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Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds, and Rain

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PREFACE

The Rand Corporation has been conducting a series of studies for the United States Air Force that examine broad implications of the development and employment of precision-guided munitions (PGMs). Attenuation due to atmospheric aerosols (e.g., haze, fog, cloud, and rain) is an important factor in assessing the potential of sensors in many applications, including target acquisition and terminal guidance for PGMs.

This report assembles, under one cover, the values obtained by many investigators for attenuation coefficients due to aerosols as a function of wavelength, for both optical-frequency and radio-frequency portions of the electromagnetic spectrum. The report is therefore usable as a handbook, by which a quick estimate of the effects of these adverse weather conditions on the sensors can be made. The report should be useful to Air Force offices concerned with application studies of sensors, such as ACS/Studies and Analysis and the Air Force Weapons Laboratory, and to all agencies involved in system studies of sensors.

The author is grateful to J. F. Digby, R. E. Huschke, and L. G. Mundie for providing many valuable comments.

For their kind permission to use slightly modified versions of figures originally appearing in their publications, the author thanks John Wiley and Sons, New York (Fig. 1), the *Proceedings of the IEEE* (Fig. 2), *Applied Optics* (Fig. 5), and *The Journal of the Optical Society of America* (Figs. 8, 9, 10, 13, 15).

SUMMARY

To detect the presence of targets, terminal guidance sensors use different parts of the electromagnetic (EM) spectrum ranging all the way from visible to infrared (IR) to radio frequency (RF). But when an EM wave propagates through the atmosphere, it is absorbed by atmospheric gases such as H_2O, CO_2, O_2, and O_3, and scattered and absorbed by atmospheric aerosols, such as haze, fog, cloud, and rain. Both actions somewhat degrade the performance of all sensors. The attenuation of EM radiation due to aerosols is sometimes so severe as to render the sensors useless.

Gaseous absorption is at a minimum in a few so-called "atmospheric windows." The following are the window bands in the visible, IR, and RF portions of the EM spectrum:

Visible: 0.4 μm to 0.7 μm
IR: 3 to 5 μm, 8 to 12 μm
RF: 0.32 cm (94 GHz), 0.85 cm (35 GHz), 3 cm (10 GHz).

Most sensors operate primarily in these bands.

This report assembles, under one cover, the values of aerosol attenuation coefficients of these spectral regions containing the atmospheric windows, to enable quantitative assessment of the sensors using those windows during adverse weather conditions. Figures S1 and S2 are summary plots of the attenuation coefficients due to haze, fog, cloud, and rain, versus wavelength or frequency, useful for making quick estimates of the effects on sensors.

Figure S1 plots the attenuation of optical-frequency radiation. Figures S1(a) and S1(b) plot attenuation due to haze and fog for selected values of visibility, V_2. It can be observed that attenuation due to haze and evolving fog decreases rapidly with increasing wavelength; therefore, IR sensors are preferable to visible sensors in hazy weather. The same is not true for transmission through stable fogs or clouds (see Figs. S1(b) and S1(c)). In general, IR attenuation due to stable fog

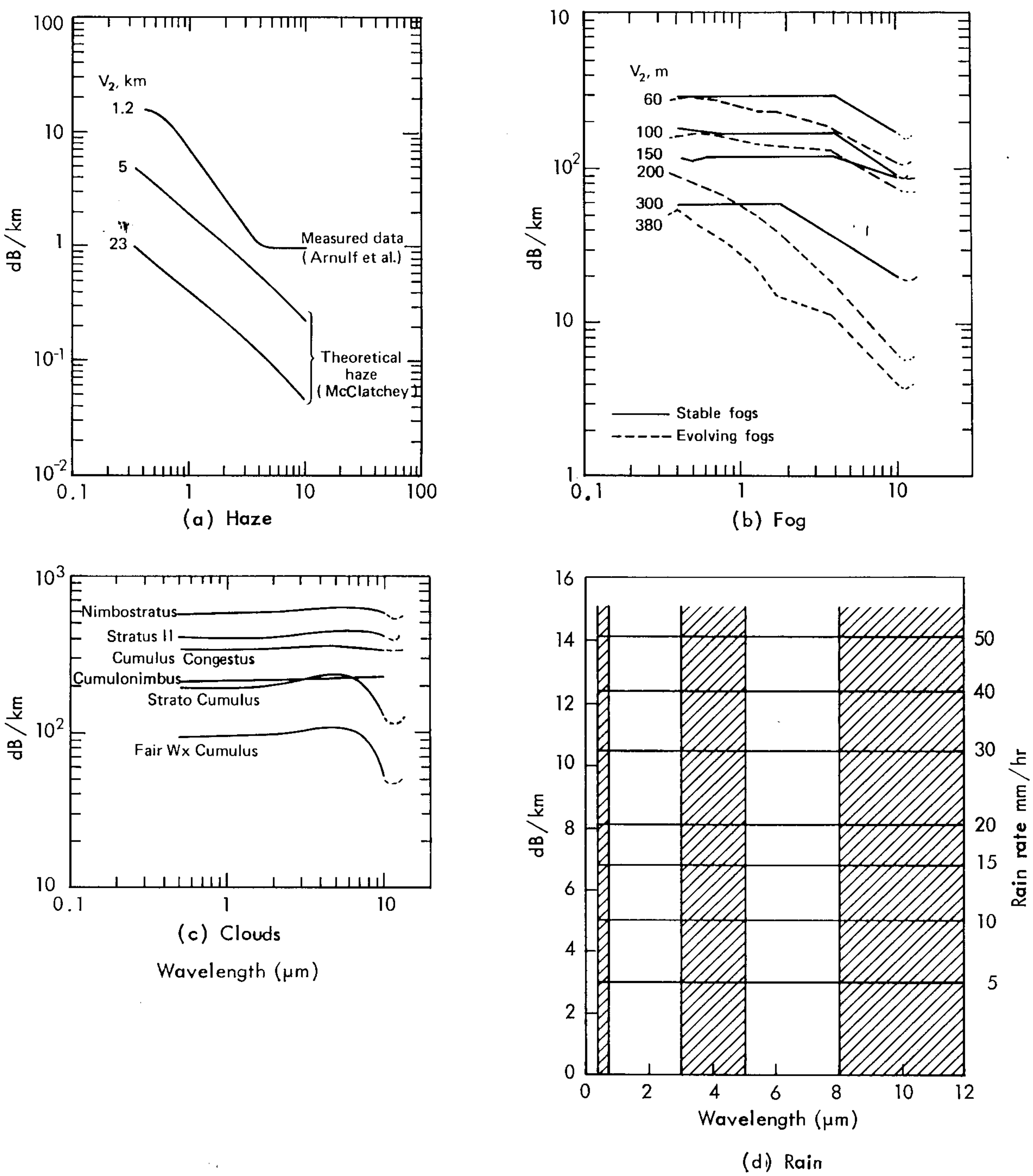
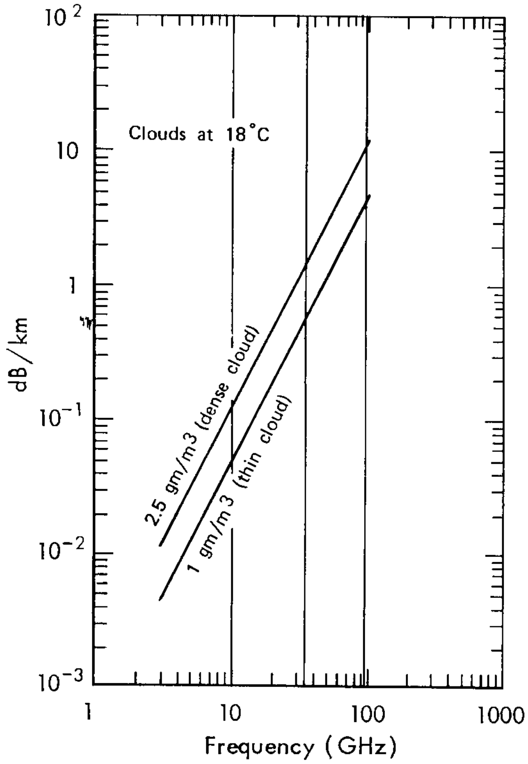
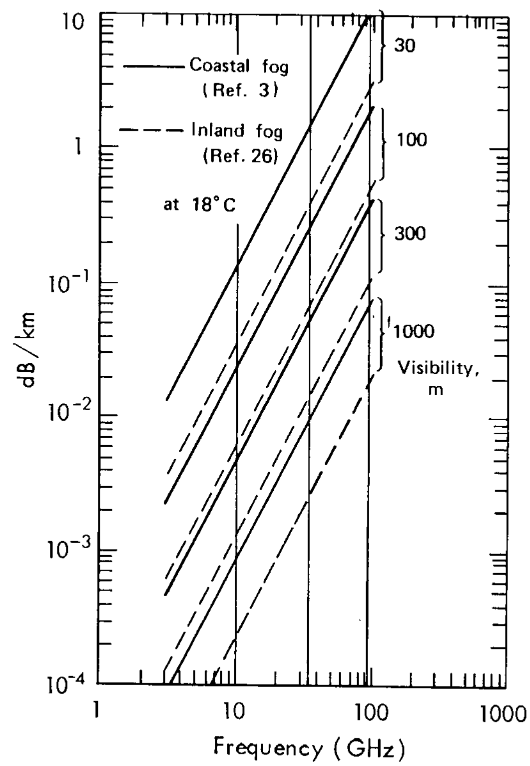


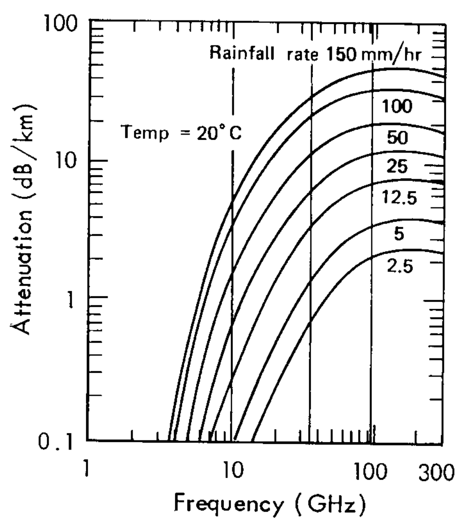
Fig. S1 — Optical attenuation due to haze, fog, clouds and rain



(a) Clouds



(b) Fog



(c) Rain

Fig. S2 — Radio frequency attenuation due to clouds, fog and rain and clouds is so severe that IR sensors have little advantage over visible sensors. Figure S1(d) plots attenuation due to rain for various precipitation rates. The attenuation is constant from visible wavelengths through middle IR wavelengths (15 μm) because the water particles are much larger than the radiation wavelengths.

Figure S2 plots the attenuation of RF frequency radiation due to fog, cloud, and rain. Haze is transparent to RF radiation because haze particles are much smaller than RF radiation wavelength. For both coastal and inland fogs, it can be concluded from Fig. S2(b) that attenuation is negligible at 10 GHz. At 35 GHz, it is less than 2 dB/km, with a 30-meter visibility for both kinds of fog. But at 94 GHz, it is about 3 dB/km for inland fog and about 10 dB/km for coastal fog, with a 30-meter visibility. Similar observations can be made for cloud attenuation. Instead of visibility, however, liquid water content (in gm/m^3) is the parameter usually used to characterize the cloud. It can be observed from Fig. S2(c) that the attenuation of RF radiation by rain is severe for the windows at 35 and 94 GHz, and is almost the same as the attenuation at visible and IR frequencies. It is almost negligible at 10 GHz, however, being less than 2 dB/km even at a precipitation rate of 50 mm/hr.

CONTENTS

I. INTRODUCTION

To detect the presence of targets, terminal guidance sensors use various parts of the electromagnetic (EM) spectrum, ranging all the way from visible to infrared (IR) to radio frequency (RF). The performance of all sensors, however, suffers to a degree from absorption of EM waves by atmospheric gases such as H_2O, CO_2, O_2, and O_3, and from attenuation by atmospheric aerosols such as haze, fog, clouds, and rain. Attenuation due to atmospheric aerosols is sometimes so severe as to render the sensors useless.

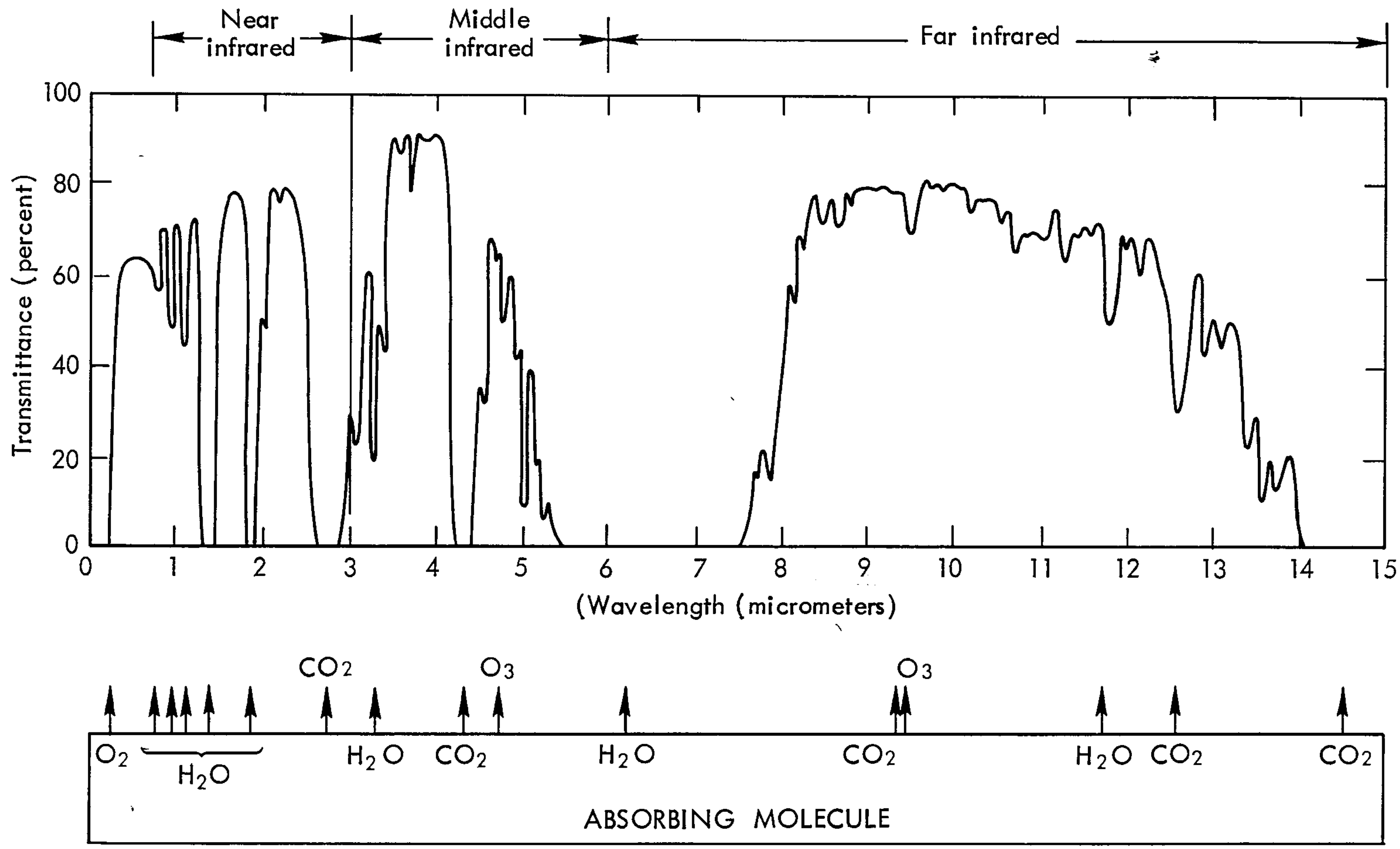
Gaseous absorption is at a minimum in a few so-called "atmospheric windows." Figures 1 and 2 depict those windows in the visible, IR, and RF portions of the EM spectrum:

Visible: 0.4 μm to 0.7 μm
IR: 3 to 5 μm, 8 to 12 μm
RF: 0.32 cm (94 GHz), 0.85 cm (35 GHz), 3 cm (10 GHz).

Most sensors operate primarily in these bands.

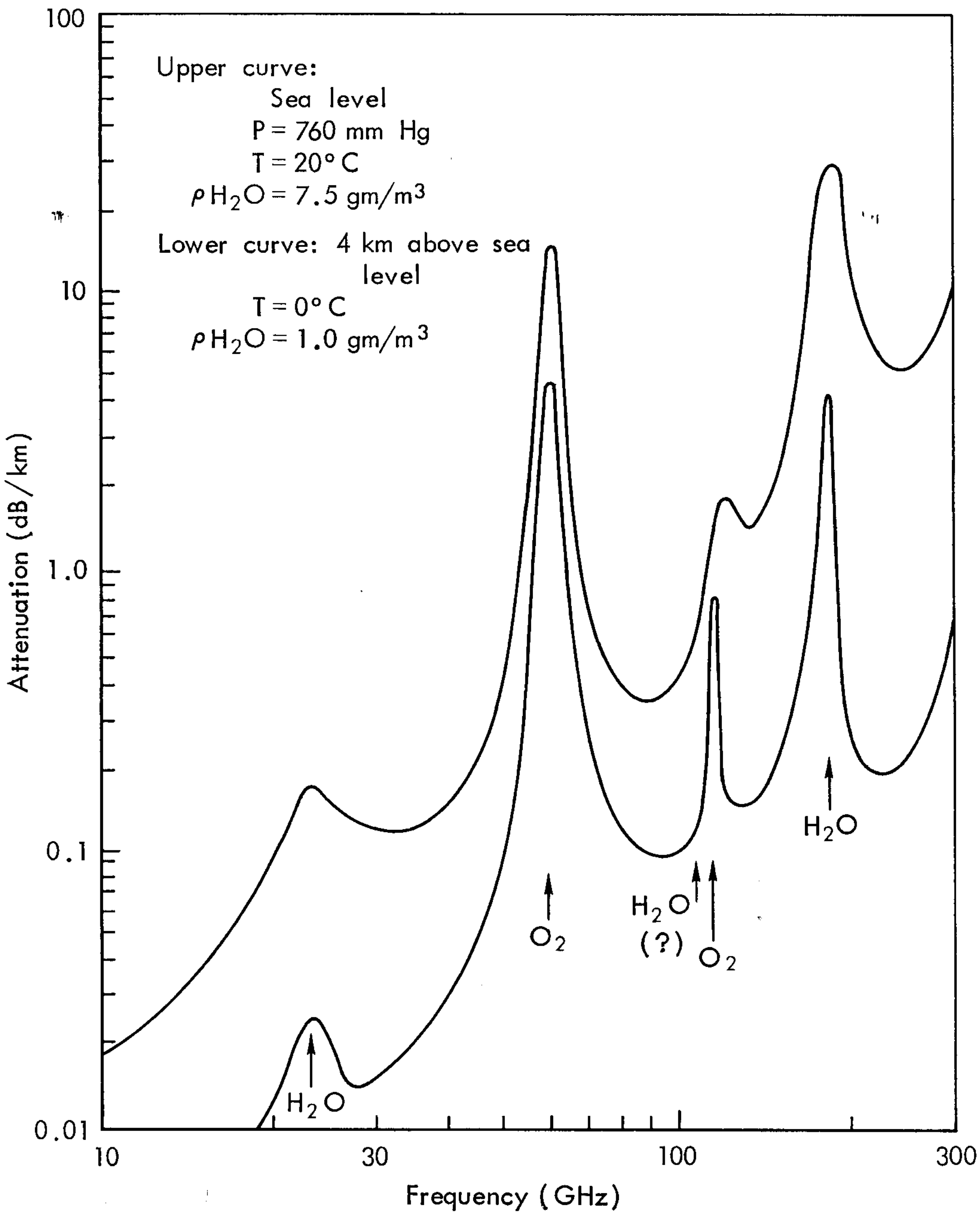
Weather effects on RF sensors have been treated thoroughly in Refs. 3 to 5. The attenuation of visible and IR radiation due to atmospheric gaseous absorption has been treated in some detail in Ref. 6 and in most books on IR technology,[1,7,8] but attenuation of EM radiation due to aerosol particles is usually glossed over quickly in such texts.

It is the purpose of this study to collect under one cover the values of aerosol attenuation coefficients of these spectral regions containing atmospheric windows, to enable quantitative assessment of sensors using these windows during adverse weather. Both calculated and available measured values are presented. Consequently, the report is more of a "handbook" than a theoretical treatise.



SOURCE: Ref. 1.

Fig. 1—Transmittance of the atmosphere for a 6000 ft horizontal path at sea level containing 17 mm of precipitable water



SOURCE: Ref. 2.

Fig. 2 — Horizontal attenuation due to oxygen and water vapor

II. ATTENUATION BY RAIN

Rain attenuates EM radiation through both absorption and scattering, the relative amounts depending on the ratio of raindrop radius to wavelength.[9,10] In the visible and IR portions of the EM spectrum, attenuation by rain is independent of wavelength because the raindrop radius (typically, about 0.05 cm) is much larger than the wavelength.[9,10] The reverse is true in the RF region, where the two measures are comparable.

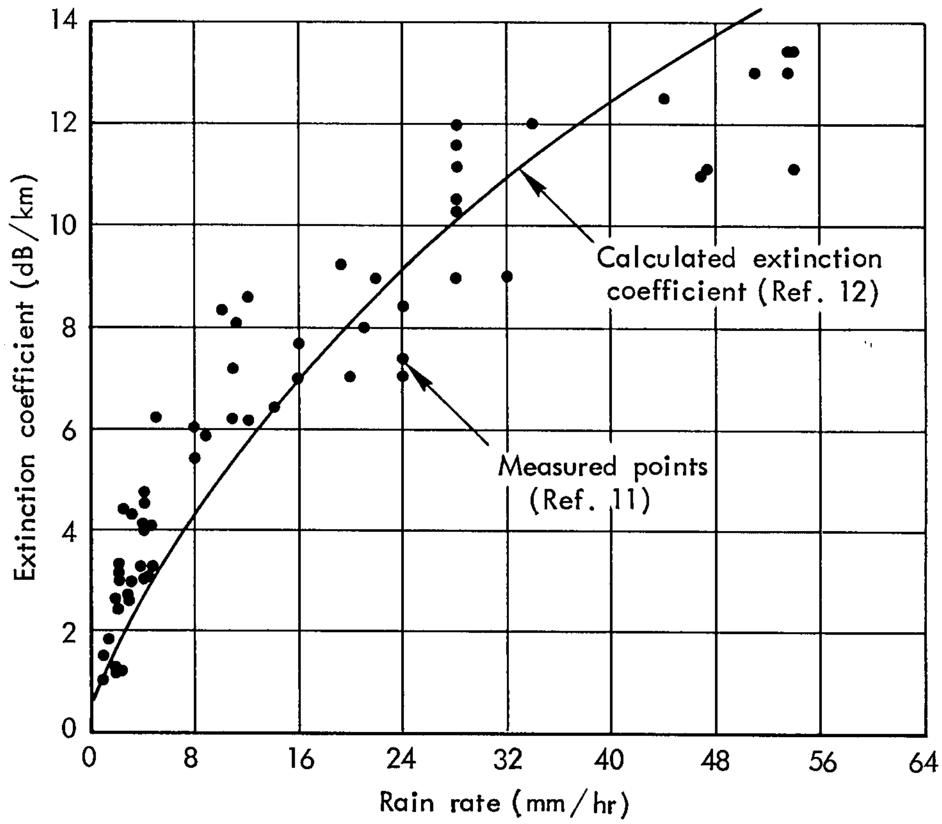
VISIBLE AND IR RADIATION ATTENUATION

According to measured values of the visible and IR extinction coefficients through rain,[11] any rain heavier than "medium," or rainfall rates greater than about 10 mm/hr, would render the visible/IR sensors almost useless through a 1.8-km path because only about 6.7 percent of visible/IR radiation passes through.[11,12] Along a 10-km path, the transmittance through a light rain with a rainfall rate of 2.5 mm/hr would be only 0.1 percent.

Figure 3 is a plot of measured values of rain extinction coefficient at 0.6328 μm versus rainfall rate. Reference 11 demonstrates that the measured values of rain extinction coefficient versus rain rate at 10.6 μm are about the same as those at 0.6328 μm. Figure 3 also presents calculated values of visible/IR extinction coefficients due to rain.[12] The values were obtained by performing numerical integration over Laws and Parsons rainfall data[13] together with the raindrop terminal velocity values quoted by Goldstein.[3] It can be observed from Fig. 3 that the calculated values compare favorably with the measured values.

RF RADIATION ATTENUATION

For millimeter wavelengths, according to Ref. 5, attenuation by rain is by far the most dominant form of atmospheric attenuation. Figure 4 presents the measured values of attenuation by rain as a function of frequency, for selected values of rainfall rate as quoted by Goldstein.[3] For comparison, Fig. 4 also presents some calculated values

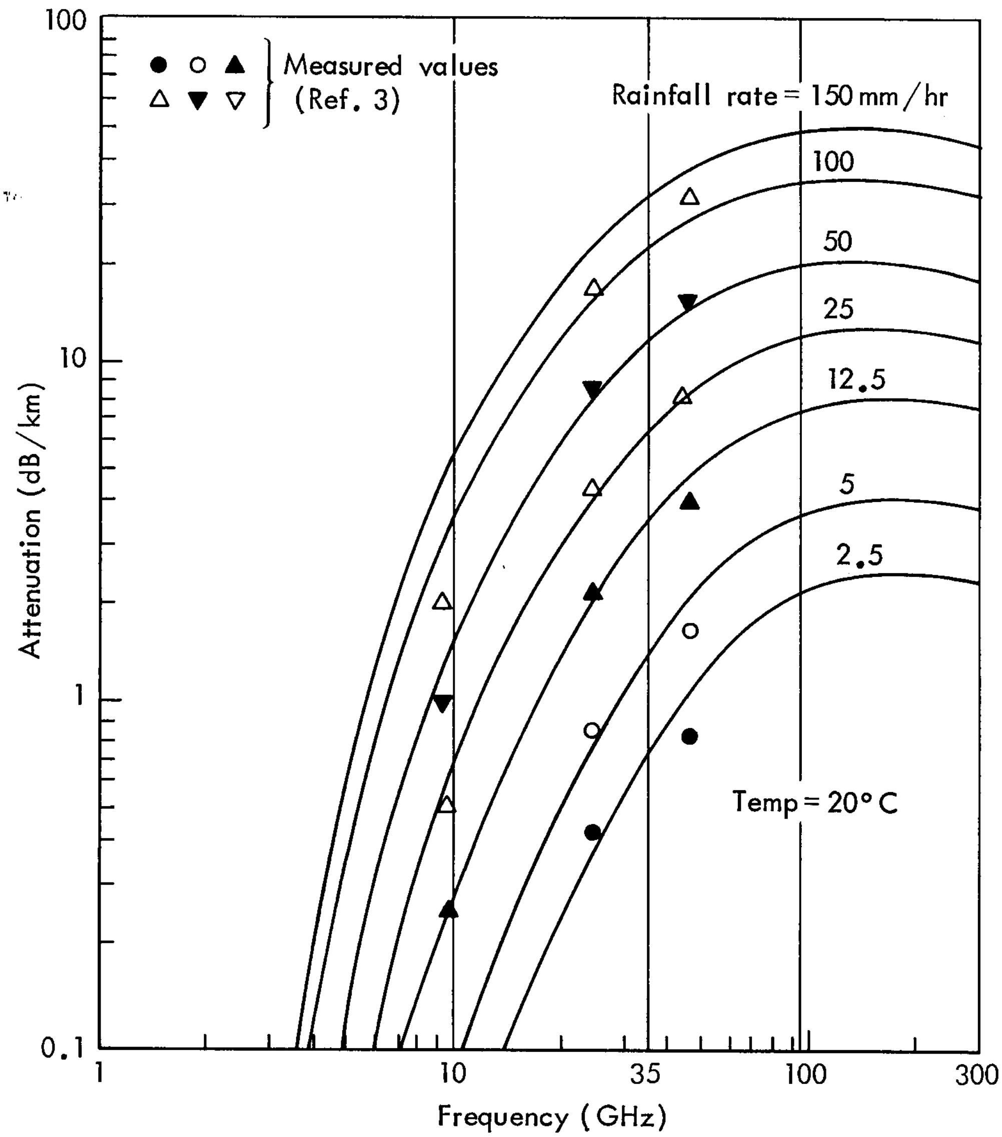


SOURCES: Refs. 11 and 12.

Fig. 3—Measured and calculated values of visible/IR extinction coefficient due to rain versus rain rate

of attenuation by rain under the same conditions as the measured values.[14] Attenuation by rain is severe for the windows at 35 and 95 GHz, almost the same as the attenuation at visible and IR frequencies; but it is almost negligible at 10 GHz, because even at a precipitation rate of 50 mm/hr, the attenuation is less than 2 dB/km.

The calculated values in Fig. 4 were based on values of the refractive index of water at 20°C. According to the Mie scattering theory,[9,10] the extinction coefficient depends not only on the ratio of water droplet radius to wavelength but also on the refractive index of water, which is temperature dependent. Thus, the values of attenuation are also temperature dependent. The correction factor $\phi(T)$ for other temperatures can be



Source: Ref. 3.

Fig. 4 — Logarithmic plot of calculated values of attenuation by rain in dB/km

calculated accordingly, and is listed in Table 1. For wavelengths of 1.25 cm and less, the effects of temperature are small, less than 20 percent over the entire range, and can usually be neglected.

Table 1

TEMPERATURE-CORRECTION FACTOR $\phi(T)$

Precipitation Rate (mm/hr)	λ,cm	Correction Factor $\phi(T)$				
		0°C	10°C	18°C	30°C	40°C
0.25	0.5	0.85	0.95	1.0	1.02	0.99
	1.25	0.95	1.0	1.0	0.90	0.81
	3.2	1.21	1.10	1.0	0.79	0.55
	10.0	2.01	1.40	1.0	0.70	0.59
2.5	0.5	0.87	0.95	1.0	1.03	1.01
	1.25	0.85	0.99	1.0	0.92	0.80
	3.2	0.82	1.01	1.0	0.82	0.64
	10.0	2.02	1.40	1.0	0.70	0.59
12.5	0.5	0.90	0.96	1.0	1.02	1.00
	1.25	0.83	0.96	1.0	0.93	0.81
	3.2	0.64	0.88	1.0	0.90	0.70
	10.0	2.03	1.40	1.0	0.70	0.59
50	0.5	0.94	0.98	1.0	1.01	1.00
	1.25	0.84	0.95	1.0	0.95	0.83
	3.2	0.62	0.87	1.0	0.99	0.81
	10.0	2.01	1.40	1.0	0.70	0.58
150	0.5	0.96	0.98	1.0	1.01	1.00
	1.25	0.86	0.96	1.0	0.97	0.87
	3.2	0.66	0.88	1.0	1.03	0.89
	10.0	2.00	1.40	1.0	0.70	0.58

SOURCE: Ref. 3.

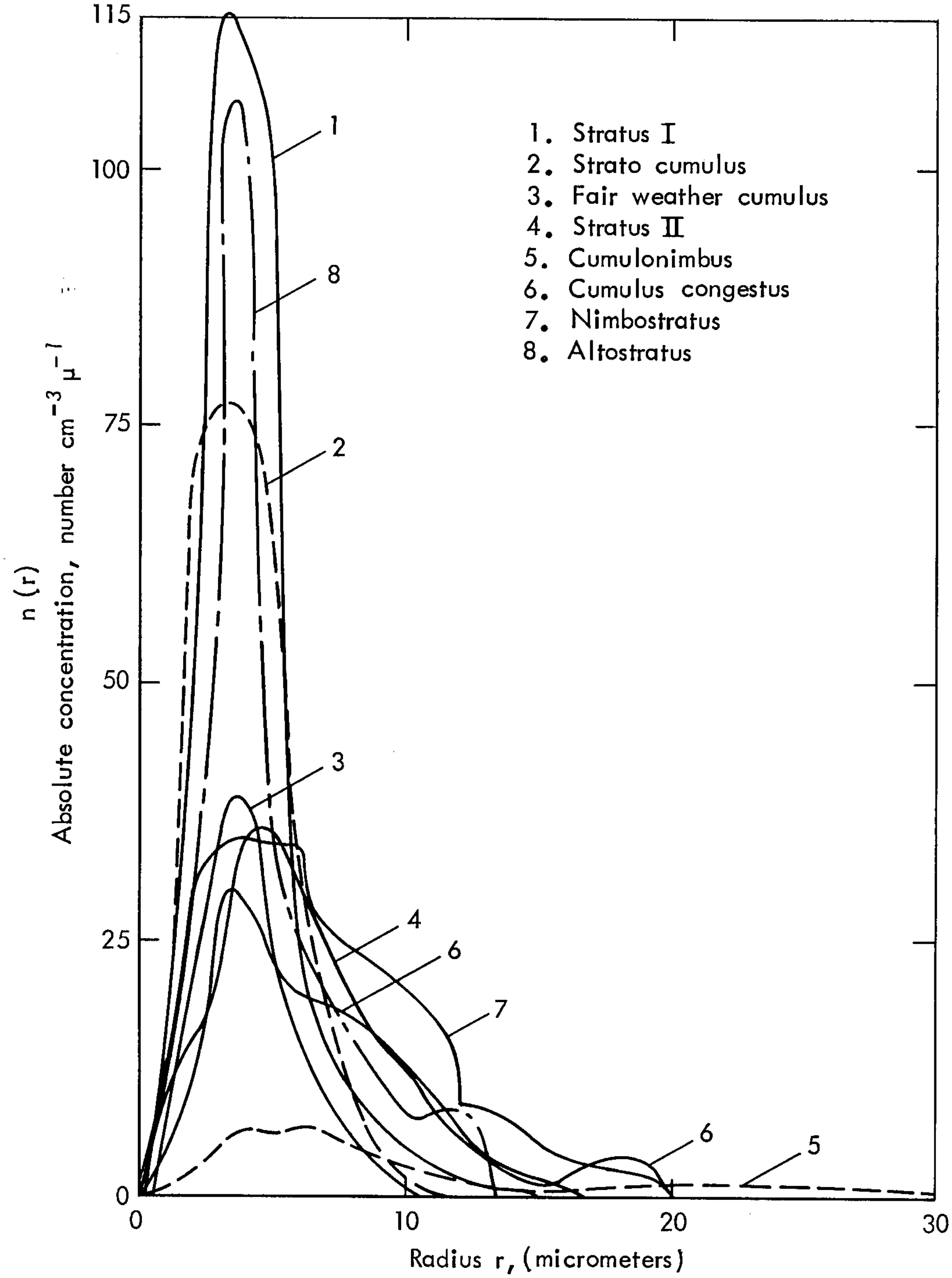
III. ATTENUATION BY CLOUDS

It is a well-known fact that clouds in general are opaque to visible and IR radiation,[9,15-21] but are partially transparent to RF radiation.[3,4,21,22] Again, attenuation of EM radiation by water droplets in the cloud is due to both absorption and scattering. According to Refs. 19 and 20, the radii of cloud water droplets range from a minimum of about 1 μm to a maximum of about 30 μm, and the maximum particle distribution occurs around 3 μm to 6 μm. Thus, it is expected that clouds will attenuate visible and IR radiation much more severely than they will RF radiation. Only water clouds are considered here.

VISIBLE AND IR RADIATION ATTENUATION

Very few data are available concerning transmission in clouds high in the atmosphere except those of Gates and Shaw,[18] who made some measurements of IR transmission through very thin clouds. Theoretical calculations using Mie scattering theory[9,15-21] show that attenuation of visible and IR radiation is almost wavelength independent, except that in certain cases attenuation is less at 10 μm than at shorter wavelengths. Furthermore, the calculated values of extinction coefficient are equal to or greater than 10 km^{-1} (conversion factor km^{-1} to dB/km: 4.343). According to Ref. 19, typical cloud thickness ranges from 1 km to 6 km. Therefore, it is obvious that clouds are opaque to visible and IR radiation because the vertical transmittance through such clouds would be less than 0.005 percent.

To show the relative wavelength dependence of the calculated extinction coefficients for visible and IR radiation, eight major cloud models were chosen for sample calculations;[20] their drop-size spectra are presented in Fig. 5. Figure 6 presents the calculated extinction coefficients as functions of wavelength for the eight cloud models as shown in Fig. 5. These calculations were made in Ref. 20 using the exact Mie theory. Using modified Deirmendjian distributions[11] to approximate the drop spectra of these eight cloud models, we also made calculations of these extinction coefficients as functions of wavelength. These values are also presented in Fig. 6 for comparison.



SOURCE: Ref. 20.

Fig. 5—Model cloud drop spectra

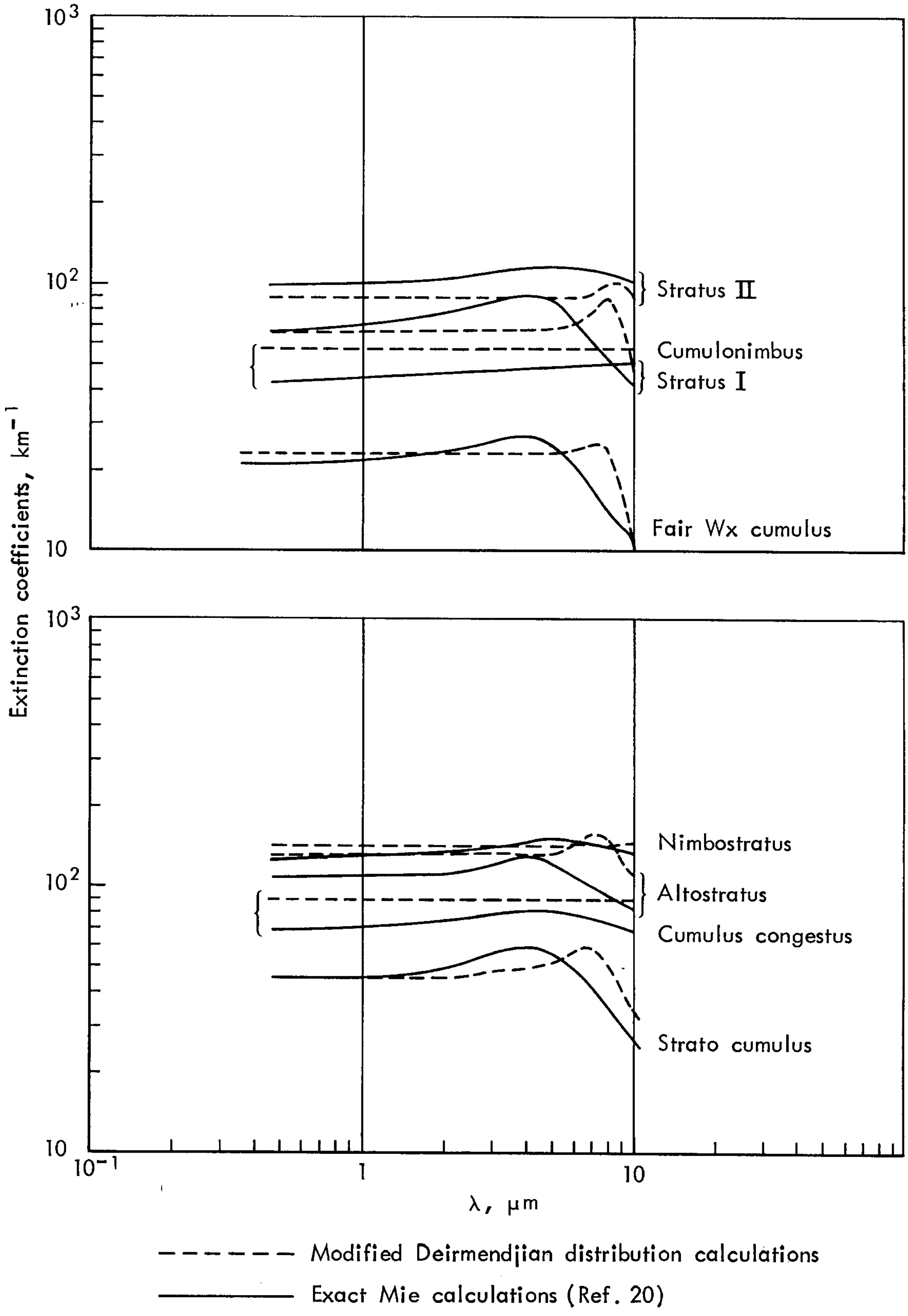


Fig. 6 — Calculated visible/IR extinction coefficient due to clouds

RF RADIATION ATTENUATION

In the RF range, the cloud water droplets are much smaller than the radiation wavelength; thus, it is expected from Mie theory that attenuation will be much less than that of visible/IR radiation. Usually, in this case, attenuation is expressed as a function of liquid water content, which in clouds generally ranges from 1 to 2.5 gm/m^3.[23]

It was found empirically that in the wavelength region from $\lambda = 0.5$ cm to $\lambda = 10$ cm, the attenuation coefficient by small water droplets, γ, can be written as

$$\gamma = \frac{0.438\ M}{\lambda^2}\ \mathrm{dB/km}\ , \tag{1}$$

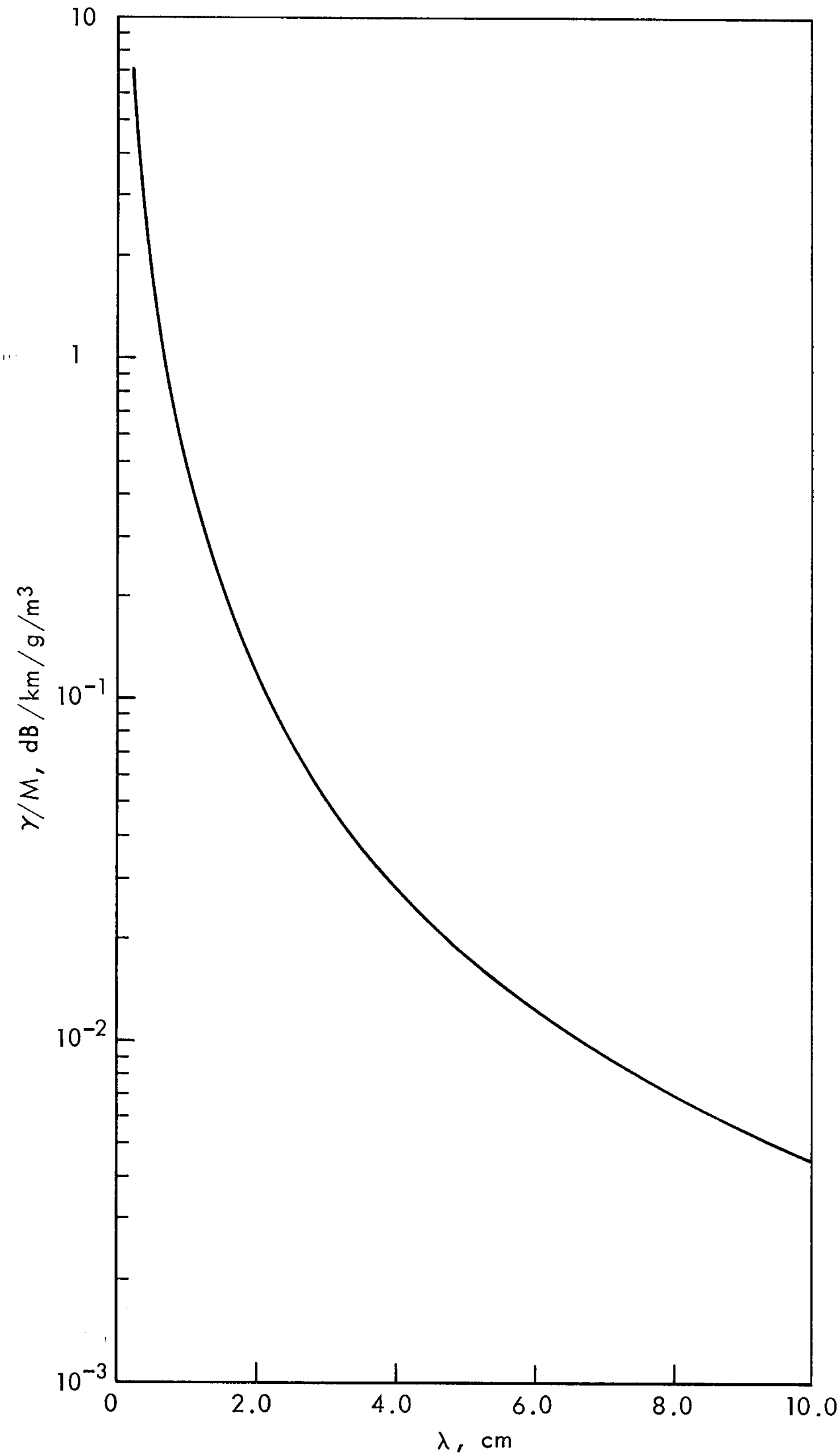
where M is the liquid water content in g/m^3, and λ is the wavelength in cm. Equation (1) is valid for both clouds and fog in which the water droplets are small, with diameters of the order of 10 μm to 50 μm. Figure 7 presents calculated attenuation coefficients by small droplets of water at 18°C versus wavelength. The correction of these attenuation coefficients for other temperatures is needed here again because of the temperature dependence of the index of refraction of water. Table 2 lists the correction factor $\phi(T)$ defined such that $\gamma(T) = \phi(T)\ \gamma(18°C)$.

Table 2

CORRECTION FACTOR $\phi(T)$ FOR $\gamma(T)$

	$\phi(T)$					
λ, cm	0°C	10°C	18°C	20°C	30°C	40°C
0.5	1.59	1.20	1.0	0.95	0.73	0.59
1.25	1.93	1.29	1.0	0.95	0.73	0.57
3.2	1.98	1.30	1.0	0.95	0.70	0.56
10	2.0	1.25	1.0	0.95	0.63	0.59

SOURCE: Ref. 3.



SOURCE: Ref. 3.

Fig. 7—Calculated attenuation coefficients by small droplets of water (e.g., clouds or fog) at 18°C

It can be observed from Fig. 7 that the attenuation of RF radiation by clouds is much less than that of visible and IR radiation. In fact, for any sensor whose wavelength is greater than 0.5 cm, the attenuation by clouds is only about 1 dB for any 1-km-thick cloud with 1 g/m^3 liquid water content.

IV. ATTENUATION BY FOG

Fog is very similar to clouds except that fog contacts the ground and clouds do not. Therefore, EM radiation attenuation by fog is expected to be the same as that by clouds. Fog is usually described in terms of visibility because reduced visibility is the characteristic feature of fog. Visibility in general is a very vague term, however. To make it more concrete, we define visibility as the meteorological range used by Middleton:(24)

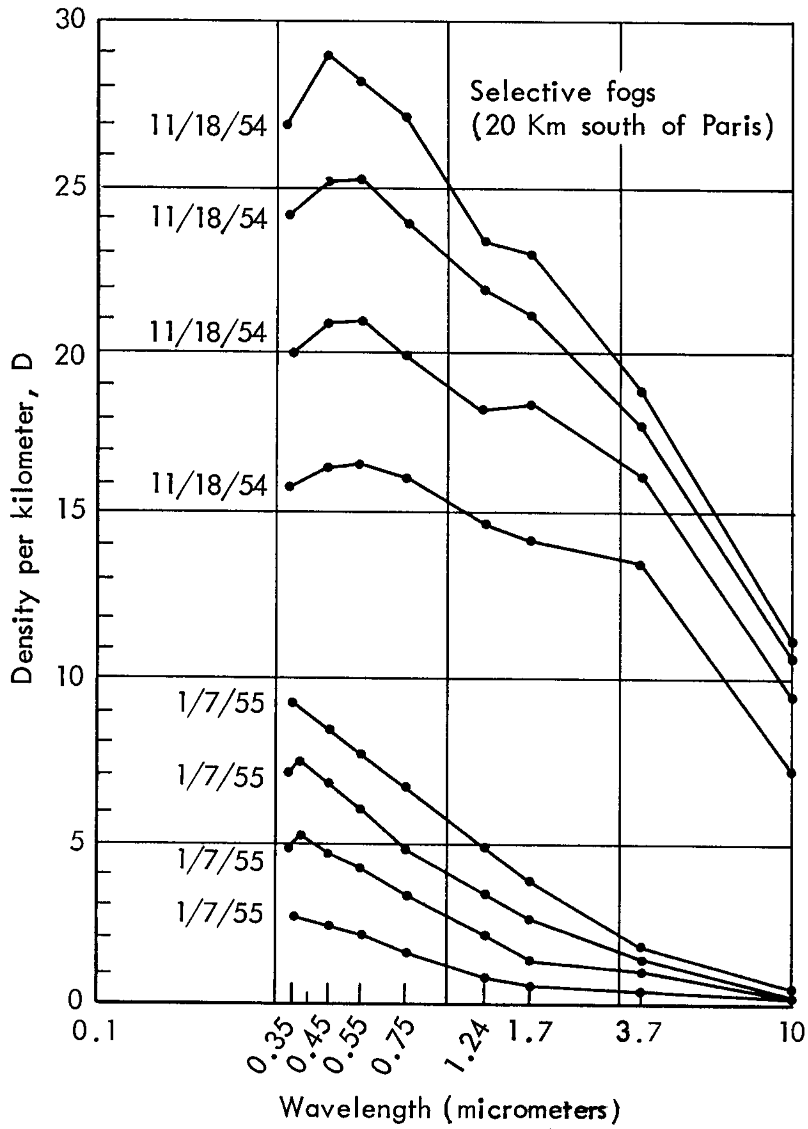
$$V_2 = \frac{3.92}{\gamma_{op}} , \tag{2}$$

where γ_{op} is the extinction coefficient at optical frequency, e.g., about 0.5 μm. According to Middleton, fog is defined such that the visibility V_2 is less than 1 km (0.62 mi); for V_2 greater than 1 km, the atmosphere is defined as hazy.

VISIBLE AND IR RADIATION ATTENUATION

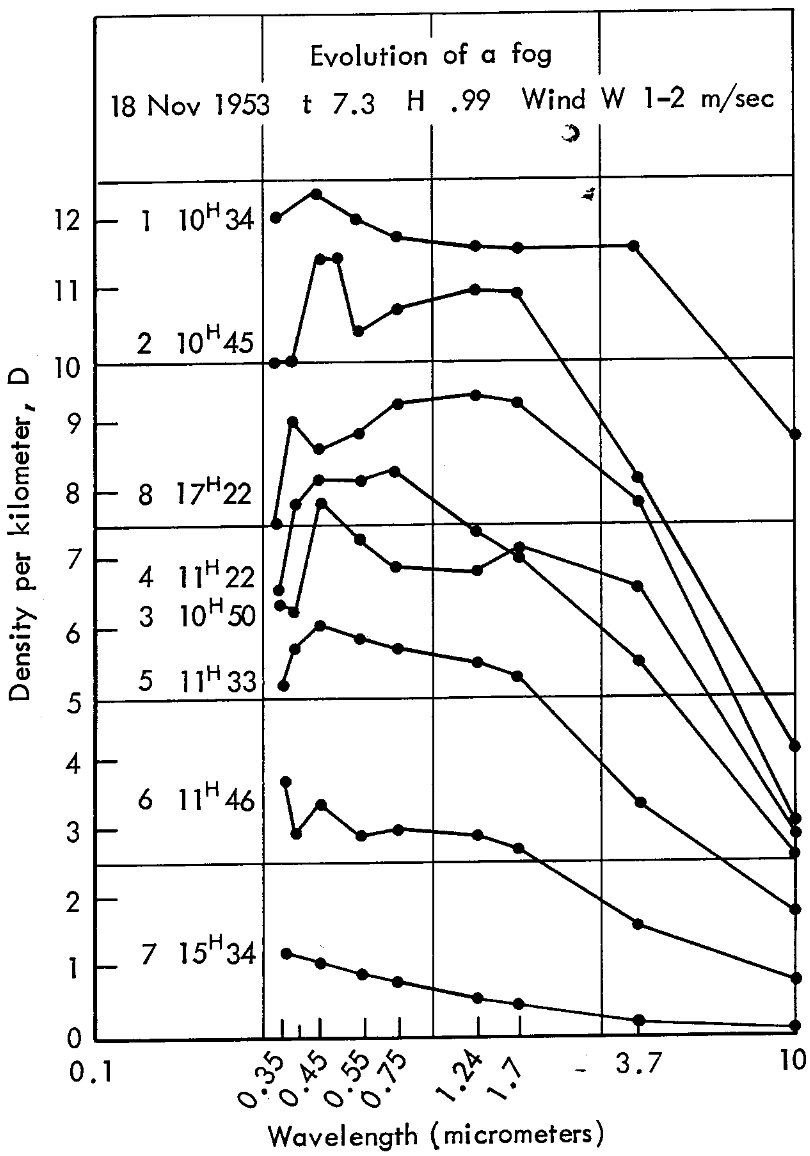
Arnulf, et al.(25) performed a series of measurements of transmission through haze and fog in the spectral region 0.35 μm to 10 μm. The measurements were carried out in the following atmospheres: hazes ($V_2 \geq 1$ km); small-drop fogs ($\gamma_o \leq 25$ km^{-1}); selective fogs ($\gamma_o \leq 70$ km^{-1}); evolving fogs (those with changing distributions of drop-diameters); non-evolving, slightly selective fogs (constant shape of the extinction coefficient versus wavelength curve); and artificial smokes. They found that transmission through haze increases markedly with increasing wavelength, from the visible to 10 μm, but this is not true for fogs. In small-drop, selective, and evolving fogs, some increase in transmission was observed with increasing wavelength, from the visible to 10 μm.

Figures 8, 9, and 10 present the measured attenuation of visible/IR radiation as a function of wavelength for various forms of fogs. It can be observed from these figures that the attenuation of visible/IR radiation by fogs is very complex, and is all the more so because fogs change



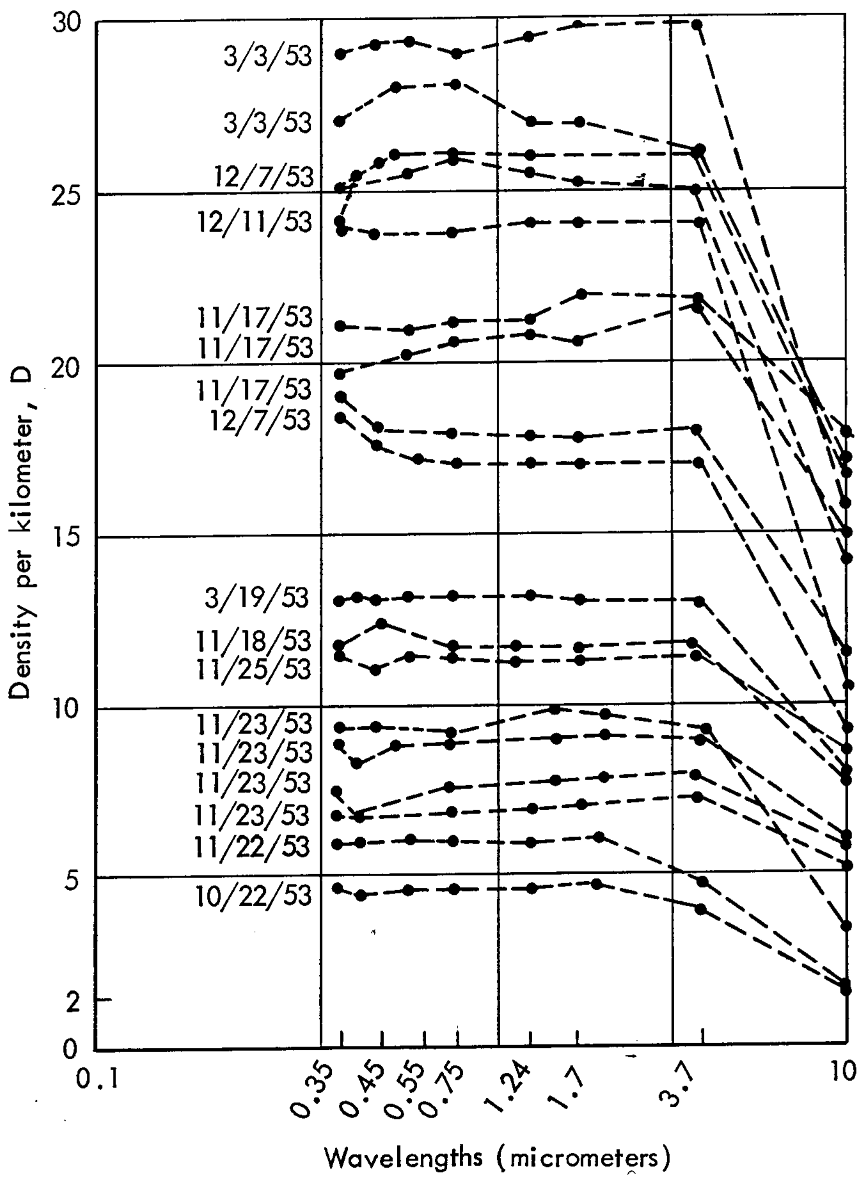
SOURCE: Ref. 25.

Fig. 8—Absorption by small-drop fogs and by selective fogs



SOURCE: Ref. 25.

Fig. 9—Absorption by an evolving fog



SOURCE: Ref. 25.

Fig. 10—Absorption by non-evolving fogs

their characteristics with time almost constantly. But it can be concluded in general that fogs are opaque to visible/IR radiation except for small-drop fogs, where most of the IR radiation may get through (see the lower curves of Fig. 8). The unit D, density per km, can be related to the extinction coefficient γ through the following expression:

$$\gamma = 2.3 \text{ D} . \tag{3}$$

The values of visibility for these curves can be obtained very easily by using Eq. (2).

It can be observed from these absorption measurements by fogs that it is very difficult to calculate these values theoretically. Eldridge[26] developed a so-called synthetic droplet distribution method to calculate spectral attenuation through haze and fogs. In essence, this method uses successive synthetic droplet distributions to calculate spectral attenuations and then compare them with those measured experimentally. When the two spectral attenuations are similar, the resulting synthetic distribution is considered to be the "best fit." The attenuations thus calculated compare favorably with those measured in Ref. 25, but the practical utility of such calculation is doubtful since it requires measured values for comparison in the calculation procedure.

RF RADIATION ATTENUATION

Since fogs resemble clouds, the values of γ/m presented in Fig. 7 can be used here. But the maximum liquid water content of fog is about 1 g/m^3, with the possible exception of heavy sea fogs.[3] M is usually less than 1. Visibility can be related to attenuation in coastal fogs, through the following empirical relationship:[3]

$$V_2 = 59.4M^{-0.7} , \tag{4}$$

where V_2 is in meters, and M is in g/m^3. For lack of more definite information on M, such a relationship as Eq. (4) may prove very helpful.

For inland fogs, the empirical relationship between V_2 and M can be represented by the following expression:[26]

$$V_2 = 24M^{-0.65} , \tag{4a}$$

where V_2 is in meters and M is in g/m^3. Equations (4) and (4a) are plotted in Fig. 11. Table 3 presents some values of attenuation at three different wavelengths in a coastal fog at 0°C temperature.

Table 3

ATTENUATION CAUSED BY FOG

(Temperature = 0°C)

Visibility in Meters	Attenuation in dB/km					
	λ = 1.25 cm		λ = 3.2 cm		λ = 10 cm	
	(a)	(b)	(a)	(b)	(a)	(b)
30	1.25	1.42	0.2	0.235	0.02	0.0238
90	0.25	0.3	0.04	0.0495	0.004	0.005
300	0.045	0.053	0.007	0.00875	0.001	0.000885

[a] From Ref. 4.
[b] From Fig. 7 and Eq. (4).

Note again that attenuation varies with temperatures. It also decreases with both increasing visibility and increasing wavelength. The decrease with wavelength is dramatic: an order of magnitude less at 10 cm than at 3.2 cm, and nearly another order of magnitude between 3.2 cm and 1.25 cm. Using the values of γ/M in Fig. 7 and Eqs. (4) and (4a), we can calculate the values of attenuation due to both coastal and inland fogs as functions of frequency. These values are presented in Fig. 12.

It can be observed from Fig. 12 that, at a visibility of 30 meters, a sensor at 0.32 cm will suffer a transmission loss of almost 10 dB/km by coastal fog. A sensor at 0.85 cm will suffer 2 dB/km loss, whereas at 3.0 cm it will suffer only 0.13 dB/km loss.

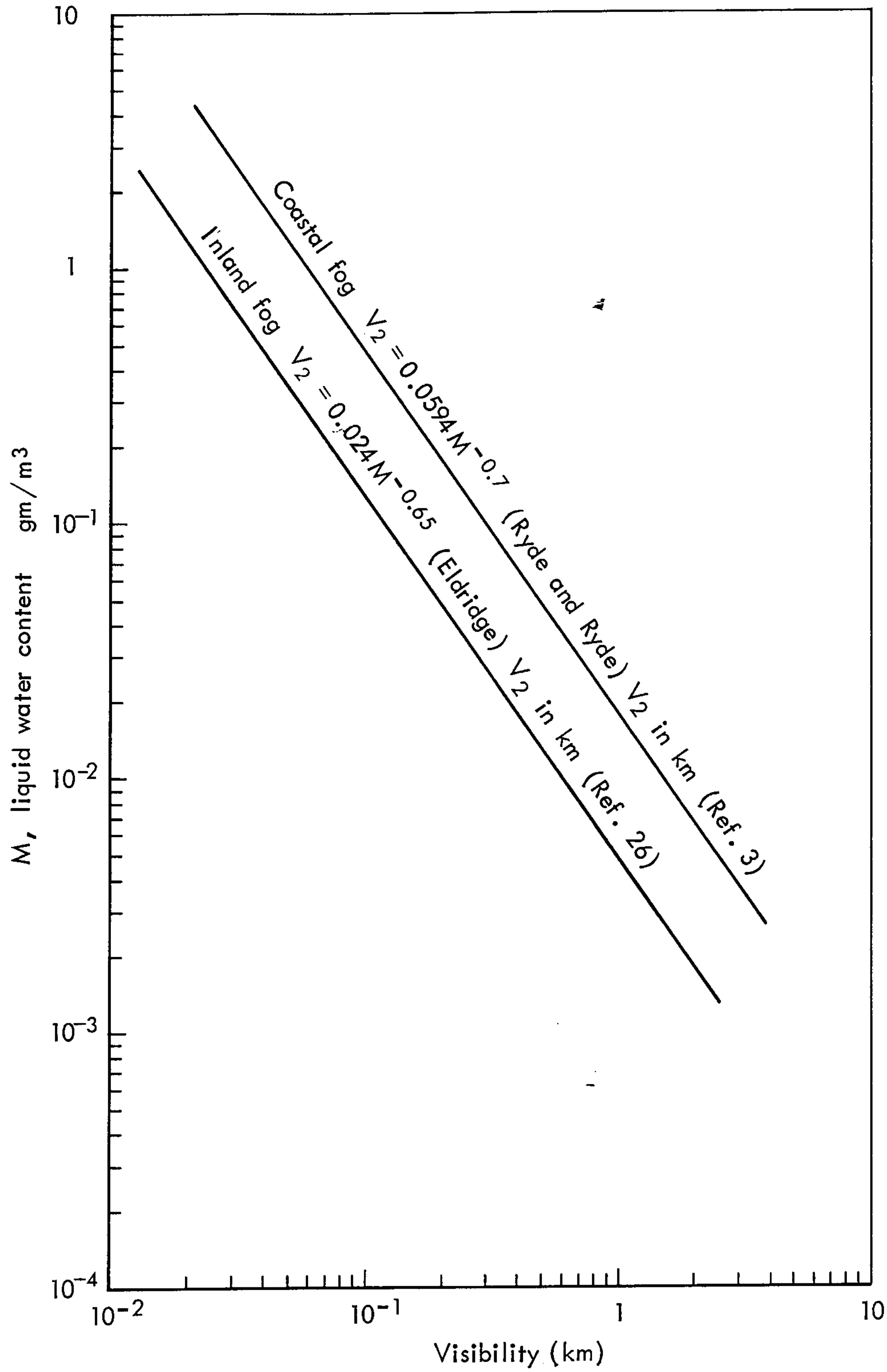


Fig. 11—Correlation of visibility in fog to liquid water content

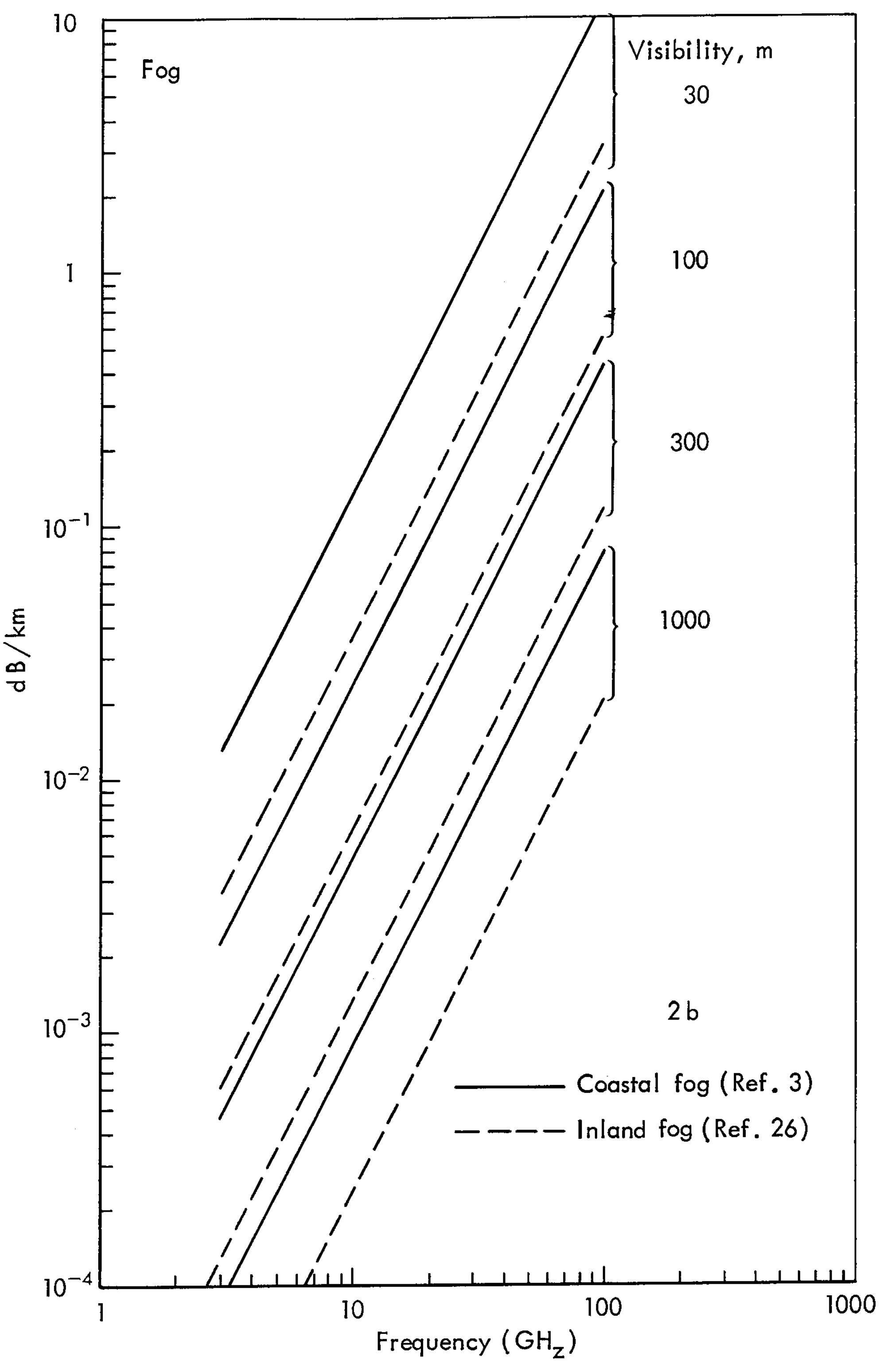


Fig. 12—Calculated attenuation by fog at 18° C

V. ATTENUATION BY HAZE

The term "haze" refers to small particles dispersed throughout the atmospheric aerosol. Haze particles consist of tiny salt crystals, exceedingly fine dust, or products of combustion, with radii varying up to 0.5 μm. In regions of high humidity, moisture can condense on these particles and may form large drops; the particle is then said to act as a condensation nucleus. By far the most important nuclei are salt particles, since they are naturally hygroscopic. Fog is formed when the condensation nuclei grow into water droplets or ice crystals with radii exceeding 1 μm.

According to Middleton,[24] the atmosphere is hazy if the meteorological range V_2 defined by Eq. (2) is greater than or equal to 0.8 km (i.e., $\sigma_o \leq 4\ km^{-1}$). His definition was based on experimental findings that the relative extinction coefficients for blue, green, and red merged into one value at the mean extinction coefficient of approximately 4 km^{-1}.

Attenuation due to haze is very complex because of the diversity of the particles in a hazy atmosphere, attenuation being dependent on the nature of the particles, e.g., their refractive index and whether they are hygroscopic. But haze is transparent to RF radiation and, in general, attenuates visible radiation more than it does IR radiation because of the smallness of the haze particles.[9,10,15,17,24-31]

Usually, only scattering is considered in studies of attenuation of visible and IR radiation due to haze.[10,24,27,28,30] But for IR wavelengths, aerosol liquid water absorption can be high under conditions of high relative humidity (R.H.).[31,32] Calculated results show that at 85 percent R.H., the percentage of the extinction coefficient due to absorption can be as high as 40 percent at certain IR wavelengths.[31] In general, however, the absorption is less than 20 percent in the 3 to 5 μm region, and about 20 percent in the 8 to 11 μm region. Thus, scattering is still the dominant attenuation mechanism.

For practical purposes, it is much more desirable to express the scattering extinction coefficient by only a few parameters, such as the following:[10]

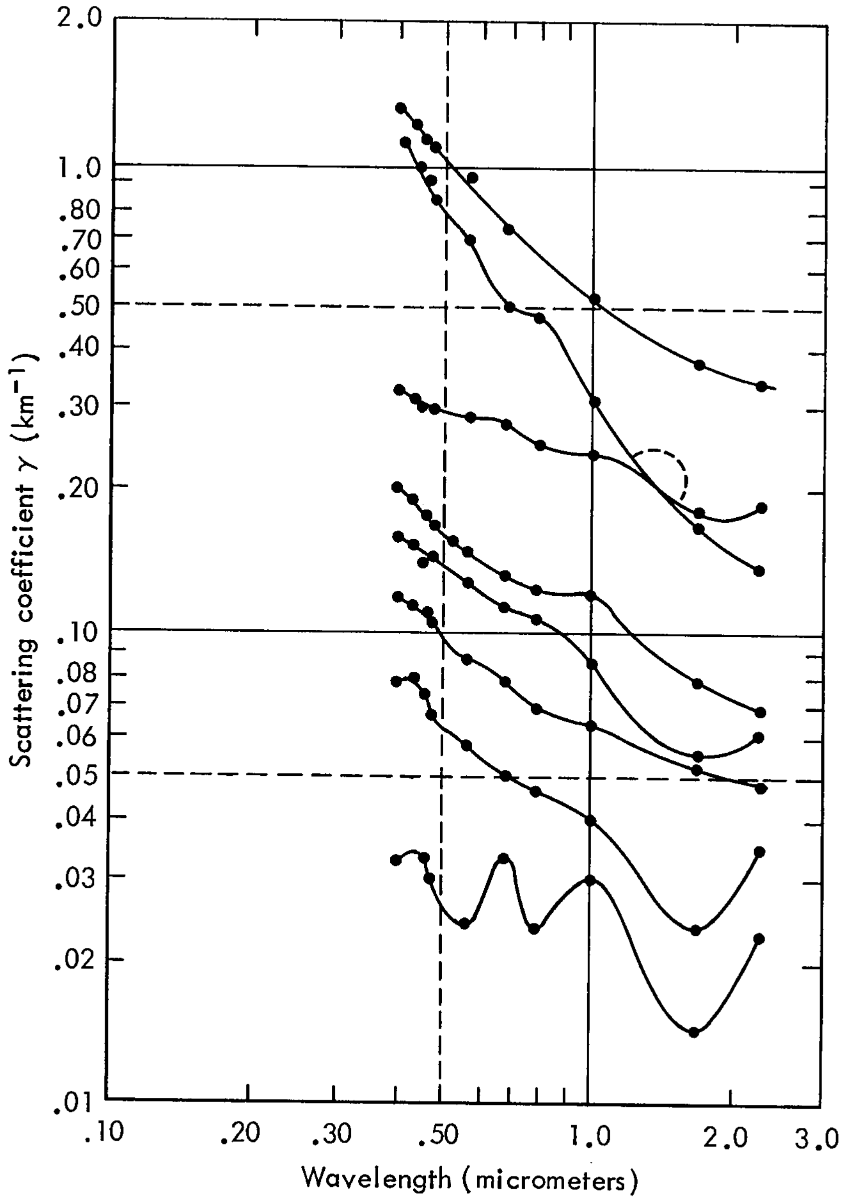
$$\gamma_{scat} \sim \lambda^{-\alpha} , \qquad (5)$$

where $\alpha = 4$ is for Rayleigh scattering (e.g., for particles much smaller than the radiation wavelengths), and $\alpha = 0$ is for neutral extinction (e.g., for particles much larger than the radiation wavelengths). In general, the empirical values of α for atmospheric haze range from 1 to 2.[10] It is also suggested in Ref. 24 that the value of α for a haze with a visual range of 30 km is 1.3, and increases with the visual range until the Rayleigh limit ($\alpha = 4$) is reached. Basing his conclusion on the published atmospheric transmission data of Gebbie et al.,[33] Gibbons[27] suggests that $\alpha = 0.7$ in the wavelength range from 0.61 to 11.48 μm regardless of the meteorological range.

Measured values of γ_{scat} as a function of λ for atmospheric haze suggest that the value of α varies from about 0.4 to 1.4.[34] Thus, no single value of α is adequate for describing atmospheric haze scattering with respect to radiation wavelength. Figure 13 presents the experimental curves of atmospheric haze scattering coefficients as a function of wavelength.[28] From the measured values of γ_{scat} versus λ in Refs. 28 and 34, one can plot α versus the meteorological range V_2; this relationship is presented in Fig. 14. As can be observed from Fig. 14, the data are so widely spread that there is no simple empirical relationship between α and V_2. In general, the dependence of γ_{scat} on wavelength for atmospheric haze is more pronounced for heavy haze than for light haze.

Figure 15 illustrates the total attenuation of visible and IR radiation by atmospheric haze as a function of wavelength at $V_2 = 0.923$ km (0.58 mi).[25] It reaches a maximum between 0.4 μm and 0.55 μm, and decreases rapidly with increasing wavelength. The attenuation at 10 μm becomes 10 to 100 times smaller than at 0.5 μm. It can be also observed that the 8 to 12 μm band is preferable to the 3 to 5 μm band for IR systems operating in this kind of hazy weather.

In general, it can be concluded that IR sensors penetrate farther through haze than visible optical sensors can.



SOURCE: Ref. 28.

Fig. 13 — Experimental curves of atmospheric haze scattering coefficients as a function of wavelength

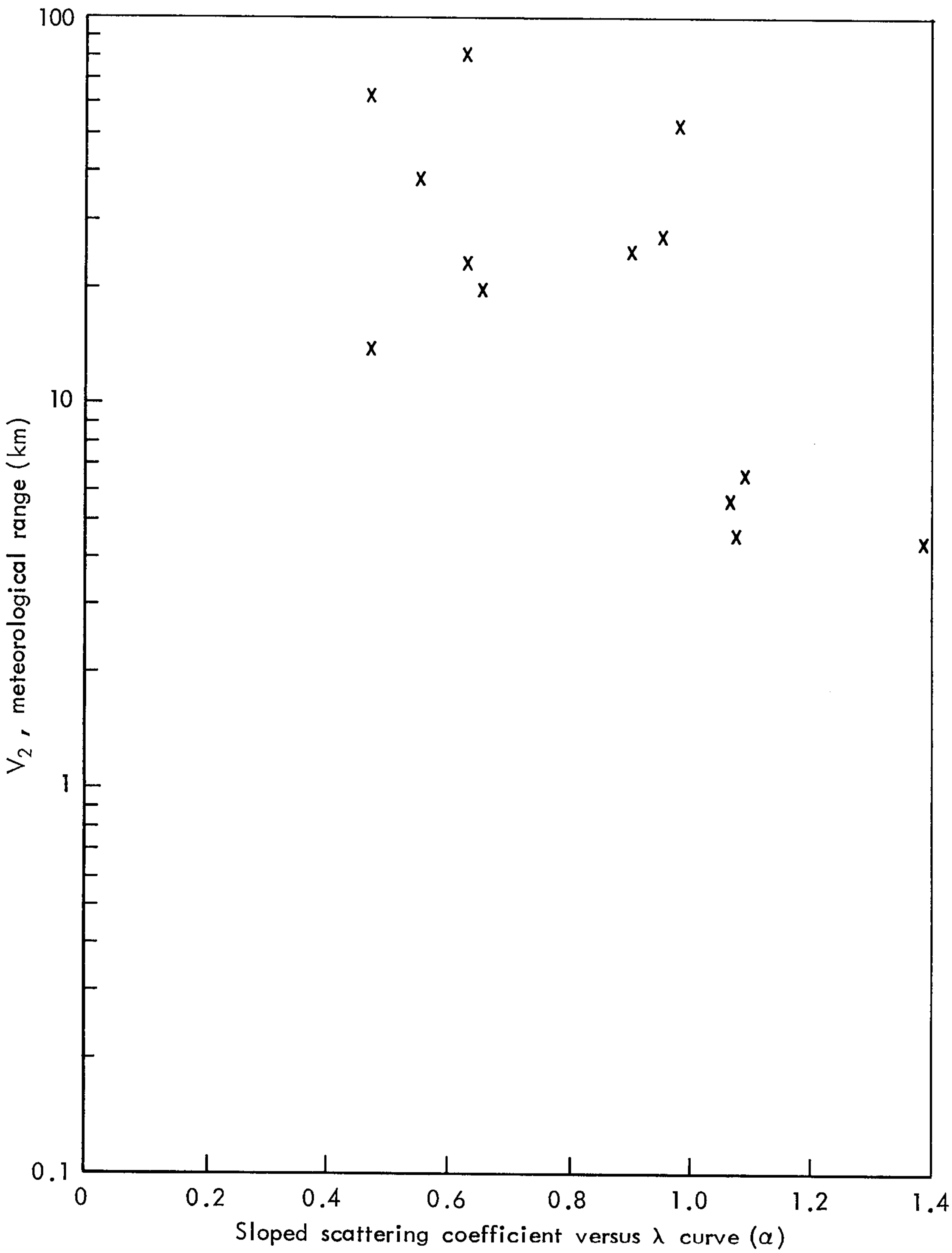
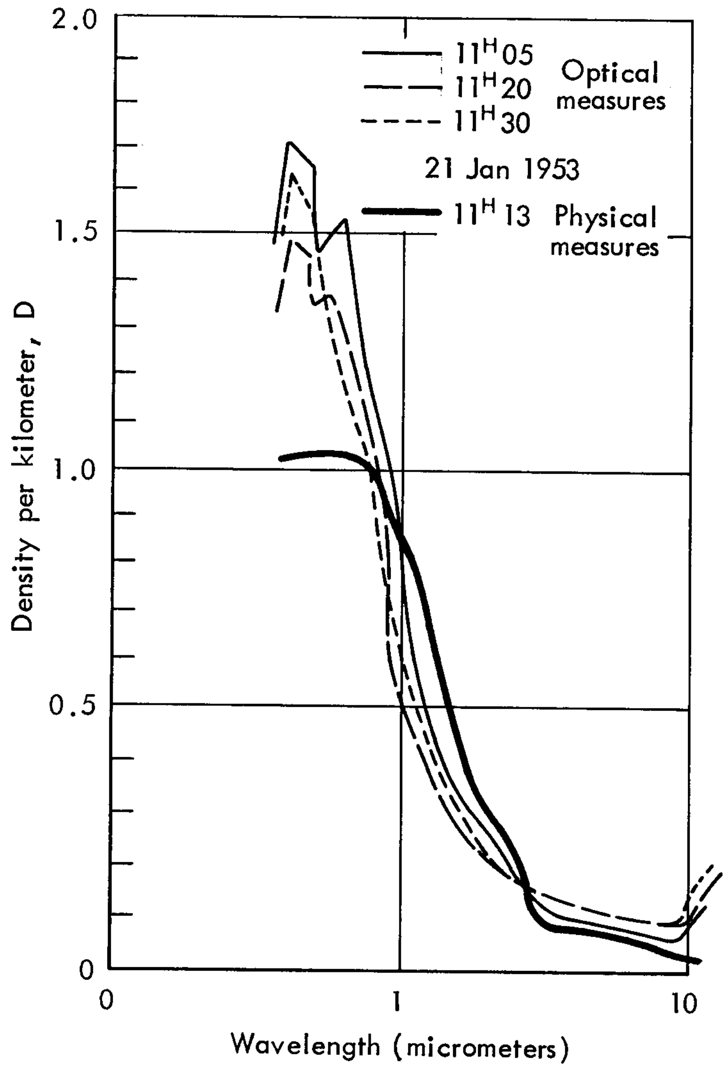


Fig. 14 — Experimental values of slope of scattering coefficient curves



SOURCE: Ref. 25.

Fig. 15—Attenuation by haze

REFERENCES

1. Hudson, R. D., Jr., *Infrared System Engineering*, John Wiley and Sons, New York, 1969.

2. Meyer, J. W., "Radar Astronomy at Millimeter and Submillimeter Wavelengths," *Proc. IEEE*, Vol. 54, No. 5, April 1966, pp. 484-492.

3. Goldstein, H., "Attenuation by Condensed Water," in D. E. Kerr (ed.), *Propagation of Short Radio Waves*, McGraw-Hill Book Co., Inc., New York, 1951, p. 671.

4. Bradford, R. B., E. J. Dutton, and B. D. Warner, "Weather Effects on Radio," in M. I. Skolnik (ed.), *Radar Handbook*, McGraw-Hill Book Co., Inc., New York, 1970.

5. Dudzinsky, S. J., Jr., *Atmospheric Effects on Terrestrial Millimeter-Wave Communications*, The Rand Corporation, R-1335-ARPA, March 1974.

6. McClatchey, K. A., et al., *Optical Properties of the Atmosphere*, rev. ed., Air Force Cambridge Research Laboratories, Report 71-0279, 1971.

7. Jamieson, J. A., et al., *Infrared Physics and Engineering*, McGraw-Hill Book Co., Inc., New York, 1963.

8. Wolfe, W. L. (ed.), *Handbook of Military Infrared Technology*, Office of Naval Research, Dept. of the Navy, Washington, D.C., 1965.

9. Deirmendjian, D., *Electromagnetic Scattering on Spherical Polydispersion*, American Elsevier Publishing Company, New York, 1969.

10. Van de Hulst, H. G., *Light Scattering by Small Particles*, John Wiley and Sons, New York, 1957.

11. Rensch, D. G., and R. K. Long, "Comparative Studies of Extinction and Backscattering by Aerosols, Fog, and Rain at 10.6μ and 0.63μ," *Appl. Opt.*, Vol. 9, No. 7, July 1970, pp. 1563-1573.

12. Chen, C. C., *A Correction for Middleton's Visible- and Infrared-Radiation Extinction Coefficients Due to Rain*, The Rand Corporation, R-1523-PR, August 1974.

13. Laws, J. O., and D. A. Parsons, "The Relation of Raindrop Size to Intensity," *Trans. Am. Geophysical Union*, Vol. 24, 1943, pp. 452-460.

14. Selzer, D. E., "Computed Transmission Through Rain at Microwave and Visible Frequencies," *Bell System Tech. J.*, Vol. 49, No. 8, October 1970, pp. 1873-1892.

15. Deirmendjian, D., "Atmospheric Extinction of Infrared Radiation," *Quart. J. Roy. Meteor. Soc.*, Vol. 86, No. 369, July 1960, pp. 371-381.

16. Deirmendjian, D., *Complete Microwave Scattering and Extinction Properties of Polydispersed Cloud and Rain Elements*, The Rand Corporation, R-422-PR, December 1963.

17. Deirmendjian, D., "Scattering and Polarization Properties of Water Clouds and Hazes," *Appl. Optics*, Vol. 3, 1964, pp. 187-196.

18. Gates, D. M., and C. C. Shaw, "Infrared Transmission of Clouds," *J. Opt. Soc. Am.*, Vol. 50, 1960, pp. 876-882.

19. Robinson, S. R., *Transmission and Scattering of IR Radiation by Clouds*, Rept. DMP 1665/1, Part 1, EMI Electronics, Ltd.

20. Carrier, L. W., G. A. Cato, and K. J. Von Essen, "The Backscattering and Extinction of Visible and Infrared Radiation by Selected Major Cloud Models," *Appl. Optics*, Vol. 6, 1967, pp. 1209-1216.

21. Deirmendjian, D., "Extinction of Submillimeter Waves by Clouds and Rain," presented at the International Conference on Submillimeter Waves and their Applications, Atlanta, Georgia, June 5-7, 1974.

22. Gunn, K.L.S., and T.W.R. East, "The Microwave Properties of Precipitation Particles," *Quart. J. Roy. Meteor. Soc.*, Vol. 80, 1964, pp. 522-545.

23. Donaldson, R. J., Jr., "The Measurement of Cloud Liquid-Water Content by Radar," *J. Meteor.*, Vol. 12, 1958, pp. 238-244.

24. Middleton, W.E.K., *Vision Through the Atmosphere*, University of Toronto Press, 1952.

25. Arnulf, A., et al., "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns," *J. Opt. Soc. Am.*, Vol. 47, 1957, pp. 491-498.

26. Eldridge, R. G., "Haze and Fog Aerosol Distributions," *J. Atmos. Sci.*, Vol. 23, 1966, pp. 608-613.

27. Gibbons, M. G., "Wavelength Dependence of the Scattering Coefficient for Infrared Radiation in Natural Haze," *J. Opt. Soc. Am.*, Vol. 48, 1958, pp. 172-176.

28. Curcio, J. A., "Evaluation of Atmospheric Aerosol Particle Size Distribution from Scattering Measurements in the Visible and Infrared," *J. Opt. Soc. Am.*, Vol. 51, 1961, pp. 548-551.

29. Eldridge, R. G., "A Comparison of Computed and Experimental Transmissions Through Haze," *Appl. Opt.*, Vol. 6, 1967, pp. 929-933.

30. Barnhardt, E. A., and J. L. Streete, "A Method for Predicting Atmospheric Aerosol Scattering Coefficients in the Infrared," *Appl. Opt.*, Vol. 9, 1970, pp. 1337-1344.

31. Hodges, J. A., "Aerosol Extinction Contribution to Atmospheric Attenuation in Infrared Wavelengths," *Appl. Opt.*, Vol. 11, 1972, pp. 2304-2310.

32. Carlon, H. R., "Infrared Emission by Fine Water Aerosols and Fogs," *Appl. Opt.*, Vol. 9, 1970, pp. 2000-2006.

33. Gebbie, H. A., et al., "Atmospheric Transmission in the 1 to 14μ Region," *Proc. Roy. Soc.*, Vol. A206, 1951, p. 87.

34. Knestrick, G. L., T. H. Cosdon, and J. A. Curcio, "Atmospheric Scattering Coefficients in the Visible and Infrared Regions," *J. Opt. Soc. Am.*, Vol. 52, 1962, pp. 1010-1016.