HANDBOOK

8.0 REFRACTION

8.1 INTRODUCTION

When electromagnetic waves are propagated through the troposphere and ionosphere, they experience a change in direction or refractive bending. For frequencies above 1 GHz (30 cm), only tropospheric refraction need be considered.

Studies of the influence of refraction of electromagnetic waves are often subdivided into the steady-state (regular) influences associated with the mean value of the refractive index, and the influences of the variations from the mean (irregular refraction). Both of these aspects of refraction will be considered.

A brief discussion of tropospheric refraction is presented in Atlas, et al., (ref. 1). A review of astronomical refraction has been given by Mahan (ref. 2) in 1962.

8.2 COMPLEX INDEX OF REFRACTION

Let the dielectric constant of a medium at frequency f be represented by ϵ. Let μ represent the magnetic permeability of the medium at the same frequency. Then

$$m = \sqrt{\epsilon\mu} \equiv n - ik, \tag{8-1}$$

where m is the complex index of refraction; $n = c/v$ is the phase refractive index (the real part of the complex index of refraction); c is the velocity of propagation of electromagnetic waves in vacuum; v is the phase velocity of propagation of the electromagnetic wave in the medium; k is the absorption index which is related to the absorption coefficient K by $K = 2\pi k/\lambda$ where λ is the wavelength of the radiation; and i is the imaginary number symbol equal to $\sqrt{-1}$. In many textbooks and papers only the real part of the complex index of refraction is discussed. The magnetic permeability is unity in the atmosphere. Thus Eq. (8-1) holds for both tropospheric and ionospheric propagation. It is discussed in Atlas et al. ref. 1.

The dielectric constant ϵ can be written as

$$\epsilon = \epsilon' - i\epsilon'' = (n - ik)^2, \tag{8-2}$$

where ε' is the real part of the dielectric constant and ε'' is the imaginary part of the dielectric constant.

Bleany and Bleany (refs. 3,4) treat the case of a gas of dielectric constant ε subjected to an oscillating electric field $\overline{E} = \overline{E}' \exp(i\omega t)$ where $\omega = 2\pi f$. They arrive at an expression for the dielectric constant

$$\left.\begin{aligned} \varepsilon' &= n^2 - k^2 \approx n^2 = 1 + \frac{n_0 e^2}{2m_e \omega \varepsilon_0} \left\{ \frac{\omega_p - \omega}{(\omega_p - \omega)^2 + \Delta\omega^2} \right\} \\ \varepsilon'' &= 2nk \approx 2k = \frac{n_0 e^2}{2m_e \omega \varepsilon_0} \left\{ \frac{\Delta\omega}{(\omega_p - \omega)^2 + \Delta\omega^2} \right\} \end{aligned}\right\} , \qquad (8\text{-}3)$$

where $n \approx 1$, $k << n$, we have assumed e is the electronic charge; m_e its mass; $\omega_p = 2\pi f_p$, where f_p is the natural frequency of oscillation of the electron; n_o is the number of molecules per unit volume; and $\Delta\omega$ the line width parameter.

The variation of n and k in the neighborhood of a weak absorption line is shown in Fig. 8-1. The absorption coefficient reaches a maximum at the resonant frequency where $\omega = \omega_p$, and falls to half its maximum value at $\omega_p - \omega = \pm\Delta\omega$. In optical usage, the quantity $2\Delta\nu = \Delta\omega/\pi$ is called the 'half-width' of the line, meaning the frequency difference between the points at which the absorption has dropped to half the maximum value. Microwave spectroscopists, however, prefer to call $\Delta\nu$ the half-width.

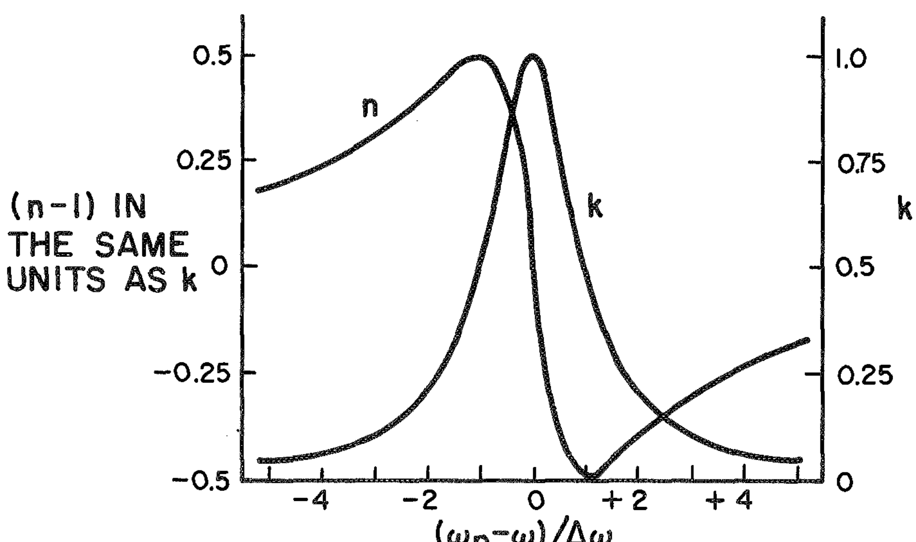

Figure 8-1.- Variation of n and k near a narrow absorption line (from Eq. 8-3), n - 1 and k are in units of $n_o e^2/4m_e \omega \varepsilon_0 \Delta\omega$ (from ref. 4).

Some recent work on refractive index measurements in air and water has been done or reviewed in refs. 5-15. Dispersion is also discussed in Section 8.3.

8.3 DISPERSION

The theory of electromagnetic waves (ref. 3) shows that the refractive index of a substance should be equal to the square root of its dielectric constant, if the magnetic permeability can be taken as unity, as is usually the case (Eq. 8-1). A comparison of the dielectric constants measured at low frequencies with the refractive indices measured in the optical region (i.e. at frequencies of the order of 10^{14} Hz (3μm)) gives very poor agreement with this relation except in the case of simple non-polar gases. Values of the dielectric constant of a few such gases measured over a wide range of frequencies are given in Table 8-1 together with the square of the optical refractive index. The latter is extrapolated to 'infinite wavelengths' to correct for dispersion in the optical region. The agreement is seen to be excellent in the cases quoted.

In the optical region, variation of the refractive index with wavelength has been known for a long time, and is called dispersion. In general, the refractive index increases as the wavelength decreases, and this is known as 'normal dispersion'. The reverse case, where the refractive index decreases with decreasing wavelength, occurs only in the vicinity of an absorption line, (Fig. 8-2) and is difficult to observe because of the absorption. This is known as 'anomalous dispersion', but both types have a simple explanation in terms of classical theory, based on the assumption that an atom contains electrons vibrating at certain natural frequencies characteristic of the type of atom, and that the application of an alternating electric field sets such electrons into forced vibration.

Work on dispersion has been reported in refs. 7-12 and ref. 15.

8.4 TYPICAL RAY PATH TRAJECTORY IN A TRANSATMOSPHERIC PATH

When electromagnetic waves are propagated through the troposphere and the ionosphere, they experience a change in direction or refractive bending. This phenomenon, which results from the nonisotropic characteristics of the media, introduces an error in the measurement of the angular position of a space vehicle.

TABLE 8-1.- MEASURED VALUES OF THE DIELECTRIC CONSTANT FOR SEVERAL GASES (FROM REF. 4)

Gas	$(\varepsilon - 1)\ 10^6$ at N.T.P.				
	0.1 MHz	1 MHz	9,000 MHz	24,000 MHz	Optical
Air	570 ±0.7	567.0 ±1.0	575.4 ±1.4	576.0 ±0.2	575.7 ±0.2
Nitrogen	578 ±0.7	579.6 ±1.0	586.9 ±2.9	588.3 ±0.2	581.3
Oxygen	528 ±1	523.3 ±1	530.0 ±1.9	531.0 ±0.4	532.7
Argon	545 ±1	545.1 ±0.5	—	555.7 ±0.4	554.7
Carbon Dioxide	987 ±1	987.5 ±2	985.5 ±3	988 ±2	—
Hydrogen	270 ±1	272	—	—	272
	A	B	C	D	E

References:

A. Lovering and Wiltshire, 1951, Proc. I.E.E. 98, Part II, 557.
B. Hector and Woernley, 1946, Phys. Rev. 69, 101.
C. Birnbaum, Kryder, and Lyons, 1951, J. Appl. Phys. 22, 95.
D. Essen and Froome, 1951, Proc. Phys. Soc. B, 64, 862.
E. $(n^2 - 1)\ 10^6$ (various authors), extrapolated to infinite wavelength.

A typical ray path trajectory in the vertical plane is shown in Figure 8-3. The elevation angle error due to refraction, ΔE, is the angle between the apparent path direction and the direct line-of-sight path.

The index of refraction in the troposphere is greater than unity, and decreases monotonically with altitude. At approximately 30 km this value can be taken as unity for most purposes. In the case of the ionosphere, which commences at about 70 km altitude, the index of refraction is less than unity and is a minimum at the level of maximum ionization density. The region of unity refractive index between the troposphere and ionosphere can be considered to be free space.

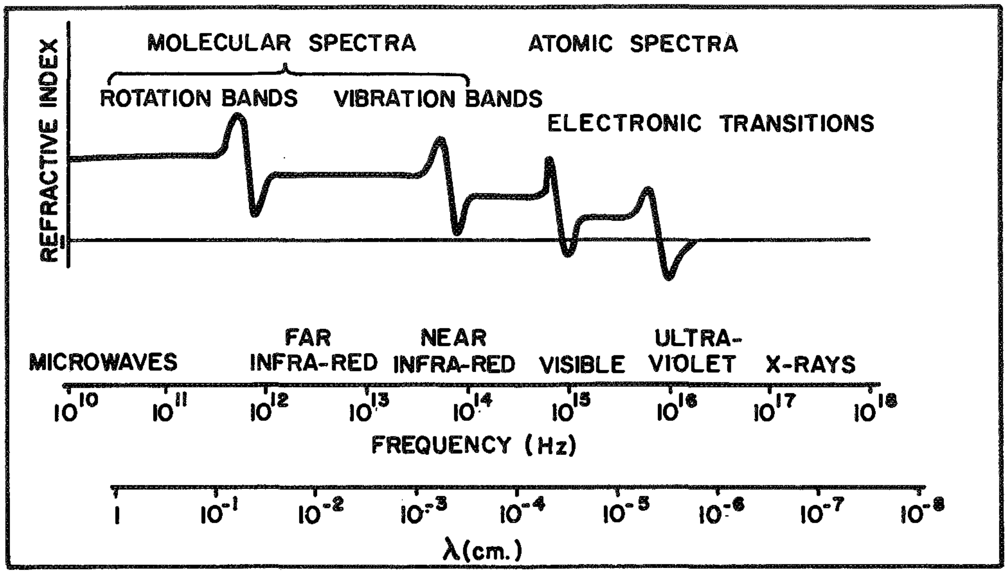

Figure 8-2.- Schematic diagram showing the variation of refractive index with frequency (from ref. 4)

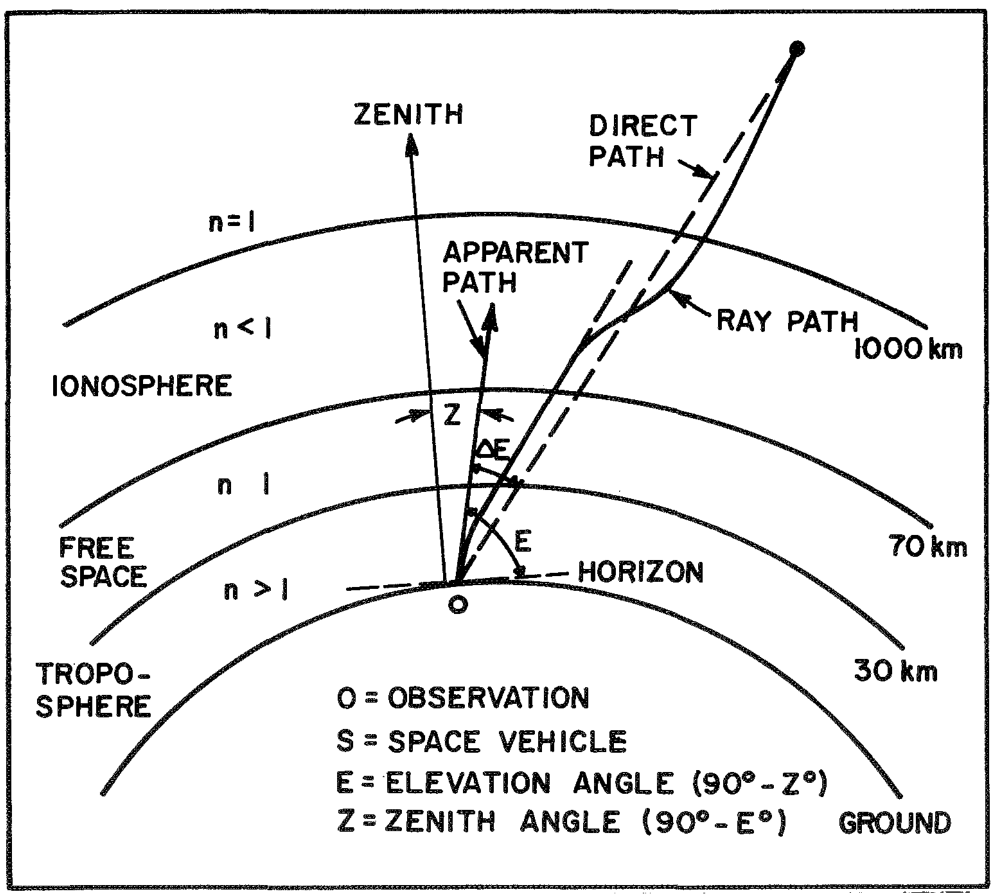

Figure 8-3.- A typical ray-path trajectory (from ref. 16)

Section 8.9 presents a graph on regular tropospheric refraction and Section 8.11 presents a detailed nomogram to determine the refraction of a radio wave entering the earth's troposphere in terms of the surface meteorological conditions and the apparent elevation angle of the incoming wave.

8.5 REGULAR IONOSPHERIC REFRACTION

The interaction of electromagnetic waves with the ionosphere results in a complex index of refraction, m. The Appleton-Hartree formula is

$$m = n - ik \tag{8-4}$$

where n is the phase refractive index and k is the index of absorption (Section 8.2). The complex index is a function of the electron density N_e (electrons/cm^3), the operating frequency f, the magnetic field intensity H, and the frequency of collisions between electrons and neutral molecules. The phase velocity is generally greater than c (the velocity in free space) and the group velocity v_g, is less than c. The index of absorption k is related to the absorption coefficient K by $K = 2\pi k/\lambda$ where λ is the wavelength of the radiation. Thus K is expressed in units of reciprocal length. K represents the loss of energy caused by collisions. The effect of the magnetic field is to split the radio wave into waves that are elliptically polarized in opposite senses (Cormier, et al. 1965, ref. 17). These waves are reflected at different levels (See Chapter 4) and suffer different degrees of absorption (Chapter 9).

In the ionosphere, the refractive index is inversely proportional to the frequency squared. Various magnetoionic formulas are given in ref. 1.

The ionospheric refraction error at a frequency of 100 MHz (3 m) is shown in Fig. 8-4 as a function of the apparent angle of elevation at the earth's surface. These theoretical curves were obtained by Millman (ref. 16). An interesting feature of this plot is that at a constant altitude the error increases with elevation angle, attaining a maximum value between approximately 3° and 5°. At the very low angles, the error remains somewhat the same for all altitudes greater than 370 km. As the elevation angle is increased, however, it becomes apparent that the error maximizes at about 555 km. Minimum error is attained at astronomical distances.

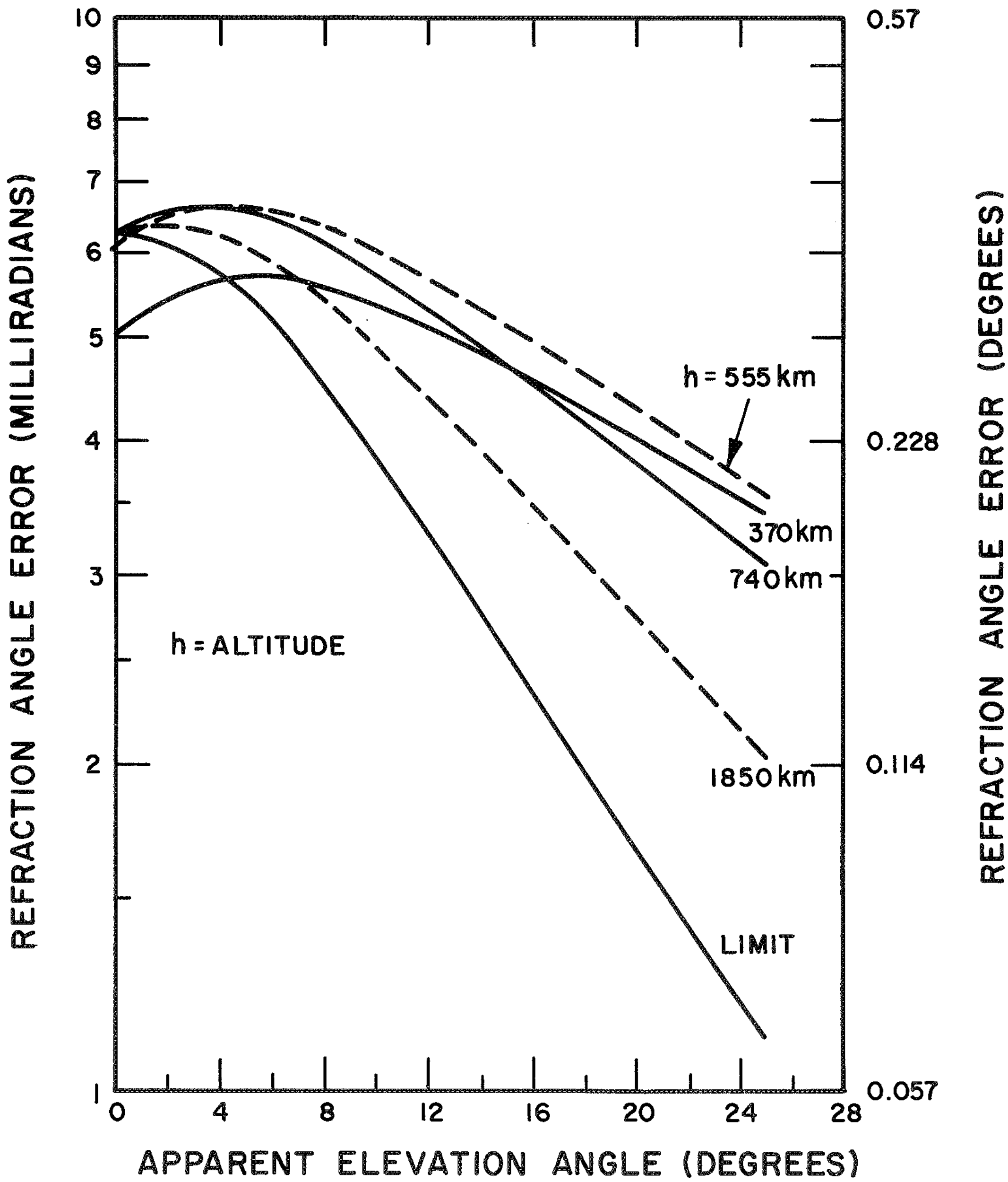

Figure 8-4.- Ionospheric refraction errors at 100 MHz (3 m) (ref. 16)

8.6 TROPOSPHERIC AND IONOSPHERIC REFRACTION ERRORS AT 555 km ALTITUDE

The tropospheric and ionospheric refraction errors computed at an altitude of 555 km are given in Figure 8-5. It can be seen that the tropospheric error is predominant for propagation near the horizon and that the ionospheric contribution takes over as the elevation angle is increased. The angle at which the ionospheric error is greater than the tropospheric error is dependent upon the transmission frequency and the characteristics of the media. For the particular refractive index models considered by Millman (ref. 16), the crossover point is a 2° elevation angle.

Similar results have been reported by Weisbrod and Colin (ref. 18). Tropospheric refraction is considered in more detail in Section 8.9.

8.7 OPTICAL REFRACTIVE MODULUS OF THE TROPOSPHERE*

In the troposphere, where the phase refractive index of the atmosphere is very nearly equal to one, it is convenient to define the quantity

$$N = (n - 1) \times 10^6. \tag{8-5}$$

N is called the refractive modulus and values are given in N-units.

An approximate relation between the optical refractive modulus and atmospheric pressure and temperature is

$$N_\infty = 77.6 \frac{P}{T}, \tag{8-6}$$

where N_∞ is the refractive modulus for wavelengths much greater than 20μm; P is the atmospheric pressure in millibars, and T is the atmospheric temperature in degrees Kelvin.

The dispersion formula of Edlen (ref. 11) which has been adopted by the Joint Commission for Spectroscopy is

*After Atlas et al. 1965, ref. 1.

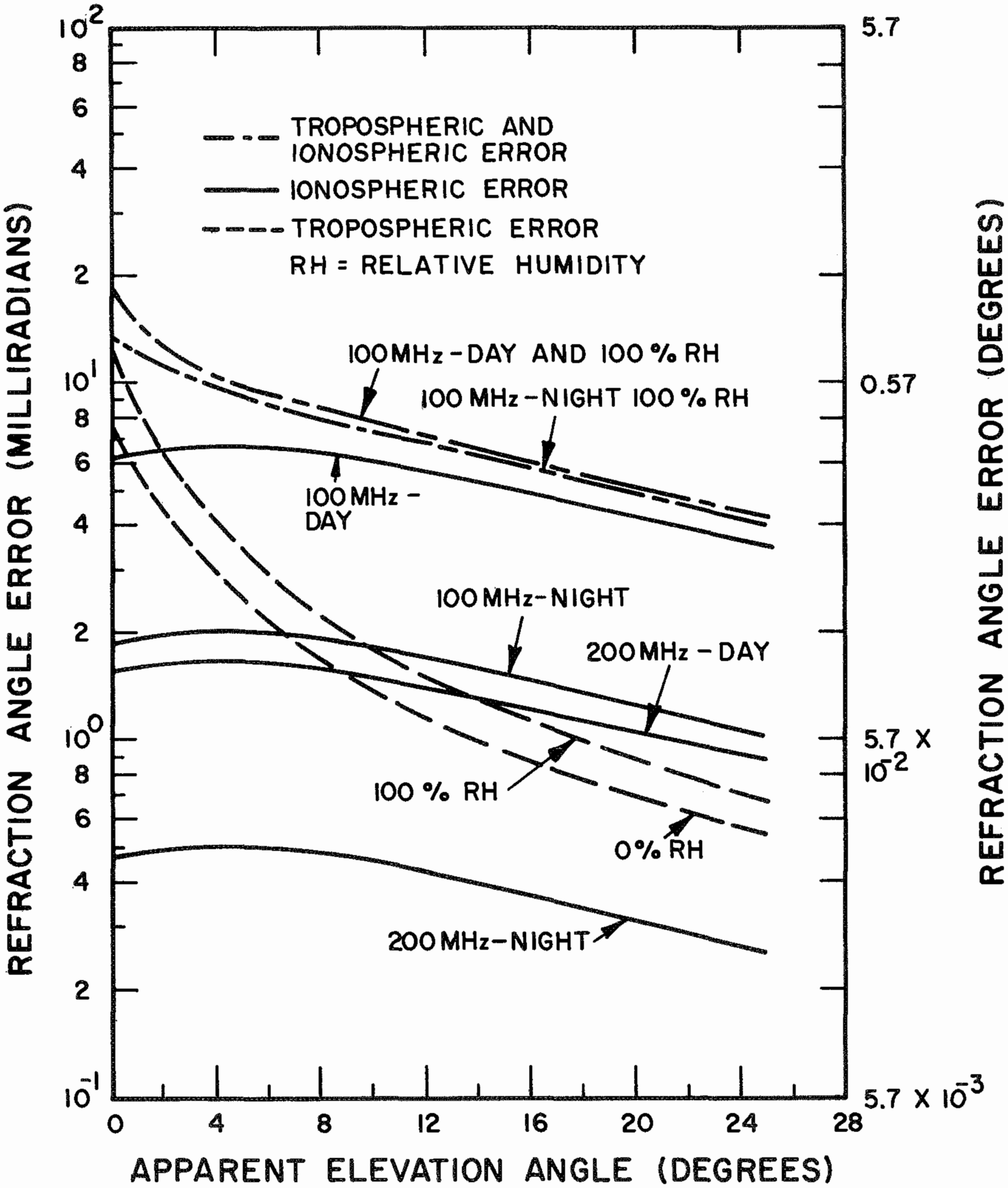

Figure 8-5.- Tropospheric and ionospheric refraction errors at 555 km altitude (from ref. 16)

$$N_S = 64.328 + \frac{29498.10}{146 - 1/\lambda^2} + \frac{255.40}{41 - 1/\lambda^2}, \tag{8-7}$$

where N_S is the refractive modulus at a wavelength λ for a temperature of 288°K and a pressure of 1013.25 mb, and λ is the wavelength in microns. A somewhat less precise but more convenient dispersion formula is

$$N = N_\infty \left[1 + \frac{7.52 \times 10^{-3}}{\lambda^2}\right]. \tag{8-8}$$

Equations (8-6) and (8-8) may be combined to give the refractive modulus as a function of pressure, temperature, and wavelength;

$$N = \frac{77.6\ P}{T} + \frac{0.584\ P}{T\lambda^2}. \tag{8-9}$$

Refractive moduli calculated by using Eq. (8-9) will be in error no more than one N-unit. Figure 8-6 is a nomograph based on Eq. (8-9) that gives values of N accurate to about 5 N-units.

8.8 RADIO REFRACTIVE MODULUS OF THE TROPOSPHERE*

At radio wavelengths the relationship of refractive modulus Eq. (8-5) to pressure, temperature, and water vapor pressure may be given by:

$$N = \frac{77.6\ P}{T} + \frac{3.7 \times 10^5\ P_{WV}}{T^2}, \tag{8-10}$$

where P is the atmospheric pressure in millibars, T is the atmospheric temperature in degrees Kelvin, and P_{WV} is the partial pressure of water vapor in millibars. This equation comes from Atlas et al. 1965 (ref. 1) and Smith and Weintraub, 1953 (ref. 19).

*After Atlas et al. 1965, ref. 1.

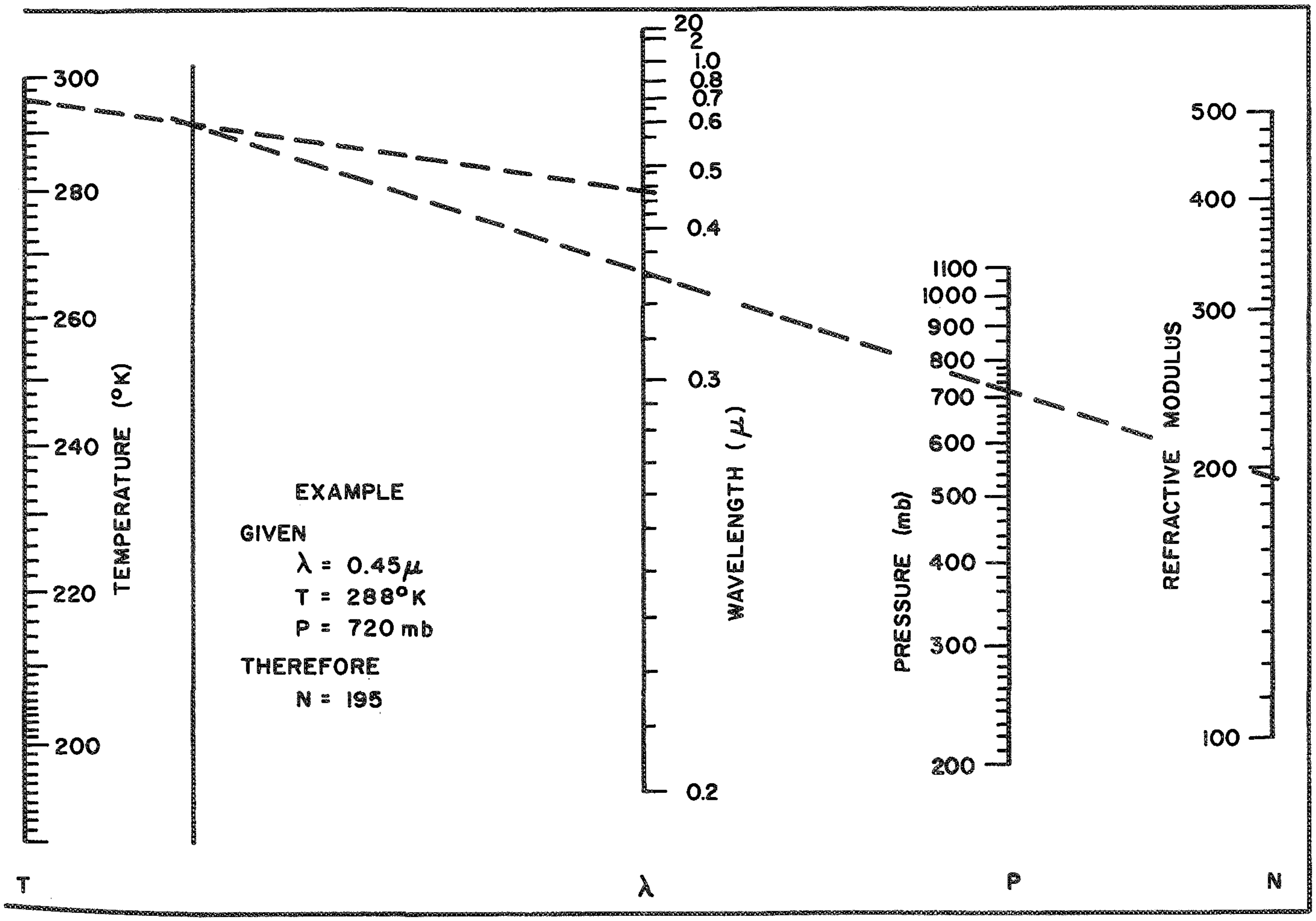

Figure 8-6.- Nomograph for computing refractive modules at optical wavelengths (from ref. 1)

Figures 8-7 and 8-8 are nomographs based on Eq. (8-10); these give values accurate to within 5 N-units.

Within an accuracy of 1 part in 10^6, the tropospheric refractive index is independent of frequency for the longest radio wavelengths in use down to 1.25 cm (24 GHz). Absorption by atmospheric constituents (Chapter 9) begins to rise to significant proportion with decreasing wavelength beyond 1.25 cm (24 GHz). Water vapor content is by far the leading factor in causing changes in N, followed in order of importance by temperature and pressure. For example, for a temperature of 15°C, pressure of 1013 mb near ground level, and a relative humidity of 60% (P_{WV} = 10 mb), the partial derivatives of N become $\partial N/\partial P_{WV} = 4.5$ (N-units mb^{-1}); $\partial N/\partial T = -1.26$ (N-units $°K^{-1}$); and $\partial N/\partial P = 0.27$ (N-units mb^{-1}).

Under normal conditions, N tends to decrease exponentially with height Z; and exponential decrease is usually an accurate description for heights greater than 10,000 ft. Below 10,000 ft, N may depart considerably from exponential behavior. The median value for the gradient dN/dZ is typically -0.012 N-units ft^{-1} for the first few thousand feet above the ground level.

8.9 VERTICAL PROFILES OF REFRACTIVE MODULUS*

For many purposes it is desirable to have standard refractive modulus profiles for the atmosphere. By using the equations of the model atmosphere (Cole, et al. 1965, ref. 20), an exact analytical expression for the standard optical refractive modulus can be derived. A simplified approximation to this is

$$N = 273 \exp(-Z/32.2), \quad (Z \leq 25); \qquad (8\text{-}11)$$

where Z is the altitude in thousands of feet.

Equation (8-11) can be differentiated to obtain the standard gradient of optical refractive modulus;

$$\frac{dN}{dZ} = -8.45 \exp(-Z/32.2), \quad (Z \leq 25) \qquad (8\text{-}12)$$

Equations (8-11) and (8-12) may be corrected for dispersion through use of Eq. (8-8).

*After Atlas et al. 1965, ref. 1.

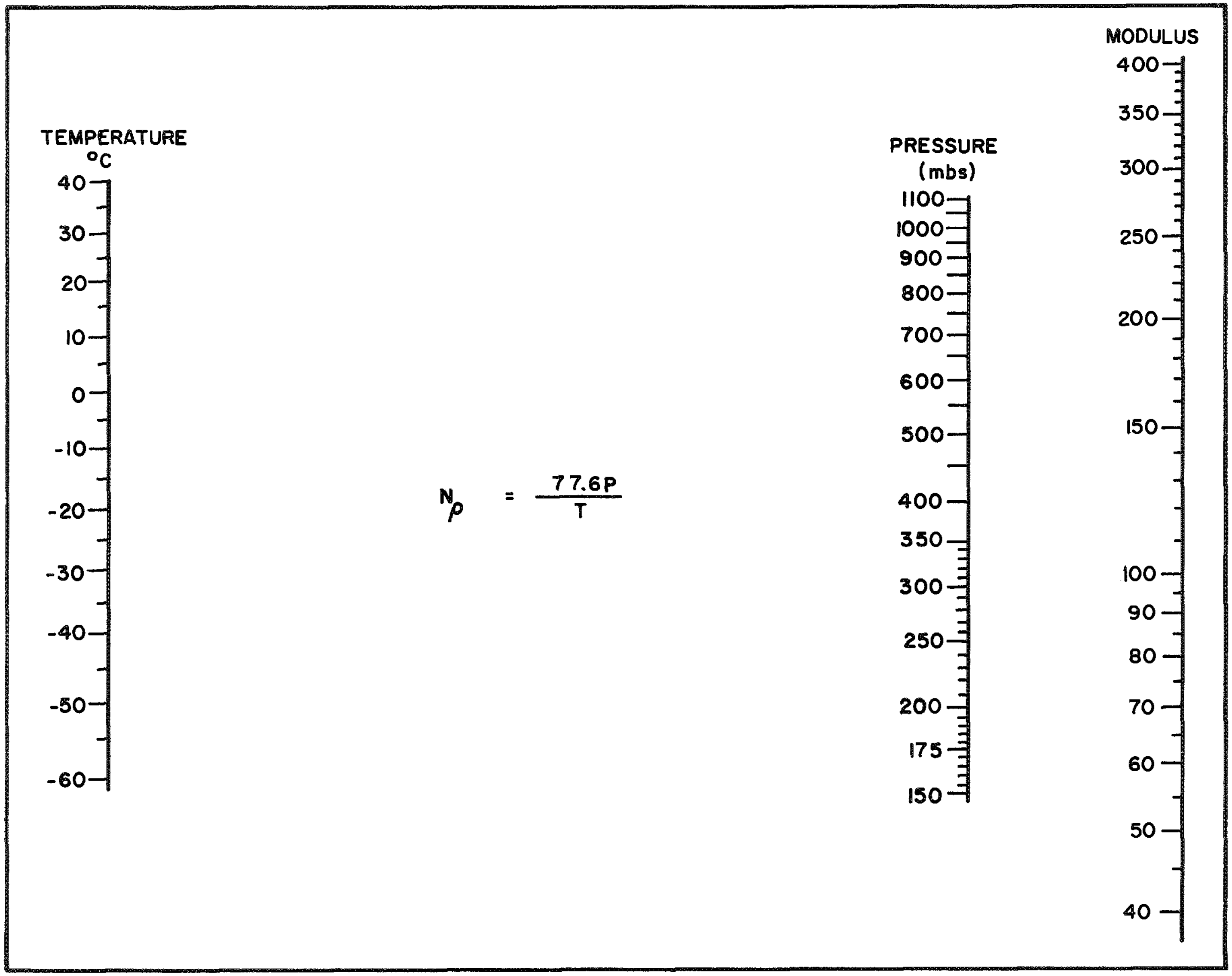

Figure 8-7.- Nomograph for computing contribution to microwave refractive modulus to density of atmosphere gas (from ref. 1)

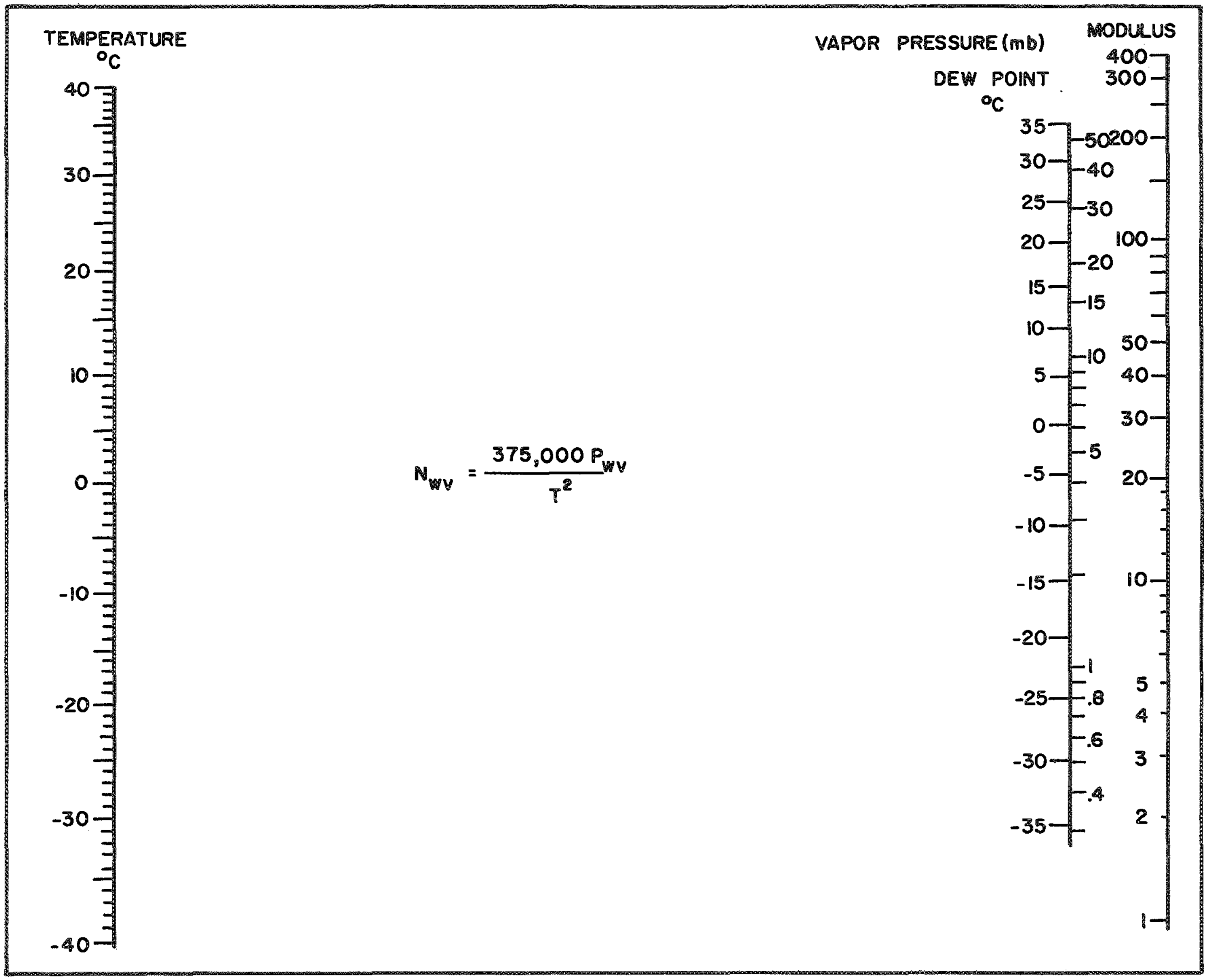

Figure 8-8.- Nomograph for computing contribution to microwave refractive modulus due to water vapor (from ref. 1)

For the radio wavelengths it is necessary to assume a distribution of water vapor in order to obtain an expression for the refractive modulus. Assuming $P_{WV} = 10.2\ (1 - 0.0195Z)^6$, for $Z \leq 25$, a simplified approximation is

$$N = 316 \exp (-Z26.5), \ (Z \leq 25). \tag{8-13}$$

The standard gradient of radio wave refractive modulus is then:

$$\frac{dN}{dZ} = -11.9 \exp (-Z/26.5), \ (Z \leq 25) \tag{8-14}$$

Figures 9-4, 9-5 of ref. 1 are graphs of standard profiles calculated from Eq. (8-12) through (8-14). Atlas et al. ref. 1 and Rogers, ref. 21 discuss and illustrate quite extensively actual profiles of the refractive index at microwave frequencies. There are examples of refractive index modulus in clouds as well as in clear air. Horizontal variations are also considered briefly.

8.10 ASTRONOMICAL REFRACTION: MEASUREMENTS AND THEORY

Astronomical refraction (or atmospheric refraction) is the angular difference between the apparent zenith distance of a celestial object (or spacecraft) and its true zenith distance, produced by refraction effects as the radiation from the object penetrates the atmosphere (See Section 8.4).

Figure 8-9 shows the average atmospheric astronomical refraction for propagation of solar radiation through the earth's atmosphere as reported by McCready, Pawsey, and Payne-Scott (ref. 22), and Marner and Ringoen (ref. 23). Additional comments and graphs are contained in the Discussion section of Millman (ref. 16), (See also Section 6.4.9).

Figure 8-10 shows the refraction correction versus elevation angle for both radio frequency and optical wavelengths as computed by Altshuler (refs. 24, 25). He assumed a model atmosphere and the type of information presented in Section 8.9.

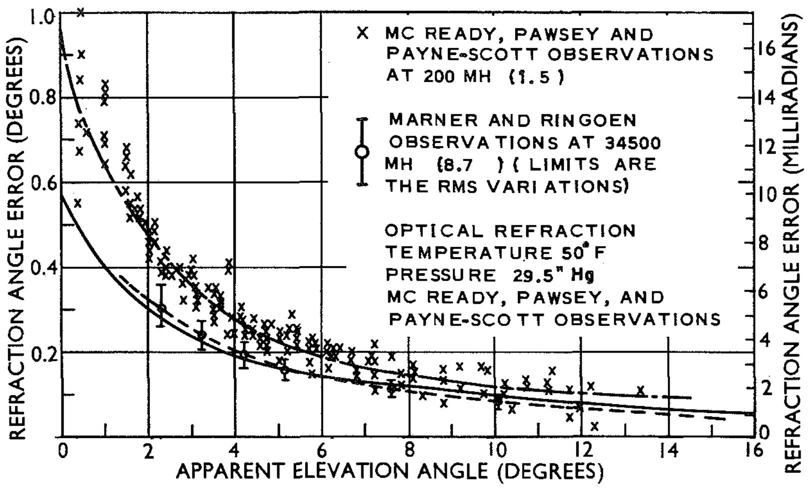

Figure 8-9.- Average atmospheric refraction for propagation of solar radiation through the atmosphere (from Millman, ref. 16).

8.11 A NOMOGRAM FOR ATMOSPHERIC RADIO REFRACTION

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Radio and Electrical Engineering Division
National Research Council
Ottawa, Canada

A six-stage nomogram is presented for determining the refraction of a radio wave entering the earth's atmosphere in terms of surface meteorological conditions and the apparent elevation angle of the incoming wave.

8.11.1 Introduction

An extraterrestrial radio wave is refracted during its passage through the earth's atmosphere. Consequently, for the true position of the source of radiation to be determined, a small negative correction must be applied to the elevation angle at which the radiation is received. This correction is a function of the elevation angle itself. The accompanying nomogram, which is based on well-known formulae and methods, gives this negative correction as a function of surface meteorological conditions and apparent elevation angle.

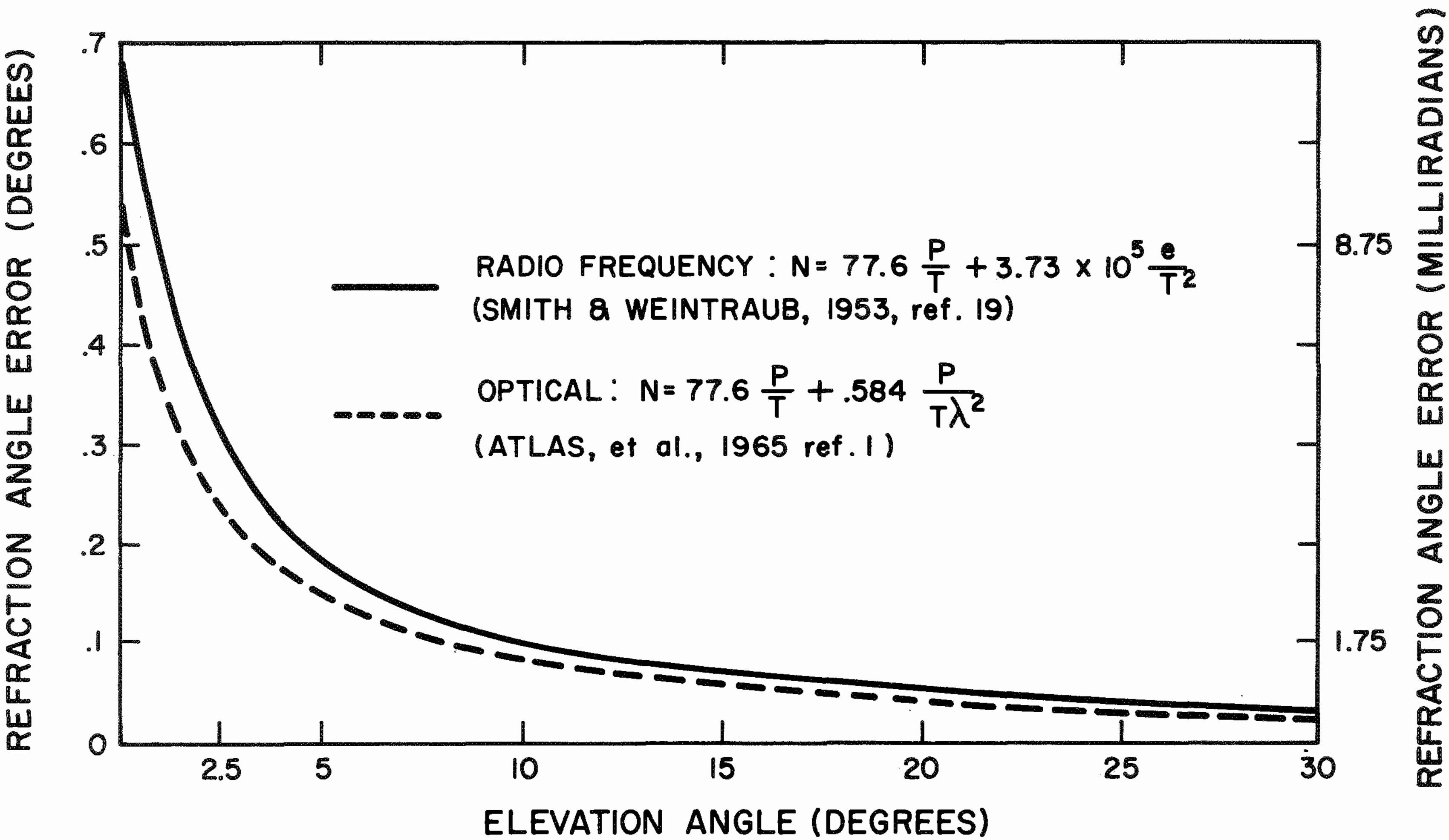

Figure 8-10 Refraction correction vs elevation angle for both radio frequency and optical wavelengths (from ref. 24)

8.11.2 Instructions for Using the Nomogram (Figure 8-11)

The following steps outline the most straightforward way to use the nomogram. Reference should be made to the key in the upper left corner. (Larger versions of the nomogram are available at nominal charge from the Division of Radio and Electrical Engineering, National Research Council of Canada, Ottawa.)

1. Enter the surface relative humidity on scale 1.

2. Enter the surface air temperature on scale 2.

3. Join these two points with a straight line, and extend this line to intersect scale 3.

4. Partial pressure of water vapor may not be read if desired.

5. Join this latter intersection on scale 3 with the temperature on scale 4 and mark the resulting intersection on scale 5.

6. Enter total atmospheric pressure on scale 6, and air temperature on scale 7, and find the intersection on scale 8.

7. Join this latter intersection to the one previously found on scale 5, and find the intersection on scale 9. This is N, the refractivity at the surface of the earth. ($N = 10^{-6}(n - 1)$ where n is the surface radio refractive index of the atmosphere.)

8. The apparent elevation angle of the incoming wave is now entered on any one of scales 10, 10a, 10b, 12, or 12a. This point is joined with the refractivity intersection on scale 9 and thus the refraction r is found on either scale 11 (calibrated in seconds of arc) or on scale 13 (calibrated in minutes of arc). It is important to note that when either scale 10a, 10b, or 12a is used to enter apparent elevation angle, the final value of r as read must be increased by 100", 200", or 20', respectively. This scale splitting has been done to increase the accuracy.

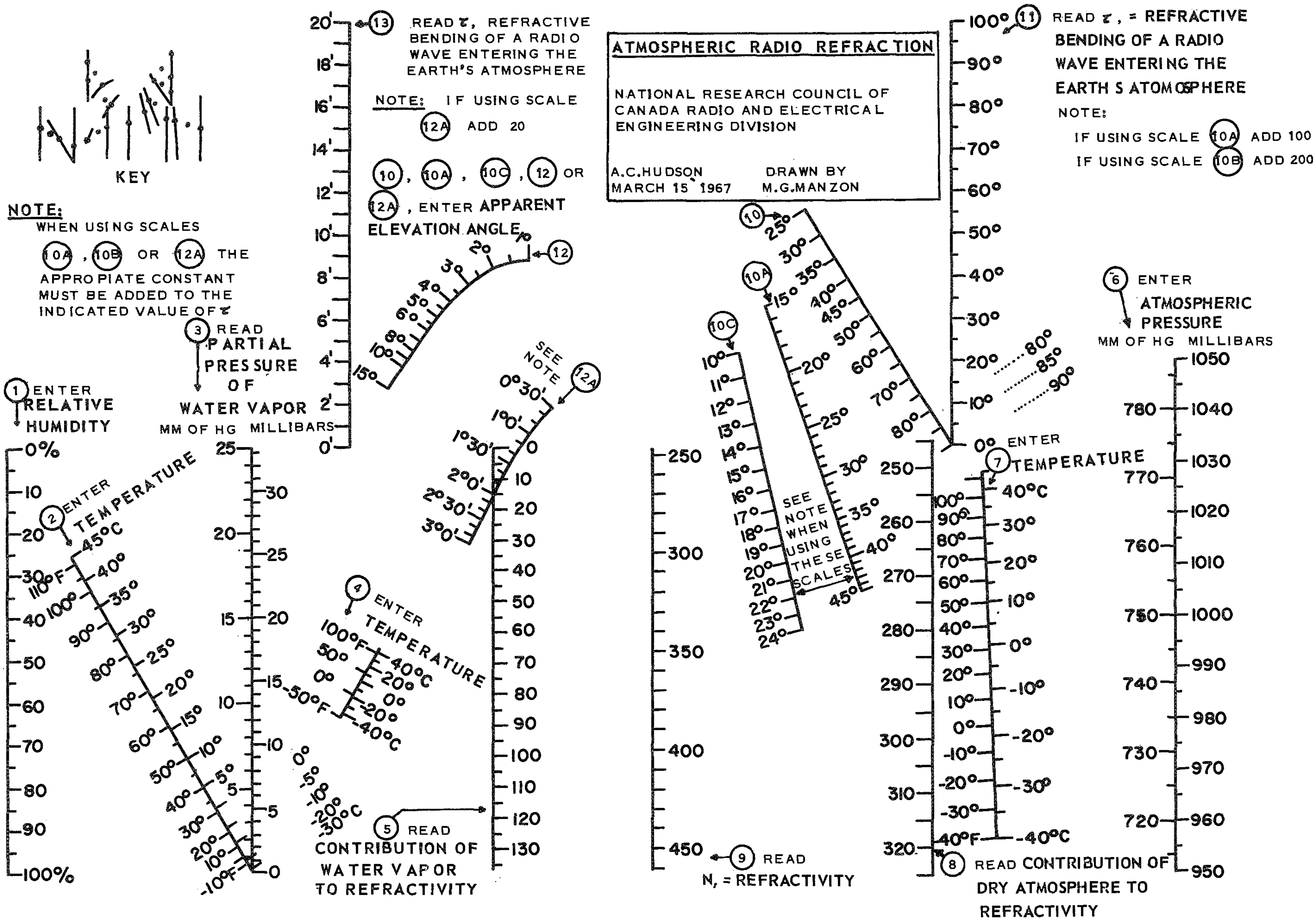

Figure 8-11.- A nomogram for atmospheric radio refraction

8.11.3 Formulae and Data Implied in the Nomogram

The surface refractivity N has been calculated from the formula:

$$N = \frac{77.6}{T}\left(P + \frac{4810e}{T}\right) \qquad (8\text{-}10)$$

where T is the absolute temperature, P is the total atmospheric pressure in millibars, e is the partial pressure of water vapor in the atmosphere, expressed in millibars. Equation (8-10) is (1.20) of Bean and Dutton (1966).[1]

Scale 2 has incorporated in it a table of saturated water-vapor pressure. (Handbook of Chem. and Phys., 42d ed., Chemical Rubber Publ. Co., Cleveland, O.). This permits the determination of e.

In order to estimate the bending τ from a knowledge of surface refractivity and the apparent elevation angle of the source, two distinctly different methods have been described (Bean and Dutton, 1966, ch. 3).[1] For elevation angles greater than 10° the following formula is conventional:

$$\tau = N \cot \theta_o \times 10^{-6}, \qquad (8\text{-}15)$$

where τ is the bending of a ray through the entire atmosphere, N is the surface refractivity, and θ_o is the apparent elevation angle of the ray. (Bean and Dutton, 1966, sec. 3.9.)[1]

In the derivation of this relation, the atmosphere is assumed to be horizontally homogeneous. Scales 10 and 10a in the nomogram cover elevation angles between 15° and 90°. These scales have been based on (2) above.

For elevation angles between 0.5° and 24° the statistical linear regression results of Bean and Cahoon (1957)[2] and

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[1]Bean, B.R., and E.J. Dutton (March 1966). Radio Meteorology, NBS Mono. No. 92.
[2]Bean, B.R., and B.A. Cahoon (Nov. 1957). The use of surface weather observations to predict the total atmosphere bending of radio waves at small elevation angles, Proc. IRE, 45, 1545-1546.

Bean, Cahoon, and Thayer (1960)[1] have been used. The relevant equation is

$$\tau = bN + a. \tag{8-16}$$

This is Eq. (3.10) (Bean and Dutton, 1966).[2] In this method Bean, Cahoon, and Thayer have analyzed a large number of radiosonde observations at 13 climatically distinct locations in order to establish the constants a and b.

Scales 10b, 12, and 12a in the nomogram have been based on a more detailed version (Bean, 1966, private communication) of table 9.9 of Bean and Dutton (1966).[2] Quadratic interpolation has been used to prepare these scales.

8.11.4 Accuracy

The accuracy of the implied formulae has been fully treated by Bean and Dutton (1966)[2] and will not be discussed here, beyond mentioning that (1) of the surface refractivity is considered correct to 0.5 percent.

The accuracy of a nomogram is difficult to specify, but careful work yields values of τ which agree to 1 sec on scale 11 and 0.2 min on scale 13, with the formulae used.

In most practical situations any discrepancy introduced by the nomogram itself will not be significant.

While the nomogram was designed and plotted automatically, the painstaking work of Mrs. M. G. Manzon, who made the drawing, is gratefully acknowledged.

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[1] Bean, B.R., B.A. Cahoon, and G.D. Thayer (1960), Tables for the statistical prediction of radio ray bending and elevation angle error using surface values of the refractive index, NBS Tech. Note No. 44.

[2] Bean, B.R., and E.J. Dutton (March 1966). Radio Meteorology, NBS Mono. No. 92.

8.12 OPTICAL ASTRONOMICAL REFRACTION

For bodies near zenith the astronomical refraction is only about 0.1 minute, but for bodies near the horizon it becomes about 30 minutes (0.5 degrees) or more and contributes measurably to the length of the apparent day (Fig. 8-10; refs. 27, 28).

The optical air mass (also called the "air mass") is the length of the atmospheric path traversed by the sun's rays in reaching the earth, measured in terms of the length of this path when the sun is at the zenith. For a zenith distance z of the sun less than 80° the optical air mass is approximately equal to sec z (See Table 8-2). At greater zenith distances the secant gives values which are increasingly too high, because of errors due to atmospheric refraction, curvature of the earth, etc. The values are tabulated for P = 760 mm Hg and T - 10°C; for other values of P and T multiply both the air mass and the refraction $R = \zeta - z$ by $P/((760(9.962 + 0.0038T))$.

Dioptric tables of the earth's atmosphere are designed for the solution of all problems in which one follows the path of light rays through the earth's atmosphere. These tables are given in refs. 30 and 31. More recently Kolchinskii et al. produced tables of corrections for refraction during observation of objects in the earth's atmosphere (ref. 32).

Table 8-3 is based on the widely used computations of Bemporad, (ref. 34), (See also refs. 35, 36). Bemporad's formula is

$$\alpha = \frac{\text{atmospheric refraction in seconds of arc}}{58.36'' \sin z} \tag{8-17}$$

If the pressure at the surface P is different from the standard sea-level pressure P_O, the values of m are to be multiplied by P/P_O.

8.13 COMMENTS ON IRREGULAR REFRACTION

The existence of small-scale variations in the index of refractions in the troposphere has been observed by microwave refractometer techniques. It is generally accepted that these fluctuations are responsible for the optical twinkling of radio stars.

The radiation emitted from discrete radio stars is relatively constant; however, at times the extraterrestrial signals impinging on the earth's surface are found to fluctuate in a

TABLE 8-2.- REFRACTION AND AIR MASS (FROM ALLEN, REF. 29)

Apparent zenith z	Apparent altitude (h=90°-z)	True zenith distance (ζ)	sec z	Air mass
90°	0°	90° 35' 21"		38
89°	1°	89° 24' 45"	57.30	26.96
88°	2°	88° 18' 24"	28.65	19.79
87°	3°	87° 14' 24"	19.11	15.36
86°	4°	86° 11' 43"	14.34	12.44
85°	5°	85° 9' 51"	11.47	10.40
84°	6°	84° 8' 27"	9.567	8.900
83°	7°	83° 7' 23"	8.206	7.768
82°	8°	82° 6' 33"	7.185	6.884
81°	9°	81° 5' 52"	6.392	6.177
80°	10°	80° 5' 18"	5.759	5.600
75°	15°	75° 3' 34"	3.864	3.816
70°	20°	70° 2' 38"	2.924	2.904
65°	25°	65° 4' 4"	2.366	2.357
60°	30°	60° 1' 41"	2.000	1.995
50°	40°	50° 1' 10"	1.556	1.553
40°	50°	40° 0' 49"	1.305	1.304
30°	60°	30° 0' 34"	1.155	1.154
20°	70°	20° 0' 21"	1.064	1.064
10°	80°	10° 0' 10"	1.015	1.015
0°	90°	0° 0' 0"	1.000	1.000

TABLE 8-3.- OPTICAL AIR MASS CORRESPONDING TO DIFFERENT ZENITH DISTANCES (AFTER LIST, REF. 33)

Sun's zenith distance	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°
						Optical air mass				
0°	1.00									
10	1.02					1.04				
20	1.06	1.07	1.08	1.09	1.09	1.10	1.11	1.12	1.13	1.14
30	1.15	1.17	1.18	1.19	1.20	1.22	1.23	1.25	1.27	1.28
40	1.30	1.32	1.34	1.37	1.39	1.41	1.44	1.46	1.49	1.52
50	1.55	1.59	1.62	1.66	1.70	1.74	1.78	1.83	1.88	1.94
60	2.00	2.06	2.12	2.19	2.27	2.36	2.45	2.55	2.65	2.77
70	2.90	3.05	3.21	3.39	3.59	3.82	4.07	4.37	4.72	5.12
80	5.60	6.18	6.88	7.77	8.90	10.39	12.44	15.36	19.79	26.96

random manner. Irregular fluctuations in the apparent angular position of the sources have also been detected. The fluctuations or scintillations both in amplitude and position have been experimentally verified as being due to irregularities in the electron density distribution in the ionosphere through which the radiation passes.

Millman (ref. 16) estimates the magnitude of the effects of the inhomogeneities in the troposphere and ionosphere on the measurement of the angle-of-arrival, phase, range and amplitude of radio-wave signals propagated in an earth-space vehicle environment.

Bean and McGavin (ref. 37) have reviewed refraction effects on the apparent angle-of-arrival of radio signals.

8.14 SUMMARY

Fluctuations in the angle-of-arrival, phase, range, and amplitude are imposed by the dynamic properties of the atmosphere (i.e., the temporal and spatial variations of the inhomogeneities). The frequency dependence of the root-mean-square scintillations in the troposphere and ionosphere is summarized in Table 8-4. The influence of the ionosphere on the various scintillation effects can be considered to be negligible, under normal ionospheric conditions, at frequencies of the order of 500 MHz (60 cm) and above.

Detailed discussions of optical scintillation are found in (refs. 35, 36). Pratt (ref. 38) considers the effects of irregular refraction on laser communication systems.

TABLE 8-4.- FREQUENCY DEPENDENCE OF THE ROOT-MEAN-SQUARE SCINTILLATIONS IN THE TROPOSPHERE AND IONOSPHERE

Scintillation effect	Troposphere	Ionosphere
Angle of arrival	Independent of f	f^{-2}
Phase	f	f^{-1}
Range	Independent of f	f^{-2}
Amplitude	--	f^{-2}

9.0 ABSORPTION

9.1 INTRODUCTION

This chapter discusses the problems of atmospheric absorption of electromagnetic radiation by various means.

Radio waves propagating through the ionosphere undergo a varying amount of absorption. Electrons and ions that oscillate in the electromagnetic field of the wave and then collide with other particles (mainly neutral atoms and molecules) absorb energy from the wave, transferring it as thermal energy of the atmospheric constituents.

Gaseous absorption is primarily the transfer of energy between the radiation and the molecules of a gas. It occurs when the molecules have an electric or magnetic dipole moment. The coupling between the electric component of the radiation field and the electric dipole or between the magnetic field component and the magnetic dipole, results in emission or absorption of radiation by the molecules in the form of a resonant energy transfer. Both types of absorption can be treated in terms of the complex index of refraction m, discussed in Sections 8.2 and 8.3.

9.2 RELATIVE TRANSPARENCY OF THE EARTH'S ATMOSPHERE

Figure 9-1 shows the relative transparency of the earth's atmosphere to electromagnetic radiation. The transmission curve is for clear weather with no atmospheric hydrometeors present in the observing instruments' field of view.

The resolution of the spectrum of Fig. 9-1 is extremely low and the figure should not be used for quantitative work. The section numbers listed under the transmission curve indicate where expanded transmission spectra in particular decades of frequency (wavelength) can be found.

A note of caution is appropriate! Transmission spectra can be taken under various conditions of resolution; thus, a window at low resolution may be a semi-window or a door at higher resolution. In particular the spectra of Fig. 9-15 in Section 9.5.10 exemplify this effect. Also, refs. 133 and 134 give detailed spectra for horizontal paths.

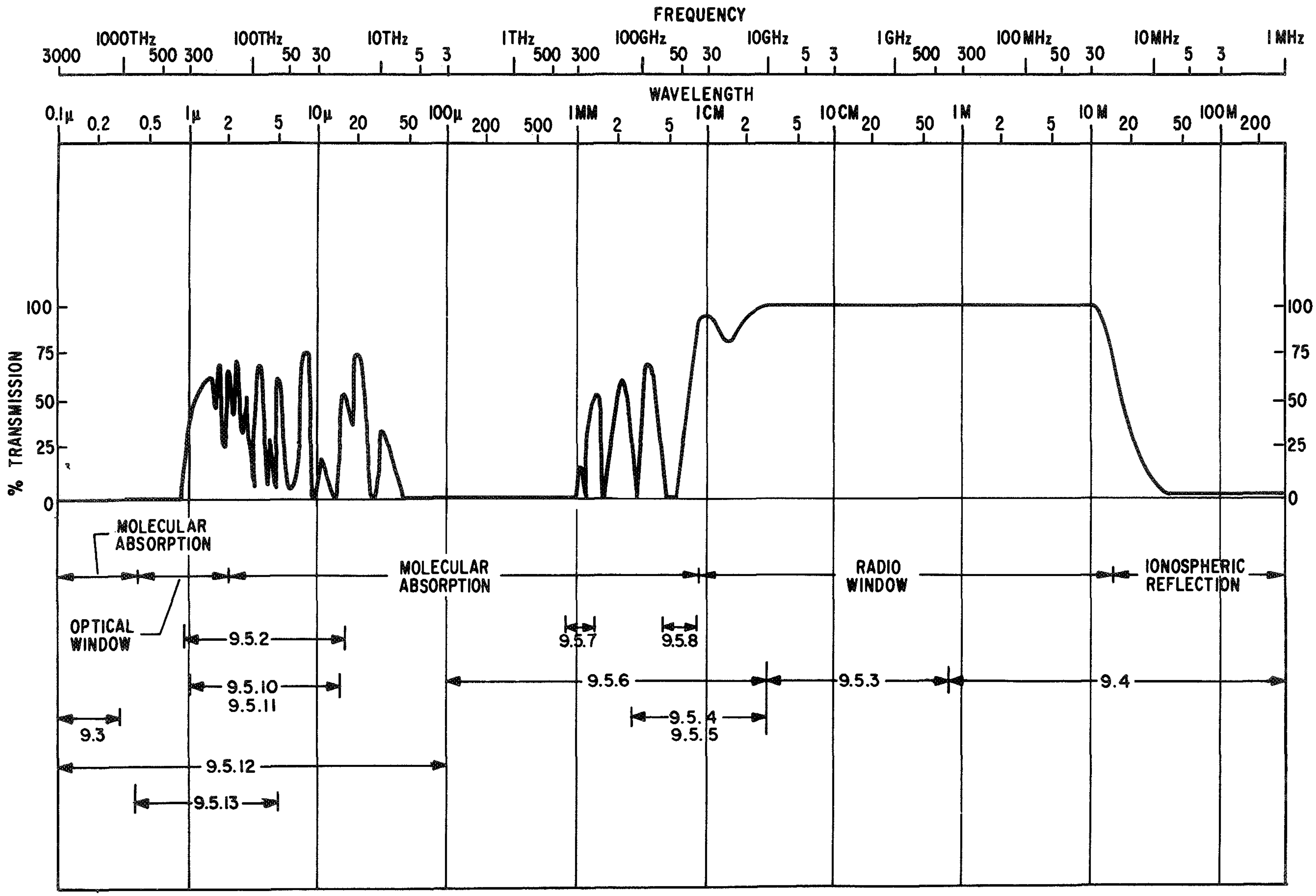


Figure 9-1.- Partial electromagnetic spectrum showing relative transparency of the Earth's atmosphere and ionosphere

9.3 ABSORPTION COEFFICIENTS

Bleany and Bleany (ref. 1) solve the case of a plane polarized electromagnetic wave propagating along the x-axis in a Cartesian coordinate system (x, y, z) in a conducting medium of finite conductivity σ. Defining the complex index of refraction m as

$$m = n - ik \tag{9-1}$$

where n is the phase refractive index and k is the absorption index of the medium (Section 8.2) we can present the form of the solution for the wave:

$$\exp \{i\omega(t-mx/c)\} = \exp (-Kx) \exp \{i\omega(t-nx/c)\}, \tag{9-2}$$

where $K = 2\pi k/\lambda$ (Section 8.2).

Equation (9-2) shows that the value of K determines the rate at which the amplitude of the wave decays (K appears in the argument of the real exponential) while n determines the wave velocity in the medium (i.e. $v = n/c$ (Section 8.2)). Thus a complex index of refraction indicates that the wave is being absorbed as it proceeds, because the finite conductivity of the medium causes a power loss by Joule heating. This is also discussed in some detail in Chapter 31 of Feynman et al., ref. 2 and in refs. 125 and 132.

The absorption coefficient is a measure of the amount of normally incident radiant energy absorbed through a unit distance of absorbing medium.

Like the analogous scattering coefficient, the absorption coefficient K is frequently identified in Bouguer's law (Section 1.2.2) as follows:

$$I_x = I_o \exp (-Kx), \tag{9-3}$$

where I_x is the flux density of radiation at a particular wavelength, initially of density I_o, after traversing a distance x in some absorbing medium. In some computations it is more convenient to express this law in the slightly different form:

$$I_x = I_o \, (10^{-qx}) \tag{9-4}$$

where q is called the decimal coefficient of absorption and equals 0.4343 K. In the above uses, K is expressed in units of reciprocal length.

Figure 9-2 presents the ultraviolet absorption coefficient of various atmospheric gases, where K is the exponential absorption coefficient per atmosphere-centimeter (i.e., per centimeter at STP). In order to determine atmospheric absorption from the curves, it would be necessary to allow for atmospheric composition (Fig. 4-1) and the degree of dissociation of some molecules. In the region of 900-1000 Å (0.09 - 0.1 μm; 3,300 - 3,000 THz) there are two curves for oxygen. Of these the curve representing the higher absorption allows for the preionization factor.

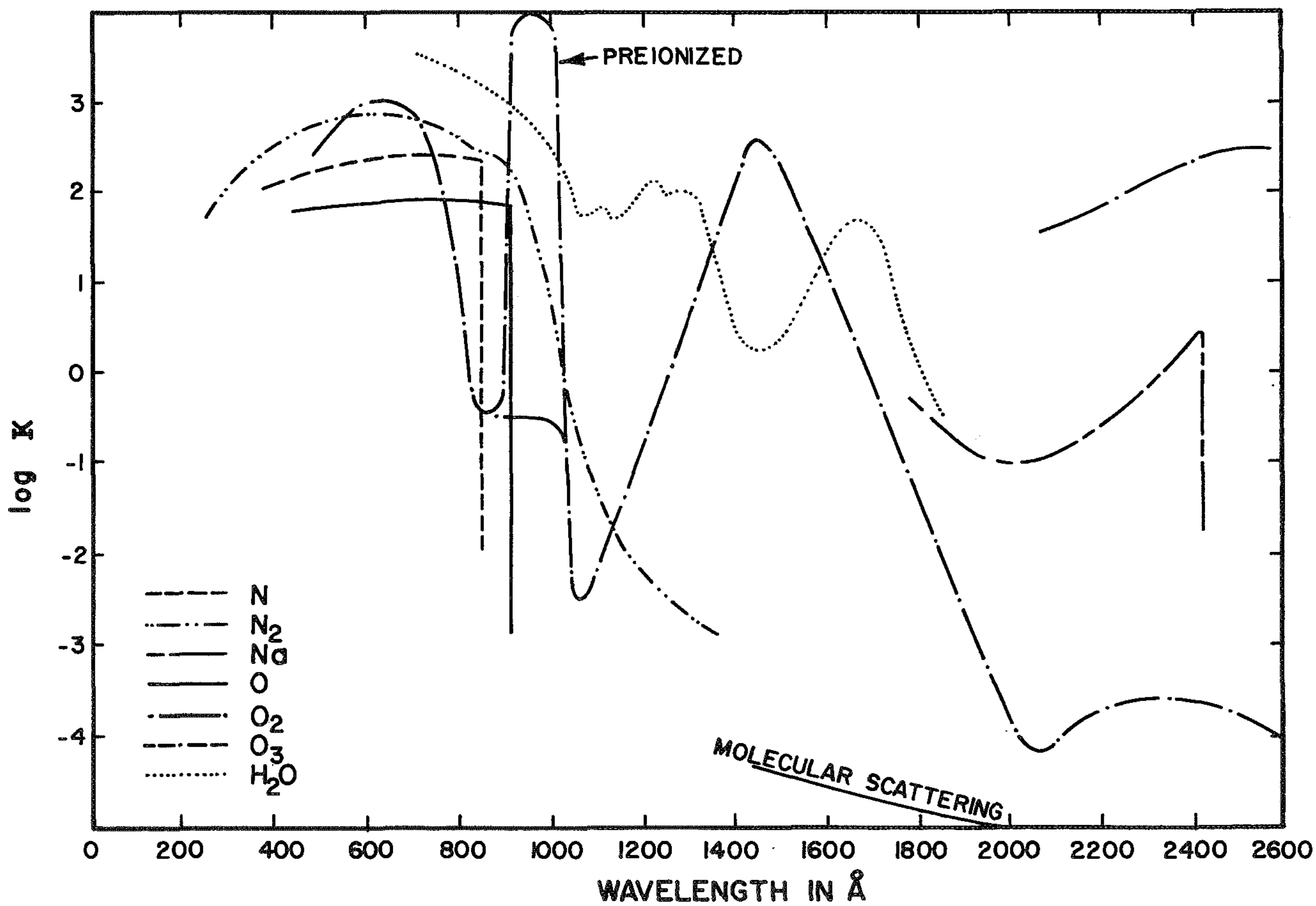


Figure 9-2.- Ultraviolet absorption coefficient for some atmospheric gases (After Allen, 1963, ref. 3; Chapter 6).

9.4 IONOSPHERIC ABSORPTION

9.4.1 Introduction

The ionosphere also has a complex index of refraction:

$$m = n - ik \tag{9-5}$$

where n is the phase refractive index and k is the index of absorption. The index of absorption is related to the absorption coefficient K by $K = 2\pi k/\lambda$, where λ is the wavelength of the radiation. K represents the loss of energy caused by collisions and is discussed further in Section 8.2.

An ionized region in the upper atmosphere can affect the transmission of radio (or radar) waves in at least two ways. First, under suitable conditions, the charged particles can remove energy from an electromagnetic wave and thus attenuate the signal; in the limiting case, the energy of the wave can be completely absorbed. Second, a wave traveling from one place to another in which the electron density is different will undergo a change in its direction of propagation (refraction, Chapter 8). In certain circumstances, the radio wave can be reflected back. (When the index of refraction becomes zero.)

Absorption in the ionosphere occurs at frequencies less than 100 MHz (3 m). "The maximum total daytime attenuation, at a frequency of 100 MHz (3 m) is approximately 1.28 dB. It thus appears that, under normal conditions, ionospheric attenuation should be negligible at frequencies above 100 MHz (3 m)." (Millman, ref. 4.)

Figure 9-3 plots the ionospheric absorption at two elevation angles for a source at 1000 km height for a model atmosphere. It gives a lower value for the absorption at 100 MHz (3 m) than that quoted above. However, it shows the variation with frequency and can be adjusted upwards.

Millman (ref. 6) and Lawrence, Little, and Chivers (ref. 7) consider this problem in greater detail.

9.4.2 Long-term Ionospheric Propagation Predictions

A report entitled "Predicting long-term operational parameters of high-frequency sky-wave telecommunication systems" has recently been issued by the Institute for Telecommunication Sciences (ITS), ref. 8. This report describes the latest methods

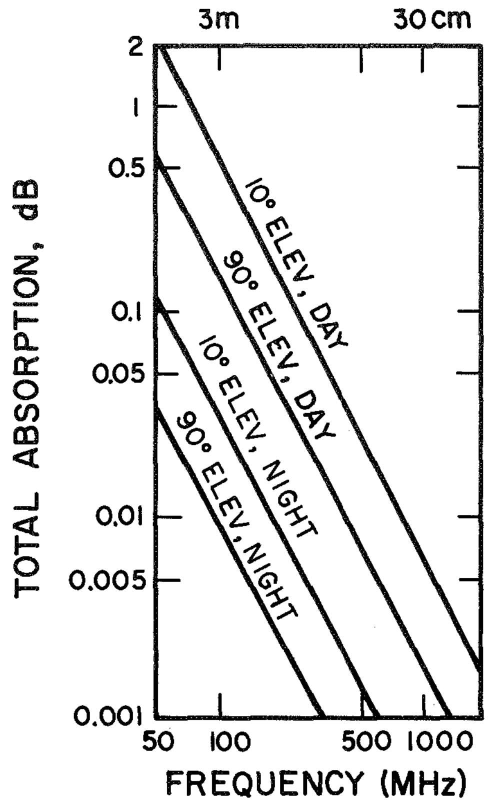


Figure 9-3.- Ionospheric absorption for a source at 1000 km height, (computation), (After Schmid, ref. 5)

and computer programs developed by the ITS for predicting the expected long-term performance of high-frequency telecommunication systems. Earlier work is described in refs. 9-14.

Emphasis is placed on solution by computer methods of the circuit operational parameters (maximum usable frequency, MUF; optimum traffic frequency, FOT; and the lowest useful frequency, LUF) and on recent improvements in the basic ionospheric and geophysical data. Propagation via the sporadic-E mode is considered as supplementing the regular E-layer mode. Improved techniques for calculating the theoretical patterns and gains of 10 most commonly used HF antennas are included. A method is described that provides short-term estimates of the F2-layer MUF from measured values of the local magnetic index. Application to communication problems is illustrated, based on concepts of circuit reliability and service probability as measures of the expected system performance, including consideration of multipath interference. An annotated listing of the program and description of input and output data are given in the appendices.

An example of predicted and observed signal strengths is given in Fig. 9-4. The comparison was for a 1292 km path from Long Branch, Illinois (40.22°N, 90.2°W), to Boulder, Colorado (40.13°N, 105.25°W). The results are described in detail in ref. 8.

The Institute for Telecommunication Sciences also publishes Ionospheric Predictions, the successor to CRPL Ionospheric Radio Predictions, (ref. 15) which are issued monthly, three months in advance, as an aid in determining the best sky-wave frequencies over any transmission path, at any time of day, for average conditions for the month. Sample copies may be obtained from

Prediction Services Section
Institute for Telecommunication Sciences
Environmental Science Services Administration
Boulder, CO 80302.

Each issue has complete ordering information and information on how to obtain the basic documents needed to understand the prediction techniques (refs. 9-13).

A sample chart giving the predicted median MUF (ZERO) F2 in MHz for December 1969 at Universal Time UT = 00 is given in Fig. 9-5.

A variation in the plot is given in Fig. 9-6.

9.4.3 HF Disturbance Warning and Short Term Prediction

A direct access time-share computer is used to provide forecasts of solar-geophysical disturbances which affect communications, (security) surveillance, and the manned space effort. Numerical coefficients representing the mapping contours of long-term ionospheric characteristics important to sky-wave propagation of high-frequency radio waves are stored in the computer. These coefficients are modified as forecasts or reports of disturbances are obtained. Typical messages automatically transmitted give operational information for specific time periods concerning the expected occurrence and severity of (a) short-wave fadeouts (SWF); (b) polar cap absorption (PCA) events; and (c) magnetic storms which cause changes in the maximum usable frequency (MUF). During disturbed propagation conditions, effective use of these solar-geophysical forecasts and short-term system performance predictions increases the likelihood of continuous communication.

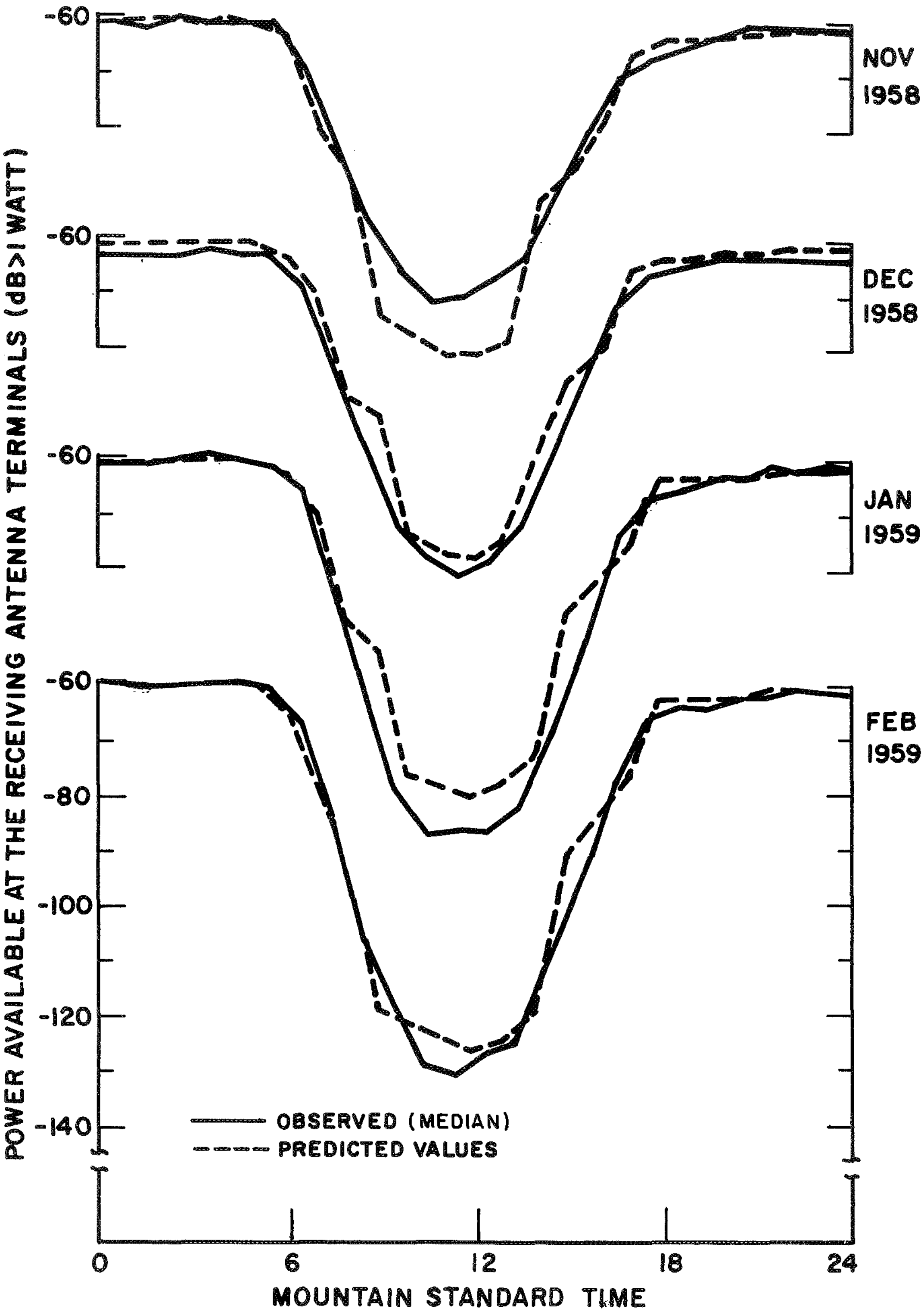


Figure 9-4.- Diurnal variation of observed and predicted available power of a 5-MHz transmission between Long Branch, Illinois, and Boulder, Colorado (1292 km), (After Barghausen, et al., 1969, ref. 8)

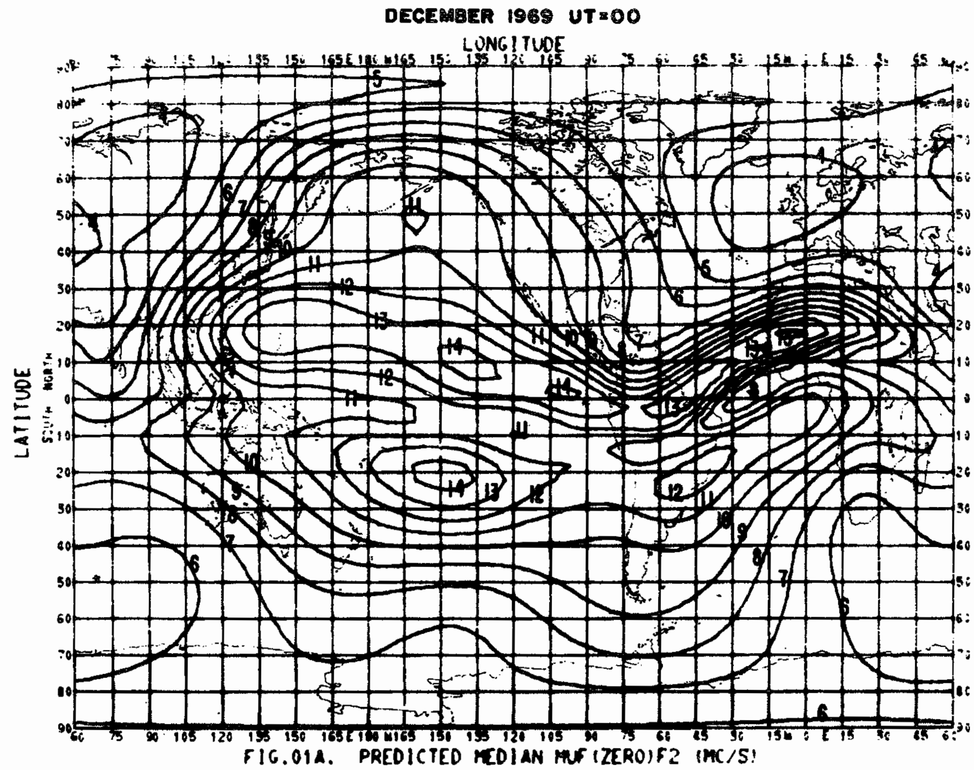


Figure 9-5.- A sample chart from <u>Ionospheric Predictions</u>, ref. 15

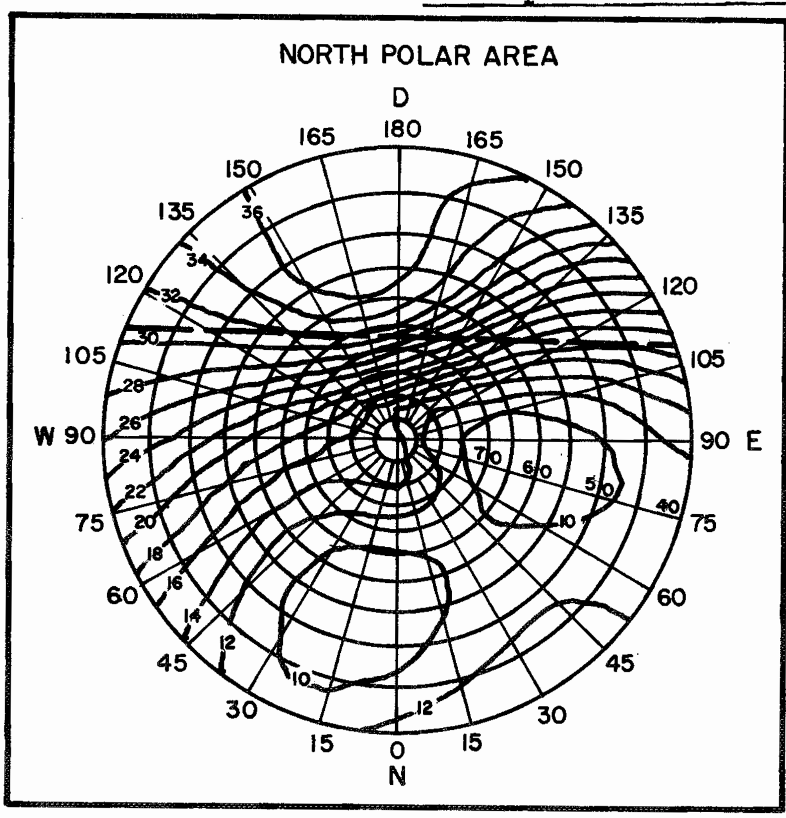


Figure 9-6.- A sample chart from <u>Ionospheric Predictions</u>, ref. 15

9.5 GASEOUS ABSORPTION

9.5.1 Introduction

The first part of this section contains information on the absorption of electromagnetic waves in the radio frequency spectrum by atmospheric gases. The principal absorbing gases are O_2, O_3, and H_2O. Other gaseous constituents (Section 9.5.2) do not exist in sufficient abundance to cause a measurable effect.

The following fact should be kept in mind when considering the absorption aspects of the earth's atmosphere in the optical region. The entire wavelength region from 0.3 to 5.0 μm (1,000 - 60 THz) contains thousands of sharp absorption lines due to H_2O, CO_2, N_2O, CH_2, O_2, CO, and their isotopes (Sections 9.5.2, 9.5.10). At low resolutions these lines are smoothed out so that only the clustering in strong bands appear to give absorption.

The data presented in this chapter is representative of the types of data available. Other information can be located by consulting the Atmospheric Transmission Bibliography: A KWIC Index of Electromagnetic Wave Transmission in the Earth's Atmosphere, to be issued under separate cover.

9.5.2 Chart of the Absorbing Gases in the Earth's Atmosphere and the Absorbing Band Intensities by Robert F. Calfee

Figure 9-7 is a chart showing the various gases which have absorbing properties in the earth's atmosphere covering the spectral range from the visible (.714 μm) to the microwave region (1.4 cm). (See Figure 4-1).

This chart was prepared by the Submillimeter Wave Area of the Wave Propagation Laboratory, Environmental Science Services Administration, Research Laboratories, Boulder, Colorado.

As can be seen from Figure 9-7 the gases contributing most extensively to atmospheric absorption are water vapor, carbon dioxide and ozone.

In the cases where detailed data are available (H_2O, CO_2, O_3, N_2O, CH_4, CO), it is possible to make accurate calculations of the transmission (or absorption) over slant paths in the earth's atmosphere for various atmospheric conditions for any desired spectral resolution.

The chart in Figure 9-7 does not give any information about the magnitude of the absorption in any region. For those gases occurring normally in the atmosphere, information about the intensity of the vibrational bands producing the absorption is available. The information is displayed graphically in Figure 9-8. Here the intensity of the band is plotted as a vertical line located at the position of the band center. The units of intensity are $cm^{-1}/(molecules/cm^2)$. The band center positions are indicated in both wave numbers (cm^{-1}) and wavelength (μm or microns). The pure rotational spectrum of water vapor is included by summing the intensities of lines within a 200 cm^{-1} interval and indicating this value by a line midway of the interval. For the other regions the graph lines represent the sum of the line intensities associated with a particular vibrational-rotational band.

Table 9-1 gives the information used for making up the graph. Most of the column headings are self-explanatory. The vibrational transition quantum numbers differ among the various molecules. For carbon dioxide there are five numbers to describe a level (V_1, V_2, ℓ, V_3, Fermi rank). For nitrous oxide only V_1, V_2, ℓ, V_3 are used. For water and ozone only V_1, V_2 V_2 are needed.

The column marked ISO indicates the isotropic species of the atoms making up the molecule e.g. 626 → $O^{16}C^{12}O^{16}$, 446 → $N^{14}N^{14}O^{16}$, 26 → $C^{12}O^{16}$, 162 → $H^1O^{16}H^2$ or HDO.

All these charts, graphs and tables are constantly being revised as more or better data become available. The values given here are very good and serve a very useful purpose for those interested in atmospheric transmission problems.

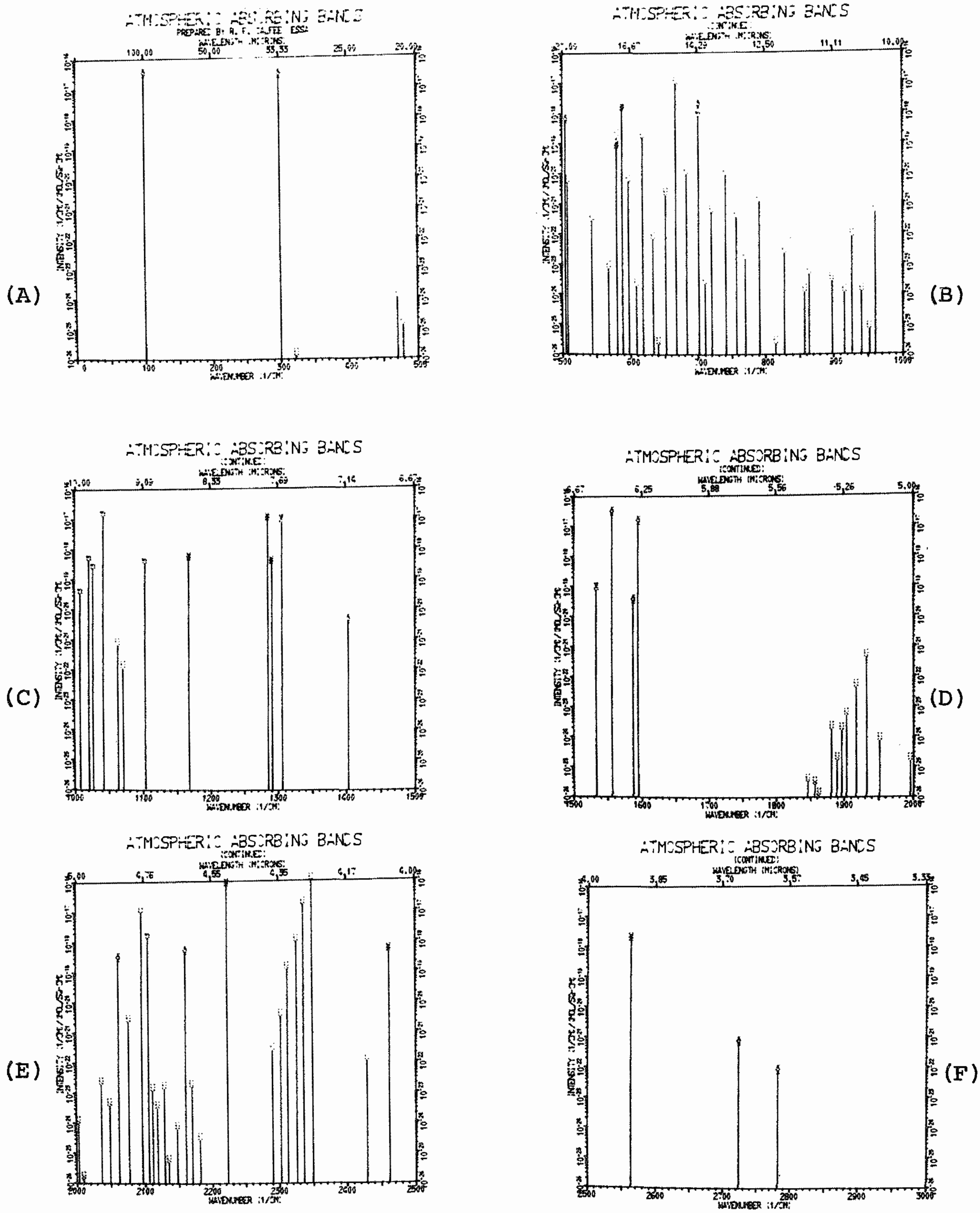


Figure 9-8.- Atmospheric absorbing bands

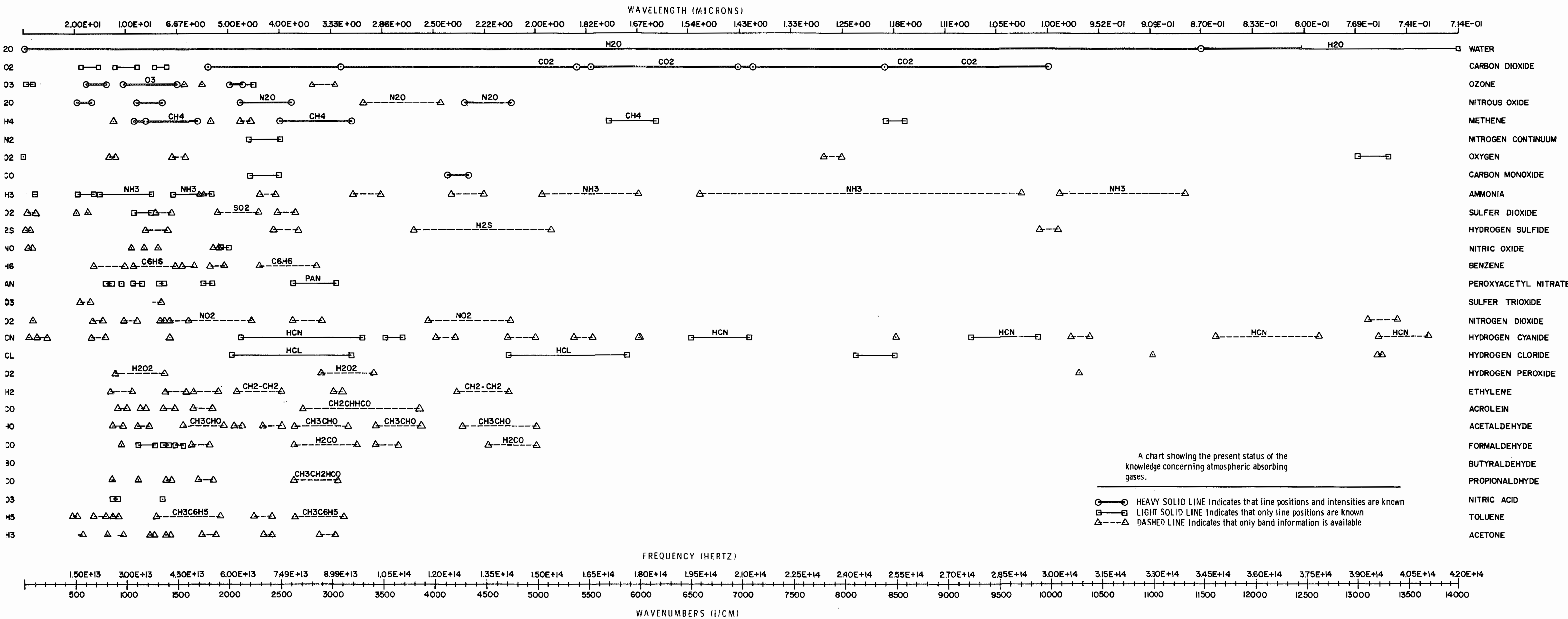


Figure 9-7-.-Chart of absorbing gases in the earth's atmosphere (Courtesy of the Wave Propagation Laboratory, ESSA Research Laboratories, Boulder, Colorado) Supported in part by ARPA.

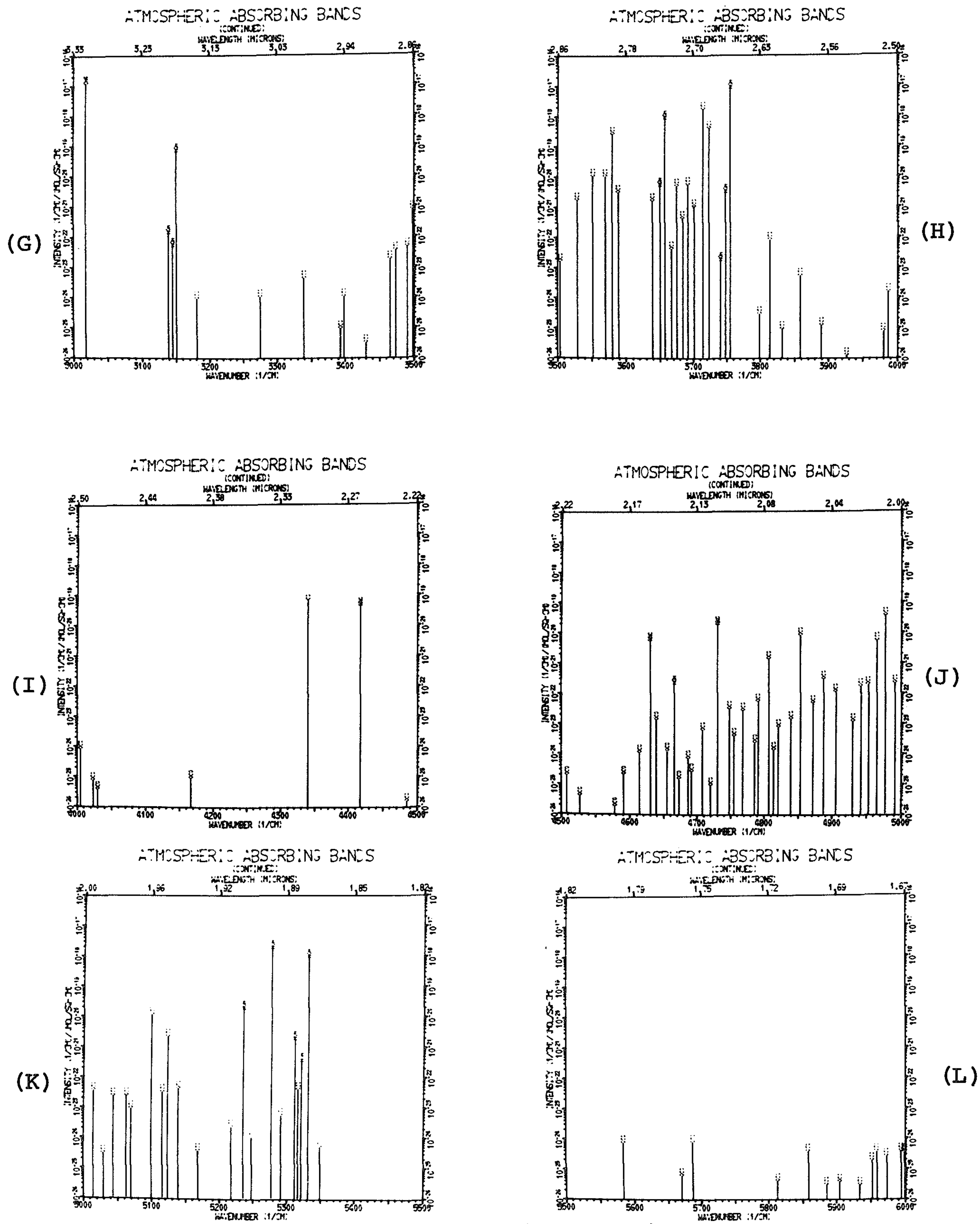
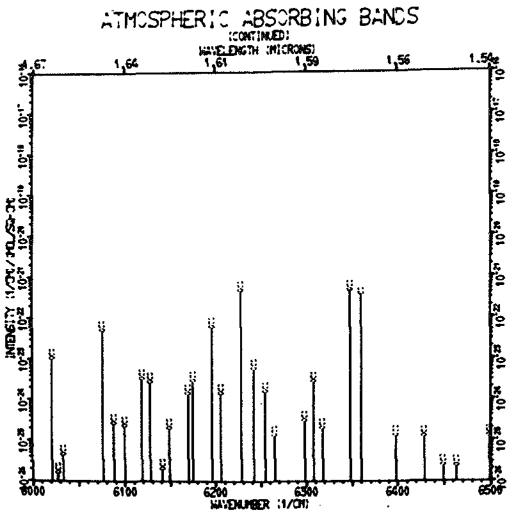
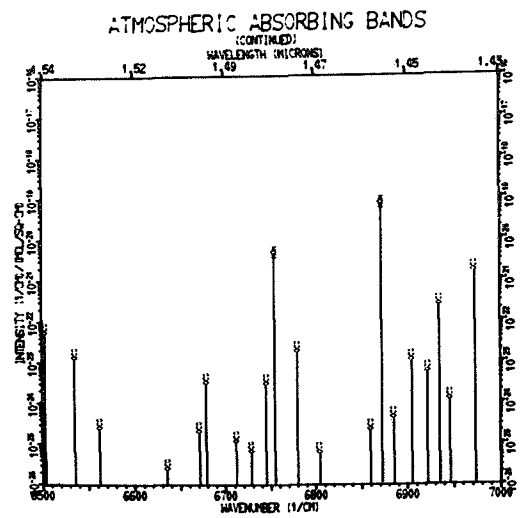


Figure 9-8.- (Continued)

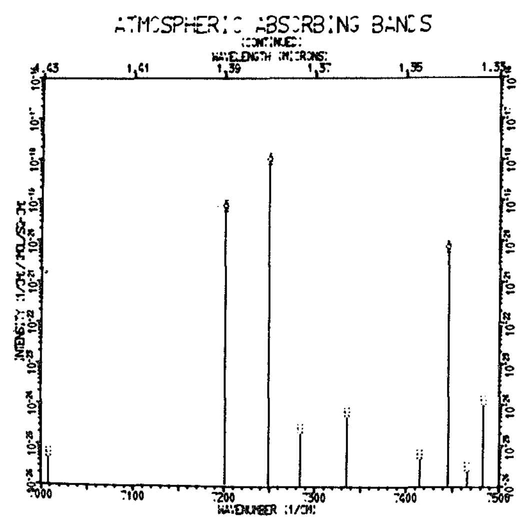
(M)



(N)



(O)



(P)

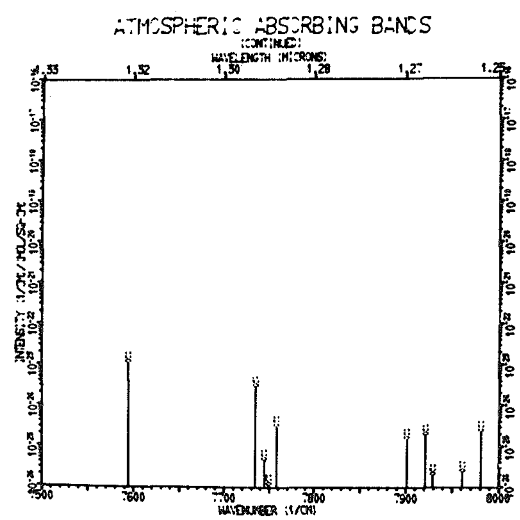


Figure 9-8.- (Concluded)

TABLE 9-1.- ATMOSPHERIC ABSORBING BANDS, PREPARED BY R. F. CALFEE, WAVE PROPAGATION LABORATORY, ESSA RESEARCH LABORATORIES MAY 1970.

BAND CENTER WAVE NUMBER (1/CM)	BAND CENTER WAVE LENGTH (MU)	BAND INTENSITY (1/CM) / (MOL/SQ CM)	VIBRATIONAL TRANSITION UPPER STATE	VIBRATIONAL TRANSITION LOWER STATE	GAS	ISO
321.971	31.059	1.239-026	20002	00011	OCO	626
448.072	22.318	8.556-027	20001	00011	OCO	626
471.513	21.208	9.746-025	20003	11101	OCO	626
479.895	20.838	1.223-025	13302	12201	OCO	626
508.142	19.680	5.163-021	12202	11101	OCO	626
510.350	19.594	4.025-025	21103	20002	OCO	626
542.190	18.444	7.105-025	21102	20001	OCO	626
544.283	18.373	2.723-022	11102	10001	OCO	626
568.664	17.585	7.157-024	13302	04401	OCO	626
578.595	17.283	3.765-024	21102	12201	OCO	626
579.367	17.260	6.994-020	0200	0110	NNO	446
581.697	17.191	1.934-022	12202	03301	OCO	626
588.767	16.985	1.228-018	0110	0000	NNO	446
588.983	16.978	6.994-020	0220	0110	NNO	446
594.248	16.828	9.077-023	20002	11101	OCO	626
596.457	16.766	2.574-023	21103	12202	OCO	626
597.341	16.741	5.208-021	11102	02201	OCO	626
605.910	16.504	9.077-027	20013	11112	OCO	626
608.828	16.425	1.748-024	10012	01111	OCO	626
615.908	16.236	6.889-022	20003	11102	OCO	626
618.033	16.180	1.436-019	10002	01101	OCO	626
633.086	15.796	6.488-023	21103	20003	OCO	626
640.266	15.619	2.113-026	12212	11112	OCO	626
652.536	15.325	1.652-021	12202	11102	OCO	626
654.874	15.270	8.854-023	01111	00011	OCO	626
655.261	15.261	7.410-025	02211	01111	OCO	626
655.637	15.252	9.895-023	13302	12202	OCO	626
656.214	15.239	2.574-026	04411	03311	OCO	626
667.379	14.984	8.258-018	01101	00001	OCO	626
667.750	14.976	6.488-019	02201	01101	OCO	626
668.180	14.966	3.824-020	03301	02201	OCO	626
668.230	14.965	3.117-023	21102	20002	OCO	626
668.670	14.955	1.845-021	04401	03301	OCO	626
668.678	14.955	1.488-020	11101	10001	OCO	626
669.219	14.943	9.761-023	05501	04401	OCO	626
681.587	14.672	4.598-023	13301	12201	OCO	626
683.884	14.622	9.047-021	12201	11101	OCO	626
701.000	14.265	7.435-019	010	000	O3	666
703.540	14.214	2.463-023	21101	20001	OCO	626
710.765	14.069	2.024-024	10011	01111	OCO	626
720.289	13.883	4.784-022	20001	11101	OCO	626
720.808	13.873	1.853-019	10001	01101	OCO	626
738.648	13.538	3.021-022	20002	11102	OCO	626
739.945	13.515	1.756-023	21101	12201	OCO	626

TABLE 9-1.- (Continued)

741.735	13.482	7.901-021	11101	02201	OCO	626
754.337	13.257	1.607-023	21102	12202	OCO	626
757.439	13.202	3.288-022	12201	03301	OCO	626
770.355	12.981	1.351-023	13301	04401	OCO	626
790.966	12.643	5.483-024	21102	20003	OCO	626
791.452	12.635	1.123-021	11101	10002	OCO	626
815.691	12.260	2.202-026	10012	20001	OCO	626
828.278	12.073	2.009-023	12201	11102	OCO	626
829.581	12.054	1.153-024	21101	20002	OCO	626
857.329	11.664	1.097-024	13301	12202	OCO	626
864.684	11.565	4.315-024	20001	11102	OCO	626
898.529	11.129	2.634-024	02211	12201	OCO	626
915.687	10.921	1.949-025	21101	12202	OCO	626
917.627	10.898	8.705-025	10011	20001	OCO	626
927.151	10.786	7.113-023	01111	11101	OCO	626
941.731	10.619	1.146-024	10012	20002	OCO	626
952.316	10.501	6.398-026	21101	20003	OCO	626
960.955	10.406	4.910-022	00011	10001	OCO	626
1008.000	9.921	9.534-021	101	100	O3	666
1008.000	9.921	2.506-020	001	000	O3	686
1021.000	9.794	4.248-019	011	010	O3	666
1027.000	9.737	1.627-019	002	001	O3	666
1029.000	9.718	6.695-020	001	000	O3	668
1042.096	9.596	1.292-017	001	000	O3	666
1043.668	9.582	1.176-024	10011	20002	OCO	626
1060.921	9.426	7.775-027	20013	30004	OCO	626
1063.730	9.401	6.324-022	00011	10002	OCO	626
1064.467	9.394	2.329-024	10012	20003	OCO	626
1065.995	9.381	2.120-026	12212	22203	OCO	626
1068.017	9.363	2.664-026	01121	11112	OCO	626
1071.546	9.332	1.080-022	01111	11102	OCO	626
1074.271	9.309	4.538-024	02211	12202	OCO	626
1103.157	9.065	3.330-019	100	000	O3	666
1166.403	8.573	8.184-027	10011	20003	OCO	626
1168.134	8.561	4.464-019	0200	0000	NNO	446
1284.907	7.783	8.705-018	1000	0000	NNO	446
1291.501	7.743	3.125-019	1110	0110	NNO	446
1306.000	7.657	7.048-018	0001	0000	CH4	21
1403.480	7.125	3.210-021	010	000	HOH	162
1533.000	6.523	7.516-020	0100	0000	CH4	21
1556.870	6.423	2.340-017	020	010	HOH	161
1587.380	6.300	2.330-020	010	000	HOH	181
1590.550	6.287	4.320-021	010	000	HOH	171
1594.730	6.271	1.170-017	010	000	HOH	161
1846.321	5.416	3.274-026	21103	02201	OCO	626
1856.820	5.386	2.604-026	20003	01101	OCO	636
1860.210	5.376	4.464-027	30004	11102	OCO	626
1865.615	5.360	6.696-027	30003	11101	OCO	626
1880.901	5.317	1.562-024	20003	01101	OCO	626
1883.180	5.310	1.488-025	12202	01101	OCO	636
1889.430	5.293	1.265-025	22203	11102	OCO	626
1894.840	5.277	3.720-026	14402	03301	OCO	626
1896.038	5.274	1.101-024	21103	10002	OCO	626
1896.490	5.273	1.488-024	11102	00001	OCO	636

PAGE 2

TABLE 9-1.- (Continued)

1901.600	5.259	2.976-024	11102	00001	OCO	628
1905.129	5.249	1.786-024	13302	02201	OCO	626
1917.663	5.215	4.226-023	12202	01101	OCO	626
1930.985	5.179	8.184-026	22202	11101	OCO	626
1932.470	5.175	4.092-022	11102	00001	OCO	626
1951.153	5.125	7.068-025	21102	10001	OCO	626
1996.100	5.010	1.488-025	20002	01101	OCO	636
2003.841	4.990	8.184-025	20002	01101	OCO	626
2004.211	4.989	1.176-025	21102	02201	OCO	626
2010.010	4.975	1.339-026	30003	11102	OCO	626
2037.093	4.909	1.860-023	11101	00001	OCO	636
2049.700	4.879	3.720-024	11101	00001	OCO	628
2062.000	4.850	5.208-025	11101	00001	OCO	627
2062.350	4.849	2.400-019	100	010	HOH	161
2075.380	4.818	8.482-025	22202	11102	OCO	626
2076.865	4.815	2.232-021	11101	00001	OCO	626
2093.356	4.777	3.958-022	12201	01101	OCO	626
2096.000	4.771	9.706-018	1	0	CO	26
2102.000	4.757	1.488-024	20001	01101	OCO	636
2106.000	4.748	1.335-018	101	000	O3	666
2107.021	4.746	2.530-023	13301	02201	OCO	626
2112.403	4.734	1.116-023	21101	10001	OCO	626
2117.235	4.723	1.176-025	12212	12201	OCO	626
2119.540	4.718	1.562-024	14401	03301	OCO	626
2120.335	4.716	1.190-024	22201	11101	OCO	626
2127.231	4.701	2.470-025	12212	12201	OCO	626
2129.775	4.695	1.302-023	20001	01101	OCO	626
2132.065	4.690	1.503-026	21112	21101	OCO	626
2135.735	4.682	3.318-026	21113	21102	OCO	626
2148.035	4.655	5.952-025	30001	11101	OCO	626
2161.190	4.627	3.900-019	001	010	HOH	161
2165.461	4.618	5.952-024	21101	02201	OCO	626
2170.841	4.607	5.074-024	11112	11101	OCO	626
2170.849	4.606	9.806-024	11112	11101	OCO	626
2180.676	4.586	9.188-026	20012	20001	OCO	626
2182.400	4.582	1.722-025	20013	20002	OCO	626
2223.756	4.497	6.882-017	0001	0000	NNO	446
2224.657	4.495	1.272-022	10012	10001	OCO	626
2286.779	4.373	3.884-023	05511	05501	OCO	626
2288.352	4.370	2.366-023	13311	13301	OCO	626
2289.890	4.367	1.786-023	21111	21101	OCO	626
2290.715	4.365	3.125-023	13312	13302	OCO	626
2293.416	4.360	3.839-023	21112	21102	OCO	626
2293.615	4.360	7.931-023	21113	21103	OCO	626
2299.219	4.349	9.791-022	04411	04401	OCO	626
2301.017	4.346	6.339-022	12211	12201	OCO	626
2301.918	4.344	2.887-024	10021	10011	OCO	626
2302.384	4.343	4.724-024	10022	10012	OCO	626
2302.508	4.343	1.324-022	20011	20001	OCO	626
2302.973	4.342	7.366-022	12212	12202	OCO	626
2305.246	4.338	4.352-022	20013	20003	OCO	626
2306.720	4.335	2.396-022	20012	20002	OCO	626
2311.675	4.326	2.455-020	03311	03301	OCO	626
2311.715	4.326	3.586-022	01121	01111	OCO	626

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TABLE 9-1.- (Continued)

2313.764	4.322	1.711-020	11111	11101	OCO	626
2315.246	4.319	3.422-020	11112	11102	OCO	626
2324.148	4.303	6.160-019	02211	02201	OCO	626
2324.182	4.303	2.098-021	00021	00011	OCO	626
2326.594	4.298	1.183-019	10011	10001	OCO	626
2327.432	4.297	1.934-019	10012	10002	OCO	626
2336.637	4.280	1.533-017	01111	01101	OCO	626
2349.142	4.257	9.598-017	00011	00001	OCO	626
2428.549	4.118	1.458-025	20011	20002	OCO	626
2429.369	4.116	1.059-022	10011	10002	OCO	626
2429.456	4.116	2.563-025	20012	20003	OCO	626
2458.158	4.068	8.035-024	11111	11102	OCO	626
2461.998	4.062	4.278-019	1200	0000	NNO	446
2490.004	4.016	3.028-027	13311	13302	OCO	626
2563.341	3.901	1.637-018	2000	0000	NNO	446
2723.700	3.671	5.400-022	100	000	HOH	162
2782.040	3.594	6.300-023	020	000	HOH	162
3018.000	3.313	1.199-017	0010	0000	CH4	21
3125.300	3.200	7.403-027	30004	01101	OCO	626
3139.100	3.186	1.320-022	020	000	HOH	181
3145.350	3.179	4.920-023	020	000	HOH	161
3151.600	3.173	6.630-020	020	000	HOH	161
3154.500	3.170	7.410-026	22206	01101	OCO	626
3181.450	3.143	2.128-025	05101	00001	OCO	626
3181.463	3.143	6.867-025	21103	00001	OCO	626
3275.100	3.053	1.019-024	30003	01101	OCO	626
3339.343	2.995	4.166-024	21102	00001	OCO	626
3342.928	2.991	1.475-026	22213	12201	OCO	626
3393.000	2.947	9.226-026		00001	OCO	636
3398.100	2.943	1.853-025	30002	01101	OCO	626
3398.213	2.943	8.258-025	21113	11101	OCO	626
3404.875	2.937	3.709-026	30014	20002	OCO	626
3430.770	2.915	3.155-026	30013	20001	OCO	626
3465.436	2.886	1.786-023	20013	10001	OCO	626
3473.680	2.879	3.422-023	12212	02201	OCO	636
3490.350	2.865	4.628-023	10012	00001	OCO	638
3498.720	2.858	7.314-022	11112	01101	OCO	636
3500.694	2.857	6.026-024	21101	00001	OCO	626
3504.944	2.853	9.508-024	14412	04401	OCO	626
3527.610	2.835	1.034-023	30014	20003	OCO	626
3527.747	2.835	7.470-024	22212	12201	OCO	626
3528.049	2.834	1.220-022	13312	03301	OCO	626
3528.250	2.834	1.295-022	13312	03301	OCO	626
3533.975	2.830	3.527-024	11122	01111	OCO	626
3538.950	2.826	4.449-022		01101	OCO	628
3542.570	2.823	3.147-022	40002	11102	OCO	626
3542.608	2.823	6.339-022	21113	11102	OCO	626
3550.708	2.816	1.953-024	30012	20001	OCO	626
3552.820	2.815	3.452-021	12212	02201	OCO	626
3552.850	2.815	6.250-021	12212	02201	OCO	626
3555.860	2.812	8.333-023	21112	11101	OCO	626
3555.894	2.812	2.202-022	21112	11101	OCO	626
3556.749	2.812	6.287-024	30013	20002	OCO	626
3566.087	2.804	2.083-023	10022	00011	OCO	626

TABLE 9-1.- (Continued)

3568.221	2.803	3.378-021	20012	10002	OCO	626
3571.110	2.800	6.495-021	10011	00001	OCO	628
3578.670	2.794	2.753-023	22213	12202	OCO	626
3580.290	2.793	9.479-020	11112	01101	OCO	626
3580.334	2.793	1.607-019	11112	01101	OCO	626
3587.510	2.787	7.031-023	10011	00001	OCO	638
3589.646	2.786	1.786-021	20012	10001	OCO	626
3591.360	2.784	1.094-021		00001	OCO	627
3639.180	2.748	1.518-021	11111	01101	OCO	636
3641.530	2.746	6.294-023	31101	02201	OCO	636
3649.680	2.740	1.920-021	100	000	HOH	181
3653.390	2.737	3.000-022	100	000	HOH	171
3657.080	2.734	8.100-019	100	000	HOH	161
3667.557	2.727	3.832-023	10021	00011	OCO	626
3675.110	2.721	4.777-021	10012	00001	OCO	628
3675.694	2.721	6.622-024	11121	01111	OCO	626
3676.749	2.720	9.151-024	30012	20002	OCO	626
3679.547	2.718	9.858-024	30013	20003	OCO	626
3684.050	2.714	3.884-022		01101	OCO	628
3692.421	2.708	4.241-021	20012	10002	OCO	626
3693.430	2.708	1.131-021		00001	OCO	627
3700.270	2.703	2.411-022	21112	11102	OCO	626
3700.289	2.702	7.098-022	21112	11102	OCO	626
3703.489	2.700	3.006-023	22212	12202	OCO	626
3705.939	2.698	5.506-024	30011	20001	OCO	626
3711.475	2.694	3.501-021	20011	10001	OCO	626
3713.680	2.693	1.481-022	21111	11101	OCO	626
3713.719	2.693	5.632-022	21111	11101	OCO	626
3713.803	2.693	2.187-023	22211	12201	OCO	626
3714.781	2.692	1.685-018	10011	00001	OCO	626
3723.249	2.686	2.783-019	11111	01101	OCO	626
3723.310	2.686	1.135-019	12211	01101	OCO	626
3726.365	2.684	1.875-023	14411	04401	OCO	626
3726.610	2.683	3.683-021	12211	02201	OCO	626
3726.636	2.683	1.141-020	12211	02201	OCO	626
3727.377	2.683	4.643-022	13311	03301	OCO	626
3727.700	2.683	1.295-022	13311	03301	OCO	626
3740.620	2.673	1.580-023	001	000	HOH	181
3748.270	2.668	2.920-021	001	000	HOH	171
3755.920	2.662	7.890-018	001	000	HOH	161
3757.500	2.661	7.410-026	22203	01101	OCO	626
3799.484	2.632	2.768-025	30012	20003	OCO	626
3814.250	2.622	7.700-023	20011	10002	OCO	626
3831.980	2.610	9.151-026	30011	20002	OCO	626
3858.113	2.592	5.104-024	21111	11102	OCO	626
3889.545	2.571	1.199-025	22211	12202	OCO	626
3927.544	2.546	1.205-026	01121	10001	OCO	626
3980.601	2.512	7.440-026	01121	02201	OCO	626
3987.610	2.508	1.488-024	30002	00001	OCO	628
4005.940	2.496	8.184-025	00021	01101	OCO	626
4023.480	2.485	7.440-026	30002	00001	OCO	627
4030.318	2.481	3.720-026	0112	10002	OCO	626
4167.910	2.399	8.928-026	30001	00001	OCO	628
4340.000	2.304	6.966-020	2	0	CO	26

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TABLE 9-1.- (Continued)

4416.150	2.264	3.720-026	31104	00001	OCO	626
4417.379	2.264	4.464-020	0002	0000	NNO	446
4485.600	2.229	1.562-026	01121	01101	OCO	638
4508.749	2.218	1.860-025	00021	00001	OCO	638
4524.880	2.210	1.711-026	00021	00001	OCO	637
4527.280	2.209	1.302-027	31103	00001	OCO	636
4529.870	2.208	2.232-026	40004	01101	OCO	626
4578.090	2.184	1.786-026	32203	01101	OCO	626
4591.118	2.178	2.046-025	31103	00001	OCO	626
4611.310	2.169	3.720-026	31114	11101	OCO	626
4614.779	2.167	1.042-024	01121	01101	OCO	628
4630.164	2.160	5.580-021	1201	0000	NNO	446
4630.370	2.160	9.672-026	01121	01101	OCO	627
4639.502	2.155	1.302-023	00021	00001	OCO	628
4655.205	2.148	1.265-024	00021	00001	OCO	627
4666.720	2.143	2.010-022	030	000	HOH	161
4673.680	2.140	1.488-025	22213	02201	OCO	636
4683.120	2.135	1.860-027	31102	00001	OCO	636
4685.780	2.134	1.860-025	30014	10002	OCO	636
4687.796	2.133	5.208-025	30014	10001	OCO	626
4692.180	2.131	2.604-025	20013	00001	OCO	638
4708.520	2.124	5.952-024	21113	01101	OCO	636
4718.350	2.119	4.464-026	20013	00001	OCO	637
4721.920	2.118	4.836-026	20013	00001	OCO	828
4730.828	2.114	1.860-020	2001	0000	NNO	446
4733.500	2.113	6.696-025	23313	03301	OCO	626
4743.700	2.108	3.348-024	21113	01101	OCO	628
4748.058	2.106	2.678-023	20013	00001	OCO	636
4753.450	2.104	2.976-025	31102	00001	OCO	626
4755.705	2.103	3.571-024	31114	11102	OCO	626
4768.541	2.097	2.604-023	22213	02201	OCO	626
4784.675	2.090	1.488-025	20023	00011	OCO	626
4786.688	2.089	1.190-024	31113	11101	OCO	626
4790.571	2.087	1.562-023	30014	10002	OCO	626
4791.260	2.087	4.687-023	20013	00001	OCO	628
4807.692	2.080	1.339-021	21113	01101	OCO	626
4814.570	2.077	1.339-024	20012	00001	OCO	638
4821.500	2.074	7.440-024	20013	00001	OCO	627
4839.737	2.066	1.376-023	30013	10001	OCO	626
4853.620	2.060	8.072-021	20013	00001	OCO	626
4871.460	2.053	4.762-023	21112	01101	OCO	636
4887.390	2.046	2.976-022	20012	00001	OCO	636
4896.185	2.042	8.928-024	21112	01101	OCO	628
4904.850	2.039	1.116-022	20012	00001	OCO	628
4925.010	2.030	4.464-025	20011	00001	OCO	638
4928.910	2.029	1.488-024	21112	01101	OCO	627
4931.083	2.028	9.672-024	31113	11102	OCO	626
4939.350	2.025	2.306-023	20012	00001	OCO	627
4942.512	2.023	1.414-022	30013	10002	OCO	626
4946.807	2.022	5.952-024	31112	11101	OCO	626
4953.363	2.019	1.042-022	22212	02201	OCO	626
4959.667	2.016	8.370-023	30012	10001	OCO	626
4965.381	2.014	5.312-021	21112	01101	OCO	626
4977.830	2.009	3.497-020	20012	00001	OCO	626

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TABLE 9-1.- (Continued)

4991.350	2.003	2.120-022	20011	00001	OCO	636
5013.785	1.995	3.422-023	21111	01101	OCO	636
5028.780	1.989	2.976-025	22211	02201	OCO	636
5042.570	1.983	2.269-023	20011	00001	OCO	628
5062.442	1.975	2.381-023	30012	10002	OCO	626
5064.680	1.974	2.604-024	21111	01101	OCO	628
5068.910	1.973	6.324-024	20011	00001	OCO	627
5099.660	1.961	1.123-020	20011	00001	OCO	626
5114.894	1.955	3.088-023	30011	10001	OCO	626
5123.200	1.952	2.128-021	21111	01101	OCO	626
5139.401	1.946	4.092-023	22211	02201	OCO	626
5168.600	1.935	3.720-025	01121	00001	OCO	636
5217.669	1.917	2.344-024	30011	10002	OCO	626
5234.950	1.910	1.830-020	110	000	HOH	161
5247.830	1.906	1.012-024	10022	01101	OCO	626
5276.770	1.895	1.800-018	012	010	HOH	161
5277.070	1.895	1.488-025	01121	00001	OCO	628
5291.160	1.890	5.506-024	02221	01101	OCO	626
5294.970	1.889	2.678-026	01121	00001	OCO	627
5310.510	1.883	1.810-021	011	000	HOH	181
5315.730	1.881	3.980-023	01121	00001	OCO	626
5320.860	1.879	3.360-022	011	000	HOH	171
5331.210	1.876	9.060-019	011	000	HOH	161
5349.360	1.869	5.059-025	10021	01101	OCO	626
5584.391	1.791	7.068-025	00031	10001	OCO	626
5670.080	1.764	5.952-026	01131	11102	OCO	626
5687.166	1.758	7.514-025	00031	10002	OCO	626
5809.460	1.721	3.720-027	10021	00001	OCO	638
5813.020	1.720	2.976-026	11122	01101	OCO	628
5858.022	1.707	3.720-025	10022	00001	OCO	628
5885.336	1.699	2.976-026	10022	00001	OCO	627
5904.470	1.694	3.720-026	31114	01101	OCO	636
5933.990	1.685	2.976-026	31114	01101	OCO	628
5951.600	1.680	1.786-025	30014	00001	OCO	636
5955.840	1.679	2.976-026	11124	01101	OCO	628
5959.954	1.678	3.348-025	10021	00001	OCO	628
5972.520	1.674	2.530-025	32214	02201	OCO	626
5987.020	1.670	1.488-026	10021	00001	OCO	627
5993.581	1.668	3.571-025	30014	00001	OCO	628
5998.569	1.667	3.348-025	40015	10002	OCO	626
6000.520	1.667	1.674-028	41103	00001	OCO	626
6020.795	1.661	9.300-024	31114	01101	OCO	626
6026.630	1.659	1.488-026	30013	00001	OCO	638
6033.478	1.657	4.092-026	30014	00001	OCO	627
6072.343	1.647	1.042-025	40014	10001	OCO	626
6075.983	1.646	4.538-023	30014	00001	OCO	626
6088.210	1.643	2.381-025	31113	01101	OCO	636
6100.300	1.639	2.083-025	31113	01101	OCO	628
6119.618	1.634	2.902-024	30013	00001	OCO	636
6127.782	1.632	2.381-024	30013	00001	OCO	628
6141.300	1.628	1.860-026	30012	00001	OCO	638
6149.760	1.626	1.786-025	41114	11102	OCO	626
6170.090	1.621	1.265-024	32213	02201	OCO	626
6175.118	1.619	2.269-024	40014	10002	OCO	626

TABLE 9-1.- (Continued)

6175.950	1.619	3.199-025	30013	00001	OCO	627
6196.174	1.614	5.357-023	31113	01101	OCO	626
6205.503	1.611	1.265-024	40013	10001	OCO	626
6227.924	1.606	4.271-022	30013	00001	OCO	626
6241.964	1.602	4.613-024	30012	00001	OCO	636
6243.570	1.602	4.092-025	31112	01101	OCO	636
6254.592	1.599	1.414-024	30012	00001	OCO	628
6265.170	1.596	1.190-025	31112	01101	OCO	628
6298.110	1.588	2.753-025	30012	00001	OCO	627
6308.278	1.585	2.455-024	40013	10002	OCO	626
6318.170	1.583	1.786-025	41113	11102	OCO	626
6346.265	1.576	1.190-024	40012	10001	OCO	626
6347.854	1.575	4.271-022	30012	00001	OCO	626
6356.293	1.573	6.547-023	31112	01101	OCO	626
6359.287	1.573	1.116-024	32212	02201	OCO	626
6360.000	1.572	2.824-022	3	0	CO	26
6363.616	1.571	1.265-024	30011	00001	OCO	636
6374.497	1.569	3.348-026	11122	00001	OCO	636
6397.545	1.563	1.190-025	31111	01101	OCO	636
6429.172	1.555	1.116-025	30011	00001	OCO	628
6449.040	1.551	2.232-026	40012	10002	OCO	626
6463.480	1.547	2.083-026	30011	00001	OCO	627
6466.440	1.546	1.042-025	20023	01101	OCO	626
6498.670	1.539	1.190-025	12222	01101	OCO	626
6503.081	1.538	4.985-023	30011	00001	OCO	626
6532.653	1.531	1.302-025	40011	10001	OCO	626
6536.445	1.530	9.523-024	31111	01101	OCO	626
6537.958	1.530	2.232-024	11122	00001	OCO	626
6562.444	1.524	2.232-025	32211	02201	OCO	626
6616.064	1.511	8.556-027	21122	10002	OCO	626
6635.428	1.507	2.232-026	40011	10002	OCO	626
6670.770	1.499	1.786-025	12221	01101	OCO	626
6679.709	1.497	2.827-024	11121	00001	OCO	626
6710.320	1.490	7.440-026	20021	01101	OCO	626
6715.360	1.489	3.348-026	10032	10002	OCO	636
6728.360	1.486	5.952-026	00031	00001	OCO	638
6745.115	1.483	2.678-024	01131	01101	OCO	636
6752.460	1.481	1.116-026	00031	00001	OCO	637
6755.100	1.480	3.530-021	120	000	HOH	161
6780.215	1.475	1.637-023	00031	00001	OCO	636
6804.369	1.470	5.580-026	10032	10001	OCO	626
6860.410	1.458	2.009-025	03331	03301	OCO	626
6867.280	1.456	1.116-025	11131	11101	OCO	626
6870.670	1.455	5.208-027	00031	00001	OCO	828
6870.796	1.455	2.411-025	11132	11102	OCO	626
6871.520	1.455	5.640-020	021	000	HOH	161
6885.150	1.452	4.018-025	01131	01101	OCO	628
6897.751	1.450	4.241-024	02231	02201	OCO	626
6897.800	1.450	5.952-026	00041	00011	OCO	626
6905.770	1.448	1.711-024	10031	10001	OCO	626
6907.144	1.448	2.902-024	10032	10002	OCO	626
6922.210	1.445	5.208-024	00031	00001	OCO	628
6935.150	1.442	2.262-022	01131	01101	OCO	626
6945.610	1.440	1.116-024	00031	00001	OCO	627

TABLE 9-1.- (Continued)

6972.578	1.434	1.495-021	00031	00001	OCO	626
7008.545	1.427	4.464-026	10031	10002	OCO	626
7201.480	1.389	5.290-020	200	000	HOH	161
7249.930	1.379	7.470-019	101	000	HOH	161
7283.981	1.373	1.860-025	40015	00001	OCO	626
7332.600	1.364	1.860-026	40014	00001	OCO	636
7339.300	1.363	2.976-026	40014	00001	OCO	628
7414.800	1.349	4.464-026	41114	01101	OCO	626
7445.040	1.343	5.290-021	002	000	HOH	161
7460.530	1.340	4.278-024	40014	00001	OCO	626
7466.400	1.339	2.232-026	40013	00001	OCO	628
7481.510	1.337	1.116-025	40013	00001	OCO	636
7583.265	1.319	8.333-025	41113	01101	OCO	626
7593.690	1.317	1.064-023	40013	00001	OCO	626
7600.130	1.316	7.440-026	40012	00001	OCO	636
7616.620	1.313	1.116-028	51102	00001	OCO	626
7734.452	1.293	2.790-024	40012	00001	OCO	626
7743.700	1.291	4.464-026	21123	00001	OCO	626
7749.100	1.290	1.116-026	40011	00001	OCO	636
7757.621	1.289	2.976-025	41112	01101	OCO	626
7901.479	1.266	1.488-025	21122	00001	OCO	626
7920.840	1.262	1.860-025	40011	00001	OCO	626
7929.920	1.261	1.934-026	11132	01101	OCO	636
7961.290	1.256	2.381-026	41111	01101	OCO	626
7981.180	1.253	2.232-025	10032	00001	OCO	636
8000.803	1.250	4.092-027	20033	10001	OCO	626
8056.024	1.241	4.464-026	21121	00001	OCO	626
8070.910	1.239	5.952-026	11131	01101	OCO	636
8084.060	1.237	1.934-025	12232	02201	OCO	626
8089.040	1.236	7.068-025	10031	00001	OCO	636
8103.578	1.234	2.046-025	20033	10002	OCO	626
8120.104	1.232	2.009-025	10032	00001	OCO	628
8128.783	1.230	7.068-026	20032	10001	OCO	626
8135.886	1.229	8.035-024	11132	01101	OCO	626
8154.470	1.226	3.720-026	10032	00001	OCO	627
8192.556	1.221	4.241-023	10032	00001	OCO	626
8220.363	1.216	2.009-025	10031	00001	OCO	628
8231.558	1.215	1.228-025	20032	10002	OCO	626
8243.163	1.213	1.079-025	20031	10001	OCO	626
8254.800	1.211	1.637-025	12231	02201	OCO	626
8255.390	1.211	4.464-026	10031	00001	OCO	627
8273.950	1.209	2.400-022	130	000	HOH	161
8276.767	1.208	9.226-024	11131	01101	OCO	626
8293.957	1.206	6.138-023	10031	00001	OCO	626
8373.820	1.194	3.600-021	031	000	HOH	161
8761.570	1.141	3.600-022	210	000	HOH	161
8807.000	1.135	4.980-020	111	000	HOH	161
9000.130	1.111	1.500-021	012	000	OCO	161
9833.580	1.017	4.800-023	041	000	HOH	161
10284.000	0.972	1.500-023	220	000	HOH	161
10328.710	0.968	2.100-021	121	000	HOH	161
10524.300	0.950	6.000-024	022	000	HOH	161
10599.660	0.943	2.700-022	300	000	HOH	161
10613.410	0.942	2.130-020	201	000	HOH	161

TABLE 9-1.- (Concluded)

10868.860	0.920	5.700-022	102	000	HOH	161
11032.400	0.906	2.400-021	003	000	HOH	161
11813.190	0.847	6.260-023	131	000	HOH	161
12139.200	0.824	1.960-023	310	000	HOH	161
12151.260	0.823	1.010-021	211	000	HOH	161

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9.5.3 Theoretical and Measured Values of Zenith Atmospheric Absorption 0.4 - 10 GHz; 75 - 3 cm

Figure 9-9 is a plot of some theoretical absorption curves of Hogg (ref. 16) and Croom (ref. 17) along with some measured data points as a function of frequency. The difference between the theoretical curves is due to the differences in the choice of the line-broadening constant in the Van Vleck-Weisskopf equation (ref. 18). Hogg used 0.75 GHz per atmosphere and Croom used 0.54 GHz per atmosphere. The value of 0.54 GHz per atmosphere is in agreement with the laboratory measurements of the line broadening constant by Maryott and Birnbaum (ref. 19), suggesting that Croom's theoretical curve may be more accurate than that of Hogg. A discussion of the data and theoretical relationships is given in Howell and Shakeshaft (ref. 20).

The absorption characteristics in this frequency range were also reviewed by Medd and Fort (ref. 21) and Benoit (ref. 22). The data available to March 1969 (ref. 23) is shown on Fig. 9-9. Pertinent information on each of the data points is given in Table 9-2. Note the variation in even the clear sky measurements.

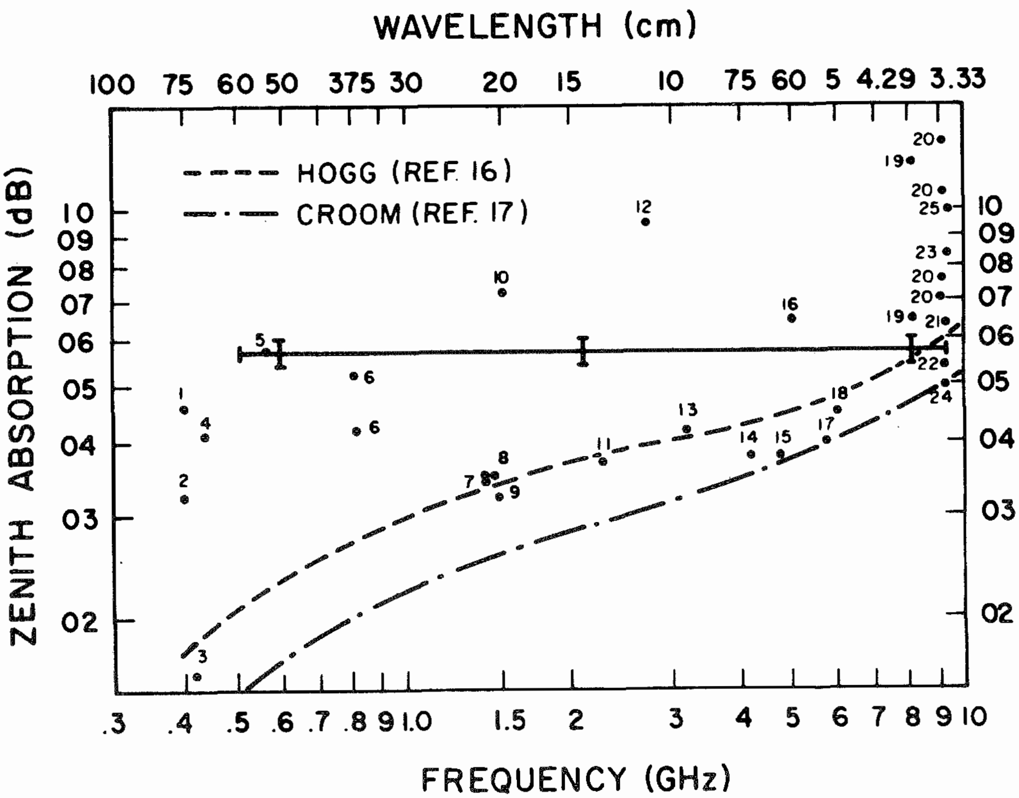

Figure 9-9.- Summary of Two Theoretical Curves and Measured Data on Atmospheric Absorption in the Zenith Direction in Clear Weather Conditions (After Thompson and Haroules, ref. 23).

TABLE 9-2.- SUMMARY OF CLEAR SKY ZENITH ATMOSPHERIC ABSORPTION MEASUREMENTS IN THE FREQUENCY RANGE 0.4 - 10 GHz (75 - 3 cm), (AFTER THOMPSON AND HAROULES, REF. 23)

Frequency (GHz)	Wavelength (cm)	Zenith Absorption (dB)	Fig. 9-9 References	Source
0.4	75.0	0.046±0.002	1	Seeger et al. (ref. 24)
0.4	75.0	0.0345±0.001	2	Seeger et al. (ref. 24)
0.408	73.5	0.016±0.007	3	Howell and Shakeshaft (ref. 20)
0.43	69.8	0.041±0.006	4	Dimitrenko (ref. 25)
0.5-9.4	60.0-3.19	0.057±10%	5	Stankevich (ref. 26)
0.82	36.6	0.051±0.001 0.042±0.002	6 6	Berkhuijson (Howell and Shakeshaft (ref. 20)
1.407	21.4	0.034±0.008 0.035±0.010	7 7	Howell and Shakeshaft (ref. 20)
1.415	21.3	0.035	8	Penzias and Wilson (Howell and Shakeshaft (ref. 20)
1.42	21.1	0.032	9	Mainka (ref. 27) Shakeshaft (ref. 20)
1.50	20.0	0.072	10	Fürstenberg (ref. 28)
2.39	12.6	0.037	11	Ohm (ref. 29)
2.70	11.1	0.095	12	Altenhoff et al. (ref. 30)
3.2	9.37	0.042±0.004	13	Medd and Fort (ref. 21)
4.08	7.35	0.038	14	Penzias and Wilson (ref. 31)
4.70	6.37	0.038	15	Castelli et al. (ref. 32)
4.995	6.0	0.065	16	Baars, Mezger, and Wendker (ref. 33)
5.65	5.31	0.04	17	DeGrasse et al. (ref. 34)
6.0	5.0	0.045	18	Hogg and Semplak (ref. 35)
8.25	3.64	0.065	19	Allen and Barrett (ref. 36)
9.18	3.27	0.07-0.14 0.11-0.15 0.05-0.10 0.05-0.085	20 20 20	Castelli (refs. 26, 37, 38, 39)
9.38	3.2	0.064	21	Aarons, Barron, and Castelli (ref. 40)
99.38	3.2	0.054	22	Lastochkin, Stankevich, and Strezhneva (ref. 41)
9.40	3.19	0.084	23	Fürstenberg (ref. 28)
9.40	3.19	0.05	24	Roll and Wilkinson (42)
9.5	3.15	0.1	25	Mayer, McCullough, and Sloanmaker (ref. 43)

9.5.4 Theoretical and Measured Values of Zenith Atmosphere Absorption 10 - 170 GHz; 3 cm - 1.76 mm (Figure 9-10).

The absorption characteristics in the 10 to 170 GHz (3 cm - 1.76 mm) frequency region were reviewed by Rosenblum (ref. 44), Fowler and LaGrone (ref. 45), and Hayes (ref. 46). Rosenblum discussed the theoretical predictions of Theissing and Caplan (ref. 47) and Hogg (ref. 16) and presented a summary of the available data. Hayes (ref. 46) presented original work at 10 frequencies (Fig. 9-10) and a discussion of the predictions of Meeks (ref. 48) and Schmelzer (ref. 49) as well as those of Thessing and Caplan (ref. 47). The lack of regularity in the relationship between absorption and water vapor content may be seen from Hayes' data points. It is pointed out that the frequency-absorption curves between 65 and 400 GHz (4.61 - 0.75 mm) by Thessing and Caplan (ref. 47) are derived from the Van Vleck-Weisskopf equation (ref. 18) using different meteorological data and integrating with respect to altitude because of the pressure, temperature, and water vapor content dependence with altitude (Fig. 4-1). Hayes used meteorological data taken by a radiosonde at intervals from 0 to 45 km which were grouped under the general classifications of dry, medium, and humid conditions before integration. Hayes also found that by revising the oxygen linewidth parameter, the work of Theissing and Caplan would be appropriate for frequencies down to 40 GHz (7.5 mm). Hayes and Theissing and Caplan pointed out that the Van Vleck-Weisskopf equation properly describes the general shape of the relation of atmospheric absorption as a function of frequency, but fails to give the proper absolute magnitude of absorption in frequency regions between resonant absorption lines except near 110 GHz (2.73 mm). In the frequency region from 10 to 140 GHz (3 cm - 2.14 mm), curves drawn through data of Hayes are lower and flatter than those of Theissing and Caplan. Hayes found Schmelzer's values in agreement with his own in the frequency range from 40 to 80 GHz (7.5 - 3.75 mm), but higher than his data in the 80 to 140 GHz (3.75 - 2.14 mm) region, apparently because Schmelzer attributed too large an absorption coefficient to water vapor at frequencies removed from the water vapor resonances.

Meeks' (ref. 48) theoretical curve is also included in the frequency range from 45 to 75 GHz (6.67 - 4.0 mm) and is presented here to supplement data presented by Hayes. His oxygen linewidth parameter was based on measurements made in air containing water vapor. This might account for his values being slightly higher than those measured by Hayes.

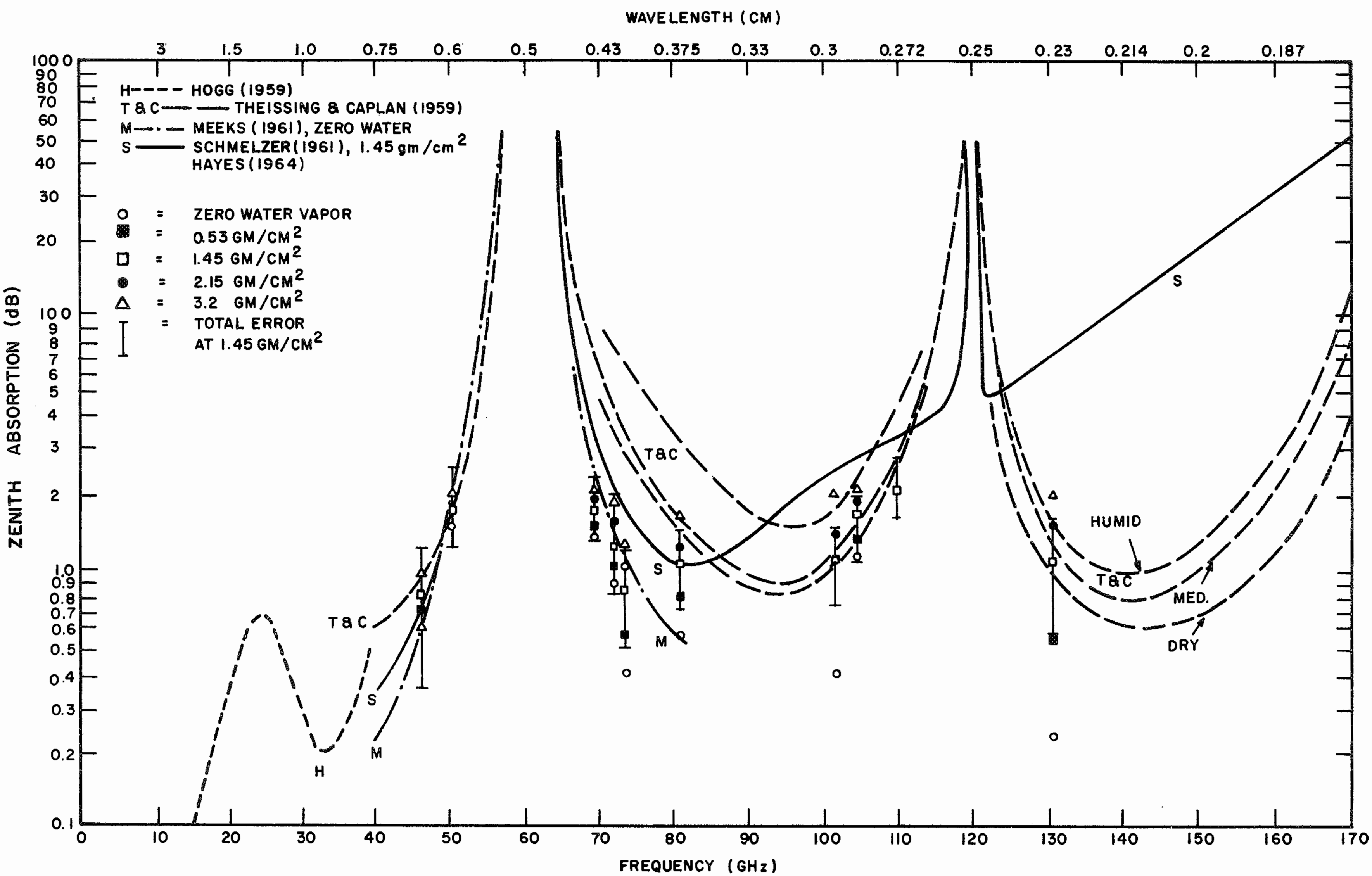

Figure 9-10.- Theoretical and Measured Values of Zenith Atmospheric Absorption in the Frequency Range 10 - 170 GHz (3 cm - 1.76 mm), (After Thompson and Haroules, ref. 23).

9.5.5 Measured Values of Clear Sky Zenith Atmospheric Absorption 10 - 150 GHz; 3 cm - 2 mm

Experimental absorption data (except that of Hayes, ref. 46, See Section 9.5.4) in the region from 10 to 150 GHz (3 cm - 2 mm) is plotted in Fig. 9-11. Table 9-3 presents pertinent information on the data points as collected from available literature to March 1969. In the 107 to 121 GHz (2.75 - 2.48 mm) portion of the spectrum, experimental work by Tolbert, Krause, and Straiton (ref. 76) reveals that a broad resonant absorption line which obscures the separation by water vapor and oxygen does exist. The peak of the water vapor line is prominent enough to be measured by 118 GHz (2.54 mm). Its amplitude is difficult to distinguish accurately, however.

Several other works having bearing on this problem are presented in the Supplemental Bibliography to Chapter 9.

9.5.6 Computed Absorption due to Atmospheric Gases Along a Zenith Path Through a Cloudless Maritime Polar Atmosphere 10 GHz - 3 THz; 3 cm - 100 μm

Figure 9-12 presents a graph of computed absorption due to atmospheric gases along a zenith path through a cloudless, maritime polar atmosphere. The entire computational procedure is described in detail in Lukes (ref. 78).

Lukes draws upon the recent work of Yaroslavskii and Stankevich (refs. 79, 80), Furashov (ref. 81), Zhevakin and Naumov (ref. 82), Bastin (ref. 83), Heastie and Martin (ref. 84), Rogers (ref. 85), Frenkel and Woods (ref. 86), Chang and Lester (ref. 87), Farmer and Key (ref. 88), Williams and Chang (ref. 89), Low (ref. 90), and many others.

The procedure adopted to evolve the absorption curves is as follows:

. Compute over the spectral range 0.3 μm to 3.2 cm (1,000 THz - 9.37 GHz) the absorption coefficients (Section 9.3) due to the four principal atmospheric gases (water vapor, oxygen, carbon dioxide, and ozone). By drawing on the literature cited above, one can accomplish a procedure in 8 segments encompassing this spectral range. In doing so, however,

. Reduce investigators' data to "standard" sea level conditions so that absorption coefficients over the spectrum are internally consistent.

. Adopt a model of a cloudless maritime polar atmosphere, representative of a clear atmosphere over a substantial area of the seas.

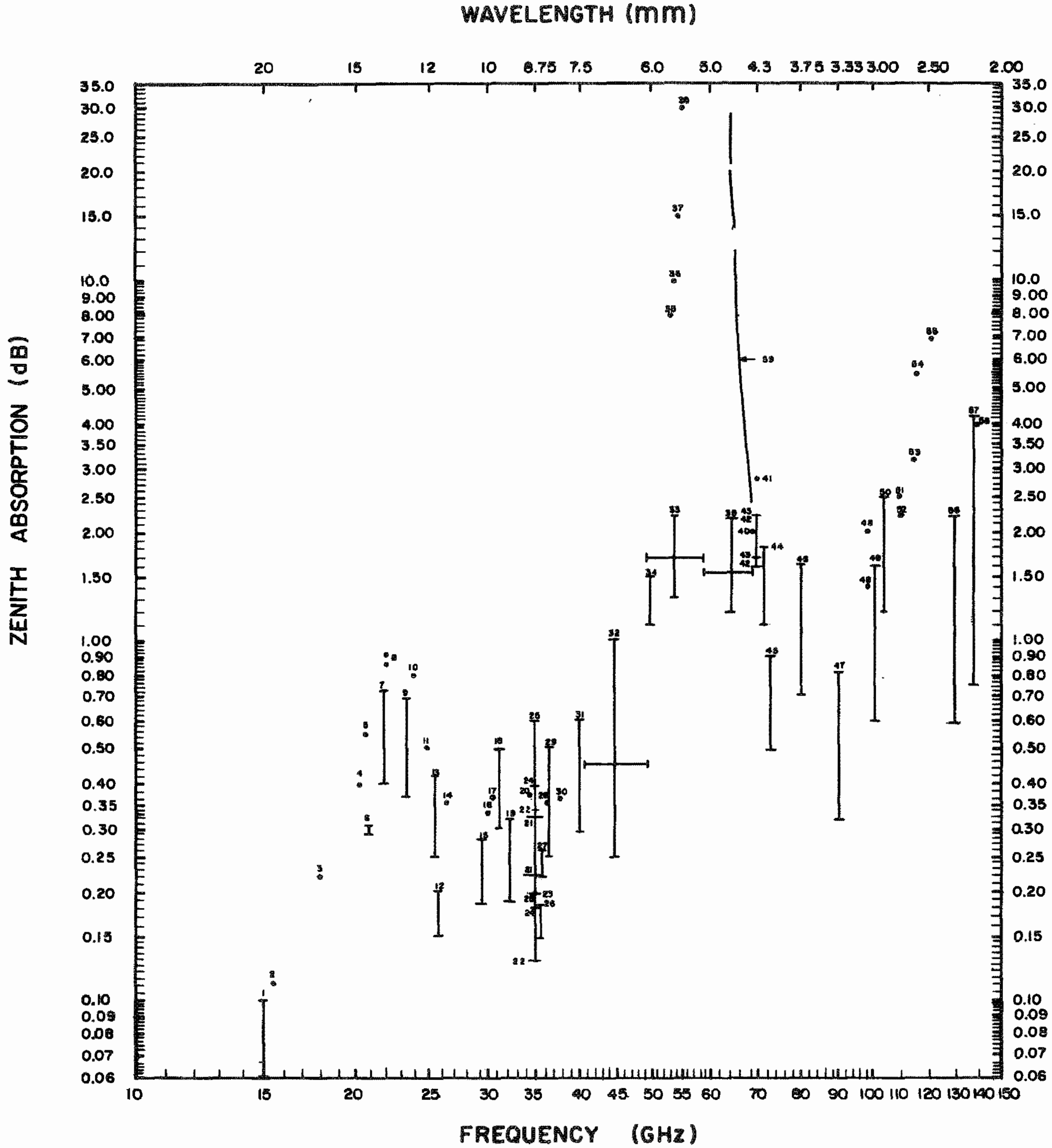

Figure 9-11.- Measured Clear Sky Zenith Atmospheric Absorption in the Frequency Range 10 to 150 GHz (3 cm - 2 mm), (After Thompson and Haroules, ref. 23).

TABLE 9-3.- SUMMARY OF CLEAR SKY ZENITH ATMOSPHERIC ABSORPTION MEASUREMENTS IN THE FREQUENCY RANGE 10 TO 150 GHz (3 cm - 2 mm)

Frequency (GHz)	Wavelength (cm)	Zenith Absorption (dB)	Fig. 9-11 References	Source
15.0	2.0 cm	0.06-0.1	1	Wulfsberg (ref. 50)
15.5	1.94 cm	0.112	2	Allen and Barrett (ref. 36)
18.15	1.62 cm	0.22	3	Griffith, Thornton, and Welch (ref. 51)
20.0	1.5 cm	0.398	4	Dicke et al. (ref. 52)
20.6	1.45 cm	0.55	5	Griffith, Thornton, and Welch (ref. 51)
21.0	1.43 cm	0.291-0.309	6	Staelin (ref. 53)
21.9	1.37 cm	0.396-0.725	7	Staelin (ref. 53)
22.2	1.35 cm	0.85 0.9	8 8	Griffin, Thornton, and Welch (ref. 51)
23.5	1.28 cm	0.368-0.687	9	Staelin (ref. 53)
24.0	1.25 cm	0.799	10	Dicke et al. (ref. 52)
24.14	1.24 cm	0.5	11	Griffith, thornton, and Welch (ref. 51)
25.4	1.18 cm	0.15-0.20	12	Staelin, Barrett, and Kusse, (ref. 54)
25.5	1.17 cm	0.247-0.409	13	Staelin (ref. 53)
26.0	1.15 cm	0.35	14	Griffith, Thornton, and Welch (ref. 51)
29.5	1.02 cm	0.184-0.282	15	Staelin (ref. 53)
30.0	1.0 cm	0.336	16	Dicke et al. (ref. 52)
30.9	9.7 mm	0.36	17	Griffith, Thornton, and Welch (ref. 51)
31.4	9.55 mm	0.3-0.5	18	Hobbs, Corbett, and Santini (ref. 55)
32.4	9.2 mm	0.190-0.318	19	Staelin (ref. 53)
34.4	8.7 mm	0.363	20	Aarons, Barron, and Castelli (ref. 40)
35.0	8.6 mm	0.22-0.32	21	Wulfsberg (ref. 50)
35.0	8.6 mm	0.13-0.34	22	Kalaghan and Albertini (ref. 56)
35.0	8.6 mm	0.2	23	Copeland and Tyler (ref. 57)
35.0	8.6 mm	0.18-0.39	24	Gibson (ref. 58)
35.0	8.6 mm	0.2-0.6	25	Gibson (ref. 59)
35.3	8.5 mm	0.15-0.18	26	Lynn, Meeks, and Sohigian (ref. 60)
35.9	8.35 mm	0.22-0.26	27	Thornton and Welch (ref. 61)
36.06	8.23 mm	0.35	28	Griffith, Thornton, and Welch (ref. 51)

TABLE 9-3.- Continued

Frequency (GHz)	Wavelength (cm)	Zenith Absorption (dB)	Fig. 9-11 References	Source
36.6	8.2 mm	0.25-0.5	29	Nicoll (ref. 62)
37.5	8.0 mm	0.36	30	Nicoll (ref. 62)
40.0	7.5 mm	0.3-0.6	31	Whitehurst, Mitchell, and Copeland (ref. 63) Whitehurst, Mitchell (ref. 64)
40.4 49.6	7.4 mm 6.0 mm	0.25-1.0	32	Hayes (ref. 46)
49.6 59.7	6.0 mm 5.0 mm	1.3-2.2	33	Hayes (ref. 46)
50.0	6.0 mm	1.1-1.5	34	Whitehurst, Copeland, and Mitchell (ref. 65)
53.5	5.61 mm	8.0	35	Carter, Mitchell, and Reber (ref. 66)
53.8	5.58 mm	10.0	36	Carter, Mitchell, and Reber (ref. 66)
54.4	5.51 mm	15.0	37	Carter, Mitchell, and Reber (ref. 66)
55.4	5.41	30.0	38	Carter, Mitchell, and Reber (ref. 66)
65.0 69.0	4.62 mm 4.35 mm	2.8-4.0	59	Tolbert and Straiton, (refs. 67, 68)
69.75	4.3 mm	2.0	40	Tolbert, Straiton, and Walker (ref. 69)
59.0 69.0	50.8 mm 4.35 mm	1.2-2.2	39	Hayes (ref. 46)
70.0	4.3 mm	2.8	41	Tolbert, Britt, and Bahn (ref. 70)
70.0	4.3 mm	1.6-2.2	42	Coates (refs. 71, 72)
70.0	4.3 mm	1.7-2.2	43	Grant, Corbett, and Gibson (ref. 73)
72.0	4.18 mm	1.1-1.8	44	Hayes (ref. 46)
73.0	4.1 mm	0.5=0.9	45	Hayes (ref. 46)
80.0	3.75 mm	0.7-1.6	46	Hayes (ref. 46)
91.0	3.3 mm	0.31-0.80	47	Shimabukuro (refs. 74, 75)
100.0	3.0 mm	2.0-1.4	48	Tolbert, Krause, and Straiton (ref. 76)
101.0	2.97 mm	0.6-1.6	49	Hayes (ref. 46)
104	2.88 mm	1.2-2.5	50	Hayes (ref. 46)
110	2.72 mm	2.5	51	Tolbert, Krause, and Straiton (ref. 76)
110	2.72 mm	2.2	52	Hayes (ref. 46)

TABLE 9-3.- Concluded

Frequency (GHz)	Wavelength (cm)	Zenith Absorption (dB)	Fig. 9-11 References	Source
114	2.63 mm	3.2	53	Tolbert, Krause, and Straiton (ref. 76)
116.8	2.56 mm	5.5	54	Tolbert, Krause, and Straiton (ref. 76)
120.2	2.48 mm	7.0	55	Tolbert, Krause, and Straiton (ref. 76)
130	2.30 mm	0.2-2.2	56	Hayes (ref. 46)
139	2.15 mm	0.75-4.2	57	Tolbert, Krause, and Bahn (ref. 77)
140	2.14 mm	4.0	58	Tolbert, Krause, and Straiton (ref. 76)

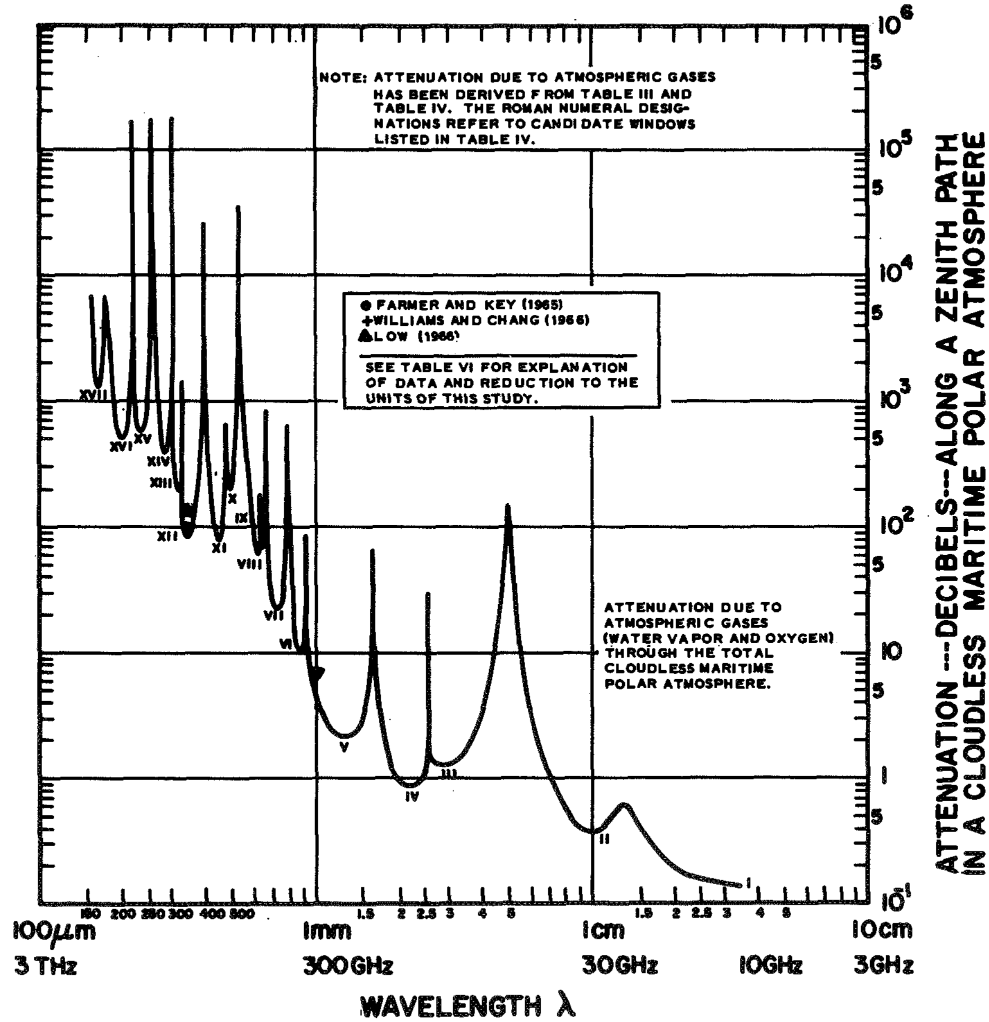

Figure 9-12.- Absorption due to atmospheric gases along a zenith path through a cloudless maritime polar atmosphere (After Lukes, ref. 78)

. Derive an additional profile of absorption (in decibels) due to atmospheric gases by integrating their effect along a zenith path through the total cloudless maritime polar atmosphere, taking account of the vertical distributions of temperature, pressure, and water vapor. The consequence is a demonstration of the wavelength dependence of absorption of radiant energy along a zenith path due to atmospheric gases, and the identification of candidate "windows" by applying the criterion of wavelength bands of transparency in the cloudless atmosphere adopted. The Roman numerals represent windows of transparency and the tables referred to are in Lukes (ref. 78).

9.5.7 Atmospheric Absorption Measurements 183 - 325 GHz; 1.64 - 0.924 mm

The absorption characteristics of the earth's atmosphere in the 183-325 GHz (1.64 - 0.924 mm) region were investigated by Ulaby and Straiton (ref. 91) and Ulaby (refs. 92, 93). Instrumentation problems associated with coherent radiometric detection dictated the use of a wideband Germanium bolometer detector. Upon cooling of the Germanium element to 4.2°K, the bolometer had a noise-equivalent power of 10^{-9} watt for a 1-Hz bandwidth.

By using the sun at two zenith angles as the signal source, measurements were made of the solar radiation as seen at the earth's surface through a set of wire mesh bandpass filters. The filters' transmission response was determined by scaling the results of 109 GHz (2.75 mm) measurements. Total zenith atmospheric absorption measurements were then obtained as a function of frequency through the use of a spectral convolution technique. The results, especially in the window between 183 and 325 GHz (1.64 - 0.924 mm) water vapor lines, seem to agree favorable with the calculated values according to the Van Vleck-Weisskopf equations (ref. 18) modified by the Schulze-Tolbert line-shape factor (ref. 94). The minimum attenuation in the region was measured to be 0.6 $dB/g \cdot m^3$ of surface water vapor density at 240 GHz (1.25 mm), (See Fig. 9-13).

The absorption was calculated for 30 increments of height to get the total zenith absorption. The measured curve exceeded the calculated one by approximately 1 dB in the center portion of the window.

9.5.8 Oxygen Absorption in the Earth's Atmosphere 48 - 72 GHz; 6.25 - 4.2 mm

Oxygen absorption in the earth's atmosphere has been studied extensively by Carter, Mitchel and Reber (refs. 66, 95-100). Their reports and articles deal with many phases of

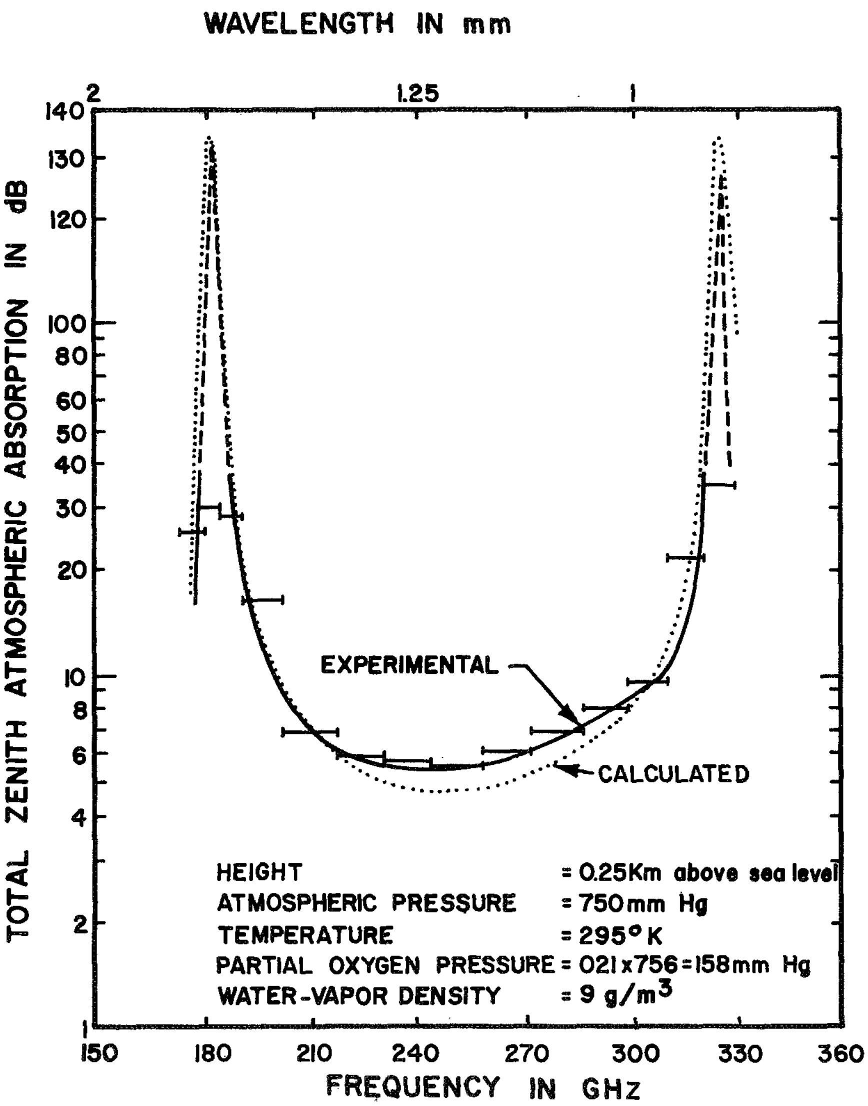

Figure 9-13.- Total zenith atmospheric absorption in the 183 - 325 GHz (1.64 - 0.924 mm) region (After Ulaby and Straiton, ref. 91)

the work, including the instrumentation, test procedures and data analysis as well as the theoretical background needed to understand this region of the spectrum.

They performed an experiment that measured absorption as a function of altitude and frequency in the real atmosphere. The measurement results were used to determine revised values for coefficients that were used to compute tables and graphs of zenith and tangential absorption and tables of horizontal absorption rates of the atmosphere in the oxygen spectrum (48 - 72 GHz; 6.25 - 4.2 mm) for several altitudes.

Various graphs are presented along with the tabulations shown in Table 9-3 in ref. 100.

In ref. 66 Carter, Mitchell, and Reber calculated new values for the Van Vleck line broadening coefficients, based on 1500 independent absorption measurements made over a slant range from various altitudes in the atmosphere. These measurements were made over a frequency range of 53.4 to 56.4 GHz (5.62 - 5.32 mm) and an altitude range from zero to 14.75 km. The results are shown in Fig. 9-14 along with the theoretical curves shown as solid lines. The average relative error between the measured and calculated absorption is 8.6%. A similar comparison based on Meeks and Lilley's line broadening coefficients yielded an average relative error of 13%. (Ref. 101).

TABLE 9-4.- LIST OF TABULATIONS OF VARIOUS QUANTITIES IN REF. 100

Table 1	Horizontal Attenuation Rates in dB/km at Oxygen Resonant Frequencies
Table 2	Horizontal Attenuation rates in dB/km at Oxygen Window Frequencies
Table 3	Zenith Attenuation in dB at Oxygen Resonant Frequencies
Table 4	Zenith Attenuation in dB at Oxygen Window Frequencies
Table 5	Tangential Attenuation in dB at Oxygen Resonant Frequencies
Table 6	Tangential Attenuation in dB at Oxygen Window Frequencies

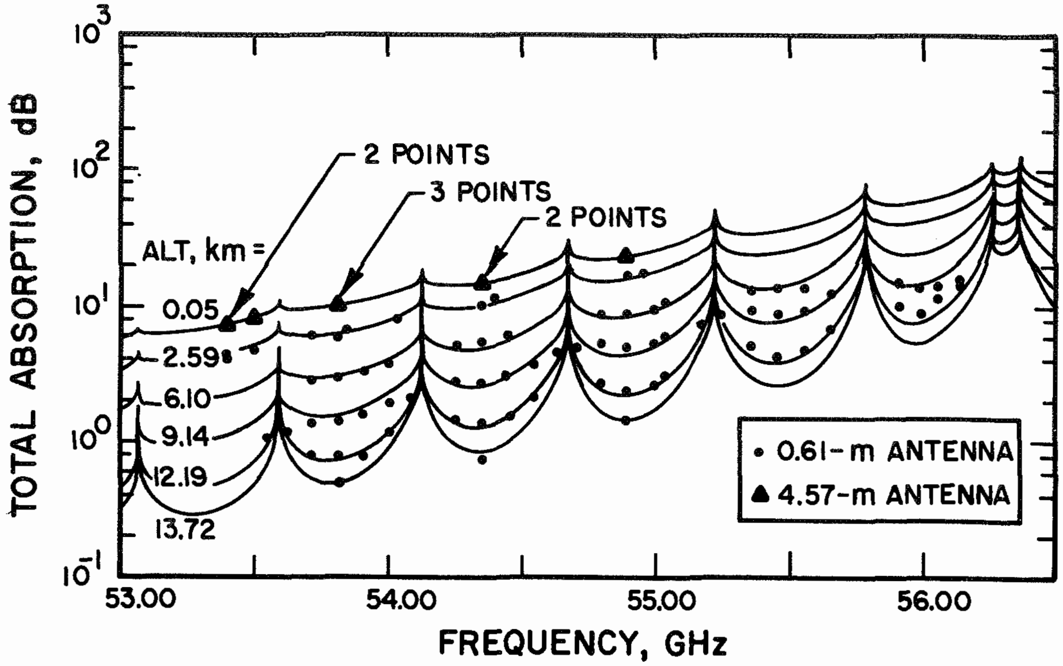

Figure 9-14.- Oxygen absorption by the earth's atmosphere between 53.4 and 56.4 GHz (5.62 - 5.32 mm) at various altitudes. (After Carter, Mitchell, and Reber, ref. 66).

9.5.9 Sources of Solar Spectra, Optical Region 3 - 3,000 THz; 100 - 0.1 μm

"Solar spectra" usually refer to absorption spectra of the earth's atmosphere using the sun as the source of radiation. Several atlases of solar spectra have been prepared. These are listed in Table 9-5.

Figure 9-15 shows a sample solar spectrum.

9.5.10 Low Resolution Solar Spectrum 20 - 300 THz; 15 - 1 μm With a High Resolution Solar Spectrum 85.7 - 88.2 THz; 3.50 - 3.40 μm

Figure 9-15 illustrates the over-all absorption spectrum of the atmosphere, made up of the superimposed spectra of all the atmospheric constituents (See Section 9.5.11) and, as the expanded section from 3.4 to 3.5 μm (88.2 - 85.7 THz) shows, the spectrum

TABLE 9-5.- LIST OF SOME REPRESENATIVE SOLAR SPECTRA*

Title	Source
1. Photometric atlas of the near infrared solar spectrum 0.8465 - 2.5242 (354 THz - 118.7 THz)	Mohler, et al. 1950, ref. 102
2. The solar spectrum from 218 to 23.7 microns (1.37 THz - 127.5 THz)	Migeotte, et al. 1957, ref. 103
3. The solar spectrum observed at the Jungfraujoch (Switzerland), 0.7500 to 0.9070 microns (400 - 333 THz)	Migeotte, 1960 ref. 104 1961, ref. 105
4. The solar spectrum 0.6600 to 1.3495 microns (455 - 222 THz)	Babcock and Moore, 1947, ref. 106
5. Photometric atlas of the solar spectrum from 0.3612 to 0.8771 microns (830 - 342 THz)	Minnaert, Mulders, 1940, and Houtgard, ref. 107.
6. The infrared telluric spectrum introductory report	Howard and Garing, 1964, refs. 108, 109

*Additional spectra are cited in Part V.

is actually quite complex. The complete transmission curve has comparable structure. In addition, the atmosphere is not constant; it changes with season, altitude, time of day, viewing angle, etc.

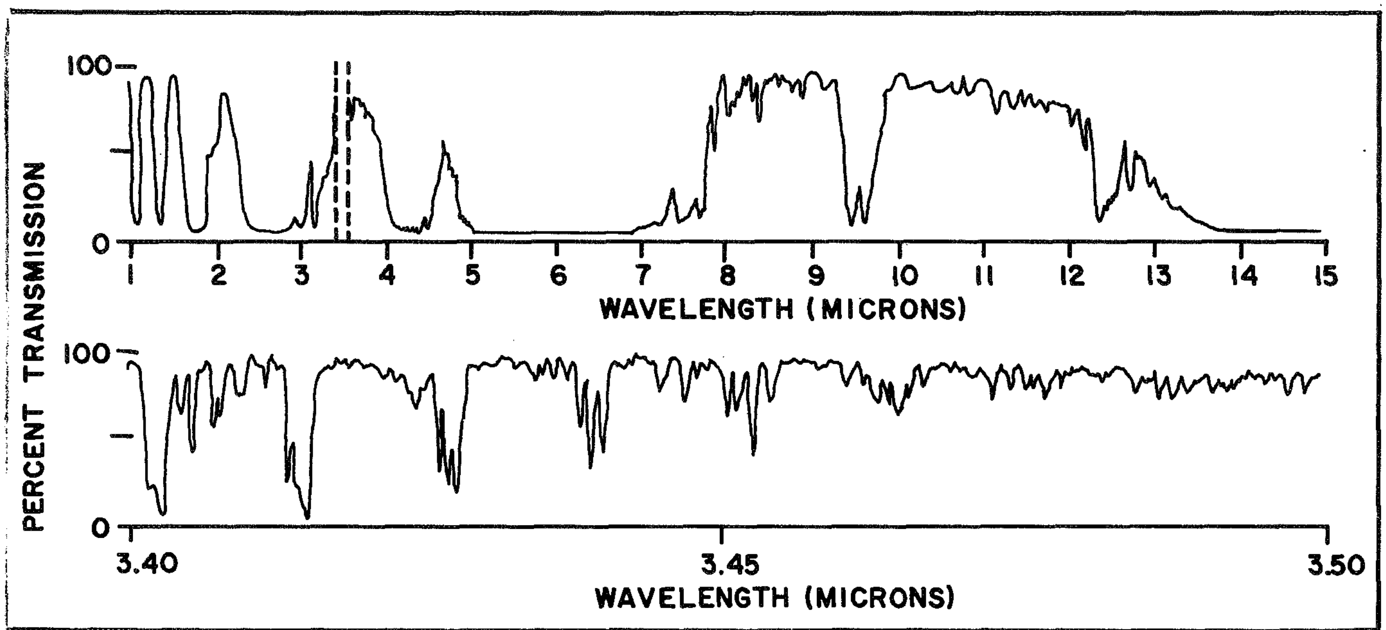

Figure 9-15.- Atmospheric transmission spectrum at high and low resolution.

9.5.11 Comparison of Near-Infrared Low Resolution Solar Spectrum With Laboratory Spectra 20 - 300 THz; 15 - 1.0 μm

Figure 9-16 presents a typical spectrum of sunlight at the earth's surface and laboratory spectra of molecules known to be present in the earth's atmosphere (Section 9.5.2). Comparison of the so-called solar spectrum with the molecular spectra shows that all the principal regions of absorption in the atmosphere are due to H_2O, CO_2, and O_3. Because ozone exists chiefly in the stratosphere, the strong absorption band near 9.6 μm (31.3 THz) can be neglected in problems of transmission along horizontal paths near ground level. (Curves from Howard, Garing, and Walker, 1965, ref. 110).

It is re-emphasized that the entire optical region contains thousands of sharp absorption lines due to the various atmospheric constituents. At low resolution these lines are smoothed out so that only the clustering in strong bands appears (Section 9.5.10).

COMPARISON OF THE NEAR-INFRARED SOLAR SPECTRUM WITH LABORATORY SPECTRA OF VARIOUS ATMOSPHERIC GASES

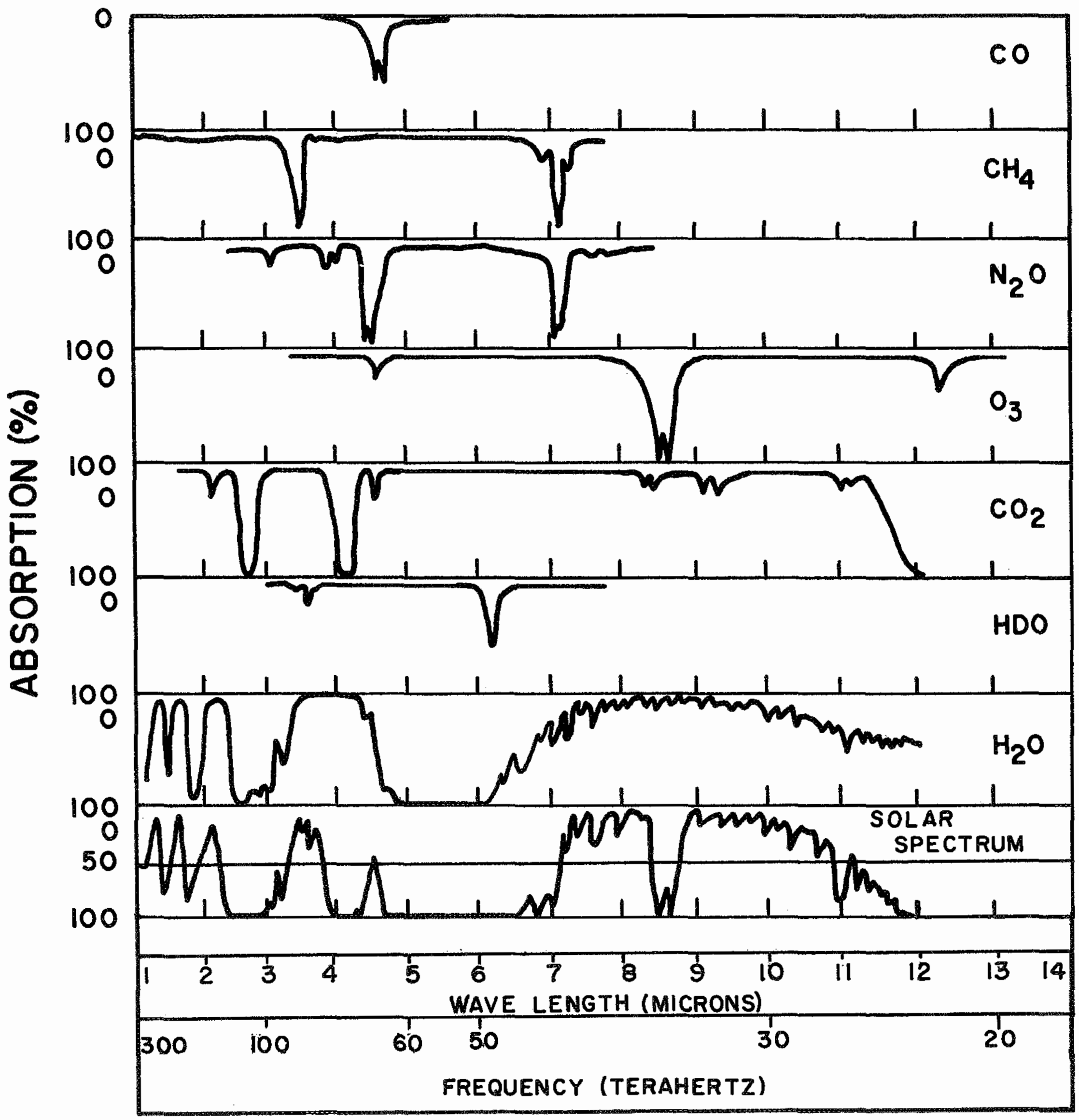

Figure 9-16.- Comparison of the near-infrared solar spectrum with laboratory spectra of various atmospheric gases, (After Howard, Garing, and Walter, 1965, ref. 110).

9.5.12 Low Resolution Absorption Spectrum of the Earth's Atmosphere from Vacuum Ultraviolet to the Far Infrared at Sea Level and 11 km 3 - 3,000 THz; 100 - 0.1 μm

Goody (ref. 111) made an attempt in Fig. 9-17 to give a general picture of the importance of different absorptions in the lower atmosphere in mid-latitudes. An indication of the energy absorbed by the stratosphere and troposphere may be obtained by multiplying (a) by (c) or (a) by {(b) - (c)} respectively.

Most of the solar absorption in the stratosphere is by the ultraviolet Hartley bands and the visible Huggins bands of ozone. At higher levels in the ionosphere, the small amount of solar energy below about 0.2 μm (1,500 THz) is absorbed mainly by molecular oxygen. In the troposphere, depletion of sunlight is principally by a group of near infrared bands of water vapor.

In addition to the absorptions of Fig. 9-17 the radiation is scattered and absorbed by dust, haze, molecules, and clouds (Chapter 10). The theory of molecular scattering and scattering by water droplets is well understood. Dust and their amounts are variable and difficult to relate to other physical phenomena.

In Fig. 9-17 (a) are black body curves for 6,000°K and 245°K. In (b) is the atmospheric gaseous absorption sp-ctrum for a solar beam reaching ground level. In (c) we have the same for a beam reaching the temperature troposphere. The axes are chosen so that areas in (a) are proportional to radiant energy. Integrated over the earth's surface and over all solid angles the solar and terrestrial fluxes are equal; consequently, the two black body curves are drawn with equal areas beneath them. An absorption continuum has been drawn beneath bands in (b). This is partly hypothetical because it is difficult to distinguish from the scattering continuum, particularly in the visible and near infrared spectrum. Conditions are typical of mid-latitudes and for a solar elevation angle of 40° (Zenith Angle of 50°) (Section 8.12) or diffuse terrestrial radiation.

9.5.13 Transmission Spectrum of the Earth's Atmosphere 60 - 1,000 THz; 5.0 - 0.3 μm

Figures 9-18 and 9-19 present the transmission of the atmosphere at low resolution over the indicated wavelength interval for good visibility conditions (greater than 50 miles) at sea level, and for 2 precipitable centimeters of water vapor in a vertical line of sight above the observation station. If all this water vapor were condensed in a container having the same

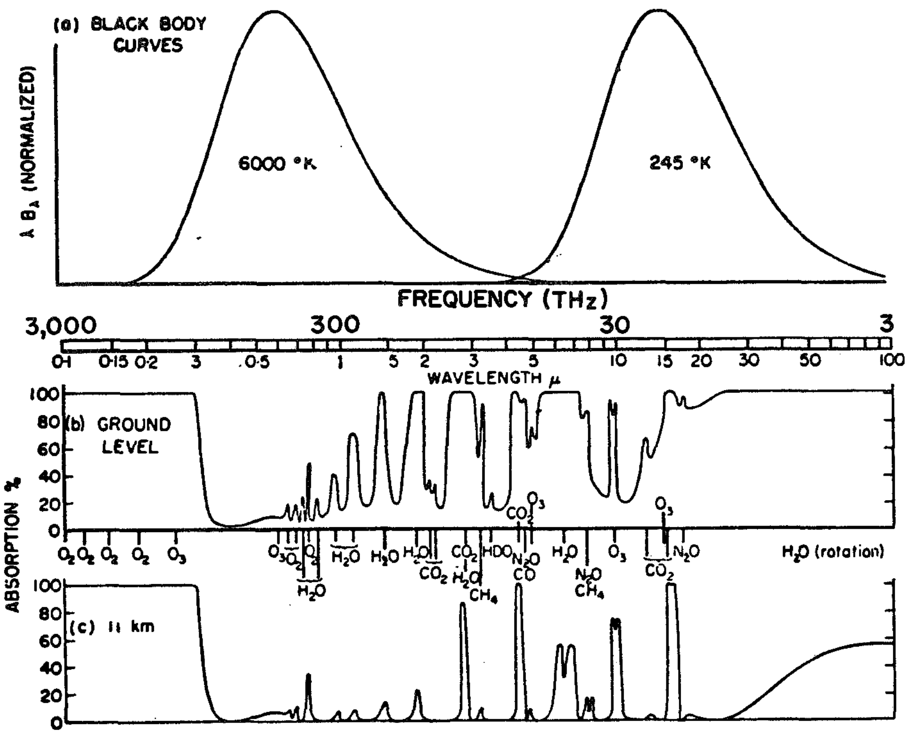

Figure 9-17.- Atmospheric absorption spectrum with black body curves for a zenith angle of 50°. See text for explanation. (After Goody, 1964, ref. 111). (See also Thekaekara, 1965, ref. 116).

cross-sectional area as the line-of-sight column, the depth of the layer of water would be two centimeters at N.T.P. (normal temperature and pressure, or standard temperature and pressure, indicating a temperature of 0°C and a pressure of one standard atmosphere; 760 mm Hg). These conditions are representative near large bodies of water for spring through fall seasons. Lower temperatures tend to reduce the amount of water vapor and give some improvement of transmission in the infrared "window" regions for a given air mass or zenith angle (Section 8.12). The transmission characteristics were published by Chapman and Carpenter (refs. 112, 113), based on data by Moon (ref. 114) and others (refs. 115).

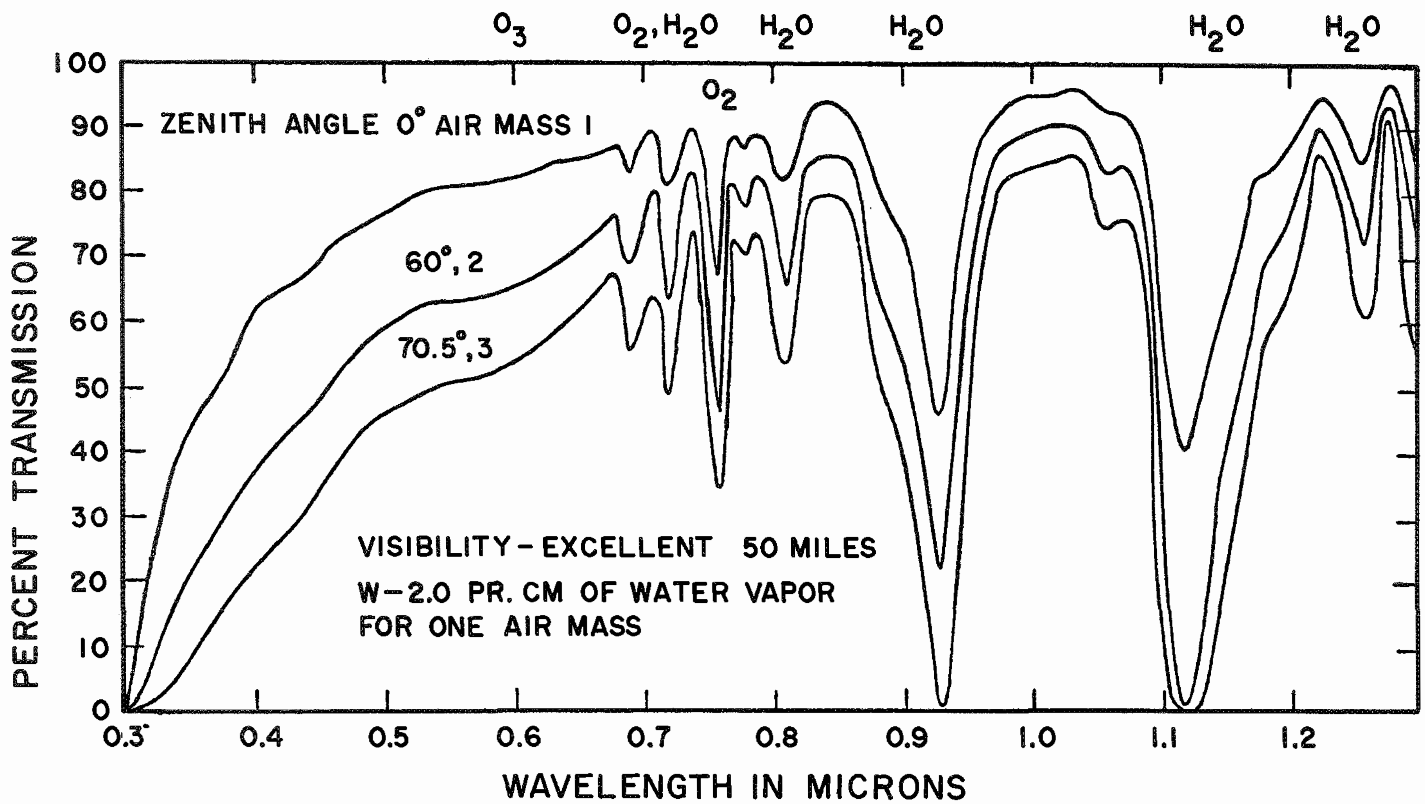

Figure 9-18.- Transmission of the earth's atmosphere from sea level for varying optical air masses from 0.3 - 1.3 μm; (1,000 - 461 THz), (After Chapman and Carpenter, 1959, ref. 112).

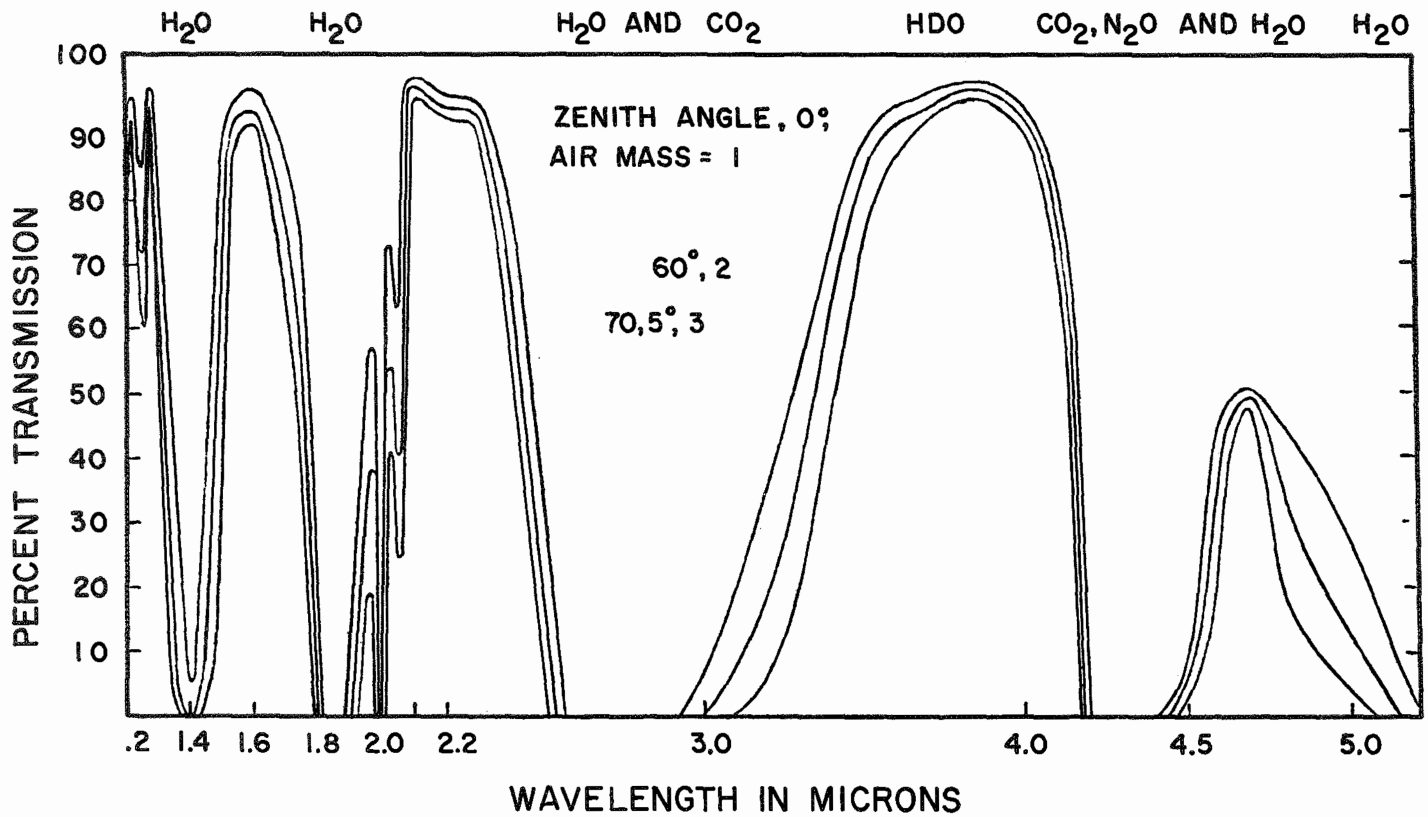

Figure 9-19.- Transmission of the earth's atmosphere from sea level for varying optical air masses from 1.3 - 5.0 μm; (461 - 60 THz), (After Chapman and Carpenter, ref. 112).

9.5.14 Variation of the Solar Spectrum with Altitude

Variation of the infrared solar spectrum with altitude has been studied by D. G. Murcray and his associated at the University of Denver for many years. To locate many of their documents, refer to D. G. Murcray, T. G. Kyle, and A. Goldman, in the Atmospheric Transmission Bibliography to be issued as a sequel to this handbook.

Figure 9-20 shows the observed spectral transmittance at various altitudes for the region 5.70 μm (52.5 THz) to 5.29 μm (57.8 THz), (Section 1.2.3). In the figure, the ordinate of successive spectra is displaced for clarity. There are many additional spectra presented in (ref. 117) and the spectral region from 9-10 μm (33.3 - 30.0 THz) is covered in ref. 118. The flight data for the spectra in Fig. 9-20 is presented in Table 9-6.

TABLE 9-6.- TIMES, ALTITUDES, PRESSURES, AND ZENITH ANGLES FOR SELECTED RECORDS TAKEN FROM A BALLOON FLIGHT ON MARCH 23, 1968, (AFTER GOLDMAN, ET AL 1969, REF. 117)

Record No.	Time (MST)	Altitude (kft)	Pressure (mb)	Zenith Angle (degrees)
54	14:11	26.5	352	42.67
58	14.19	33.8	253	43.57
63	14.29	43.7	158	45.63
73	14.49	57.9	80.5	49.18

9.6 ATMOSPHERIC AEROSOLS

Atmospheric aerosols are discussed in detail in Section 10.8. Scattering rather than absorption by aerosols affects transmission in the atmosphere in the visible and infrared spectral range. In the microwave spectral range, investigated by Hajovsky and LaGrone, the presence of natural aerosols does not affect transmission in the atmosphere (ref. 119).

Absorption by aerosols in the infrared and visible regions was considered by Livshits, Pavlov, and Miliutin (1966, ref. 120).

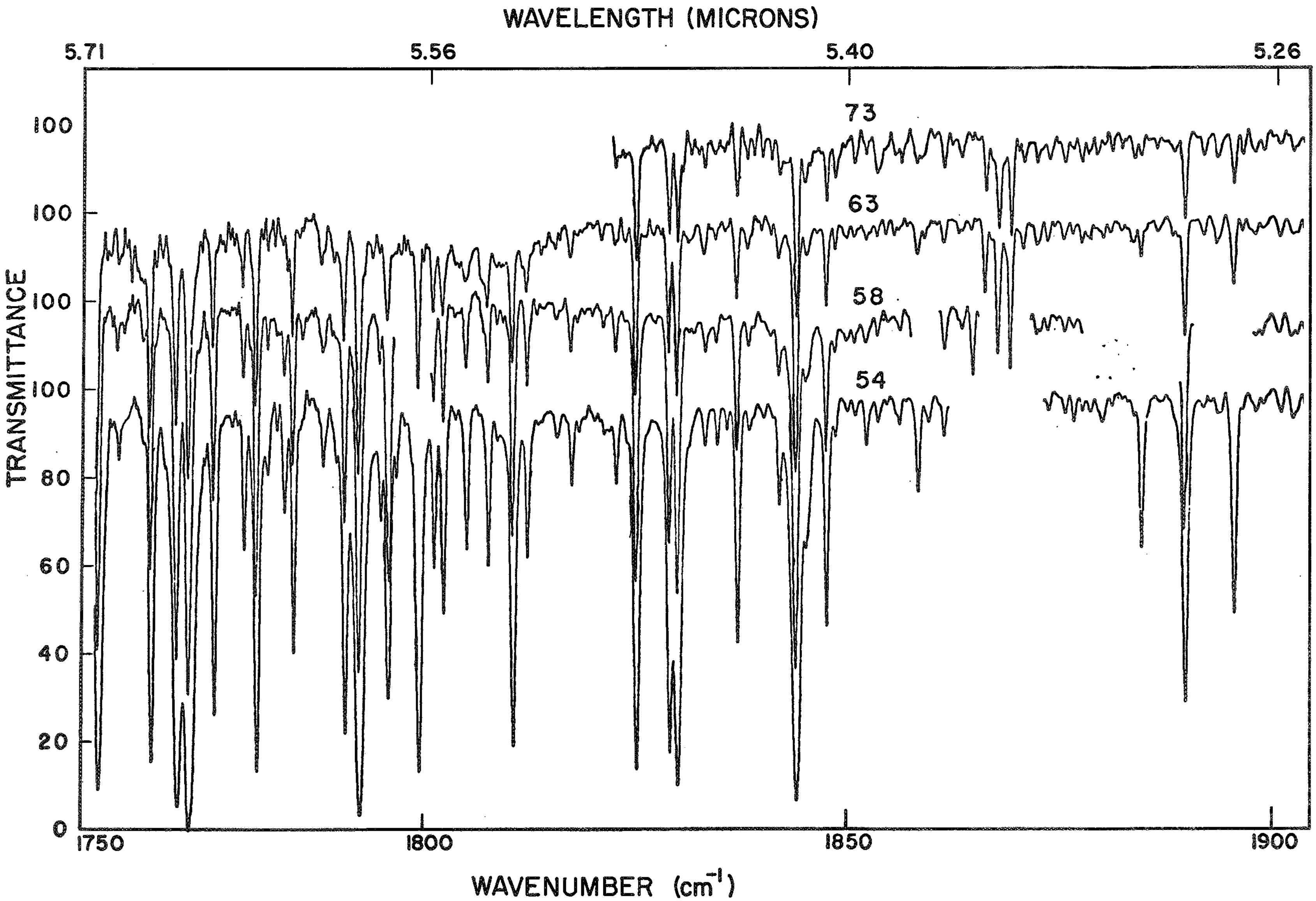

Figure 9-20.- Observed spectral transmittance at various altitudes for the region 5.70 µm (52.5 THz) to 5.29 µm (57.8 THz). Flight details are given in the text, (After Murcray, et al. 1969, ref.).

9.7 ATMOSPHERIC HYDROMETEORS

A hydrometeor is any product of condensation or sublimation of atmospheric water vapor, whether formed in the free atmosphere or at the earth's surface; also any water particles blown by the wind from the earth's surface.

Hydrometeors typically may be classified as follows (ref. 121): (a) Liquid or frozen particles formed and remaining suspended in the air: damp haze, cloud, fog, ice fog, and mist. (b) Liquid precipitation: drizzle and rain. (c) Freezing precipitation: freezing drizzle and freezing rain. (d) Solid (frozen) precipitation: ice pellets, hail, snow, snow pellets, snow grains, and ice crystals. (e) Falling particles that evaporate before reaching the ground: virga. (f) Liquid or frozen particles lifted by the wind from the earth's surface: drifting snow, blowing snow, blowing spray. (g) Liquid or frozen deposits on exposed objects: dew, hoarfrost, rime, and glaze. By the term atmospheric hydrometeor is meant items (a) through (f).

Precipitation is any form of water particles, whether liquid or frozen, that reaches the ground. It is a major class of hydrometeor; but is distinguished from cloud, fog, rime, and dew, etc. in that it must "fall"; and is distinguished from cloud and virga in that it must reach the ground. Precipitation includes drizzle, rain, snow, snow pellets, snow grains, ice crystals, ice pellets, and hail. (ref. 121).

There have been several review papers on the subject of atmospheric hydrometeor effects on microwave-millimeter wave propagation. Holzer (ref. 122) discusses the 4-6 GHz, 7.5 - 5 cm) region and presents a methodology to extend the estimates to other climatic regions. Benoit (ref. 123) discusses the frequency region up to 20 GHz (1.5 cm). Fowler and LaGrone (ref. 124) discuss from 10 to 100 GHz (33cm - 3 mm), and Liebe (ref. 125) discusses the region from 10 - 75 GHz (3 cm - 4 mm). Hogg (ref. 126) considers earth-to-space communications below 35 GHz (8.6 mm).

Extensive work has been reported by Haroules and Brown (refs. 127-130) on multifrequency radiometer work in various types of weather. Wilson (ref. 131) also reported work on a dual frequency radiometer facility.

Lukes (ref. 78) has given a very detailed analytical methodology for considering the effects of atmospheric hydrometeors. Figures 9-21 and 9-12 show some of his results.

Some ongoing work on the computed transmission characteristics of rain at microwave and visible frequencies will soon be reported by Setzer (ref. 135). Table containing the Mie scattering coefficient, absorption coefficient, extinction coefficients, equivalent medium index of refraction, and phase delay for rains conforming to the Laws and Parsons drop size distribution are presented.

Much more information can be gained by consulting the Atmospheric Transmission Bibliography described in Part IV.

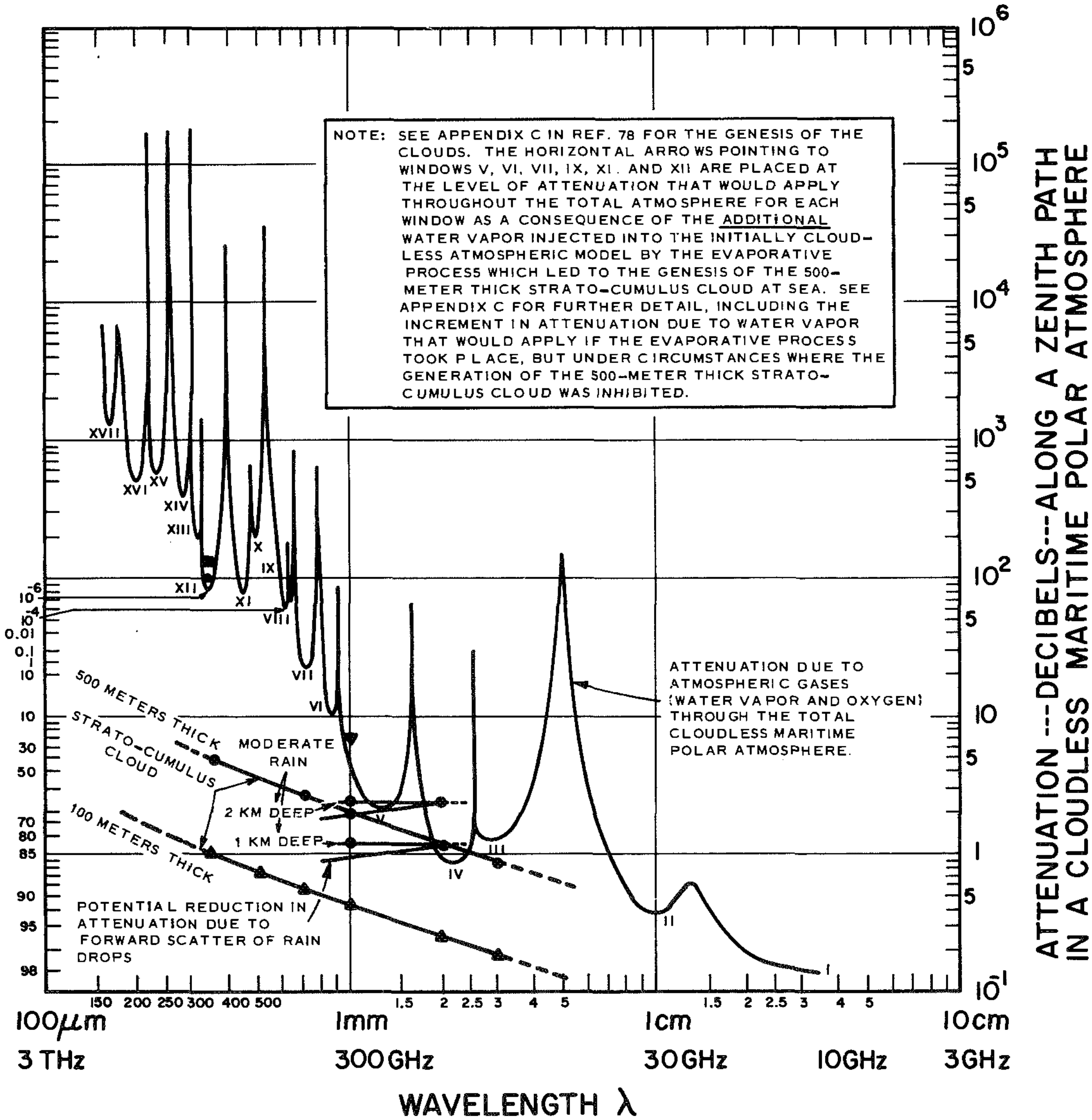

Figure 9-21.- Comparative attenuation due to atmospheric gases, stratocumulus clouds, and moderate rain, along a zenith path in a "standard" maritime polar atmosphere. The attenuation for combinations is additive. (After Lukes 1968, ref. 78).

10.0 SCATTERING

10.1 INTRODUCTION

This chapter discusses the scattering of electromagnetic waves in the earth's atmosphere. Fundamentally, scattering is the process by which small particles suspended in a medium of a different index of refraction (Section 8.2) diffuses a portion of the incident radiation. In scattering no energy transformation results, only a change in the spatial distribution of the radiation. Along with absorption, scattering is a major cause of the attenuation of radiation in the atmosphere (Chapter 9).

Scattering is a function of (1) the ratio of the particle diameter to the wavelength of the radiation, (2) the complex index of refraction of the particles, (3) the size distribution, and (4) the shape of the scattering particles.

When the ratio of particle diameter (assuming spherical particles) to the wavelength of the radiation is less than about 0.1, Rayleigh scattering occurs in which the scattering coefficient (Section 10.5) varies inversely as the fourth power of the wavelength. At larger values of the ratio of particle diameter to wavelength, the scattering varies in a complex fashion described by the Mie theory (Mie, 1908, ref. 1); at a ratio of the order of 10, the laws of geometric optics begin to apply and this serves to mark the somewhat diffuse upper boundary of the realm of scattering (which realm, it is here implied, includes diffraction). These problems are discussed by Feynman (ref. 2) and Stone (ref. 3).

10.2 SCATTERING COEFFICIENTS

The scattering coefficient (also called the total scattering coefficient) is a measure of the attenuation due to scattering of radiation as it traverses a medium containing scattering particles.

Like the analogous absorption and attenuation (or extinction) coefficient, the scattering coefficients is frequently defined in Bouguer's law (Section 1.2.2) as follows:

$$I_x = I_o \exp(-\sigma_s x), \qquad (10.1)$$

where I_x is the flux density of the radiation that was initially of flux density I_o, after passing through a distance x in the scattering medium (Fig. 1-1).

TABLE 10-1.- PARTICLES RESPONSIBLE FOR ATMOSPHERIC SCATTERING (AFTER McCARTNEY, 1967, REF. 4; LUKES, 1968, REF. 5)

Particle	Nature	Radius (microns)	Number Density (cm^{-3})
electron	electron	10^{-9}	
air molecule	molecule	10^{-4}	2.7×10^{19}
small 'ion'	group of water molecules	10^{-3}	
combustion product	hygroscopic	10^{-2} to 10^{-1}	10^{4}
sea-salt mucleus	hygroscopic and soluble	0.1 to 0.3	50 to 400
dust	generally in-soluble	0.1 to 10	highly variable
haze	water droplet	0.3 to 3	50 to 400
fog	water droplet	1 to 30	1 to 100
cloud	water droplet	1 to 30	50 to 500
rain	water droplet	3 to 3,000	highly variable
hail	ice particle	highly variable	"
snow	ice particle	"	"

A scattering coefficient has dimensions of reciprocal length. Information on various scattering coefficients is found in McCartney, 1966, ref. 6; McCartney, 1967, ref. 4; Allen, 1963, ref. 7; and in Table 7.4 in Section 7.7.

Much theoretical work on scattering coefficients has been done by D. Deirmendjian and much of his work is listed in the Part IV of this handbook.

Kerker (ref. 8) has presented an excellent monograph which covers essentially all aspects of scattering.

10.3 RAYLEIGH SCATTERING COEFFICIENTS

Rayleigh scattering has been discussed by many authors. Several references are listed in Table 7.4 and in Section 10.2. Rayleigh scattering is any scattering process produced by spherical particles whose radii are smaller than about one-tenth (0.1) of the wavelength of the incident radiation.

In Rayleigh scattering,

(1) The amount of scattering, hence attenuation, varies approximately with the fourth power of the wavelength, a relation known as Rayleigh's law.

(2) The spatial distribution of the scattered radiation has a simple dependence on the angle between directions of illumination and observation.

(3) There is complete symmetry of scattering about a plane normal to the direction of the incident radiation, so that forward scatter equals the backward scatter.

(4) Radiation scattered at 90° is plane polarized. This condition exists in a very clear sky along an arc everywhere at 90° from the sun.

In many situations involving atmospheric attenuation and visibility, a matter of interest is the total amount of energy removed from an illuminating beam by a volume of scattering molecules. For unpolarized or polarized light, the volume total coefficients σ_{s_R} is given by the expression

$$\sigma_{s_R} = \frac{32\pi^3 \, (n - 1)^2}{3 \, N\lambda^4} \qquad (10\text{-}2)$$

where

n is the refractive index of the gas (Section 8.2).

λ is the wavelength of the incident radiation.

N is the number density of the gas molecules.

Equation (10-2) is the usual form of the Rayleigh total coefficient for a unit volume; e.g., an illuminated cross-sectional area of 1 cm^2 and a path length of 1 cm. The dimension is reciprocal length. If no additional absorption occurs, this is also the attenuation coefficient which can be used in Eqs. (10-1) and (1-2), with the cautions mentioned in Section 1.2.2.

Numerical values of the total coefficient σ_{s_R} are usually quite small. Table 10-2, adapted from Kuiper (ref. 9), lists values of (n - 1) and σ_{s_R} for air at standard conditions (Temperature 0°C; Pressure 760 mm Hg or 1013 millibars). To adjust the values to other nonstandard conditions, see the corrections given below. The values of σ_{s_R} can be used for any other common gas, with little error, by multiplying the ratio of refractive indices. The values of σ_{s_R} vary over a range of 200, between the wavelength extremes. Rayleigh scattering actually varies as $\lambda^{-4.08}$ rather than λ^{-4} at the wavelength of visible light.

Corrections for Nonstandard Conditions

The angular and total coefficients (Eqs. 10-2) and the refractive index term (n - 1) vary directly as the actual mass density ρ, or the actual molecular density N per unit volume. Numerical values of either coefficient, or of refractive index, computed for one density, can be corrected to another density through multiplication by the factor

$$\frac{N}{N_s} \quad \text{or} \quad \frac{\rho}{\rho_s} \tag{10-3}$$

where N_s and ρ_s refer to the density employed for the computation, usually that corresponding to 0°C and 760 mm Hg or 1013 millibars (mb).

Usually the measured parameters of actual pressure p in mm Hg and actual temperature t in °C will be known more readily than N or ρ. Correction can thus be made directly through multiplication by

TABLE 10-2.- NUMERICAL VALUES OF RAYLEIGH TOTAL COEFFICIENT, AND REFRACTIVE INDEX TERM (n - 1) VARIOUS WAVELENGTHS (AFTER McCARTNEY, REF. 6 AND KUIPER, REF. 9)

Wavelength (microns)	Refractive Index Term $(n - 1) \times 10^4$	Rayleigh Total Coefficient $\sigma_{sR} \times 10^7$ (cm^{-1})
0.30	3.072	14.790
0.32	3.043	11.210
0.34	3.019	8.658
0.36	3.001	6.808
0.38	2.987	5.430
0.40	2.974	4.358
0.42	2.964	3.583
0.44	2.954	2.955
0.46	2.947	2.474
0.48	2.941	2.068
0.50	2.935	1.750
0.52	2.931	1.491
0.54	2.927	1.277
0.56	2.922	1.102
0.58	2.019	0.955
0.60	2.916	0.833
0.62	2.914	0.729
0.64	2.911	0.641
0.66	2.909	0.566
0.68	2.907	0.502
0.70	2.904	0.446
0.80	2.896	0.260
0.90	2.892	0.162
1.00	2.889	0.106
1.10	2.887	0.072
1.20	2.885	0.051
1.40	2.883	0.027
1.60	2.881	0.016
1.80	2.880	0.010
2.00	2.879	0.007

$$\frac{p}{760} \times \frac{1}{(1 + \alpha t)} \qquad (10\text{-}4)$$

where α is the expansion coefficient of gas, which equals 1/273.

Corrections sufficiently accurate for many purposes in atmospheric optics can be made if the altitude above sea level is known, even though temperature and pressure are unknown. This is possible because atmospheric density decreases exponentially with height. Assuming an isothermal atmosphere, it follows from the barometric equation that

$$\rho = \rho_o \exp\ (-gH/RT) \qquad (10\text{-}5)$$

where

ρ = density at altitude H

ρ_o = density at sea level

g = acceleration due to gravity, 980 cm sec^{-2}

R = universal gas constant, 2.87×10^6 erg/gram-°K

T = isothermal temperature in °K

H = altitude in cm.

10.4 MIE SCATTERING COEFFICIENTS

Many scattering coefficients are given in the publications listed in Section 10.3 and Table 7.4. McCartney discusses the various coefficients (ref. 6). Reference is made below to sources of additional information.

Gustav Mie (ref. 1) developed an elegant analytical solution for the optical behavior of spheres of any size or substance. Although his objective was the analysis of the experimentally observed characteristics of a suspensing of small gold spheres in water, his solution was not restricted to this particular problem but covers the broader case of dielectric particles with finite conductivity. Water droplets display such properties over the spectral range being studied in this handbook.

Mie found a great angular variation in the intensity of light scattered; with coarser gold particles he determined that the greater part of the scattered light was reradiated in the direction of the primary ray. This effect is known as the "Mie Effect." Since reradiation by the secondary waves is superimposed on the incident plane waves, not all the energy which is initially abstracted by the scattering particles is, under conditions of the Mie effect, necessarily lost to transmission in the direction of the primary ray.

The Mie theory does not apply to scattering by particles small compared to the wavelength of the incident radiation, and thus is important in meteorological optics, where diameter-to-wavelength ratios of the order of unity and larger are characteristic of many problems regarding haze and cloud scattering. Scattering of microwave energy by raindrops constitutes another significant application of the Mie theory. The whole field of radar meteorology is concerned with this problem (ref. 10).

In actual use, the Mie theory is somewhat cumbersome by the required summing of slowly convergent infinite series which express the scattering functions. In recent years extensive tabulations of the Mie functions have been made. Table 7.4 lists several such tables; other work on the Mie scattering theory can be located in Part IV of this handbook under such names as Bullrich, Deirmendjian, Kerker, Eiden, Penndorf, Plass, Rozenberg, Shifrin, and van de Hulst.

Lukes (ref. 5) has recently completed a comprehensive analysis of the effects of atmospheric water droplets on electromagnetic wave propagation. He discusses the Mie theory and its applications in great detail. He also draws together much of the material on the complex dielectric constant of water over a wide frequency range.

10.5 Ionospheric Scattering

Radiation at Very High Frequencies (30 - 300 MHz; 10 m - 1 m) is propagated via the ionosphere (80 - 95 km level) by a process of forward scatter from inhomogeneities in the electron distribution. Only single-hop transmission (maximum distance about 2,000 km) is feasible; for longer distance communications relay stations are required. Furthermore, since the scatter process is relatively inefficient, large transmitted powers and high gain antennas are necessary. (Susskind, ref. 11; Davies, refs. 12, 13). Section 9.4 of this handbook should also be consulted.

10.6 TROPOSPHERIC SCATTERING

The term "Tropospheric Scattering" may refer either to the long-range propagation of radio signals by scattering due to index of refraction (Chapter 8) inhomogeneities in the lower atmosphere or to the scattering of radio waves by atmospheric hydrometeors, etc. This latter aspect will be considered in Sections 10.7 and 10.8.

Tropospheric scatter, or tropo, is utilized as a "beyond-the-horizon" means of communication. The principal reflection of the signal occurs in the troposphere. Although characterized by severe fading, operational systems of this type provide reliable, moderate bandwidth, point-to-point communication, with the transmitter and receiver separated by 100 to 600 miles.

A typical troposcatter system is shown in Fig. 10-1. The transmit and receive antenna beams intercept in the troposphere where energy is scattered from one to the other in a "common volume".

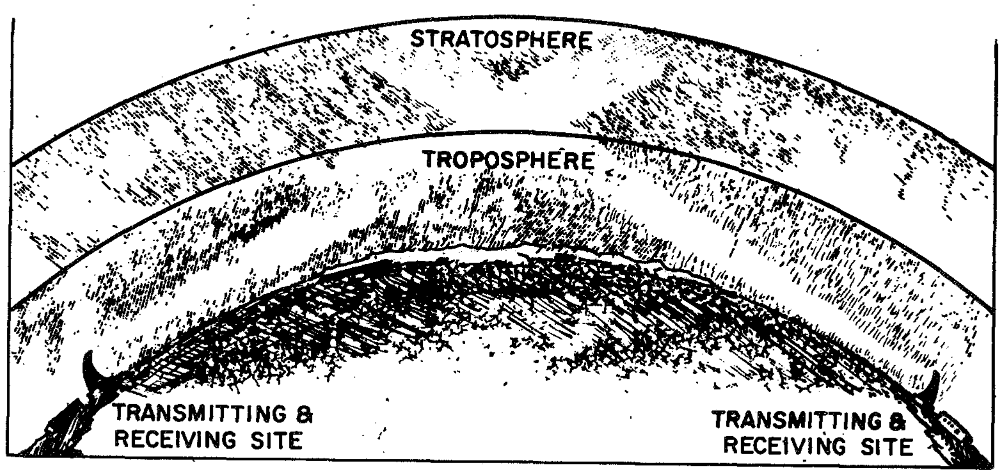

Figure 10-1.- A schematic drawing of a troposcatter link

The received signal is characterized by continuous fading and phase changes, due to changes in the tropospheric medium and to multiple-length signal paths. The latter results in those differences of the several components which are scattered from different locations in the common volume. These components add or subtract according to their relative phases, causing severe fading of the resultant signal amplitude.

For transmission of intelligence, one must also consider what happens to a band of frequencies, such as is always involved in radio communications. The amplitude of each frequency is the pass band will vary or fade with time as described above. Not all frequencies vary or fade in time in the same manner, because different components at one frequency may be out of phase and cancel, while at a nearby frequency path components may be in phase and add, providing a strong signal. When the frequencies within a pass band fade together, the fading is said to be non-selective. The band of correlated frequencies that fade together is defined as the coherent bandwidth.

The coherent bandwidth in troposcatter is a function of distance and is also related to the fading rate. If the transmitted signal band of frequencies is less than the coherent bandwidth of the troposphere, good transmission results. The fading phenomenon still exists and the signal is weak but not distorted. The use of high power transmitters, high gain antennas, sensitive receivers, and diversity techniques overcomes the fading phenomenon.

When the coherent bandwidth is smaller than the modulated carrier band, distortions in the form of intermodulation noise result. No improvement results by increasing the transmitter power or by using diversity techniques since this distortion noise is independent of signal strength.

Tropospheric propagation is reviewed in Rice and Herbstreit (ref. 14) and Rice et al. (ref. 15). Experiments for studying the feasibility of tropospheric scatter propagation between the earth and satellites were planned in Hartman and Decker (ref. 16).

10.7 ATMOSPHERIC HYDROMETEOR SCATTERING

The most complete analysis of this problem over a wide range of frequencies (3 GHz - 3,000 THz; 10 cm - 0.1 m) was conducted by Lukes (ref. 5). Some of his work is shown in Figs. 9-12 and 9-21. Figure 9-21 shows the comparative attenuation due to atmospheric gases, stratocumulus clouds, and moderate rain, along a zenith path in a "standard" maritime polar atmosphere. Information of atmospheric hydrometeors is presented in Section 9.7. Most of the references listed in Section 9-7 contain information on the scattering of electromagnetic waves as well as on the absorption by atmospheric hydrometeors.

The basic problem in understanding the scattering by atmospheric hydrometeors is their spatial and temporal variation (ref. 17). Because the detailed and timely report by Lukes (ref. 5) is a storehouse of information on these topics his abstract is presented below. An outline is presented in Section 7.4.39.

Abstract of Lukes (ref. 5)

To determine attenuation values over a wide range of wavelengths, an analytical methodology is developed to accommodate the population of droplets according to size in unit volume of several models of water-occluded atmospheres. The extent of penetrability of cloudy and rainy atmospheres is then demonstrated analytically as a function of wavelength. Unique phenomena appear at wavelengths from about 100 microns to 2 millimeters, in part due to the population of droplets by size in clouds and rain but also due to the strong wavelength dependence of the complex index of refraction of liquid water. The submillimeter band is accordingly given special emphasis. Most layer-type water clouds, especially if of maritime origin, are readily penetrable at these wavelengths. Attenuation due to rain of moderate intensity is found to decrease slowly with decreasing wavelength below 2 millimeters. Further, pronounced forward scatter in moderate rain, adding to the forward transmission, first begins to appear at a wavelength of 2 millimeters and becomes increasingly more pronounced the shorter the wavelength. None of these trends would be predicted by simple extrapolation from experience at microwave frequencies.

The analysis of attenuation by water droplet atmospheres draws on the Mie theory of absorption and scatter by spherical droplets. It is shown that the essential condition of incoherent scattering is satisfied by haze, fog, clouds, and rain. Multiple scatter in clouds for radiation at submillimeter wavelengths and longer is found to be exceedingly weak and may be ignored. The question of possible effects of multiple scatter in rain is not settled analytically, but if such scatter cannot be ignored, it is unquestionably multiple incoherent scatter. This suggests the application of radiative transfer theory to elucidate more definitively the effects of scatter in rain.

The absorption profile arising from atmospheric gases is structured in fine detail from 0.4 micron to 3.2 centimeters by extensive search of the literature. Gaseous absorption along a zenith path through a cloudless maritime polar atmosphere is computed for wavelengths from 164 microns to 3.2 centimeters. Seventeen windows of elevated transparency in this profile are identified. A stratocumulus cloud and rain are then induced by turbulence in this model atmosphere, and comparative and composite values of attenuation due to clouds, rain, and gases are derived. From 345 microns to 3 millimeters, the contribution by cloudy and rainy atmospheres to total atmospheric attenuation is found to be relatively minor, even at the wavelengths of gaseous windows.

Because of requirements forged by its scope, the study provides an extensive data base on the population of droplets by size invarious water-occluded atmospheres. The extremes are remarkable: thick fog may have over 100 billion droplets per cubic meter of 0.4 micron droplet-radius peak population compared to a mere 200 in mist of 75 micron peak population. The chemical properties of liquid water are drawn from some 80 sources in order to structure the real and imaginary parts of the complex index of refraction over the spectral range of 0.1 micron to 10 centimeters, essential to the application of the Mie theory.

10.8 ATMOSPHERIC AEROSOL SCATTERING

An aerosol is a colloidal system in which the dispersed phase is composed of either solid or liquid particles, and in which the dispersion medium is a gas, usually air.

There is no clear-cut upper limit to the size of particles comprising the dispersed phase in an aerosol, but as in all other colloidal systems, it is rather commonly set at 1 micron. Haze, most smokes, and some fogs and clouds may thus be regarded as aerosols. However, it is not good usage to apply the term to ordinary clouds whose drops are so large as to rule out the usual concept of colloidal stability. It is also poor usage to apply the term to the dispersed particles alone; an aerosol is a system of dispersed phase and dispersing medium taken together.

Haze consists of fine dust or salt particles dispersed through a portion of the atmosphere; a type of lithometeor. The particles are so small that they cannot be felt or individually seen with the naked eye, but they diminish horizontal visibility and give the atmosphere a characteristic opalescent appearance that subdues all colors.

Many haze formations are caused by the presence of an abundance of condensation nuclei which may grow in size, due to a variety of causes, and become mist, fog, or cloud. Distinction is sometimes drawn between dry haze and damp haze, largely on the basis of differences in optical effects produced by the smaller particles (dry haze) and the larger particles (damp haze) which develop from slow condensation upon the hygroscopic haze particles. Dry haze particles with diameters of the order of 0.1 micron, are small enough to scatter short wavelengths of light preferentially, though not according to the inverse fourth-power law of Rayleigh (Section 10.3). Such haze particles produce a bluish color when the haze is viewed against a dark background, for dispersion (Section 8.3) allows only the slightly bluish scattered light to reach the eye. The same type of haze, when viewed against a light background, appears as a yellowish veil, for here the principal effect is the removal of the blue component from the light originating in the distant light-colored background. Haze may be distinguished by this same effect from mist, which yields only a gray obscuration, since in mist the particle sizes are too large to yield appreciable differential scattering of various wavelengths (ref. 18).

The reduction of visibility and the attenuation of solar radiation are the most obvious manifestations of the presence of aerosol in the earth's atmosphere (refs. 19, 20). Experimental and theoretical studies in this field have been recently summarized by Zuev (ref. 21), whose monograph includes quantitative data on absorption, scattering, and attenuation of visible and infrared radiation in narrow spectral bands for different geometrical patterns of the source and the receiver positions under a great variety of meteorological conditions. The book also contains a discussion of the applicability of the Bouguer law to the results of experimental investigations of aerosol attenuation (Section 1.2.2).

Another recent monograph of significance is that of Barteneva, Dovgiallo, and Boliakova (ref. 22). This book presents experimental investigations on the optics of the lower atmosphere carried out by the laboratory of Atmospheric Optics of the Main Geophysics Observatory over a ten-year period. One of the aims of the book was to establish relationships between transparency and other meteorological factors. The contents of the book are outlined in Section 7.4.37.

A review paper on atmospheric optics and radiation transfer by Howard and Garing (ref. 23) summarizes the effort of American authors during the years 1964-1968. It contains more than 300 references, classified into sections: General Studies; Pyrheliometry; Solar Insolation and Distribution of Daylight; Earth Radiance and Albedo; Sky Brightness and Cloud and Terrain Reflectance Studies; Transmission and Absorption Studies; Scattering Studies; Atmospheric Refraction, Seeing and Scintillation; and Radiative Transfer Studies.

Recent analysis of other general aspects of visibility in the atmosphere include measurements of the transparency of the atmospheric surface layer to the radiation of various lasers (ref. 24), vertical distribution of horizontal visibility under clouds and within clouds (ref. 25), and absorption of light by aerosols in the visual and near infrared (ref. 26) and scattering by irregular particles (ref. 27).

Germogenova, et al. (ref. 19) present more material on general transmission studies than is presented here.

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