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REVIEW OF CALCULATIONS OF EXTINCTION FOR VISIBLE AND INFRARED WAVELENGTHS IN RAIN

August 1983

By

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Many theoretical and experimental investigations have been done to determine the influence of rain on visible and infrared radiation at single wavelengths under certain meteorological conditions. These studies are summarized in this report and typical results for the extinction of visible and infrared radiation by rain are shown. Basic equations and experimental data from these studies were used to derive the extinction coefficients for selected visible and infrared wavelengths. Theory has predicted and measurements have shown that visible and infrared light are both attenuated by nearly the same amount

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20. ABSTRACT (cont)

during rain. Some measurements showed that extinction in heavy r 'nfall was an order of magnitude less than measured extinction in heavy fog for the 10.6μm wavelength.

-micrometer

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INTRODUCTION

Propagation through the atmosphere in the visible and infrared wavelengths is limited by various atmospheric phenomena such as fog and rain. Rayleigh[1] showed that an atmosphere containing only the permanent gases scatters light in proportion to the inverse fourth power of the wavelength. If the atmosphere were a mixture of only the pure dry gases, the visual range would be more than 350 km. Attenuation by clear air results from two factors, absorption by nonaqueous gases and Rayleigh scattering.

Absorption by nonaqueous gases is negligible in the visible region and, except for a weak band (CO_2) at 10.6µm, also can be ignored for the commonly used infrared wavelengths of 1.06µm, 2.3µm, and 3.8µm. The well-known atmospheric windows are from 0.25µm to 2µm, 3µm to 5µm, and 8µm to 12µm. Water vapor has a weak absorption band near 1.35 cm and stronger bands near 0.2 cm.

Atmospheric scattering is the process by which incident radiation is deflected by small particles suspended in the atmosphere. This type of atmospheric scattering is governed by the size or diameter (d) of the particle in relation to the wavelength (λ) of incident energy. Rayleigh scattering occurs when $d/\lambda < 1/10$. This type of Rayleigh scattering is effective only for short wavelengths since it is proportional to λ^{-4}. For d/λ ratios greater than 1 but less than 10, Mie scattering occurs, and for ratios greater than 10, ray reflection and geometric optical effects begin to occur. Mie scattering is generally concentrated in the forward direction with a minimum near 100° (as measured from the direction of the incident ray) and a secondary peak in the backward direction.

Rayleigh scattering is described by McCartney,[2] and the attenuation due to scattering is given by

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

where N is the molecular concentration (2.67×10^{19} cm^{-3} at sea level), n is the index of refraction of pure air, and λ is the wavelength (µm) of the radiation. Table 1 gives the Rayleigh scattering coefficient as a function of a few wavelengths.

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[1](Lord) Rayleigh, 1899, "On the Transmission of Light Through an Atmosphere Containing Small Particles in Suspension," Phil Mag, 47:375-384

[2]E. J. McCartney, 1966, Scattering - The Interaction of Light and Matter, Sperry Report AB-1272-0057, Sperry Rand Corporation, Boston, MA

TABLE 1. RAYLEIGH SCATTERING COEFFICIENTS AS A FUNCTION OF WAVELENGTH*

λ (μm)	0.55	1.06	2.3	3.8	10.6
σ (km^{-1})	1.2×10^{-2}	8.2×10^{-4}	3.7×10^{-5}	5.0×10^{-6}	8×10^{-8}

*A. R. Downs, 1976, A Review of Atmospheric Transmission Information in the Optical and Microwave Spectral Regions, BRL Report 2710, Aberdeen Proving Ground, MD.

Mie scattering was developed[3] from a consideration of the electromagnetic waves of light inside and outside a small sphere. Mie derived differential equations that may be solved to yield the electric and magnetic vectors at any point in space in polar coordinates. Mie also showed that the illuminance at this point is proportional to the average vector product of these vectors. Furthermore, if the particle is illuminated with natural light, the illuminance in a direction making an angle ϕ with the incident light, and thus the intensity due to scattering, can be expressed as the sum of two squares, each being an infinite series in ϕ.

Many theoretical and experimental investigations have been made to determine the influence of rain and certain other meteorological conditions on visible and infrared radiation at single wavelengths. This report summarizes these studies and presents typical results for the extinction of visible and infrared radiation by rain.

OPTICAL EXTINCTION BY CLOUDS AND RAINFALL

The visual range (V) of objects seen against the horizon sky through an atmosphere having an extinction coefficient σ is

$$V = \sigma^{-1} \ln(\varepsilon^{-1}) , \qquad (2)$$

[3]G. Mie, 1908, "Beitrage zur Optik Truber Medien, Speziell Kolloidaher Metallosungen," Ann der Phys, 25:377-445

where ϵ is the threshold of contrast.[4] Various laboratory and field experiments[5 6 7] have given values of ϵ ranging from 0.008 to 0.06. These field experiments were performed during periods when no significant hydrometers were present and when fog was present. Values of ϵ ranging from 0.031 to 0.098 will not change the visibility estimated from equation (3) by more than ±20 percent. Therefore, using ϵ = 0.055 permits equation (2) to be written as

$$V \approx 2.9/\sigma \; . \qquad (3)$$

The approximation sign is used to indicate the variability of the threshold of contrast. For water clouds, Aufm Kampe and Weichmann[8] have expressed equation (3) in the form

$$V = 1.93(\rho/W)\ (\Sigma_i N_i a_i^3/\Sigma_i a_i^2)\ , \qquad (4)$$

where ρ is the density of the scattering material (water droplets), W is the liquid water content per unit volume, and N_i is the number of particles per unit volume of radius a_i. ϵ is given the value 0.055 and V is expressed in meters. Equation (4) follows from their equation

$$V = (3.9 \times 10^{12})/(2\pi \Sigma N_i a_i^2)\ , \qquad (5)$$

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[4]W. E. K. Middleton, 1952, Vision Through the Atmosphere, Toronto Press

[5]H. R. Blackwell, 1946, "Contrast Thresholds of the Human Eye," J Opt Soc Am, 36:624-643

[6]C. A. Douglas and L. L. Young, 1945, "Development of a Transmissometer for Determining Visual Range," Civil Aeronautics Administration Technical Development Reports, No 47, Washington DC

[7]H. G. Houghton, 1939, "On the Relation Between Visibility and the Constitution of Clouds and Fog," J Aeron Sci, 9:103-107

[8]H. J. Aufm Kampe and H. K. Weickmann, 1952, "Trabert's Formula and the Determination of Water Content in Clouds," J Meteorol, 9:167-171

where the denominator represents the scattering function. Atlas and Bartnoff[9] have shown that equation (4) may be expressed as

$$\sigma = [3.9W/K(n)d_0] \times 10^{-6} \tag{6}$$

by using equation (3) and equation (5) where K(n) is a dimensionless coefficient that varies slowly with the spread of the drop-size distribution, and d_0 (millimeters) is the median volume diameter and W (milligrams per cubic meter) is the liquid water content per unit volume. Equation (6) may be used directly when the obstruction to visibility is due to a single size of particles. If two or more sizes are present, the effect is a summation ($\sigma = \sigma_1 + \sigma_2 \ldots$). Atlas and Bartnoff[9] computed K(n) for several drop-size distributions (total of 65) given by Diem.[10] These sizes were obtained by the rotating multicylinder method. This method yields only average values and cannot respond to rapid changes in drop-size diameter. To obtain a drop-size distribution, the general form of the distribution curve must be assumed. These curves are applicable to rainfall since they are normalized with respect to the median volume diameter. The values for K(n) ranged from 1.30 down to 0.38. The K(n) value for a perfectly monodisperse distribution was 1.30.

The raindrop-size distributions of Marshall and Palmer[11] indicate spectra corresponding to a value of K(n) of about 1.0 and can be approximated by a negative exponential distribution [equation (7)]. Since K(n) varies very slowly with increasing spread of the drop-size distribution, the K(n) value of 1.0 is within ±16 percent for all drop-size spectra of the Marshall and Palmer distributions.

Marshall and Palmer express their raindrop distributions in the form

$$N = N_0 e^{-\lambda d} , \tag{7}$$

where N is the number of drops per unit volume of space in the size interval d to d + Δd, d is the drop diameter in millimeters, N_0 is a constant equal to 0.08 cm^{-4}, and $\lambda(mm^{-1})$ is a parameter that depends only on the rain intensity R(mm/h) in the form

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[9]D. Atlas and S. Bartnoff, 1953, "Cloud Visibility, Radar Reflectivity, and Drop Size Distribution," J Meteorol, 10:143-148

[10]M. Diem, 1948, "Messung der Grosse von Wolkenelementen II," Meteorol Rundschau, No 9/10, pp 261-273

[11]J. S. Marshall and W. Mck Palmer, 1948, "The Distribution of Raindrops with Size," J Meteorol, 5:165-166

$$\lambda = 4.1\ R^{-0.21}\ . \tag{8}$$

Rigby and Marshall[12] converted equation (7) to a distribution of λ^3 times liquid water content and plotted it against the quantity λd. This procedure resulted in a single normalized distribution for all rain intensities. Atlas[13] has shown that the parameter λ is simply inversely proportional to the median volume diameter ($\lambda d_o = 3.75$) and equation (7) may be written as

$$N = N_o e^{-3.75d/d_o}\ . \tag{9}$$

Using equation (8) d_o becomes

$$d_o = 0.92\ R^{0.21}\ . \tag{10}$$

Then using the relationship derived by Marshall and Palmer[11]

$$W = 72\ R^{0.88}\ , \tag{11}$$

where W is the liquid water content (milligrams per cubic meter) and R is the rainfall rate (millimeters per hour). The extinction coefficient can be expressed as a function of rain intensity.

$$\sigma = 0.312\ R^{0.67}\ , \tag{12}$$

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[12] E. C. Rigby and J. S. Marshall, 1952, The Modification of Rain with Distance Fallen, Report MW-3, Stormy Weather Research Group, McGill University, Montreal, Canada

[13] D. Atlas, 1953, "Optical Extinction by Rainfall," J Meteorol, 10:486-488

[11] J. S. Marshall and W. Mck Palmer, 1948, "The Distribution of Raindrops with Size," J Meteorol, 5:165-166

where σ is the extinction coefficient (kilometers^{-1}) and R is the rainfall intensity (millimeters per hour). This is the relationship that we would expect for all raindrop-size spectra resembling those reported by Marshall and Palmer.[11]

Atlas,[13] using 58 raindrop samples taken in Massachusetts, found that these drop-size distributions were somewhat narrower than those of Marshall and Palmer[11] (K(n) = 1.19 instead of 1.0). The extinction coefficient for these measurements was found to be

$$\sigma = 0.204\ R^{0.68} \tag{13}$$

with a standard error of 45 percent.

Table 2 (from Atlas[13]) shows values for the liquid water content (W) and extinction coefficient (σ) and gives an estimate of the consistency of the σ - R relationship.

TABLE 2. VALUES OF LIQUID WATER CONTENT (W) AND EXTINCTION COEFFICIENT (σ)

Source	W(mg/m^3)	σ(km^{-1})
Ynyslas[14]	$74\ R^{0.85}$	$0.247\ R^{0.64}$
Shoeburyness[14]	$59\ R^{0.82}$	$0.158\ R^{0.61}$
Lenard[14]	$61\ R^{0.84}$	$0.173\ R^{0.57}$
Laws and Parsons	$72\ R^{0.87}$	$0.241\ R^{0.68}$
Marshall and Palmer	$72\ R^{0.88}$	$0.312\ R^{0.67}$
East Hill[14]	$65\ R^{0.83}$	$0.222\ R^{0.56}$
Hilo, Hawaii	$82\ R^{0.84}$	$0.329\ R^{0.55}$
Blanchard (orographic rain)		
within clouds	$235\ R^{0.58}$	$2.64\ R^{0.18}$
cloud base	$150\ R^{0.70}$	$1.27\ R^{0.33}$
nonorographic	$61\ R^{0.89}$	$0.175\ R^{0.70}$
Massachusetts	N/A	$0.204\ R^{0.68}$

[14]A. C. Best, 1950, "The Size Distribution of Raindrops," Quart J Roy Meteorol Soc, 76:16-36

[11]J. S. Marshall and W. Mck Palmer, 1948, "The Distribution of Raindrops with Size," J Meteorol, 5:165-166

[13]D. Atlas, 1953, "Optical Extinction by Rainfall," J Meteorol, 10:486-488

The coefficient in the σ - R relationship is a function of the nature of the drop-size distribution, increasing roughly as the square root of the number concentration per unit volume and decreasing as the normalized spectrum broadens. The exponent on R is a function of the variation of dropfall velocity with drop diameter. Atlas[13] also noted that the relative constancy of the coefficients of the σ - R relationships (table 2) for widespread rain implies the existence of a preferred drop-size spectrum and concentration. Also, the fact that the exponents on R generally exceed 0.57 may be evidence of either a slight tendency for the number concentration to increase with rain intensity or for the normalized spectrum to become narrow with increasing intensity. From the values listed in table 2, a good estimate of the extinction coefficient in widespread rain is

$$\sigma(\mathrm{km}^{-1}) = 0.25\ R^{0.63}\ , \tag{14}$$

and from Blanchard's[15] data the extinction coefficient for orographic rainfall or drizzle is estimated to be

$$\sigma(\mathrm{km}^{-1}) = 1.2\ R^{0.33}\ . \tag{15}$$

VARIATIONS IN DROP-SIZE SPECTRA AND EXTINCTION COEFFICIENT

As seen in the previous section, raindrop-size distributions are important in determining the extinction coefficient. Waldvogel[16] measured raindrop spectra with an electromechanical raindrop spectrometer that detected drops > 0.3 mm in diameter. Several investigators (Ohtake,[17] Diem and Strantz,[18] and

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[13]D. Atlas, 1953, "Optical Extinction by Rainfall," J Meteorol, 10:486-488

[15]D. C. Blanchard, 1953, "Raindrop Size Distribution and Associated Phenomena in Hawaiian Rain," J Meteorol, 10:457-473

[16]A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067-1078

[17]T. Ohtake, 1970, "Factors Affecting the Size Distribution of Raindrops and Snowflakes," J Atmos Sci, 27:804-813

[18]M. Diem and R. Strantz, 1971, "Typen der Regentropfen-Spektren II. Akhangigkeit von der Regenintensitat," Meteorol Rundschau, 24:23-26

Czerwinski and Pfisterer[19]) found independently that most raindrop spectra may be approximated by a negative exponential distribution and the value of N_0 [equation (9)] is not at all constant. By considering only coalescence as a modification mechanism during the fall of drops, Srivastava[20] showed theoretically that raindrops fit the exponential distribution. Rigby et al[21] have demonstrated that evaporation and accretion of cloud droplets do not greatly influence the nature of the distribution.

Waldvogel[16] presented several raindrop spectra for different rainfall cases (table 3) and observed sudden variations in the spectra even though the rainfall rates did not change significantly. In his September 1969 case, the spectra changed several times from "small drop" (widespread rain) spectra ($\overline{N}_0$ > 16,000) to "large drop" (thundershower) spectra ($\overline{N}_0$ < 8,000) in intervals of about 30 min (N_0 = m^{-3} mm^{-1}). The radar reflectivity patterns reported by Waldvogel[16] indicated that the two types of raindrop spectra originated from different areas within the precipitation area. One pattern belonged to an area with weak or moderate convective activity, and the second pattern belonged to an area without convective activity. The horizontal extent of these areas was about 20 km. This change in raindrop spectra is interpreted as a transition from one mesoscale precipitation area to another having different convective activities. The 6 June 1968 example shows a "large drop" spectra associated with widespread rain and a "small drop" spectra associated with a cold front thunderstorm. Apparently the convective activity was weak at this time and produced a larger proportion of small drops (large number). The 19 June 1969 example originates from an orographic situation lasting 14 h during which the type of rain changed several times from a widespread rain to a shower and vice versa. In the 26 May 1969 case, the rainfall rate, as well as the type of precipitation, did not change drastically when the spectra changed. All of the examples given by Waldvogel[16] were apparently of the orographic widespread rain type mixed with mesoscale convective areas. The storms lasted several hours and during their course all of them showed some pronounced variations in their drop-size spectra, depending upon the strength of the convective activity.

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[19] N. Czerwinski and W. Pfisterer, 1972, "Typen von Regentropfen-Spektren von polar bis zu Tropischen Zonen und ihere Abhangigkeit von der Regenintensitat," Meteorol Rundschau, 25:88-94

[20] R. C. Srivastava, 1967, "On the Role of Coalescence Between Raindrops in Shaping Their Size Distribution," J Atmos Sci, 24:287-292

[21] E. C. Rigby, J. S. Marshall, and W. Hitschfeld, 1954, "The Development of the Size Distribution of Raindrops During Their Fall," J Meteorol, 11:362-372

[16] A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067-1078

TABLE 3. MEAN VALUES OF N_0 AND R WITH PRECIPITATION TYPE[16]

Date	Time	$\overline{N}_0 (m^{-3} mm^{-1})$	$\overline{R} (mm\ h^{-1})$	Precipitation Type
18 Sep 69	1430-1500	6,347	5.6	widespread rain
18 Sep 69	1500-1520	6,571	2.5	widespread rain
18 Sep 69	1520-1545	15,523	5.7	moderate shower
18 Sep 69	1545-1620	3,804	5.0	widespread rain
6 Jun 68	2205-2235	35,000	10.2	thunderstorm
6 Jun 68	2235-2310	4,000	5.8	widespread rain
19 Jun 69	0510-0540	16,000	4.0	moderate shower
19 Jun 69	0550-0620	8,000	8.0	widespread rain
26 May 69	0950-1020	16,000	1.5	shower superimposed on widespread rain
26 May 69	1030-1110	4,000	1.5	widespread rain

Using the above drop-size distributions and the relationship

$$\Delta = 4.343 \times 10^{-3} \int_0^{\infty} N(D) Q_T(\lambda, D) dD \ , \qquad (16)$$

where Δ = specific attenuation in dB/km, $N(D)dD$ = number of drops per volume unit volume with diameter between D(mm) and D + dD(mm)(m^{-3}), and $Q_T(\lambda, D)$ = extinction cross section of raindrops with diameter D at wavelength λ(mm) (mm^2), and the knowledge that for infrared and visible light the extinction cross section is twice the geometric cross section, the following extinction coefficients for the various rainfall types were computed.[16]

$$\sigma(km^{-1}) = 0.51\ R^{0.63}, \text{ drizzle} \ , \qquad (17)$$

$$\sigma(km^{-1}) = 0.32\ R^{0.63}, \text{ widespread rain} \ , \qquad (18)$$

[16]A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067-1078

and

$$\sigma(km^{-1}) = 0.16\ R^{0.63}\text{, thunderstorm .} \tag{19}$$

Waldvogel[16] concluded that N_0 decreases with increasing activity (spectrum shifts toward larger drops), but if the convective activity is weak the raindrop spectrum shows a larger proportion of small drops (N is large). However, some of the mean values of N_0 for convective activity are much higher than those found in uniform widespread rain of comparable rainfall rate (table 3). The intensity of the convective activity probably accounts for the lack of correlation between rain events.

Shirvaikar et al,[22] using raindrop-size distributions of monsoon rains, found N_0 values ranging from 647 to 7633 $mm^{-1}\ m^{-3}$ for rainfall intensities up to 195 mm h^{-1}. Using Shirvaidar et al values, an extinction coefficient was found to be

$$\sigma(km^{-1}) = 0.21\ R^{0.74}\ . \tag{20}$$

Other parameters within the limit of measurement errors were essentially the same as given by Best[14] and show that Best's results are valid even in high rainfall rates. Other values of the extinction coefficient have been given by Zuev[23]

$$\sigma(km^{-1}) = 0.21\ R^{0.74} \tag{21}$$

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[16]A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067-1078

[22]V. V. Shirvaikar, I. Achothan Kutty, and M. S. Patil, 1981, "Raindrop Size Distributions in Monsoon Rains," Meteorol Rundschau, 34:40-46

[14]A. C. Best, 1950, "The Size Distribution of Raindrops," Quart J Roy Meteorol Soc, 76:16-36

[23]V. E. Zuev, 1966, Atmospheric Transparency in the Visible and Infrared, translated from Russian by the Israel Program for Scientific Translations in 1970, Clearing House, Federal Science and Technical Information, Springfield, VA

and Reiter[24]

$$\sigma(km^{-1}) = 0.223\ R^{0.423}\ . \qquad (22)$$

ATTENUATION OF INFRARED ENERGY BY RAIN

Buijs and Janssen[25] have shown that during rain a relationship between the infrared attenuation (a) and visibility (V) exists in the form

$$a = \frac{C}{V} \qquad (23)$$

where C is a constant. Theory (Zuev[23]) also shows that infrared and visible light are both attenuated by about the same amount during rain (figure 1). Buijs and Janssen[25] compared the transmittances of infrared and visible light taken over the same 500-m pathlength and found a relationship that was very nearly one to one. The figures presented in their paper showed that the theoretical prediction is fulfilled rather well. Therefore, the relationship between infrared attenuation and visible attenuation during rain is assumed to be nearly independent of rainrate and drop-size distribution. Table 4 gives some extinction coefficient relationships with rainfall intensities (R) for the 10.6μm infrared wavelength.

Chimelis[26] found that measured extinction in heavy rainfall was an order of magnitude less than measured extinction in heavy fog for the 10.6μm wavelength. However, no information was given on the liquid water content of the rain, but the fog values were as high as 0.4707 g/m^3 and the maximum rainfall rate was 75 mm/h.

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[24]R. Reiter, 1981, Atmospheric Conditions Influencing Slant Path Low Visibility, Contract No DAJA37-80-C-0345, US Army European Research and Standardization Group, 223 Old Marylebone Rd, London NW 1 5th, England

[25]J. H. Buijs and L. H. Janssen, 1981, Comparison of Simultaneous Atmospheric Attenuation Measurements at Visible Light, Infrared (3-5μm) and mm-Waves (94 GHz), National Defense Research Organization TNO, Physics Laboratory, Report PHL 1981-04

[23]V. E. Zuev, 1966, Atmospheric Transparency in the Visible and Infrared, translated from Russian by the Israel Program for Scientific Translations in 1970, Clearing House, Federal Science and Technical Information, Springfield, VA

[26]V. Chimelis, 1982, "Extinction of CO_2 Laser Radiation by Fog and Rain," Appl Opt, 21:3367-3372

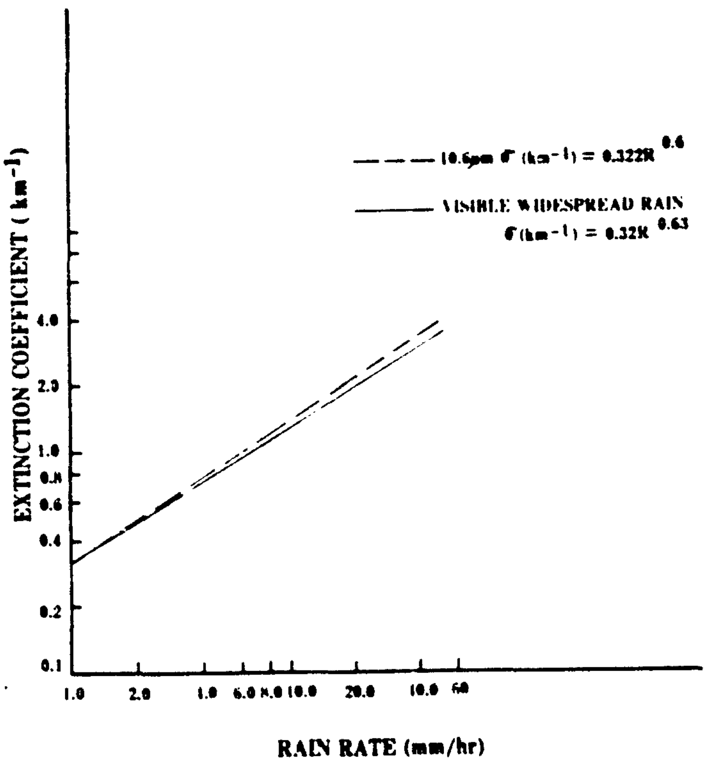

Figure 1. Extinction coefficient for visible and infrared wavelengths versus rain rate.

TABLE 4. EXTINCTION COEFFICIENTS FOR THE 10.6µm WAVELENGTH AS A FUNCTION OF RAINFALL RATE (R)

Wavelength (µm)	Extinction Coefficient (km^{-1})	Author
10.6	$0.322\ R^{0.6}$	Chimelis
10.6	$0.424\ R^{0.501}$	Rensch and Long
10.6	$0.250\ R^{0.659}$	Chen
10.6	$0.373\ R^{0.397}$	Reiter

SUMMARY AND RECOMMENDATIONS

Theory has predicted and measurements have shown that visible and infrared radiation are both attenuated by nearly the same amount during rain. Expressions for the extinction coefficient (σ) in kilometers^{-1} as a function of rainrate ranged from 1.2 $R^{0.33}$ for orographic rain or drizzle to 0.16 $R^{0.63}$ for thunderstorm rainfall. The relationship for an infrared wavelength of 10.6μm ranged from 0.373 $R^{0.397}$ to 0.250 $R^{0.659}$. These relationships appear to be valid for rainrates up to 195 mm/h.

Large variations in the raindrop spectra are probably due to the variations in the intensity of convective activity. To get a better understanding of the precipitation process as a whole, simultaneous measurements of raindrop spectra, concentrations of freezing nuclei and ice particles, and parameters characterizing the convection of precipitating cells should be made. These measurements will lead to more consistent relationships between the extinction coefficient and the routinely measured meteorological parameters.

A library of existing raindrop spectra measurements and their relationship to extinction should be collected so that more definitive relationships between sensor transmission and rainfall may be determined.

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