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HIGH RESOLUTION COMPUTER CALCULATION
OF OPTICAL TRANSMITTANCE
AT SEA LEVEL OVER MONTEREY

by

Nusret Guner

December 1978

Thesis Advisor: A. W. Cooper

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Computer programs have been developed for calculation of the molecular absorption and aerosol extinction for horizontal path propagation of radiation in the wavelength range above 0.55 μm. The AFCRL line parameters compilation is used as input data with local weather conditions for the Monterey Bay and model of typical aerosol size distribution from Shettle and Fenn. Wind speed and relative humidity are included in the form developed by Wells, cont'd

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ABSTRACT (Cont'd)

CONT

Gal and Munn. Infinite resolution computations have been carried out for 1.06, 3.8 and 10.6 μm and results tabulated for monthly and yearly average weather conditions on Monterey Bay. Bandwidth-averaged spectral transmittances have been calculated at 0.01 cm^{-1} and 0.5 cm^{-1} resolution for the same conditions.

Comparisons with previously published data show agreement to 1.8% with maritime model aerosol Mie-scattering calculations by Selby using LOWTRAN III B [Ref. 12].

Analysis of sensitivity to changes of pressure and temperature for the 3.8 μm range showed only small effects of these parameters. However a change in water vapor partial pressure results in a 0.75%/mbar change in transmittance in the 3.8 μm region.

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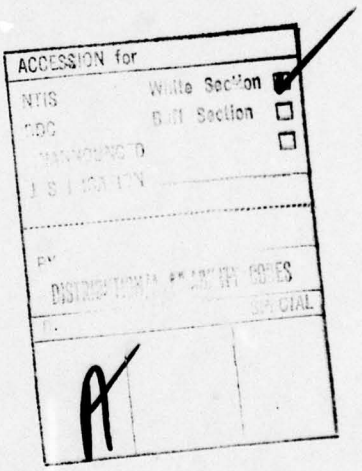

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High Resolution Computer Calculation of Optical Transmittance at Sea Level Over Monterey

by

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Lieutenant, Turkish Navy
B.S., Naval Postgraduate School, 1978

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Computer programs have been developed for calculation of the molecular absorption and aerosol extinction for horizontal path propagation of radiation in the wavelength range above 0.55 μm. The AFCRL line parameters compilation is used as input data with local weather conditions for the Monterey Bay and model of typical aerosol size distribution from Shettle and Fenn. Wind speed and relative humidity are included in the form developed by Wells, Gal and Munn. Infinite resolution computations have been carried out for 1.06, 3.8 and 10.6 μm and results tabulated for monthly and yearly average weather conditions on Monterey Bay. Bandwidth-averaged spectral transmittances have been calculated at 0.01 cm^{-1} and 0.5 cm^{-1} resolution for the same conditions.

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TABLE OF CONTENTS

I. INTRODUCTION ---------- 10

A. BACKGROUND ---------- 10

B. ATMOSPHERIC PHENOMENA ---------- 13

C. HF/DF LASER AT THE NAVAL POSTGRADUATE SCHOOL ---------- 20

II. OPTICAL PROPAGATION THROUGH THE ATMOSPHERE ---- 23

A. MOLECULAR SCATTERING COEFFICIENT ---------- 23

B. MOLECULAR ABSORPTION COEFFICIENT ---------- 30

C. CONTINUUM ABSORPTION COEFFICIENT ---------- 37

1. Water Vapor Continuum ---------- 38

2. Nitrogen Continuum ---------- 39

D. AEROSOL EXTINCTION COEFFICIENT ---------- 40

III. ALGORITHM FOR CALCULATION OF MOLECULAR ABSORPTION COEFFICIENT ---------- 45

IV. RESULTS ---------- 48

APPENDIX A ---------- 53

APPENDIX B ---------- 59

APPENDIX C ---------- 65

LIST OF REFERENCES ---------- 109

INITIAL DISTRIBUTION LIST ---------- 111

LIST OF TABLES

1. Modification factor for CO_2 lines ---------- 68

2. Vibrational partition functions ---------- 69

3. Self-broadening absorption coefficients for water vapor in the 3.5-4.2 micrometer region ------ 70

4. Concentrations of uniformly mixed gases in the air ---------- 71

5. Models of atmosphere at sea level ---------- 72

6. Size distribution parameters of aerosol models----- 73

7. HF laser frequencies ---------- 74

8. DF laser frequencies ---------- 76

9. Midlatitude winter model molecular absorption coefficients for infinite resolution ---------- 78

10. Refractive indices of aerosol particles [Ref. 12] - 79

11. Water vapor pressure and density for different dew point temperatures ---------- 81

12. Monterey Bay area weather conditions [Ref. 16,17] - 82

13. Molecular absorption and scattering coefficients for yearly averages in the Monterey Bay area ------ 83

14. Molecular absorption and scattering coefficients at 1.06 micrometers in the Monterey Bay area ------ 84

15. Molecular absorption coefficients at 3.8007 micrometers in the Monterey Bay area ---------- 85

16. Molecular absorption coefficients at 10.591033 micrometers in the Monterey Bay area ---------- 86

17. Amounts of air constituents in the Monterey Bay Area (molecules/cm^2 km) ---------- 87

18. Aerosol extinction coefficients for maritime model with 75% seaspray and 25% rural aerosols ---- 88

LIST OF FIGURES

1. a. Model of an elemental scatterer ---------- 89
   b. Creation of an induced dipole moment by an electric field ---------- 89

2. The geometry of scattering with the scatterer at the origin ---------- 90

3. Relative intensities of DF laser wavelengths produced in the cavity ---------- 91

4. Relative intensities of HF laser wavelengths produced in the cavity ---------- 92

5. HF/DF laser system block diagram ---------- 93

6. Midlatitude winter model molecular scattering coefficients ---------- 95

7. Extinction efficiency factor as function of size parameter ---------- 96

8. Aerosol extinction coefficient as function of wavelength for rural model ---------- 97

9. Aerosol extinction coefficient as function of wavelength for maritime model with 75% sea spray and 25% rural aerosols ---------- 98

10. Aerosol extinction coefficient as function of wavelength for different wind speeds ---------- 99

11. Aerosol extinction coefficient as function of wavelength for different relative humidities --------100

12. Transmittance along 10 km path with high spectral resolution of 0.01 cm^{-1} for Monterey yearly averages (near 3.8 μm) ----------101

13. Transmittance along 10 km path with degraded resolution for Monterey yearly averages (near 3.8 μm) ----------102

14. Transmittance along 10 km path with high spectral resolution of 0.01 cm^{-1} for Monterey yearly averages (near 10.6 μm) ----------103

15. Transmittance along 10 km path with degraded resolution for Monterey yearly averages (near 10.6 μm) ---------- 104

16. Transmittance along 10 km path with high spectral resolution of 0.01 cm^{-1} for P = 1018 mb., T = 290 degrees Kelvin, P_{H_2O} = 7.48 mb ---------- 105

17. Transmittance along 10 km path with degraded resolution for P = 1018 mb, T = 290 degrees Kelvin, P_{H_2O} = 7.48 mb ---------- 106

18. Transmittance along 10 km path with high spectral resolution of 0.01 cm^{-1} for P = 1018 mb, T = 290 degrees Kelvin, P_{H_2O} = 15.48 mb ---------- 107

19. Transmittance along 10 km path with degraded resolution for P = 1018 mb, T = 290 degrees Kelvin, P_{H_2O} = 15.48 mb ---------- 108

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I. INTRODUCTION

A. BACKGROUND

The light bringing us information from a distance, illuminating our surroundings and carrying energy, performs these functions only by travelling in the atmosphere. Laser light in the form of a highly collimated beam with very narrow frequency bandwidth and high radiant power is equally dependent on the propagation properties of the atmosphere. The characteristics of the light: notably its color (wavelength), intensity, polarization and spatial distribution are all modified by interaction with the constituents of the atmosphere - mostly the absorbing trace gases and suspended particles in the size range up to the order of hundreds of micrometers.

In modern military technology a wide range of systems are in use or under development for surveillance, imaging, target detection, designation, identification and tracking, for communications, for precision guidance of munitions and possibly even as a directed energy weapon. These operate over the entire "optical" range of wavelengths, from the visible or near ultra-violet through the "far infra red" — from about 0.3 to 20 micrometers. Operation of these systems is limited by the properties of the atmosphere as a transmission medium, particularly the degradation of resolution by scattering from particulates and turbulence,

and loss of radiant intensity through absorption and scattering. Due to strong absorption by atmospheric molecules, systems are constrained to operate in limited wavelength ranges or "windows", relatively free of absorption lines. Of these windows, the radiating temperatures of many sources of military interest and the desirability of day/night operating capability have concentrated attention on the 3-5 μm and 8-14 μm infra-red windows.

In particular the navy has a special interest in the DF laser as a candidate moderate or high power laser at a wavelength in the 3-5 μm range, unaffected by the high humidity levels found in the naval environment. Of particular interest is the 3.8007 $P_2(8)$ transition line which shows up to 96% transmission over a kilometer path at sea level.

The need to predict the operational performance of these systems leads to a requirement to predict the spectral transmittance of the atmosphere in the infra-red, as a function of the meteorological parameters which determine the absorption and scattering levels – the pressure, temperature, air composition, vertical gradients, number density composition and size distribution of suspended particles.

Large scale measurement programs have been undertaken in many countries with the objective of building a large library of meteorological and transmission data. Considerable effort (notably at AFGL) has been devoted to the

development of computer programs for transmittance calculation based on weather data, and the establishment of a number of "standard" atmospheric models.

The current modelling effort was undertaken in support of the experimental program of transmittance measurement on ranges over Monterey Bay being carried out by the Environmental Physics Group at the Naval Postgraduate School. This work involves measurement in all the suitable atmospheric windows from the visible to 14 μm, with both laser and broadband sources. The calculational program has therefore been directed to computation of molecular absorption and aerosol extinction coefficients for sea level propagation under a range of weather conditions statistically typical of Monterey. This has been done for a variety of wavelengths appropriate to the measurements, and at high resolution for use with laser sources, and averaged over filter bandwidths for broadband sources. The Air Force Cambridge Research Laboratory Atmospheric Absorption Line Parameters Compilation [Ref. 7] in magnetic tape form is used as input data for the absorption calculations. A Mie scattering program based on the Van De Hulst approximation with the model particle distribution of Shettle and Fenn [Ref. 8] has been used for the aerosol scattering. Wind speed and relative humidity effects have been included using the drop size growth model of Wells, Gal and Munn [Ref. 18]. A sensitivity analysis has been carried out with respect to pressure and temperature.

Basically, this thesis describes a program to

a) Develop a computer code to calculate atmospheric transmittance for specific wavelengths in the near and mid IR.

b) Develop a code to give transmittance and molecular absorptance with bandwidth appropriate to grey-body sources in the near and mid IR.

c) Apply these to prediction of transmittance over marine optical paths, over Monterey Bay, based on the available meteorological data base for the area, for conditions appropriate to the optical propagation experimental measurement program.

Curves have been prepared giving predicted molecular and aerosol extinctions for statistical monthly and yearly average meteorological conditions on Monterey Bay.

Further sections of this thesis describe the theoretical background and the details of the algorithms, and provide tabular and graphical results of the calculations. Computer program listings are given in the appendices.

B. ATMOSPHERIC PHENOMENA

Optical transmission of energy is usually described by the transmittance,

$$\tau = \exp(-\mu L) = \frac{I(L)}{I(0)} \qquad (1\text{-}1)$$

where μ is called the extinction coefficient, and L represents the length of the path which the light has traveled. This expression follows from Beer's Law, which for linear propagation of monochromatic radiation at frequency ν has the form

$$\frac{d}{dz} I(z,\nu) = -\mu(\nu)\ I(z,\mu) \qquad (1\text{-}2)$$

Here $I(z,\mu)$ represents the intensity of monochromatic radiation at a distance z.

Beer's Law in differential form (1-2) may also be written as

$$I(L,\mu) = I(0,\mu)\ e^{-\mu(\nu)L} \qquad (1\text{-}3)$$

for a given path length L. The transmittance τ over a path of length L is then given from the equation (1-3)

$$\tau(\nu) = \frac{I(L,\nu)}{I(0,\nu)} = e^{-\mu(\nu)L}$$

which is the same as equation (1-1) for monochromatic radiation.

The extinction coefficient μ is generally the result of two processes: absorption and scattering. Both molecules and particles suspended in the atmosphere cause absorption and scattering. It may be useful to define the extinction coefficient μ as a sum of four terms

$$\mu = k_m + \beta_m + k_a + \beta_a \qquad (1\text{-}4)$$

where k_m, β_m, k_a, β_a are molecular absorption, molecular scattering, aerosol absorption, aerosol scattering coefficients.

An aerosol extinction coefficient μ_a is sometimes used for the summation of aerosol absorption and scattering. Similarly a molecular extinction coefficient μ_m is used for the summation of molecular absorption and scattering.

From equations (1-1) and (1-4) the total transmittance through a path in the atmosphere may be written as

$$\begin{aligned}\tau(\text{total}) = {} & \tau(\text{molecular absorption}) \times \\ & \tau(\text{molecular scattering}) \times \\ & \tau(\text{aerosol absorption}) \times \\ & \tau(\text{aerosol scattering})\end{aligned}$$

where τ(molecular absorption) may be written in terms of the atmospheric components as

$$\begin{aligned}\tau(\text{molecular absorption}) = {} & \tau(\text{uniformly mixed gases line abs.}) \times \\ & \tau(\text{ozone line abs.}) \times \\ & \tau(\text{water vapor line abs.}) \times \\ & \tau(\text{water vapor continuum abs.}) \times \\ & \tau(\text{nitrogen continuum abs.})\end{aligned}$$

Although the molecular scattering, aerosol absorption and aerosol scattering coefficients are smooth functions of frequency of monochromatic radiation, the molecular absorption coefficient is strongly dependent on frequency.

Molecules which cause absorption and scattering of a light beam in the atmosphere may be divided into two types: uniformly and non-uniformly mixed gases. Carbon dioxide, nitrous dioxide, carbon monoxide, methane, oxygen and nitrogen are assumed as uniformly mixed gases for which their mixing ratios by volume with each other are constant, independent of pressure and temperature. These mixing ratios are tabulated in table 4. Water vapor and ozone are considered as non-uniformly mixed gases, whose relative concentrations must be specified.

Six different models of the atmosphere are frequently used in calculations; these are the tropical, midlatitude summer, midlatitude winter, subarctic summer, subarctic winter and U.S. Standard atmosphere 1962 model described by McClatchey and D'agati [Ref. 4]. Pressure, temperature, density, water vapor and ozone concentrations in the air for each model at sea level are tabulated in table 5.

The number densities of aerosol particles which also cause absorption and scattering of a light beam are more complicated to determine. It is necessary to know the size distribution of aerosol particles in addition to the number density, in order to compute the aerosol scattering and

absorption coefficients. The size distribution function is denoted by n(r) and given as

$$n(r) = \frac{dN(r)}{dr} \qquad (1\text{-}5)$$

where N(r) is called the number density which is the number of aerosol particles with radius less than r per unit volume.

Several different analytical models have been developed for the size distribution. A "continental" aerosol model, which includes both rural and urban aerosol conditions, and a "maritime" aerosol model are used for the lower atmosphere.

The rural aerosol model used by Shettle and Fenn is assumed to be composed of a mixture of 70% water soluble substance, consisting of ammonium and calcium sulfate and organic compounds, and 30% dustlike aerosols [Ref. 8].

In urban areas the rural aerosol background is modified by the addition of aerosols from combustion products and industrial sources. The proportions of soot-like aerosols and the rural aerosol type aerosol mixture are assumed to be 35% and 65% respectively [Ref. 8].

The maritime aerosol model represents the aerosol composition and size and number distributions over the oceans. It is significantly different from the continental aerosol types. The maritime model is due to salt particles caused by the evaporation of the seaspray droplets also added to

the rural type aerosols, from which most of the very large particles have been eliminated.

The general form of the size distribution for these models is given by Shettle and Fenn [Ref. 8] as

$$n(r) = \sum_{i=1}^{2} \left(\frac{N_i}{(\ln 10) r \sigma_i (2\pi)^{1/2}}\right) \exp\left[-\frac{(\log r - \log r_i)^2}{2\sigma_i^2}\right] \quad (1\text{-}6a)$$

where the parameters in the equation above are tabulated in table 6.

The size distribution given by equation (1-6a) is relative humidity and wind speed independent. Since the number of oceanic particles with greater radius in the size distribution increases with increasing relative humidity and wind speed, a modified maritime model has been proposed for calculation of aerosol extinction coefficients taking care of the growth of particle radius [Ref. 18]. This gives

$$n(r) = \frac{C}{F^{\tau}}\left\{0.47\left(\frac{r}{F^{\tau}}\right)^{-4} + 2.3 M_R a \left(\frac{r}{F^{\tau}}\right) \exp\left[-8.5\left(\frac{r}{F^{\tau}}\right)^{\gamma}\right]\right\} \quad (1\text{-}6b)$$

where C is a normalization constant, and M_R is the mixing ratio of seaspray aerosols with the rural aerosols. Or more clearly, the mixing ratio of rural-oceanic aerosols in the equation (1-6b) is $1:M_R$.

Particle growth is included through the growth factor F which adds the effect of relative humidity into the equation

(1-6b). It is given as

$$F = 1 - 0.9 \ln(1 - \frac{R.H.}{100})$$

where R.H. is the percent relative humidity. The effect of F is to increase the drop radius to

$$r_{R.H.} = F\, r_o$$

where r_o is the radius for zero percent relative humidity. F is normalized to 80% relative humidity, given F'. Therefore factor F' in the equation (1-6b) is

$$F' = \frac{F(R.H.)}{F(80)}$$

γ in equation (1-6b) describes the dependence on the wind speed. It has the form

$$\gamma = 0.384 - 0.00293\, V^{1.25}$$

where V is the wind speed in meters per second. a in equation (1-6b) also represents the wind speed dependence and it is given as

$$a = 250 + 750\, V^{1.16}, \quad \text{when } V < 7 \text{ m/sec.}$$

$$a = 6900\, V^{0.29}, \quad \text{when } V \geq 7 \text{ m/sec.}$$

So the inputs for equation (1-6b) are wind speed V and relative humidity R.H. The normalization constant C may be determined from the relation between visibility and aerosol extinction coefficient at 0.55 micrometers.

C. HF/DF LASER AT THE NAVAL POSTGRADUATE SCHOOL

Although this thesis will deal with propagation at sea level at any frequency of radiation, primary interest will be the frequencies of the HF/DF laser. These frequencies are tabulated in tables 7 and 8.

To be used for the propagation measurement program at the Naval Postgraduate School, a small scale hydrogen fluoride (HF) or deuterium fluoride (DF) laser was located on the roof of Spanagel Hall. The system consists of a vacuum system, a power supply and the laser head. The laser is centered around a laser head which contains discharge tube, mixing chamber or cavity and resonant cavity. The system uses four gases: a) Sulfur hexafluoride, b) oxygen, c) helium, d) hydrogen or deuterium. A mixture of sulfur hexafluoride, oxygen and helium is injected into the discharge tube at the end opposite the mixing chamber. Then the sulfur hexafluoride is dissociated by electron impact in the discharge tube by making use of an electric discharge. Oxygen helps the sulfur hexafluoride to dissociate into free fluorine radicals by the reaction

$$SF_4 + O_2 \rightarrow SO_2F_2 + 2F$$

The hydrogen or deuterium is injected perpendicular to the flow in the mixing chamber. Then chemical reaction takes place in this mixing region forming the vibrationally excited HF or DF molecules.

The optical resonator of the system consists of a pair of Brewster windows and mirrors. The Brewster windows which linearly polarize the output are chosen from two interchangeable pairs, one of BaF_2 (0.25-15 μm transmitting) and the other sapphire (0.14-6.5 μm transmitting).

The system has two options for operation: a) Multiline operation, b) Single line operation. The output mirror should be replaced by the diffraction grating for single line operation, while two mirrors (one partially transmitting) are used for multiline operation.

Optimized power output from lasing of hydrogen fluoride was reported [Ref. 9] as 6.5 Watts with the mass flow rates

SF_6 = 0.600 grams/sec.

O_2 = 0.182 grams/sec.

H_2 = 0.019 grams/sec.

He = 0.053 grams/sec.

Optimized multiline power output of deuterium fluoride lasing was also reported [Ref. 9] as 2.5 Watts with the mass flow rates

SF_6 = 0.680 grams/sec.

O_2 = 0.270 grams/sec.

D_2 = 0.043 grams/sec.

He = 0.063 grams/sec.

In the case of single line operation, the wavelengths and corresponding relative intensities of fourteen individual DF and fifteen individual HF lasing transitions are shown in figure 3 and figure 4.

The block diagram of the main elements of the system is also shown as figure 5.

II. OPTICAL PROPAGATION THROUGH THE ATMOSPHERE

A. MOLECULAR SCATTERING COEFFICIENT

The simple Lorentz-type molecular model presented here is shown in figure 1. It is assumed nonionized, nonpolar, isotropic, linear and lightly damped.

The model contains molecular mass residing in the atomic nuclei and carrying a net positive charge. Orbital electrons shared by the constituent atoms are represented by a concentric shell, providing a balancing negative charge. Force directed toward the central mass is characterized by a spring constant k. Let m be the electron mass. If the system is disturbed by an electric field E in the z direction, then the equation of motion may be written for a displaced electron as

$$- eE_z - kz = m \frac{d^2z}{dt^2} \tag{2-1}$$

where

$$E_z = E_{oz} \sin \omega t.$$

Equation (2-1) can also be written as

$$\frac{d^2z}{dt^2} + \omega_o^2 z = \frac{-eE_{oz}}{m} \sin \omega t \tag{2-2}$$

where $\omega_o = (k/m)^{1/2}$ is defined as the resonance frequency, corresponding to a molecular transition.

The steady state solution to equation (2-2) is

$$z = \frac{-e}{m(\omega_o^2 - \omega^2)} E_{oz} \sin \omega t$$

Now, the oscillator dipole moment can be written as

$$p = -ez = \frac{e^2/m}{\omega_o^2 - \omega^2} E_{oz} \sin \omega t$$

If we denote the maximum value of the dipole moment as p_o, then it is

$$p_o = \frac{e^2/m}{\omega_o^2 - \omega^2} E_{oz} \qquad (2\text{-}3)$$

The oscillating dipole moment has maximum value p_o given by equation (2-3) and produces secondary waves. Reradiation from the oscillating dipole then produces electric and magnetic fields at every point in the coordinate system shown in figure 2. In the short dipole approximation (i.e., radius of scatterer is much less than wavelength of incident wave) and far field (i.e., distance to scatterer is much larger than radius of scatterer) the electric and magnetic field vectors can be written as

$$\vec{E} = \frac{\omega^2 p_o}{4\pi} \frac{\mu \sin\theta}{r} \sin(kr-\omega t)\ \hat{\theta}$$

$$\vec{B} = \frac{\omega^2 p_o}{4\pi} \frac{\mu \sin\theta}{vr} \sin(kr-\omega t)\ \hat{\phi}$$

where

v is the velocity of wave,

μ is the magnetic permeability,

θ, ϕ and r are the variables in spherical coordinates.

The poynting vector denoted by $\vec{S}$ describes scattered power per unit area, and is given here as

$$\vec{S} = \frac{\vec{E}\times\vec{B}}{\mu} = \frac{\mu}{v}\left(\frac{\omega^2 p_o}{4\pi}\right)^2 \left(\frac{\sin\theta}{r}\right)^2 \sin^2(kr-\omega t)\hat{r} \qquad (2\text{-}4)$$

Scattered power per unit solid angle can be found from equation (2-4), first taking the time average, then multiplying by r^2. This gives the scattered intensity as

$$I(\theta) = \frac{\mu}{2v}\left(\frac{\omega^2 p_o}{4\pi}\right)^2 \sin^2(\theta) = \frac{\mu}{2v}\left(\frac{\omega^2 e^2}{4\pi m(\omega_o^2 - \omega^2)}\right)^2 E_{oz}^2 \qquad (2\text{-}5)$$

the power of the incident wave contained in unit area can be given as

$$\langle S\rangle_{incident} = \frac{1}{2} v \varepsilon E_{oz}^2 \qquad (2\text{-}6)$$

where ε is the permittivity of the medium.

The angular cross section of a molecule, denoted by $\sigma_m(\theta)$, may be defined as that cross section of incident wave acted on by the molecule, having an area such that power flowing across it is equal to the power scattered by the molecule per unit solid angle at an angle θ. It is

$$\sigma_m(\theta) = \frac{I_{scat}(\theta)}{\langle S \rangle_{incident}} = \frac{\text{equation (2-5)}}{\text{equation (2-6)}} \quad \text{or}$$

$$\sigma_m(\theta) = \left(\frac{\mu\omega^2}{4\pi}\right)^2 \left(\frac{e^2}{m(\omega_o^2 - \omega^2)}\right)^2 = \left(\frac{\mu\omega^2}{4\pi}\right)^2 \left(\frac{p_o}{E_{oz}}\right)^2 \qquad (2\text{-}7)$$

It is necessary to define the polarization P in order to find a suitable form for the second term in the right hand side of equation (2-7). P is defined as total dipole moment per unit volume and it is given as

$$P = Np_o = \chi\varepsilon_o E_{eff} = (K-1)\varepsilon_o E_{eff}$$

for a linear and isotropic medium, where

N is number of molecules per unit volume,

χ is electric susceptibility,

K is dielectric constant,

E_{eff} is the effective electric field which is $E_{oz} + \frac{P}{3\varepsilon_o}$.

Now we can write P in terms of K and E_{oz}, as

$$P = \frac{3(K-1)\varepsilon_o}{K+2} E_{oz} ,$$

from which

$$\frac{P_o}{E_{oz}} = \frac{3(K-1)\varepsilon_o}{N(K+2)}$$

The index of refraction is given here as

$$n = \frac{c}{v} = \sqrt{KK_m} = \sqrt{K}$$

since $K_m = 1$ for a nonmagnetic medium.

Now equation (2-7) can be written as

$$\sigma_m(\theta) = (\frac{\mu\omega^2}{4\pi})(\frac{3\varepsilon_o(n^2-1)}{N(n^2+2)})^2 .$$

σ_m, defined by the equation below, is called the total scattering cross section.

$$\sigma_m = \int_0^{4\pi} \sigma_m(\theta)\, d\Omega$$

or

$$\sigma_m = \frac{8\pi^3}{3N^2\lambda^4}(\frac{3(n^2-1)}{(n^2+2)})^2 \qquad (2-8)$$

where

$$\omega = \frac{2\pi v}{\lambda}$$

was substituted.

The total scattering cross section given by equation (2-8) is defined similarly to the angular scattering cross section, as the power scattered in all directions.

For air the refractive index is very close to one. Therefore n^2+2 is nearly equal to three, and equation (2-8) may be written as

$$\sigma_m = \frac{8\pi^3}{3N^2\lambda^4}(n^2-1)^2 \qquad (2\text{-}9)$$

This form of the total scattering cross section (2-9) has been derived for a single molecule disturbed by incoming electromagnetic radiation. It has the units of area. For many molecules in a unit volume, the total scattering coefficient β_m may be defined, assuming each molecule has the same total scattering cross section,

$$\beta_m = N\sigma_m = \frac{8\pi^3}{3N\lambda^4}(n^2-1) \qquad (2\text{-}10)$$

The molecular scattering coefficient (2-10) has the units of 1/length.

Since atmospheric gases are not quite isotropic, a depolarization factor P_d is introduced [Ref. 1] and inserted into equation (2-10). The molecular scattering coefficient

may then be written as

$$\beta_m = \frac{8\pi^3}{3N\lambda^4}(n^2-1)^2\left(\frac{6 + 3P_d}{6 - 7P_d}\right)\frac{P}{P_o}\frac{T_o}{T}$$

taking into account the pressure and temperature dependence. Here P_o and T_o refer to standard conditions, 1013 mb, 273 K.

Assuming air to be an ideal gas and using the ideal gas law, air is found to have a mole density of 44.631 moles per cubic meter at a pressure of 1013 millibars and temperature of 273 degrees Kelvin. This is equivalent to 2.688×10^{25} molecules per cubic meter.

For a depolarization factor, a value of 0.035 is used, following Penndorf [Ref. 1]. Although the index of refraction of air depends on the wavelength, this variation is small. Therefore $(n^2-1)^2$ is taken as 3.0884×10^{-7} which corresponds to a wavelength 0.55 micrometers [Ref. 2]. Using these parameter values given above, the atmospheric molecular scattering coefficient may be written as

$$\beta_m = \frac{10.07 \times 10^{-20}}{\lambda^4}\left(\frac{P}{1013}\right)\left(\frac{273}{T}\right) \text{ units of 1/km}$$

where

λ has units of cm.

P has units of mbars.

T has units of degrees Kelvin.

McClatchey and d'Agati [Ref. 4] have used the slightly different form of the molecular scattering coefficient,

$$\beta_m = \frac{9.807 \times 10^{-20}}{\lambda^{4.0117}} \left(\frac{P}{1013}\right) \left(\frac{273}{T}\right) \qquad (2\text{-}11)$$

which was selected as giving a "best fit" to the experimental data of Penndorf [Ref. 6].

B. MOLECULAR ABSORPTION COEFFICIENT

The model to derive the molecular absorption coefficient is the same as the one we developed in the previous section, but now it is heavily damped. When the model is disturbed by an electric field, the electron moves with a damping coefficient and restoring force strength k. The equation of motion may be written in differential form such that

$$m \frac{d^2\vec{r}}{dt^2} + m\gamma \frac{d\vec{r}}{dt} + k\vec{r} = -e\vec{E} = -e\vec{E}(\vec{r})e^{-i\omega t}$$

The steady state solution to this equation is

$$\vec{r} = \frac{-e/m}{\omega_o^2 - \omega^2 - i\gamma\omega} \vec{E}$$

The polarization due to N molecules per unit volume is

$$\vec{P} = -eN\vec{r} = \frac{e^2 N}{m} \frac{1}{\omega_o^2 - \omega^2 - i\gamma\omega} \vec{E}_{eff} \qquad (2\text{-}12)$$

where we again replaced the applied electric field with an effective electric field to account for polarizability of the medium.

After substituting $\vec{E}_{eff} = \vec{E} + \vec{P}/3\varepsilon_o$, the polarization becomes

$$\vec{P} = \frac{e^2 N/m}{\omega_1^2 - \omega^2 - i\gamma\omega} \vec{E}$$

where

$$\omega_1^2 = \omega_o^2 - \frac{e^2 N}{3\varepsilon_o m}$$

But the polarization is also given as

$$\vec{P} = \chi\varepsilon_o \vec{E}_{eff} = (K-1)\ \varepsilon_o \vec{E}_{eff} = (\eta^2-1)\ \varepsilon_o \vec{E}_{eff} \tag{2-13}$$

Combining equation (2-12) and (2-13) one can get

$$\eta = (1 + \frac{P}{\varepsilon_o E})^{1/2} = (1 + \frac{e^2 N/\varepsilon_o m}{\omega_1^2 - \omega^2 - i\gamma\omega})^{1/2} \tag{2-14}$$

for the index of refraction.

A more general form for equation (2-14) is written below with j referring to different types of molecules with oscillator strength f_j.

$$\eta = (1 + \frac{e^2}{\varepsilon_o m} \sum_j \frac{N_j f_j}{\omega_1^2 - \omega^2 - i\gamma\omega})^{1/2} \tag{2-15}$$

Near a resonance frequency, equation (2-15) can be approximated by

$$\eta = [1 + \frac{e^2 N_j f_j}{2\varepsilon_o m} \frac{(\omega_{1j}^2 - \omega^2)}{(\omega_{1j}^2 - \omega^2)^2 + \gamma^2\omega^2}] + [\frac{e^2 N_j f_j}{2\varepsilon_o m} \frac{\omega\gamma}{\omega_{1j}^2 - \omega^2)^2 + \gamma^2\omega^2}]i \quad (2\text{-}16)$$

using the Binomial Expansion, since η is very close to unity.

A plane wave going in the z direction with wave vector K may be written as

$$\vec{E} = \vec{E}_o e^{i(Kz-\omega t)} \quad (2\text{-}17)$$

The relation between wave vector and refractive index is

$$K = \frac{\omega}{c} \eta \quad (2\text{-}18)$$

K is complex, since η is complex, so defining K and η

$$K = \beta + i\alpha \quad (2\text{-}19)$$

$$\eta = n + ik \quad (2\text{-}20)$$

where β, α, n, k are the so-called propagation constant, absorption coefficient, index of refraction, and extinction coefficient respectively.

Using equations (2-16,18,19,20), it can be shown that

$$\alpha = \frac{e^2 N_j f_j}{2\varepsilon_o mc\gamma} \frac{\omega^2 \gamma^2}{(\omega_{1j}^2 - \omega^2)^2 + \omega^2 \gamma^2} \qquad (2\text{-}21)$$

Substituting K from equation (2-19) into equation (2-17) one can get

$$\vec{E} = \vec{E}_o \, e^{-\alpha z} \, e^{i(\beta z - \omega t)}$$

The electric field decreases by a factor of $e^{-\alpha z}$, and the intensity falls off by a factor of $e^{-2\alpha z}$ along the path length z. Since α corresponds to absorption, many workers use the so-called Lorentzian line shape given in equation (2-21) in order to find an expression for molecular absorption coefficient.

Substituting the expressions for frequency $\omega = 2\pi\nu$ and $\omega_{1j} = 2\rho\nu_o$ into equation (2-21) α becomes

$$\alpha = \frac{A}{[\frac{4\pi}{\gamma}(\nu_o - \nu)]^2 + 1}$$

or

$$\alpha = \frac{A \, \Delta\nu^2}{(\nu_o - \nu)^2 + \Delta\nu^2} \qquad (2\text{-}22)$$

where A is a constant, $\Delta\nu$ is $\gamma/4\pi$ and defined as half width at half maximum.

If α is normalized in the range from minus infinity to plus infinity, the expression for the Lorentzian line shape becomes

$$g(\nu) = \frac{\Delta\nu}{\pi[(\nu_o-\nu)^2 + \Delta\nu^2]} ,$$

describing the spectral distribution of absorption.

Finally, the molecular absorption coefficient can be written as

$$K_m(\nu) = \frac{S\alpha}{\pi[(\nu_o-\nu)^2 + \alpha^2]} ,$$

provided $S = \int K_m(\nu)d\nu$ for single absorbing line, where

- S is line intensity per absorbing molecule in the units of $cm^{-1}/(molecules/cm^2)$,
- α is $\Delta\nu$ half width at half maximum in the units of cm^{-1},
- ν is incoming wave frequency in the units of cm^{-1},
- ν_o is resonance frequency for absorbing line in the units of cm^{-1}.

The radiant frequency ν is unique: this gives absorption as a spectral quantity. Radiation from laser sources has very narrow line width, which may be assumed infinitely narrow for calculation purposes. The resonance frequency for each absorbing line is independent of pressure and

temperature. The line width is assumed to be a pressure broadened Lorentzian, with its pressure and temperature dependence given by the expression [Ref. 7]

$$\alpha = \alpha(P_o, T_s) \frac{P}{P_o} \left(\frac{T_s}{T}\right)^{1/2} \qquad (2\text{-}23)$$

where

P_o = 1 atm. and

T_s = 296 degrees Kelvin.

The total intensity of any line is pressure independent and its temperature dependence is given by the expression [Ref. 7]

$$S(T) = S(T_s) \frac{Q_V(T_s)}{Q_V(T)} \times \frac{Q_r(T_s)}{Q_r(T)} \times \exp[1.439E''(\frac{T-T_s}{TT_s})] \qquad (2\text{-}24)$$

where Q_V and Q_r are vibrational and rotational partition functions respectively, E" is the lower state energy of the transition corresponding to that line, in units of cm^{-1}.

Rotational partition functions are also temperature dependent, of the form

$$\frac{Q_r(T_s)}{Q_r(T)} = \left(\frac{T}{T_s}\right)^j$$

The corresponding values of Q_V and j are tabulated for each molecule in the air [Ref. 7] and presented in table 2.

Finally the total molecular absorption coefficient due to water vapor, ozone, carbon dioxide, methane, carbon monoxide, oxygen, and nitrous oxide in the air is given by

$$K_m = \sum_j \sum_i \frac{S_{ij}\alpha_{ij}m_j}{\pi[(\nu-\nu_{ij})^2 + \alpha_{ij}^2]} \qquad (2\text{-}25)$$

Summation over j corresponds to different types of molecules, and summation over i corresponds to different lines for a given molecule.

Values of ν_{ij}, $\alpha_{ij}(P_o,T_s)$, $S_{ij}(T_s)$ have been compiled for 100,000 lines between 1 μm and the far infrared by McClatchey and others at Air Force Cambridge Research Laboratories and are available on magnetic tape [Ref. 7]. Also a new version of the compilation including over 139,000 lines between 0.2 μm and 30 μm was recently reported by Air Force Geophysics Laboratory [Ref. 3].

Calculation for K_m at any pressure and temperature may be made by using equations (2-23,24,25) with the data from this tape.

m_j in equation (2-25) represents the number of j type molecules per unit volume. The resultant K_m is in the units of 1/length and generally 1/kilometer is used.

It should be noted that the Lorentzian line shape must be modified for pressures less than 100 millibars; at pressures between 10 and 100 millibars doppler broadening becomes

dominant [Ref. 7], while at pressures less than 10 millibars, the Voigt profile should be used. The Lorentzian line shape is good enough to be used at low altitudes, but line wings should be truncated at 20 cm^{-1} from the line centers, since uncertainties begin to arise beyond that range.

A computer program calculating the molecular absorption coefficient is prepared and presented as Appendix A. This program also includes the water vapor continuum absorption calculation which will be explained in the next section. The algorithm for the program is also discussed in Section III.

C. CONTINUUM ABSORPTION COEFFICIENT

Continuous regions of absorption in the atmospheric windows occur near 2500 cm^{-1} (4 μm) and from 700 cm^{-1} to 1250 cm^{-1} (8-14 μm).

In other spectral regions, the contribution from nearby absorption lines is much greater than that from the continuum absorption, so that for practical purposes the continuum effect can be neglected, although it may be greater than in the windows.

Extreme wings of strong collision broadened absorption lines centered more than 20 cm^{-1} away or pressure induced absorption resulting from transitions that are forbidden for unperturbed molecules may cause continuous absorption. In

the 8-14 μm region, existence of the water dimer (H_2O:H_2O) may also cause continuous absorption.

1. Water Vapor Continuum

The absorption coefficient due to the water vapor continuum can be described empirically by the expression [Ref. 4]

$$K_{m_{cont.}} = [C_S(\nu,T)P_s + C_N(\nu,T)P_N]W \qquad (2\text{-}26)$$

where C_S is a self broadening coefficient due to self broadening from collisions of water molecules with other water molecules, C_N is a foreign gas broadening coefficient due to nitrogen broadening from collisions of water molecules with air molecules which are mostly nitrogen.

C_S and C_N are both temperature and frequency dependent.

a. 8-14 μm region [Ref. 4]

C_N is given by the expression

$$C_N(\nu,T) = 0.002 \times C_S(\nu,296).$$

C_S is given by the expression

$$C_S(\nu,T) = C_S(\nu,296) \times \exp[1800(\frac{1}{T} - \frac{1}{296})]$$

where $C_S(\nu,296)$ is given as

$$C_S(\nu,296) = 4.18 + 5578 \times \exp(-7.87 \times 10^{-3}\ \nu)$$

where C_S is in the units of $(\text{precipitable-cm})^{-1}\ \text{atm}^{-1}$ or $(\text{pr. cm})^{-1}\ \text{atm}^{-1}$ which is $(\text{grams/cm}^2)^{-1}\ \text{atm}^{-1}$.

b. 3.5-4.2 μm region [Ref. 4]

C_S and C_N are given by the expressions below;

$$C_N(\nu,T) = 0.12 C_S(\nu,T)$$

$$C_S(\nu,T) = C_S(\nu,296) \times \exp[1350(\tfrac{1}{T} - \tfrac{1}{296})]$$

where C_S has the units of $(\text{pr. cm})^{-1}\ \text{atm}^{-1}$. The values of $C_S(\nu,296)$ at different frequencies are reproduced [Ref. 4] and tabulated in table 3. W in the equation (2-26) has the units of (pr. cm) per kilometer which is the same as grams per square centimer per kilometer. Then the water vapor continuum absorption coefficient $K_{m_{cont.}}$ can be obtained in $(\text{kilometers})^{-1}$.

2. Nitrogen Continuum

Although the nitrogen continuum is not included in this thesis, the magnitude of this effect is of the order of 0.001 km^{-1} at a wavelength of 3.8 μm. The maximum effect which is of the order of 0.1 km^{-1} occurs at a wavelength of 4.3 μm. This effect may be neglected outside the 3.7-4.7 μm region [Ref. 4].

D. AEROSOL EXTINCTION COEFFICIENT

Aerosol extinction includes absorption and scattering by aerosol particles. Although scattering by aerosol particles whose radius is smaller than about 0.03 times the wavelength of the light may be calculated by Rayleigh theory, for the whole range of particle radius Mie theory must be applied. The bases for Mie scattering are the interactions between electromagnetic waves and the electric charges that constitute matter. In the molecular scattering case which was described before, only a single dipole is involved, but in the case of aerosol scattering, a particle consists of many closely packed, complex molecules. Thus it may be considered an array of multipoles, since an aerosol particle is a dispersed system of small particles suspended in the air, such as combustion products, dust grains, bits of sea salt surrounded by water molecules, volcanic ash, etc. The multipoles give rise to secondary electric and magnetic partial waves. In the far field two kinds of waves combine to produce the scattered wave. Interference between two waves is mainly determined by the wavelength of incident light, and the size and relative refractive index of the particle. A useful parameter used in Mie theory is the size parameter α, a dimensionless quantity defined by the relation

$$\alpha = \frac{2\pi r}{\lambda} = kr \qquad (2\text{-}27)$$

where r is the radius of the scatterer or absorber, and λ is the wavelength of the incident radiation. α is the parameter on which aerosol scattering and absorption depend most strongly, rather than on radius of particle alone or on the wavelength of incident radiation alone. The refractive indices used in calculations are the relative refractive indices of the aerosol particles with respect to the refractive index of the medium surrounding the particles. Since air has refractive index very close to unity, the relative refractive index is assumed equal to the absolute refractive index of the aerosol particle, and is generally represented by a complex number, where the imaginary part takes care of possible absorption by the particle. The refractive indices of different kinds of particles used in calculations are reproduced and presented in table 10 [Ref. 12], taking into account the wavelength dependence.

Total light scattered or scattered and absorbed by a single particle is given by its total scattering or extinction cross section which is related to the geometric cross section by a parameter generally called the efficiency factor. According to the Mie theory, the scattering and extinction efficiency factors are given by the equations

$$Q_{sc} = \frac{\sigma_{sc}}{\pi r^2} = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} (2n+1)[|a_n|^2+|b_n|^2] \qquad (2\text{-}28)$$

$$Q_{ex} = \frac{\sigma_{ex}}{\pi r^2} = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} (2n+1)[\mathrm{Re}(a_n+b_n)] \qquad (2\text{-}29)$$

Thus the efficiency factor is defined as the ratio of apparent cross section to geometric cross section of the particle. σ_{sc}, σ_{ex} in the above are the apparent scattering and extinction total cross sections respectively. Re represents the real part of the argument. The coefficients a_n, b_n are the complex functions which represent the amplitude of n^{th} electric partial wave and n^{th} magnetic partial wave respectively. These coefficients may be found from Ricatti-Bessel functions for a given complex refractive index and size parameter α.

The scattering efficiency factor approaches the value of two in the short wavelength approximation, which implies that the scattering cross section is almost twice as large as the geometric cross section of the particle.

Since the infinite series represented by equations (2-28) and (2-29) are slowly converging, calculations are generally computer time consuming. For particles with real part of refractive index between 1 and 1.5 and imaginary part of refractive index between 0 and 0.25, the Van de Hulst approximation may be used with some correction factors. Within the approximation range, it was reported by Deirmendjian [Ref. 13] that the efficiency factor could be predicted within the precision range of $\pm$ 0.05 Q_{ex}.

The method of calculation using the Van de Hulst approximation is presented in Appendix C.

The efficiency factor of a single particle then may be extended for use in calculation of the aerosol extinction

coefficient due to many particles for a given size distribution such that

$$\beta_a = \frac{\pi}{K^3} \int_{\alpha_1}^{\alpha_2} \alpha^2 Q_{sc} n(\alpha) d\alpha \qquad (2\text{-}30)$$

$$\mu_a = \frac{\pi}{K^3} \int_{\alpha_1}^{\alpha_2} \alpha^2 Q_{ex} n(\alpha) d\alpha \qquad (2\text{-}31)$$

where K is the propagation constant and $n(\alpha)$ is the size distribution defined by equations (1-6) and (2-27).

Once the aerosol scattering and extinction coefficients are determined, then the aerosol absorption coefficient may be found from $K_a = \mu_a - \beta_a$, if needed.

Size distributions used here for calculation of aerosol extinction coefficient are a) equation (1-6a) which is independent of wind velocity and relative humidity having 75% sea spray and 25% rural aerosol mixture which is composed of 30% dustlike and 70% water soluble substance. b) equation (1-6b) which adds the effects of wind velocity and relative humidity.

If the total number of particles is not known, then the size distribution $n(\alpha)$ or $n(r)$ is generally normalized to one particle per cubic centimeter. Whatever value the size distribution is normalized to we can put a normalization constant into equations (2-30) and (2-31). Thus we may write

$$\beta_a = C \frac{\pi}{K^3} \int_{\alpha_1}^{\alpha_2} \alpha^2 Q_{sc} n(\alpha) \, d\alpha$$

where C is the normalization constant and may be found from the relation [Ref. 19]

$$R = \frac{3.9}{\beta_a(0.55 \ \mu m)}$$

Here R is the visibility in kilometers providing $\beta_a(0.55)$ in inverse kilometers.

Therefore knowing the range R for visibility, the aerosol scattering coefficient can be found from the equation above. The aerosol scattering coefficient at 0.55 micrometers calculated by equation (2-30) then allows determination of the value of the normalization constant C. Once C is determined at 0.55 micrometers, it is the same for the whole range of wavelengths.

Since aerosol absorption by particles is much less than scattering, the visibility range may also be written as

$$R = \frac{3.9}{\mu_a \ (0.55 \ \mu m)}$$

The curves of extinction coefficient versus wavelength for varied wind speed and relative humidity shown as figures 10 and 11 are normalized so that the total aerosol extinction coefficient at 0.55 μm is 0.17 km^{-1}. This corresponds to a visibility of 23 kilometers.

III. ALGORITHM FOR CALCULATION OF MOLECULAR ABSORPTION COEFFICIENT

The computer program presented as Appendix A is intended to calculate the molecular absorption coefficient including the water vapor continuum effect. As described in Section II.B, the program reads the line parameters (ν_{ij}, α_{ij}, S_{ij}) from a magnetic tape. However, other inputs of the program are the amounts of the air molecules which have to be specified in the units of molecules per square centimeter per kilometer path, and they should be supplied by the user.

The amounts of different types of air molecules excluding the ozone and water vapor are calculated from the ideal gas law,

$$P = \rho R T$$

where P is air pressure in Newtons per square meter, T is air temperature in degrees Kelvin, R is the gas constant for air in Joules per kilogram per degree Kelvin and has the value of 287.06 Joules per kilogram per degree Kelvin. For given values of pressure and temperature, the density of air can be found in the units of kilograms per cubic meter. Then the density of air is used to find the amounts of the uniformly mixed gases (O_2, N_2, CO_2, CO, N_2O, CH_4) such that

$$\rho_i = X_i \, 10^{-6} \, \rho_{air}$$

where X_i is the concentration in PPM by volume taken from table 4, and ρ_i is the density or the mass per unit volume of the corresponding constituent. After finding the amount of a given type of molecule in air in the units of mass per unit volume, it is necessary to convert it to the units of molecules per unit volume to be able to use it in the computer program. This can be done through the relation

$$W_i = \frac{\rho_i \, N_A}{M_i \, 10^{-3}} ,$$

where ρ_i has the units of kilograms per cubic meter, N_A is Avagadro's number which is $6.023 \times 10^{+23}$ molecules per mole and M_i is the molecular weight in grams per mole of the corresponding constituent. Now the amount of the i^{th} constituent of air is given by the formula above in units of molecules per cubic meter. Final conversion may be made into units of molecules per square centimeter per kilometer which may be used directly as input to the computer program presented in Appendix A. W_i may also be expressed in terms of P and T as

$$W_i = 2.0982 \times 10^{19} \frac{P}{T} \frac{X_i}{M_i} \qquad (3\text{-}1)$$

where P is air pressure in millibars, T is temperature in degrees Kelvin, X_i and M_i are as defined before. Now W_i is the amount in molecules per square centimeter per kilometer for the i^{th} type of air molecules.

Using the equation (3-1), the amount of carbon dioxide which has $X_i = 330$ and $M_i = 44$ is 5.5943×10^{20} molecules per square centimeter per kilometer in the air where P = 1017.5 millibars and T = 286.22 degrees Kelvin.

The densities of non uniformly mixed gases are more complicated to determine. For ozone at sea level, it is taken as 6×10^{-5} grams per cubic meters or 7.5288×10^{16} molecules per square centimeter per kilometer at any given temperature and pressure.

The amount of water vapor and its partial pressure can be found from the dew point temperature or relative humidity in the air [Ref. 15]. Different dew point temperatures and corresponding density and partial pressure of water vapor are tabulated in table 11.

The water vapor density determined by interpolating from table 11 may be converted into number density (per square centimeter per kilometer path) as previously described.

IV. RESULTS

Although several band models were introduced by many workers in order to fit the molecular absorption lines in the atmosphere, line by line calculations are made here, making use of the experimentally found and compiled data. The molecular absorption coefficient is the most important attenuation coefficient to be calculated, since mainly it is the one which determines the atmospheric windows which are good enough for propagation of light. Also it depends strongly on the frequency of propagation. For any frequency of laser radiation, the molecular absorption coefficient can not be computed by interpolating between two close, known values. It can be computed either by the line by line method (infinite resolution) or by interpolation from calculations with resolution less than 0.01 cm^{-1}. Therefore the reported values of molecular absorption coefficients may be used directly. If any other frequency or condition is needed, the computer program presented as Appendix A may be used. Atmospheric windows in the 3-5 micrometer and 8-14 micrometer regions are mainly available for atmospheric transmission. HF/DF laser wavelengths fall in the near and middle infrared region of the spectrum. In particular the $P_2(8)$ transition of the DF laser with wavelength 3.8007 micrometers shows relatively high transmittance falling in the 3-5 micrometer region of the spectrum. The molecular

absorption coefficient for this particular wavelength is 0.0104 km^{-1} in the midlatitude winter model where the molecular scattering coefficient is essentially zero. This shows 99 percent transmittance along a one kilometer path.

Calculations intended for use in the propagation studies in the Monterey Bay area make use of the known range of conditions in Monterey, taking into account the yearly and monthly averages of air pressure, air temperature and dew point temperature in the Monterey Bay area. These yearly and monthly averages are taken from [Ref. 16] and [Ref. 17]; the quantities used in calculations are tabulated in table 12. In this table the mean temperature is used which is the mean value of maximum and minimum average temperatures corresponding to day/night condition.

Also the amounts of air constituents used in the calculations are reported in table 17.

Table 9 shows the calculated molecular absorption for some selected wavelengths for the midlatitude winter model, using the computer program presented in Appendix A. Table 13 contains the molecular absorption coefficients for yearly averages in the Monterey Bay area.

Tables 14, 15, 16 show the molecular scattering and absorption at 1.06, 3.8007 and 10.591033 micrometers respectively for the monthly averages in the Bay area. Since the molecular scattering is negligible, it is assumed to be zero at 3.8007 and 10.591033 micrometers.

The aerosol extinction coefficients are calculated for the rural and maritime models using the size distribution given by equation (1-6a) and presented in figure 8 and figure 9 respectively. The maritime model with 75% sea spray is normalized so that the total number of particles is about 44 per cubic meter. These results agree with the previously reported values [Ref. 12] within 1.8 percent.

The relative humidity and wind velocity dependent size distribution is used in figure 10 and figure 11, normalizing the curves to a visibility of 23 kilometers. In both figures 71% sea spray and 29% rural aerosols are assumed. Although at 0.55 micrometers, the rural aerosol refractive indices are outside the approximation range, the results seem to be valid since the percentage of rural aerosols is low.

As seen in figure 10, increasing wind speed increases the attenuation in the longer wavelength region. Similarly in figure 11, increasing relative humidity increases the attenuation in the longer wavelength region.

Figures 12 through 19 show the transmittance along a path length of 10 kilometers, due to the molecular absorption only.

Figures 12, 14, 16, 18 are produced, using a spectral resolution of 0.01 cm^{-1} for use with laser sources.

A degraded resolution is used in figures 13, 15, 17, 19 by averaging the transmittance at each point over a spectral

bandwidth of 0.5 cm^{-1}. Therefore the figures 13, 15, 17, 19 are for use with the broadband sources only.

Each one of the figures 12, 13, 16, 17, 18, 19 covers a spectral interval of about 25 cm^{-1} near the wavelength of 3.8 micrometers (i.e., 2631.09 cm^{-1}). The figures 14 and 15 are for the region about the wavelength of 10.6 micrometers (i.e., 943.936 cm^{-1}).

Figures 12 through 15 show the transmittances for yearly averages in the Monterey Bay area.

Figures 16 through 19 are produced for the different partial pressures of water vapor, having the same air temperature of 290 degrees Kelvin and the air pressure of 1018 millibars. The partial pressure of water vapor in figures 16 and 17 is 7.48 mbars, and it is 15.48 mbars in figures 18 and 19.

Using the high resolution of 0.01 cm^{-1} and a degraded resolution, a sensitivity analysis due to the air pressure, temperature and partial pressure of water vapor has been carried out near the wavelength of 3.8 micrometers.

It has been observed that the change in the air pressure and/or temperature which could affect the line widths, line intensities and amounts of the absorbing air molecules, does not contribute to the transmittance significantly, at the region near 3.8 micrometers. The reason could be the small number of absorbing lines which are mostly due to water vapor. Comparing figures 12, 16, 18 or

figures 13, 17, 19 it can easily be seen that the change of the partial pressure of water vapor effects the transmittance significantly. 8 millibars change in the partial pressure of water vapor changes the transmittance of the order of 6-7 percent at 3.8 micrometers region.

```
//MOABS16 JOB (1884,0534,WS72,,20),'NUSRET1',TIME=5
// EXEC FORTCLG,REGION.GO=250K
//FORT.SYSIN DD *
C      ************************21  AUGUST  1978 ************************
C      THIS PROGRAM COMPUTES THE ABSORPTION DUE TO MOLECULES IN THE
C      ATMOSPHERE .
C      THIS PROGRAM READS THE LINE PARAMETERS FROM DATA COMPILED IN A
C      MAGNETIC TAPE .
C      THE TAPE HAS TOTAL 321 RECORDS , EACH CONTAINING AN INITIAL
C      CONTROL WORD WHICH INDICATES NUMBER OF WORDS TO FOLLOW AND
C      FOLLOWING 40 CARD IMAGES .THE FORMAT TO READ A RECORD IS
C      I10,40(F10.3,E10.3,F5.3,F10.3,5A6,A5,I3,I4,F3.0)
C      I10    (CONTROL WORD WHICH IS USUALLY 40)
C      F10.3  (FREQUENCY IN  1/CM.)
C      E10.3  (INTENSITY IN  1/CM.)
C      F5.3   (LINE WIDTH IN  1/CM.)
C      F10.3  (LOWER STATE ENERGY IN  1/CM.)
C      5A6,A5    (INFORMATION ABOUT WATER AND OZONE . FOR OUR PURPOSES
C      THEY ARE SKIPPED . SINCE IT ALLOWS US TO USE THE TAPE ON IBM/360
C      WITHOUT ANY LANGUAGE CONVERSION )
C      I3    (DATE AT WHICH THE DATUM WAS ENTERED)
C      I4    (INFORMATION ABOUT ISOTOPES ), (E.G.  666 OR 668 OR 686 FOR
C      OZONE)
C      F3.0 (IDENTIFICATION NUMBER OF MOLECULE ,,
C      1   FOR H2O
C      2   FOR CO2
C      3   FOR O3
C      4   FOR N2O
C      5   FOR CO
C      6   FOR CH4
C      7   FOR O2    )
C      DATA IN TAPE IS FREQUENCY ORDERED AND CONTAINED IN  6  FILES.
C      END OF FILE MARKS ARE PUT AT FREQUENCIES 500, 1000, 2000, 5000 .
C      7500 AND AT 10000 1/CM. WITH DOUBLE MARKS .
C
C      ************************************************************
C      THE MAGNETIC TAPE IS LABELED AS  ' AFCRL  ' BY THE USER
C      ************************************************************
C
C
C
C      THIS PROGRAM CAN READ MAXIMUM 5000 LINES
C
C      FRL***LOWER FREQUENCY LIMIT TO BE READ
C      FRU***UPPER FREQUENCY LIMIT TO BE READ
C      FRL+20.0***SHOULD BE LESS THAN LOWEST LASER FREQUENCY AT
```

```
C       WHICH ABSORPTION WILL BE CALCULATED
C       FRU-20.0***SHOULD BE GREATER THAN HIGHEST LASER FREQUENCY AT
C       WHICH ABSORPTION WILL BE CALCULATED
C       PR***PRESSURE IN MBARS
C       TEM***TEMPARATURE IN DEGREES KELVIN
C       A,B,C,D,KD,LI,MO,***INTERMEDIATE VARIABLES TO READ FROM TAPE
C       FR***LINE FREQUENCY
C       S***LINE INTENSITY
C       AL***LINE WIDTH
C       EN***LOWER STATE ENERGY OF LINE
C       MOL***MOLECULE  ID  NUMBER
C       QRR***TEMPERATURE DEPENDENCE OF ROTATIONAL PARTITION FUNCTION
C       FLASER***THE LASER FREQUENCY AT WHICH ABSORPTION WILL BE CALCULATED
C       PUT 0.0 AFTER LAST  CARD FOR FLASER TO STOP THE PROGRAM
C       AMOUNT (MOL. ID. NO.)***AMOUNT OF SPECIFIED ABSORBER IN
C       MOLECULES/CM.2KM.
C       ABT***THE TOTAL ABSORPTION IN THE UNITS OF 1/KM.

C       OPD***THE TRANSMISSION DUE TO ABSORPTION ALONG THE 1 KM. PATH
C
C       IT IS ASSUMED THAT THE LINES INSIDE THE RANGE OF +,-20 1/CM.
C       ABOUT FLASER CONTRIBUTE THE ABSORPTION
C
C
C
C
        REAL A(40),B(40),C(40),D(40),KD(40),LI(40),MO(40)
        DIMENSION FR(5000),S(5000),AL(5000),EN(5000),MOL(5000)
        DIMENSION QRR(7),SUM(7),SUMT(7),ABST(7),AMOUNT(7)
        PI=3.14159
        TS=296.0
        PO=1013.0
        J=0
        READ (5,99) FRL, FRU, PR, TEM, PP
3       READ (2,100) N, (A(I),B(I),C(I),D(I),KD(I),LI(I),MO(I), I=1,N)
100     FORMAT (I10,40(F10.3,E10.3,F5.3,F10.3,35X,I3,I4,F3.0))
        IF (A(N) .LT. FRL) GO TO 3
        DO 10 I=1,N
        M=I+J
        IF (M .EQ. 5001) GO TO 116
        FR(M)=A(I)
        S(M)=B(I)
        AL(M)=C(I)
        EN(M)=D(I)
        MOL(M)=MO(I)
10      CONTINUE
        J=J+N
        IF (A(N) .LE. FRU) GO TO 3
```

```
C       TEMPERATURE DEPENDENCE OF ROTATION PARTITION FUNCTIONS
C       IS CALCULATED HERE
        DO 11 M=1,7
        IF (M .EQ. 1) GO TO 2
        IF (M .EQ. 2) GO TO 1
        IF (M .EQ. 3) GO TO 2
        IF (M .EQ. 4) GO TO 1
        IF (M .EQ. 5) GO TO 1
        IF (M .EQ. 6) GO TO 2
        IF (M .EQ. 7) GO TO 1
2       QRR(M)=(TEM/TS)**1.5
        GO TO 11
1       QRR(M)=(TEM/TS)
11      CONTINUE
        WRITE (6,38)
        WRITE (6,39)
        DO 32 I=1,J
        WRITE (6,33) FR(I),S(I),AL(I),EN(I),MOL(I)
32      CONTINUE
        WRITE (6,30)
        RAL=(PR/PO)*((TS/TEM)**0.5)
        RT=(TEM-TS)/(TEM*TS)
        DO 12 I=1,J
        M=MOL(I)
        S(I)=S(I)*QRR(M)*EXP(1.439*EN(I)*RT)
        AL(I)=AL(I)*RAL
12      CONTINUE
        DO 27 M=1,7
        READ (5,28) AMOUNT(M)
        WRITE (6,28) AMOUNT(M)
27      CONTINUE
6       READ (5,71) FLASER
        IF (FLASER .EQ. 0.0) GO TO 41
        DO 103 M=1,7
        SUM(M)=0.0
        SUMT(M)=0.0
103     CONTINUE
        DO 76 I=1,J
        DIF=ABS(FR(I)-FLASER)
        IF (DIF .GT. 20.0) GO TO 76
        M=MOL(I)
        SUM(M)=(S(I)*AL(I))/(PI*((DIF**2)+((AL(I))**2)))
C       CO2 LINES AT SEA LEVEL ARE ASSUMED HAVE SUPER LORENTZ LINE
C       PROFILE,AND CORRECTIONS ARE MADE HERE.
        IF ( .NOT. (M .EQ. 2)) GO TO 79
        IF (DIF .LE. 0.5) GO TO 79
        IF (DIF .GT. 0.5 .AND. DIF .LE. 0.6) X=1.0-(0.4*(DIF-0.5))
        IF (DIF .GT. 0.6 .AND. DIF .LE. 0.7) X=0.96-(0.7*(DIF-0.6))
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```
      IF (DIF .GT. 0.7 .AND. DIF .LE. 0.8) X=0.89-(0.7*(DIF-0.7))
      IF (DIF .GT. 0.8 .AND. DIF .LE. 0.9) X=0.82-(0.5*(DIF-0.8))
      IF (DIF .GT. 0.9 .AND. DIF .LE. 1.0) X=0.77-(0.7*(DIF-0.9))
      IF (DIF .GT. 1.0 .AND. DIF .LE. 1.2) X=0.70-(0.5*(DIF-1.0))
      IF (DIF .GT. 1.2 .AND. DIF .LE. 1.5) X=0.60-((0.1*(DIF-1.2))/0.3)
      IF (DIF .GT. 1.5 .AND. DIF .LE. 2.0) X=0.5-((0.09*(DIF-1.5))/0.5)
      IF (DIF .GT. 2.0 .AND. DIF .LE. 2.5) X=0.41-(0.14*(DIF-2.0))
      IF (DIF .GT. 2.5 .AND. DIF .LE. 3.0) X=0.34-0.06*(DIF-2.5)
      IF (DIF .GT. 3.0 .AND. DIF .LE. 5.0) X=0.31-(0.02*(DIF-3.0))
      IF (DIF .GT. 5.0 .AND. DIF .LE. 8.0) X=0.29-(0.02*(DIF-5.0))
      IF (DIF .GT. 5.0 .AND. DIF .LE. 8.0) X=0.29-(0.02*(DIF-5.0))
      IF (DIF .GT. 8.0 .AND.DIF .LE. 10.0) X=0.23-(0.02*(DIF-8.0))
      IF (DIF .GT. 10.0 .AND. DIF .LT. 15.0) X=0.19-((0.19*(DIF-10.0))/5
     1.0)
      IF (DIF .GE.15.0) X=0.0
      SUMT(M)=SUMT(M)+X*SUM(M)
      GO TO 76
   79 SUMT(M)=SUMT(M)+SUM(M)
   76 CONTINUE
      ABT=0.0
      DO 18 M=1,7
      ABST(M)=(SUMT(M))*(AMOUNT(M))
      ABT=ABST(M)+ABT
   18 CONTINUE
      WRITE (6,30)
      WRITE (6,84) ABT
C     3-5 MICROMETER H2O CONTINUUM IS CALCULATED HERE.
      PCPK=(18.0*AMOUNT(1))/(6.023E+23)
      IF ( .NOT. (FLASER .GE. 2350.0 .AND. FLASER .LE. 3000.0)) GO TO 7
      IF (FLASER .GE. 2350.0 .AND. FLASER .LT.2400.0) CTS=0.23-((0.043*(
     1FLASER-2350.0))/50.0)
      IF (FLASER .GE. 2400.0 .AND. FLASER .LT.2450.0) CTS=0.187-((0.04*(
     1FLASER-2400.0))/50.0)
      IF (FLASER .GE. 2450.0 .AND. FLASER .LT.2500.0) CTS=0.147-((0.03*(
     1FLASER-2450.0))/50.0)
      IF (FLASER .GE. 2500.0 .AND. FLASER .LT.2550.0) CTS=0.117-((0.02*(
     1FLASER-2500.0))/50.0)
      IF (FLASER .GE. 2550.0 .AND. FLASER .LT.2600.0) CTS=0.097-((0.01*(
     1FLASER-2550.0))/50.0)
      IF (FLASER .GE. 2600.0 .AND. FLASER .LT.2650.0) CTS=0.087+((0.013*
     1(FLASER-2600.0))/50.0)
      IF (FLASER .GE. 2650.0 .AND. FLASER .LT.2700.0) CTS=0.1+((0.02*(FL
     1ASER-2650.0))/50.0)
      IF (FLASER .GE. 2700.0 .AND. FLASER .LT.2750.0) CTS=0.12+((0.027*(
     1FLASER-2700.0))/50.0)
      IF (FLASER .GE. 2750.0 .AND. FLASER .LT.2800.0) CTS=0.147+((0.03*(
     1FLASER-2750.0))/50.0)
      IF (FLASER .GE. 2800.0 .AND. FLASER .LT.2850.0) CTS=0.174+((0.026*
```

```
     1(FLASER-2800.0))/50.0)
      IF (FLASER .GE. 2850.0 .AND. FLASER .LT.2900.0) CTS=0.2+((0.04*(FL
     1ASER-2850.0))/50.0)
      IF (FLASER .GE. 2900.0 .AND. FLASER .LT.2950.0) CTS=0.24+((0.04*(F
     1LASER-2900.0))/50.0)
      IF (FLASER .GE. 2950.0 .AND. FLASER .LE.3000.0) CTS=0.28+((0.05*(F
     1LASER-2950.0))/50.0)
      CST=CTS*EXP(-1350.0*RT)
      ABT=ABT+((0.88*PP+0.12*PR)*CST*PCPK)/1013.0
      GO TO 8
C     8-14  MICROMETER H2O CONTINUUM IS CALCULATED HERE .
7     IF ( .NOT. (FLASER .GE. 700.0 .AND. FLASER .LE. 1250.0)) GO TO 8
      CS2=4.18+5578.0*EXP((-7.87E-03)*FLASER)
      CS1=CS2*EXP(-1800.0*RT)
      CN1=0.002*CS2
      ABT=ABT+((CS1*PP+CN1*(PR-PP))*PCPK)/PO
8     OPD=100.0*EXP(-ABT)
      WRITE (6,31) PR,TEM,PP
      WRITE (6,34) FLASER
      WRITE (6,83) ABT
      WRITE (6,35) OPD
      GO TO 6
116   WRITE (6,117)
41    CONTINUE
28    FORMAT ( E10.3)
30    FORMAT ('1')
31    FORMAT ( ' PRESSURE = ',F10.3,2X,'MBARS',6X,'TEMPARATURE =',F7.2,
     12X,'DEGREES KELVIN',8X,' PARTIAL PRESSURE OF H2O = ',F8.3,2X,'MBAR
     2S ',//)
33    FORMAT ( F10.3,10X,E10.3,15X,F5.3,15X,F10.3,18X,I3)
34    FORMAT ( ' FREQUENCY AT WHICH ABSORPTION IS CALCULATED =',F10.3,
     12X,'1/CM.',//)
35    FORMAT ( /,' TRANSMITTANCE ALONG 1 KM. PATH LENGTH =',F6.2,2X,
     1'%')
38    FORMAT ( //,20X,' LINES  RESPONSIBLE   FROM   ABSORPTION ')
39    FORMAT ( /, 'FREQUENCY IN 1/CM.',2X,'INTENCITY IN 1/CM.',2X,'LINE
     1WIDTH IN 1/CM.',2X,'LOWER STATE ENERGY IN 1/CM.',2X,'MOL. ID NO')
71    FORMAT ( F10.3)
83    FORMAT ( //,' ABSORPTION DUE TO MOLECULES =',E9.3,2X,'1/KM.')
84    FORMAT (//,' ABSORPTION WITHOUT H2O CONTINUUM = ',E9.3,2X,' 1/KM')
99    FORMAT ( F10.3,F10.3,F10.3,F7.2,F8.3)
117   FORMAT ( ' DIMENSION EXCEEDED ')
      STOP
      END
//GO.FT02F001 DD UNIT=2400,VOL=SER=AFCRL,DISP=(OLD,PASS),
//    LABEL=(4,NL,,IN),DCB=(RECFM=F,BLKSIZE=3210)
//GO.SYSIN DD *
  3063.000  3151.000  1017.500 286.22  11.48
```

29.513E+21
55.924E+19
75.288E+15
47.450E+16
19.973E+16
74.565E+17
48.824E+22
3083.830
3110.340
3122.140
3130.090
0.0

```
C*****************************20 OCTOBER 1978*****************************
C       THIS PROGRAM COMPUTES THE AEROSOL EXTINCTION COEFFICIENT FOR THE
C       MARITIME MODEL USING NPGS LIBRARY SUBROUTINE ' DQATR ' FOR THE
C       INTEGRATION
C       THIS MODEL CONTAINS 100*AM PERCENT SEA SPRAY AND 100*(1-AM)
C       PERCENT RURAL PARTICLES WHICH ARE TWO TYPES DUST LIKE AND WATER
C       SOLUBLE
C       SN(1),SN(2),S(1),S(2),R11(1),R11(2)*** SIZE DISTRIBUTION
C       PARAMETERS FOR RURAL AEROSOLS
C       SN(3),S(3),R11(3)*** SIZE DISTRIBUTION PARAMETERS FOR SEASPRAY
C       RRR*** REAL PART OF REFRACTIVE INDEX
C       RRI*** IMAGINARY PART OF REFRACTIVE INDEX
C       TO INCREASE THE ACCURACY OF INTEGRATING PROCESS INTEGRATION REGION
C       IS DIVIDED TO FIVE PARTS
C       R1-R6**** LIMITS OF INTEGRAL
C       SCL*** SCALE FACTOR.  IF SCL=1 THEN THERE ARE 1000 PARTICLES/CM.3
C       WHILE BETA BECOMES EXTINCTION COEFFICIENT IN ' 1/KM. '
C       SSD*** SIZE DISTRIBUTION FUNCTION
C       CP*** UNCORRECTED EXTINCTION EFFICIENCY
C       Q*** CORRECTED EXTINCTION EFFICIENCY
C
C                       MAIN PROGRAM
C
        EXTERNAL XINTEG
        REAL*8 XINTEG,R,BE,CE,DE,FE,GE,HE,BETA,R1,R2,R3,R4,R5,R6,AUX,WWL
        REAL*8 A,A1,A2,A3,D,FG,RO,G,Q,QP,SSD,R11,SN,S,AM
        REAL*8 RRR,RRI,WL,RR,RI,PI,BER
        COMMON WWL(3),RRR(3),RRI(3),SN(3)
        DIMENSION AUX(1000)
        NEISC=1000
        PI=3.1415927D+0
        SCL=4.38573D-2
        ERO=0.01
        BER=ERO*PI*SCL
        R1=1.0D-3
        R2=1.0D-2
        R3=1.0D-1
        R4=1.0D0
        R5=1.0D+1
        R6=6.0D+1
        READ (5,11) AM
        SN(1)=0.7D0*(1.0D0-AM)
        SN(2)=0.3D0*(1.0D0-AM)
        SN(3)=AM
        WRITE (6,80) AM
        WRITE (6,79) BER
3       DO 77 J=1,3
        READ (5,10) WWL(J),RRR(J),RRI(J)
```

```
77    CONTINUE
      IF (WWL(1) .EQ. 0.0) GO TO 99
      CALL DQATR (R1,R2,ERO,NBISC,XINTEG,CE,IER,AUX)
      IF ( .NOT. (IER .EQ. 0)) GO TO 3
      CALL DQATR (R2,R3,ERO,NBISC,XINTEG,DE,IER,AUX)
      IF ( .NOT. (IER .EQ. 0)) GO TO 3
      CALL DQATR (R3,R4,ERO,NBISC,XINTEG,FE,IER,AUX)
      IF ( .NOT. (IER .EQ. 0)) GO TO 3
      CALL DQATR (R4,R5,ERO,NBISC,XINTEG,GE,IER,ALX)
      IF ( .NOT. (IER .EQ. 0)) GO TO 3
      CALL DQATR (R5,R6,ERO,NBISC,XINTEG,HE,IER,ALX)
      IF ( .NOT. (IER .EQ. 0)) GO TO 3
      BE=CE+DE+FE+GE+HE
      BETA=PI*BE*SCL
      WRITE (6,78) WWL(1),RRR(1),RRI(1),SN(1),RRR(2),RRI(2),SN(2),RRR(3)
     1,RRI(3),SN(3),BETA
      GO TO 3
99    CONTINUE
10    FORMAT ( F10.7,F10.7,F10.7,F10.7)
11    FORMAT ( D10.2)
78    FORMAT (//,' WAVELENGTH IN MICROMETERS = ',F12.7,/,' NREAL = ',F12
     1.7,2X,' NIMAGINARY = ',F12.7,4X,' PERCENTAGE RATIO ',F8.5,/,' NREA
     2L = ',F12.7,2X,' NIMAGINARY = ',F12.7,4X,' PERCENTAGE RATIO ',F8.5
     3,/,' NREAL = ',F12.7,2X,' NIMAGINARY = ',F12.7,4X,' PERCENTAGE RAT
     410 ',F8.5,/,' TOTAL EXTINCTION COEFFICIENT IN 1/KM. = ',D16.4,//)
79    FORMAT ( ' MAXIMUM ERROR IN EXTINCTION = ',D10.3,//)
80    FORMAT (//,F5.3, ' *100  PERCENT SEA SPRAY  MARITIME MODEL ',//)
      STOP
      END
C
C           FUNCTION SUBPROGRAM
C
      DOUBLE PRECISION FUNCTION XINTEG (R)
      REAL*8 XINTEG,R,BE,CE,DE,FE,GE,HE,BETA,R1,R2,R3,R4,R5,R6,AUX,WWL
      REAL*8 A,A1,A2,A3,D,FG,RO,G,Q,QP,SSD,R11,SN,S,AM
      REAL*8 RRR,RRI,WL,RR,RI,PI,BER
      COMMON WWL(3),RRR(3),RRI(3),SN(3)
      DIMENSION R11(3),S(3)
      PI=3.1415927D+0
      R11(1)=0.005D0
      R11(2)=0.005D0
      R11(3)=0.3D0
      S(1)=0.475D0
      S(2)=0.475D0
      S(3)=0.4D0
      XINTEG=0.0D0
      DO 18 I=1,3
      WL=WWL(I)
```

```
      RR=RRR(I)
      RI=RRI(I)
      G=DATAN(RI/(RR-1.0D0))
      A1=2.5D0
      A2=2.04/((1.0+3.0*DTAN(G))*(RR-1.0))
      A3=2.04/((1.0+DTAN(G))*(RR-1.0))
      FG=1.0+4.0*DTAN(G)+3.0*((DTAN(G))**2)
      A=2.0D0*PI*R/WL
      RO=2.0*A*(RR-1.0)
      QP=2.0-((4.0*DCOS(G)*DEXP(-RO*DTAN(G))*DSIN(RO-G))/RO)+(4.0*((DCOS
     1(G)/RO)**2)*(DCOS(2.0*G)-DCOS(RO-2.0*G)*DEXP(-RO*DTAN(G))))
      IF (A .GT. A1 .AND. A .LE. A2) GO TO 12
      IF (A .GT. A2 .AND. A .LE. A3) GO TO 13
      IF (A .GT. A3) GO TO 14
      D=((((RR-1.0)**2)*(1.0+FG))/(1.632*RR))+((0.2*RO-RR+1.0)/((RR-1.0)
     1*FG))
      GO TO 15
12    D=((RR-1.0)*(1.0+FG)*RO)/(8.16*RR)
      GO TO 15
13    D=((RR-1.0)*(1.0+FG))/(2.0*RR*(1.0+(3.0*DTAN(G))))
      GO TO 15
14    D=(2.04*(RR-1.0)*(1.0+FG))/(RR*FG*RO)
15    Q=(1.0+D)*QP
      SSD=(SN(I)/(DLOG(10.0D0)*S(I)*DSQRT(2.0D0*PI)*R))*DEXP(-((DLOG10(R
     1)-DLOG10(R11(I)))**2)/(2.0D0*(S(I)**2)))
      XINTEG=(R**2)*Q*SSD+XINTEG
18    CONTINUE
      RETURN
      END
C                                                                       DQAT  10
CCC   .....................................................................DQAT  20
CCC                                                                     DQAT  30
CCC      SUBROUTINE DQATR                                               DQAT  40
CCC                                                                     DQAT  50
CCC                                                                     DQAT  60
CCC      PURPOSE                                                        DQAT  70
CCC         TO COMPUTE AN APPROXIMATION FOR INTEGRAL(FCT(X), SUMMED     DQAT  80
CCC         OVER X FROM XL TO XU).                                      DQAT  90
CCC                                                                     DQAT 100
CCC      USAGE                                                          DQAT 110
CCC         CALL DQATR (XL,XU,EPS,NDIM,FCT,Y,IER,AUX)                   DQAT 120
CCC         PARAMETER FCT REQUIRES AN EXTERNAL STATEMENT.               DQAT 130
CCC                                                                     DQAT 140
CCC      DESCRIPTION OF PARAMETERS                                      DQAT 150
CCC         XL      - DOUBLE PRECISION LOWER BOUND OF THE INTERVAL.     DQAT 160
CCC         XU      - DOUBLE PRECISION UPPER BOUND OF THE INTERVAL.     DQAT 170
CCC         EPS     - SINGLE PRECISION UPPER BOUND OF THE ABSOLUTE ERROR.DQAT 180
C           NDIM    - THE DIMENSION OF THE AUXILIARY STORAGE ARRAY AUX. DQAT 190
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C                NDIM-1 IS THE MAXIMAL NUMBER OF BISECTIONS OF          DQAT 200
C                THE INTERVAL (XL,XU).                                  DQAT 210
C        FCT     - THE NAME OF THE EXTERNAL DOUBLE PRECISION FUNCTION   DQAT 220
C                  SUBPROGRAM USED.                                     DQAT 230
C        Y       - RESULTING DOUBLE PRECISION APPROXIMATION FOR THE     DQAT 240
C                  INTEGRAL VALUE.                                      DQAT 250
C        IER     - A RESULTING ERROR PARAMETER.                         DQAT 260
C        AUX     - AUXILIARY DOUBLE PRECISION STORAGE ARRAY WITH        DQAT 270
C                  DIMENSION NDIM.                                      DQAT 280
C                                                                       DQAT 290
C    REMARKS                                                            DQAT 300
C       ERROR PARAMETER IER IS CODED IN THE FOLLOWING FORM              DQAT 310
C       IER=0   - IT WAS POSSIBLE TO REACH THE REQUIRED ACCURACY.       DQAT 320
C                 NO ERROR.                                             DQAT 330
C       IER=1   - IT IS IMPOSSIBLE TO REACH THE REQUIRED ACCURACY       DQAT 340
C                 BECAUSE OF ROUNDING ERRORS.                           DQAT 350
C       IER=2   - IT WAS IMPOSSIBLE TO CHECK ACCURACY BECAUSE NDIM      DQAT 360
C                 IS LESS THAN 5, OR THE REQUIRED ACCURACY COULD NOT    DQAT 370
C                 BE REACHED WITHIN NDIM-1 STEPS. NDIM SHOULD BE        DQAT 380
C                 INCREASED.                                            DQAT 390
C                                                                       DQAT 400
C    SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED                      DQAT 410
C       THE EXTERNAL DOUBLE PRECISION FUNCTION SUBPROGRAM FCT(X)        DQAT 420
C       MUST BE CODED BY THE USER. ITS DOUBLE PRECISION ARGUMENT X      DQAT 430
C       SHOULD NOT BE DESTROYED.                                        DQAT 440
C                                                                       DQAT 450
C    METHOD                                                             DQAT 460
C       EVALUATION OF Y IS DONE BY MEANS OF TRAPEZOIDAL RULE IN         DQAT 470
C       CONNECTION WITH ROMBERGS PRINCIPLE. ON RETURN Y CONTAINS        DQAT 480
C       THE BEST POSSIBLE APPROXIMATION OF THE INTEGRAL VALUE AND       DQAT 490
C       VECTOR AUX THE UPWARD DIAGONAL OF ROMBERG SCHEME.               DQAT 500
C       COMPONENTS AUX(I) (I=1,2,...,IEND, WITH IEND LESS THAN OR       DQAT 510
C       EQUAL TO NDIM) BECOME APPROXIMATIONS TO INTEGRAL VALUE WITH     DQAT 520
C       DECREASING ACCURACY BY MULTIPLICATION WITH (XU-XL).             DQAT 530
C       FOR REFERENCE, SEE                                              DQAT 540
C       (1) FILIPPI, DAS VERFAHREN VON ROMBERG-STIEFEL-BAUER ALS        DQAT 550
C           SPEZIALFALL DES ALLGEMEINEN PRINZIPS VON RICHARDSON,        DQAT 560
C           MATHEMATIK-TECHNIK-WIRTSCHAFT, VOL.11, ISS.2 (1964),        DQAT 570
C           PP.49-54.                                                   DQAT 580
C       (2) BAUER, ALGORITHM 60, CACM, VOL.4, ISS.6 (1961), PP.255.     DQAT 590
C                                                                       DQAT 600
C.....................................................................DQAT 610
C                                                                       DQAT 620
      SUBROUTINE DQATR(XL,XU,EPS,NDIM,FCT,Y,IER,AUX)                    DQAT 630
C                                                                       DQAT 640
C                                                                       DQAT 650
      DIMENSION AUX(1)                                                  DQAT 660
      DOUBLE PRECISION AUX,XL,XU,X,Y,H,HH,HD,P,Q,SM,FCT                 DQAT 670
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```
C                                                                       DQAT  680
C       PREPARATIONS OF ROMBERG-LOOP                                    DQAT  690
        AUX(1)=.5D0*(FCT(XL)+FCT(XU))                                   DQAT  700
        H=XU-XL                                                         DQAT  710
        IF(NDIM-1)8,8,1                                                 DQAT  720
    1   IF(H)2,10,2                                                     DQAT  730
C                                                                       DQAT  740
C       NDIM IS GREATER THAN 1 AND H IS NOT EQUAL TO 0.                 DQAT  750
    2   HH=H                                                            DQAT  760
        E=EPS/DABS(H)                                                   DQAT  770
        DELT2=0.                                                        DQAT  780
        P=1.D0                                                          DQAT  790
        JJ=1                                                            DQAT  800
        DO 7 I=2,NDIM                                                   DQAT  810
        Y=AUX(1)                                                        DQAT  820
        DELT1=DELT2                                                     DQAT  830
        HD=HH                                                           DQAT  840
        HH=.5D0*HH                                                      DQAT  850
        P=.5D0*P                                                        DQAT  860
        X=XL+HH                                                         DQAT  870
        SM=0.D0                                                         DQAT  880
        DO 3 J=1,JJ                                                     DQAT  890
        SM=SM+FCT(X)                                                    DQAT  900
    3   X=X+HD                                                          DQAT  910
        AUX(I)=.5D0*AUX(I-1)+P*SM                                       DQAT  920
C       A NEW APPROXIMATION OF INTEGRAL VALUE IS COMPUTED BY MEANS OF   DQAT  930
C       TRAPEZOIDAL RULE.                                               DQAT  940
C                                                                       DQAT  950
C       START OF ROMBERGS EXTRAPOLATION METHOD.                         DQAT  960
        Q=1.D0                                                          DQAT  970
        JI=I-1                                                          DQAT  980
        DO 4 J=1,JI                                                     DQAT  990
        II=I-J                                                          DQAT 1000
        Q=Q+Q                                                           DQAT 1010
        Q=Q+Q                                                           DQAT 1020
    4   AUX(II)=AUX(II+1)+(AUX(II+1)-AUX(II))/(Q-1.D0)                  DQAT 1030
C       END OF ROMBERG-STEP                                             DQAT 1040
C                                                                       DQAT 1050
        DELT2=DABS(Y-AUX(1))                                            DQAT 1060
        IF(I-5)7,5,5                                                    DQAT 1070
    5   IF(DELT2-E)10,10,6                                              DQAT 1080
    6   IF(DELT2-DELT1)7,11,11                                          DQAT 1090
    7   JJ=JJ+JJ                                                        DQAT 1100
    8   IER=2                                                           DQAT 1110
    9   Y=H*AUX(1)                                                      DQAT 1120
        RETURN                                                          DQAT 1130
   10   IER=0                                                           DQAT 1140
        GO TO 9                                                         DQAT 1150
```

```
11 IER=1                                                    DQAT1160
   Y=H*Y                                                    DQAT1170
   RETURN                                                   DQAT1180
   END                                                      DQAT1190
```

APPENDIX C

CALCULATION OF EXTINCTION EFFICIENCY BY USING THE VAN DE HULST APPROXIMATION

This approximation was first developed by Van de Hulst [Ref. 13] following the Huygens principle. It is good for spherical particles of arbitrary size but $|m| \to 1$.

The refractive index of the particle is denoted by m which has real and imaginary parts.

$$m = n_r - in_i$$

Defining the normalized size parameter ρ and absorption parameter g such that

$$\rho = 2\alpha(n_r - 1)$$

$$g = \tan^{-1} \frac{n_i}{n_r - 1} ,$$

the extinction efficiency may be written as

$$Q'_{ex} = 2 - \frac{4 \cos g}{\rho} \exp[-\rho \tan g] \sin(\rho - g)$$

$$+ 4\left(\frac{\cos g}{\rho}\right)^2 \{\cos 2g - \exp[-\rho \tan g] \cos(\rho - 2g)\}$$

This uncorrected extinction efficiency Q'_{ex} overestimates the cross section for small ρ and underestimates it in

varying degrees as ρ approaches and surpasses the value 4.08, corresponding to the first maximum in Q'_{ex}.

A correction to the extinction efficiency is made in the form

$$Q_{ex} = (1 + D)\, Q'_{ex}$$

where D, the correction factor, is given by the expressions

$$D = \frac{(n_r-1)^2}{1.632\, n_r}[f(g)+1] + \frac{0.2\rho-n_r+1}{(n_r-1)f(g)} \quad \text{when} \quad \rho \leq 5(n_r-1)$$

$$D = \frac{(n_r-1)}{8.16\, n_r}[f(g)+1]\rho \quad \text{when} \quad 5(n_r-1) \leq \rho \leq \frac{4.08}{1+3\tan g}$$

$$D = \frac{(n_r-1)}{2n_r(1+3\tan g)}[f(g)+1] \quad \text{when} \quad \frac{4.08}{1+3\tan g} \leq \rho \leq \frac{4.08}{1+\tan g}$$

$$D = \frac{2.04(n_r-1)}{n_r\rho f(g)}[f(g)+1] \quad \text{when} \quad \rho > \frac{4.08}{1+\tan g}$$

where

$$f(g) = 1 + 4\tan g + 3(\tan g)^2$$

Within the limits of

$$1 < n_r \leq 1.5$$

$$0 \leq n_i \leq 0.25$$

Q_{ex} is accurate within an error of about ± 0.05 Q_{ex} for a wide range of sizes and types of index of refraction.

TABLE 1. MODIFICATION FACTOR FOR CO_2 LINES

$\nu - \nu_o$ 1/CM	x
0.0	1.00
0.5	1.00
0.6	0.96
0.7	0.89
0.8	0.82
0.9	0.77
1.0	0.70
1.2	0.60
1.5	0.50
2.0	0.41
2.5	0.34
3.0	0.31
5.0	0.29
8.0	0.23
10.0	0.19
15.0	0.00

TABLE 2. VIBRATIONAL PARTITION FUNCTIONS

MOLECULE	J	TEMPERATURE (DEGREES KELVIN)						
		175	200	225	250	275	296	325
H2O	1.5	1.0000	1.0000	1.0000	1.0000	1.0000	1.000	1.0000
CO2	1.0	1.0095	1.0192	1.0327	1.0502	1.0719	1.093	1.1269
O3	1.5	1.0040	1.0070	1.0130	1.0220	1.0330	1.046	1.0660
N2O	1.0	1.0170	1.0300	1.0480	1.0720	1.1000	1.127	1.1700
CO	1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.000	1.0000
CH4	1.5	1.0000	1.0000	1.0010	1.0020	1.0040	1.007	1.0110
O2	1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.000	1.0010

TABLE 3. SELF BROADENING ABSORPTION COEFFICIENTS FOR WATER VAPOR IN THE 3.5-4.2 MICROMETER REGION

ν	$C_s(\nu,296)$
1/CM	1/(PR.CM)ATM.
2350	0.230
2400	0.187
2450	0.147
2500	0.117
2550	0.097
2600	0.087
2650	0.100
2700	0.120
2750	0.147
2800	0.174
2850	0.200
2900	0.240
2950	0.280
3000	0.330

TABLE 4. CONCENTRATIONS OF UNIFORMLY MIXED GASES IN THE AIR

CONSTITUENT	CONCENTRATION PPM BY VOLUME
CO2	3.300E+2
N2O	2.800E-1
CO	7.500E-2
CH4	1.600E+0
O2	2.095E+5
N2	7.808E+5

TABLE 5. MODELS OF ATMOSPHERE AT SEA LEVEL

MODEL	PRES. MB.	TEMP. DEG. KEL.	DENSITY GR/M3	H2O GR/M3	O3 GR/M3
TROPICAL	1013	300.0	1167	19.0	5.6E-5
MIDLATITUDE SUMMER	1013	294.0	1191	14.0	6.0E-5
MIDLATITUDE WINTER	1018	272.2	1301	3.5	6.0E-5
SUBARCTIC SUMMER	1010	287.0	1220	9.1	4.9E-5
SUBARCTIC WINTER	1013	257.1	1372	1.2	4.1E-5
U.S. STANDARD ATM. ,1962	1013	288.1	1225	5.9	5.4E-5

TABLE 6. SIZE DISTRIBUTION PARAMETERS OF AEROSOL MODELS

MODEL	N_1	r_1	σ_1	N_2	r_2	σ_2
RURAL	0.9999975	0.005μ	0.475	2.5E-6	0.5μ	0.475
URBAN	0.9999975	0.005μ	0.475	2.5E-6	0.5μ	0.475
MARITIME (CONTINENTAL)	1	0.005μ	0.475			
MARITIME (SEA SPRAY)	1	0.3μ	0.4			

N IS NORMALIZED TO 1 PARTICLE/CM3

TABLE 7. HF LASER FREQUENCIES [10]

VIBRATIONAL TRANSITION ID	ROTATIONAL TRANSITION ID	EMISSION FREQUENCY (1/CM)
1-0	P6	3693.50
	P7	3644.16
	P8	3593.80
	P9	3542.20
	P10	3489.59
	P11	3436.12
	P12	3381.50
	P13	3326.21
	P14	3269.90
	P15	3212.80
2-1	P2	3708.86
	P3	3666.38
	P4	3622.71
	P5	3577.47
	P6	3531.31
	P7	3483.63
	P8	3435.17
	P9	3385.34
	P10	3334.55
	P11	3282.86
	P12	3230.18
	P13	3176.60
	P14	3122.14
	P15	3067.22
3-2	P2	3544.51
	P3	3503.80
	P4	3461.54
	P5	3418.16
	P6	3373.46
	P7	3327.73
	P8	3280.64
4-3	P5	3262.53
	P6	3219.50

TABLE 7. HF LASER FREQUENCIES [10] (Continued)

	P7	3175.34
	P8	3130.09
	P9	3083.83
5–4	P4	3150.67
	P5	3110.34
	P6	3068.63
	P7	3026.21
	P8	2982.51
	P9	2937.79
6–5	P5	2961.68
	P6	2921.74
	P7	2880.70
	P8	2838.59

TABLE 8. DF LASER FREQUENCIES [4]

VIBRATIONAL TRANSITION ID	ROTATIONAL TRANSITION ID	EMISSION FREQUENCY (1/CM)
1-0	P1	2884.934
	P2	2862.652
	P3	2839.779
	P4	2816.362
	P5	2792.437
	P6	2767.914
	P7	2743.028
	P8	2717.536
	P9	2691.409
	P10	2665.200
	P11	2638.396
	P11	2611.125
	P10	2584.910
	P14	2557.090
	P15	2527.060
	P16	2498.020
2-1	P3	2750.050
	P4	2727.380
	P5	2703.980
	P6	2680.280
	P7	2655.970
	P8	2631.090
	P9	2605.870
	P10	2580.160
	P11	2553.970
	P1I	2527.470
	P13	2500.320
	P16	2417.270
3-2	P3	2662.170
	P4	2640.040
	P5	2617.410
	P6	2594.230
	P7	2570.510

TABLE 8. DF LASER FREQUENCIES [4] (Continued)

	P8	2546.370
	P9	2521.810
	P10	2496.610
	P11	2471.340
	P12	2445.290
	P13	2419.020
	P14	2392.460
4-3	P5	2532.500
	P6	2509.860
	P7	2486.830
	P8	2463.250
	P9	2439.290
	P10	2414.890
5-4	P7	2404.630
7-6	P8	2222.680
	P10	2177.990
	P11	2155.030
	P12	2131.680
8-7	P7	2165.930
	P8	2144.800
	P9	2123.240
	P10	2101.270
	P11	2056.140
	P10	2033.010
9-8	P6	2108.480
	P7	2088.340
	P8	2067.760
	P10	2025.360
	P11	2003.560
	P12	1981.380

TABLE 9. MIDLATITUDE WINTER MODEL MOLECULAR ABSORPTION COEFFICIENTS FOR INFINITE RESOLUTION

FREQUENCY (1/CM)	MOLECULAR ABSORPTION COEFFICIENT (1/KM)
924.975	4.27E-1
942.384	6.17E-2
944.195	6.61E-2
945.981	6.66E-2
947.743	7.22E-2
959.393	3.45E-2
973.289	7.49E-2
974.623	6.96E-2
975.931	1.32E-1
977.215	7.28E-2
1046.854	8.27E-2
1048.661	8.97E-2
1050.441	9.81E-2
1075.988	8.90E-2
1077.303	8.21E-2
1078.591	7.87E-2
2177.990	3.89E-2
2414.890	1.16E-2
2463.250	1.26E-2
2611.125	7.19E-2
2617.410	7.19E-3
2631.090	1.04E-2
2638.396	7.90E-2
2640.040	1.67E-2
2655.970	2.24E-2
2662.170	1.24E-2
2665.200	1.64E-2
2703.980	9.55E-3
2717.536	3.37E-2
2727.380	1.38E-2
2743.028	1.16E-2
2750.050	1.61E-2

TABLE 10. REFRACTIVE INDICES OF AEROSOL PARTICLES [Ref. 12]

WAVELENGTH	WATER SOLUBLE		DUST LIKE		SOOT LIKE		OCEANIC	
(μm)	n_r	n_i	n_r	n_i	n_r	n_i	n_r	n_i
0.2	1.530	0.070	1.53	0.070	1.50	0.35	1.429	2.87E-5
0.25	1.530	0.030	1.53	0.030	1.62	0.45	1.404	1.45E-6
0.3	1.530	0.008	1.53	0.008	1.74	0.47	1.395	5.83E-7
0.3371	1.530	0.005	1.53	0.008	1.75	0.47	1.392	1.20E-7
0.4	1.530	0.005	1.53	0.008	1.75	0.46	1.385	9.90E-9
0.488	1.530	0.005	1.53	0.008	1.75	0.45	1.382	6.41E-9
0.5145	1.530	0.005	1.53	0.008	1.75	0.45	1.381	3.70E-9
0.55	1.530	0.006	1.53	0.008	1.75	0.44	1.381	4.26E-9
0.6328	1.530	0.006	1.53	0.008	1.75	0.43	1.377	1.62E-8
0.6943	1.530	0.007	1.53	0.008	1.75	0.43	1.376	5.04E-8
0.86	1.520	0.012	1.52	0.008	1.75	0.43	1.372	1.09E-6
1.06	1.520	0.017	1.52	0.008	1.75	0.44	1.367	6.01E-5
1.3	1.510	0.020	1.46	0.008	1.76	0.45	1.365	1.41E-4
1.536	1.510	0.023	1.40	0.008	1.77	0.46	1.359	2.43E-4
1.8	1.460	0.017	1.33	0.008	1.79	0.48	1.351	3.11E-4
2.0	1.420	0.008	1.26	0.008	1.80	0.49	1.347	1.07E-3
2.25	1.420	0.010	1.22	0.009	1.81	0.50	1.334	8.50E-4
2.5	1.420	0.012	1.19	0.009	1.82	0.51	1.309	2.39E-3
2.7	1.400	0.055	1.18	0.013	1.83	0.52	1.249	1.56E-2
3.0	1.420	0.022	1.16	0.012	1.84	0.54	1.439	1.97E-1
3.2	1.430	0.008	1.22	0.010	1.86	0.54	1.481	6.69E-2
3.3923	1.430	0.007	1.26	0.013	1.87	0.55	1.439	1.51E-2
3.5	1.450	0.005	1.28	0.011	1.88	0.56	1.423	7.17E-3
3.75	1.452	0.004	1.27	0.011	1.90	0.57	1.398	2.90E-3
4.0	1.455	0.005	1.26	0.012	1.92	0.58	1.388	3.69E-3
4.5	1.460	0.013	1.26	0.014	1.94	0.59	1.377	9.97E-3
5.0	1.450	0.012	1.25	0.016	1.97	0.60	1.366	9.57E-3
5.5	1.440	0.018	1.22	0.021	1.99	0.61	1.333	9.31E-3
6.0	1.410	0.023	1.15	0.037	2.02	0.62	1.306	7.96E-2
6.2	1.430	0.027	1.14	0.039	2.03	0.63	1.431	6.91E-2
6.5	1.460	0.033	1.13	0.042	2.04	0.63	1.374	2.94E-2
7.2	1.400	0.070	1.40	0.055	2.06	0.95	1.343	2.49E-2

TABLE 10. REFRACTIVE INDICES OF AEROSOL PARTICLES (Continued)
[Ref. 12]

7.9	1.200	0.065	1.15	0.040	2.12	0.67	1.324	2.79E-2
8.2	1.010	0.100	1.13	0.074	2.13	0.68	1.324	3.08E-2
8.5	1.300	0.215	1.30	0.090	2.15	0.69	1.336	3.36E-2
8.7	2.400	0.290	1.40	0.100	2.16	0.69	1.336	3.56E-2
9.0	2.560	0.370	1.70	0.140	2.17	0.70	1.373	3.65E-2
9.2	2.200	0.420	1.72	0.150	2.18	0.70	1.356	3.71E-2
9.5	1.950	0.160	1.73	0.162	2.19	0.71	1.339	3.68E-2
9.8	1.870	0.095	1.74	0.162	2.20	0.72	1.324	3.88E-2
10.0	1.820	0.090	1.75	0.162	2.21	0.72	1.310	4.06E-2
10.591	1.760	0.070	1.62	0.120	2.22	0.73	1.271	5.22E-2
11.0	1.720	0.050	1.62	0.105	2.23	0.73	1.246	7.31E-2
11.5	1.670	0.047	1.59	0.100	2.24	0.74	1.227	1.05E-1
12.5	1.620	0.053	1.51	0.090	2.27	0.75	1.208	1.90E-1
13.0	1.620	0.055	1.47	0.100	2.28	0.76	1.221	2.23E-1
14.0	1.560	0.073	1.52	0.085	2.31	0.78	1.267	2.71E-1
14.8	1.440	0.100	1.57	0.100	2.33	0.79	1.307	2.92E-1
15.0	1.420	0.200	1.57	0.100	2.33	0.79	1.321	2.97E-1
16.4	1.750	0.160	1.60	0.100	2.36	0.81	1.407	3.31E-1
17.2	2.080	0.240	1.63	0.100	2.38	0.82	1.487	3.41E-1
18.0	1.980	0.180	1.64	0.115	2.40	0.83	1.525	3.41E-1
18.5	1.850	0.170	1.64	0.120	2.41	0.83	1.536	3.39E-1
20.0	2.120	0.220	1.68	0.220	2.45	0.85	1.560	3.24E-1
21.3	2.060	0.230	1.77	0.280	2.46	0.86	1.568	3.18E-1
22.5	2.000	0.240	1.90	0.280	2.48	0.87	1.579	3.16E-1
25.0	1.880	0.280	1.97	0.240	2.51	0.89	1.596	3.13E-1
27.9	1.840	0.290	1.89	0.320	2.54	0.91	1.612	3.20E-1
30.0	1.820	0.300	1.80	0.420	2.57	0.93	1.614	3.20E-1
35.0	1.920	0.400	1.90	0.500	2.63	0.97	1.597	3.16E-1
40.0	1.860	0.500	2.10	0.600	2.69	1.00	1.582	3.61E-1

TABLE 11. WATER VAPOR PRESSURE AND DENSITY FOR DIFFERENT DEW POINT TEMPERATURES

DEW POINT TEMP. (DEG. KEL.)	VAPOR PRESSURE (MILIBARS)	VAPOR DENSITY (GRAMS/M3)
233	0.189	0.176
238	0.314	0.286
243	0.509	0.453
248	0.807	0.705
253	1.254	1.074
258	1.912	1.605
263	2.863	2.358
268	4.215	3.407
273	6.108	4.847
278	8.719	6.797
283	12.273	9.399
288	17.044	12.830
293	23.373	17.500
298	31.671	23.050
303	42.430	30.380
308	56.236	39.630
315	73.777	51.190

TABLE 12. MONTEREY BAY AREA WEATHER CONDITIONS [Refs. 16, 17]

	MEAN PR. (MBARS) 16	MEAN TEMP. (DEG.KEL.) 17	MEAN DEW (DEG.KEL.) 17	H2O PR. (MBARS)	H2O DENSITY (GRAMS/M3)	REL. HUM. (%) 17
JANUARY	1020.0	283.18	279.27	9.51	7.37	77
FEBRUARY	1020.0	283.72	279.83	9.91	7.67	76
MARCH	1017.5	283.99	279.83	9.91	7.67	75
APRIL	1018.0	284.83	281.49	11.09	8.53	77
MAY	1017.0	286.49	282.60	11.87	9.11	77
JUNE	1015.0	287.60	284.27	13.33	10.16	79
JULY	1017.0	287.88	284.83	13.87	10.55	83
AUGUST	1017.5	288.44	285.38	14.39	10.92	84
SEPTEMBER	1013.5	288.99	287.88	13.87	10.55	79
OCTOBER	1017.5	287.88	283.16	12.27	9.40	75
NOVEMBER	1019.0	285.94	280.38	10.30	7.95	72
DECEMBER	1018.0	284.27	279.27	9.51	7.37	73
YEARLY	1017.5	286.22	282.04	11.48	8.82	77

TABLE 13. MOLECULAR ABSORPTION AND SCATTERING COEFFICIENTS FOR YEARLY AVERAGES IN THE MONTEREY BAY AREA

FREQUENCY (1/CM)	TRANSITION ID		MOL. ABS. COEF. (1/KM)	MOL. SCAT. COEF. (1/KM)	TRANS. ALONG 1 KM. PATH (%)
944.195	P(20)	CO2	0.1520	-	85.86
942.384	P(22)	CO2	0.1460	-	86.44
2471.340	P(11)	DF	0.0230	-	97.72
2496.610	P(10)	DF	0.0184	-	98.17
2527.470	P(12)	DF	0.0172	-	98.29
2553.970	P(11)	DF	0.0199	-	98.03
2580.160	P(10)	DF	0.0293	-	97.11
2605.870	P(9)	DF	0.0340	-	96.65
2631.090	P(8)	DF	0.0218	-	97.84
2638.396	P(11)	DF	0.2210	-	80.17
2655.970	P(7)	DF	0.0531	-	94.83
2665.200	P(10)	DF	0.0357	-	96.49
2680.280	P(6)	DF	0.0547	-	94.68
2703.980	P(5)	DF	0.0208	-	97.94
2717.536	P(8)	DF	0.0930	-	91.12
2743.028	P(7)	DF	0.0246	-	97.57
2767.914	P(6)	DF	0.0594	-	94.23
2792.437	P(5)	DF	0.0439	-	95.70
3373.460	P(6)	HF	0.1240	-	88.37
3435.170	P(3)	HF	0.3470	-	70.71
3483.630	P(7)	HF	2.1800	-	11.32
3531.310	P(6)	HF	86.5000	-	0.00
3577.470	P(5)	HF	35.0000	-	0.00
3593.800	P(8)	HF	67.2000	-	0.00
3622.710	P(4)	HF	35.6000	-	0.00
9433.962			0.000014	0.0008283	99.92

TABLE 14. MOLECULAR ABSORPTION AND SCATTERING COEFFICIENT AT 1.06 MICROMETERS IN THE MONTEREY BAY AREA

	MOL. ABS. COEF. (1/KM)	MOL. SCAT. COEF. (1/KM)	TOTAL MOL. EXTINCTION (1/KM)	TRANS. ALONG 1 KM. PATH (%)
JANUARY	9.270E-6	8.393E-4	8.486E-4	99.92
FEBRUARY	9.700E-6	8.377E-4	8.474E-4	99.92
MARCH	9.710E-6	8.349E-4	8.446E-4	99.92
APRIL	10.900E-6	8.328E-4	8.437E-4	99.92
MAY	11.800E-6	8.272E-4	8.390E-4	99.92
JUNE	13.300E-6	8.223E-4	8.361E-4	99.92
JULY	13.900E-6	8.232E-4	8.371E-4	99.92
AUGUST	14.500E-6	8.220E-4	8.365E-4	99.92
SEPTEMBER	14.100E-6	8.172E-4	8.313E-4	99.92
OCTOBER	12.500E-6	8.236E-4	8.361E-4	99.92
NOVEMBER	10.400E-6	8.304E-4	8.408E-4	99.92
DECEMBER	9.410E-6	8.344E-4	8.438E-4	99.92
YEARLY	11.400E-6	8.283E-4	8.397E-4	99.92

TABLE 15. MOLECULAR ABSORPTION COEFFICIENTS AT 3.8007 MICROMETERS IN THE MONTEREY BAY AREA

	MOL. ABS. COEF. (1/KM)	TRANS. ALONG 1 KM. PATH (%)	ORDER OF BEST MONTH TO PROPAGATE
JANUARY	0.0194	98.08	2
FEBRUARY	0.0199	98.02	4
MARCH	0.0199	98.03	3
APRIL	0.0215	97.88	6
MAY	0.0223	97.79	7
JUNE	0.0242	97.61	9
JULY	0.0249	97.54	11
AUGUST	0.0256	97.48	12
SEPTEMBER	0.0247	97.56	10
OCTOBER	0.0227	97.75	8
NOVEMBER	0.0202	98.00	5
DECEMBER	0.0193	98.09	1
YEARLY	0.0218	98.84	

TABLE 16. MOLECULAR ABSORPTION COEFFICIENTS AT 10.591033 MICROMETERS IN THE MONTEREY BAY AREA

	MOL. ABS. COEF. (1/KM)	TRANS. ALONG 1 KM. PATH (%)	ORDER OF BEST MONTH TO PROPAGATE
JANUARY	0.122	88.51	2
FEBRUARY	0.128	88.01	4
MARCH	0.128	88.02	3
APRIL	0.147	86.37	6
MAY	0.159	85.29	7
JUNE	0.185	83.15	9
JULY	0.195	82.32	11
AUGUST	0.204	81.54	12
SEPTEMBER	0.193	82.43	10
OCTOBER	0.165	84.78	8
NOVEMBER	0.133	87.53	5
DECEMBER	0.121	88.57	1
YEARLY	0.152	85.86	

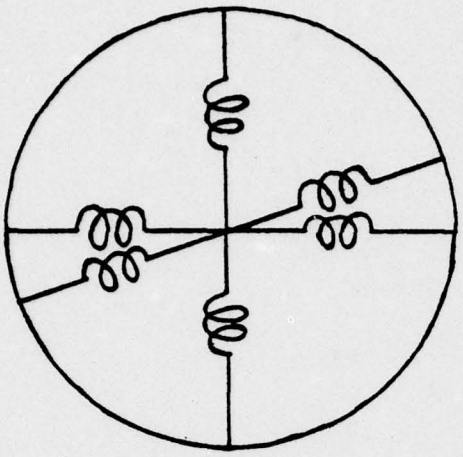
TABLE 17. AMOUNTS OF AIR CONSTITUENTS IN THE MONTEREY BAY AREA

(MOLECULES/CM^2 KM)

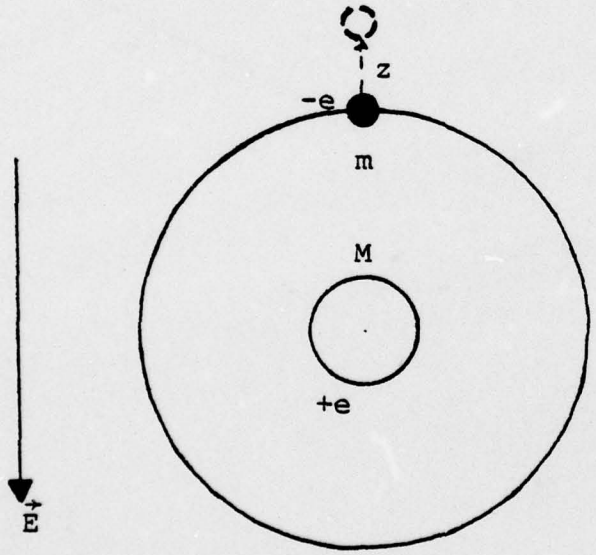
	WATER VAPOR	CARBON DIOXIDE	OZONE	NITROUS DIOXIDE	CARBON MONOXIDE	METHANE	OXYGEN
JANUARY	2.4661E22	5.6683E20	7.5288E16	4.8094E17	2.0244E17	7.5577E18	4.9479E23
FEBRUARY	2.5665E22	5.6574E20	7.5288E16	4.8002E17	2.0205E17	7.5432E18	4.9384E23
MARCH	2.5665E22	5.6380E20	7.5288E16	4.7837E17	2.0136E17	7.5173E18	4.9215E23
APRIL	2.8542E22	5.6244E20	7.5288E16	4.7722E17	2.0087E17	7.4992E18	4.9097E23
MAY	3.0483E22	5.5860E20	7.5288E16	4.7397E17	1.9950E17	7.4480E18	4.8761E23
JUNE	3.3996E22	5.5535E20	7.5288E16	4.7121E17	1.9834E17	7.4047E18	4.8477E23
JULY	3.5301E22	5.5594E20	7.5288E16	4.7170E17	1.9855E17	7.4125E18	4.8529E23
AUGUST	3.6540E22	5.5512E20	7.5288E16	4.7102E17	1.9826E17	7.4017E18	4.8458E23
SEPTEMBER	3.5301E22	5.5187E20	7.5288E16	4.6826E17	1.9710E17	7.3583E18	4.8174E23
OCTOBER	3.1453E22	5.5621E20	7.5288E16	4.7193E17	1.9865E17	7.4161E18	4.8552E23
NOVEMBER	2.6602E22	5.6077E20	7.5288E16	4.7581E17	2.0028E17	7.4770E18	4.4951E23
DECEMBER	2.4661E22	5.6353E20	7.5288E16	4.7814E17	2.0126E17	7.5137E18	4.9191E23
YEARLY	2.9513E22	5.5924E20	7.5288E16	4.7450E17	1.9973E17	7.4565E18	4.8824E23

TABLE 18. AEROSOL EXTINCTION COEFFICIENTS FOR MARITIME MODEL WITH 75% SEA SPRAY AND 25% RURAL AEROSOLS

WAVELENGTH (MICROMETERS)	AEROSOL EXTINCTION COEFFICIENT (1/KM) CALCULATED	AEROSOL EXTINCTION COEFFICIENT (1/KM) REPORTED [Ref. 12]
2.0	0.11330	0.11530
2.5	0.09895	0.09962
2.7	0.08258	
3.0	0.10430	0.10426
3.2	0.10800	
3.3923	0.10250	
3.5	0.09945	0.09899
3.75	0.09299	0.09191
4.0	0.08802	0.08670
4.5	0.07875	
5.5	0.06007	0.05928
6.0	0.05555	0.05485
6.5	0.05825	
7.2	0.04804	0.04758
7.9	0.04105	0.04063
8.2	0.03958	0.03960
8.5	0.03972	0.04045



a.



b.

FIGURE 1. a. MODEL OF AN ELEMENTAL SCATTERER
b. CREATION OF AN INDUCED DIPOLE MOMENT BY AN ELECTRIC FIELD

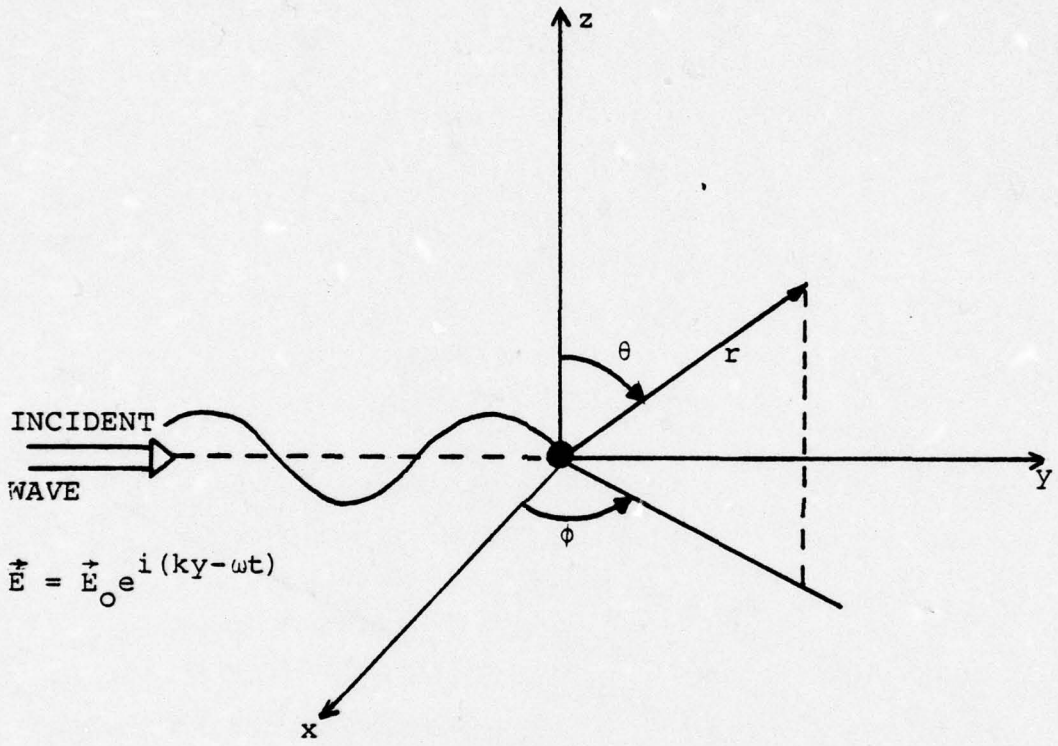


FIGURE 2. THE GEOMETRY OF SCATTERING WITH THE SCATTERER AT THE ORIGIN

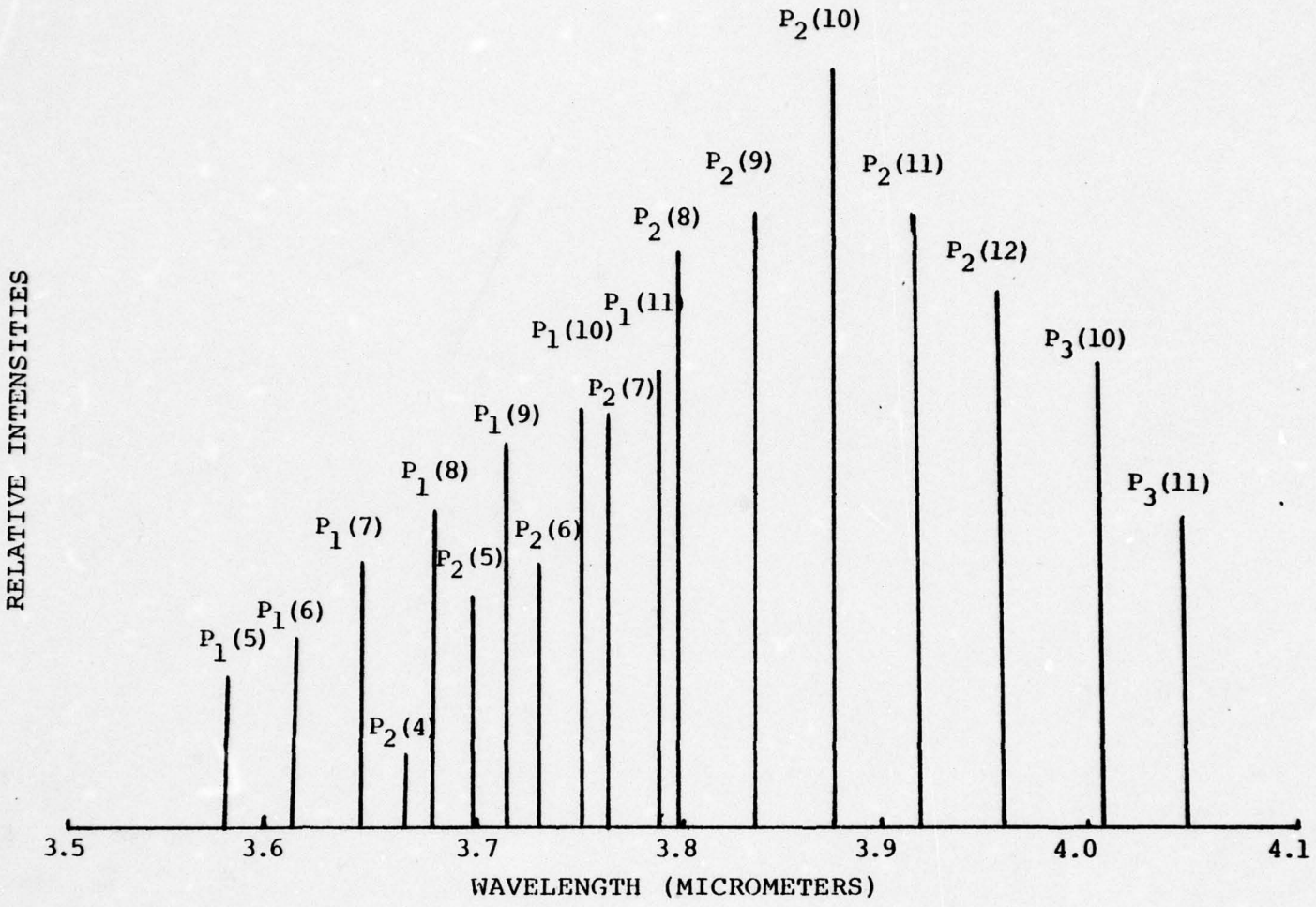


FIGURE 3. RELATIVE INTENSITIES OF DF LASER WAVELENGTHS PRODUCED IN THE CAVITY

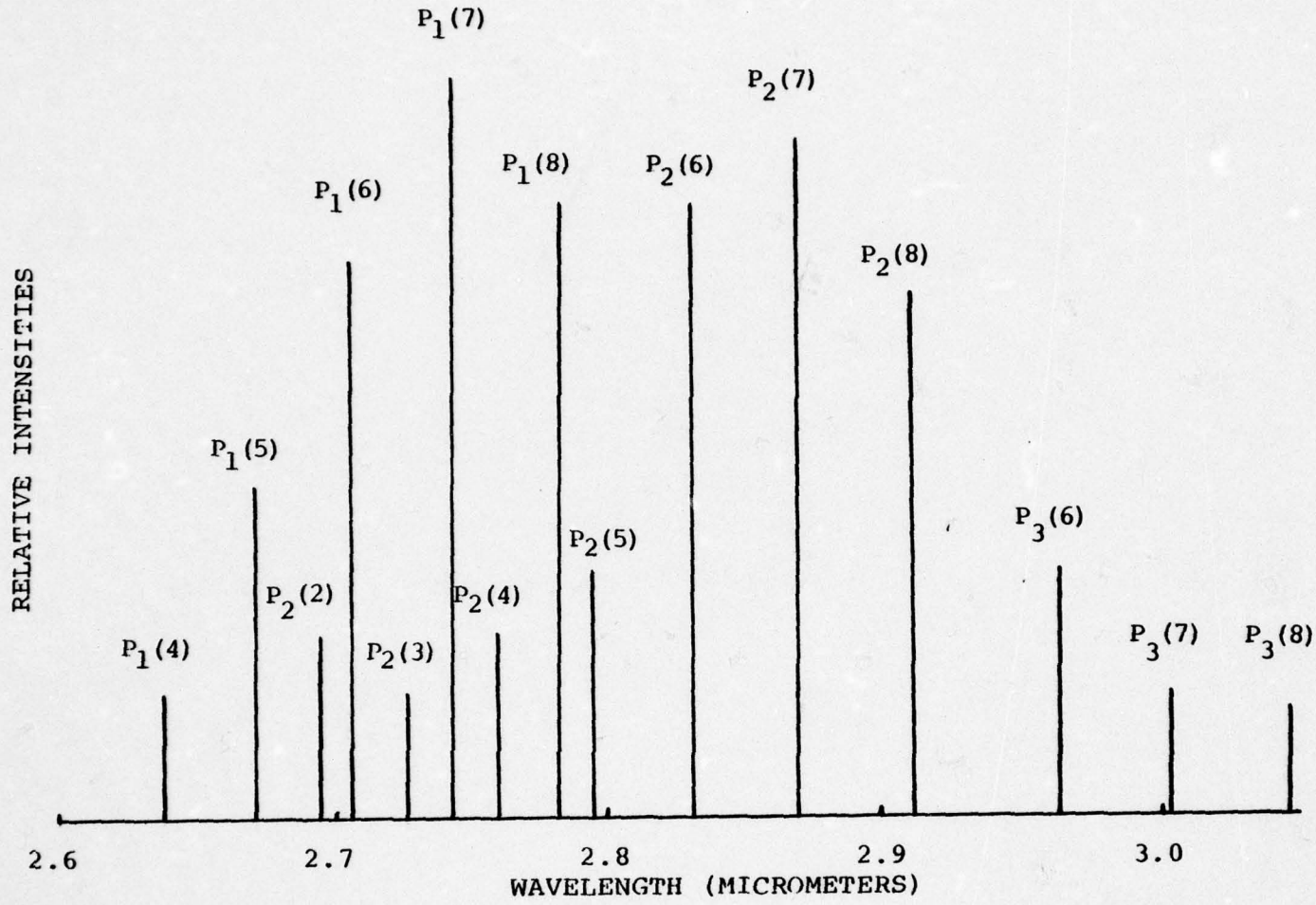


FIGURE 4. RELATIVE INTENSITIES OF HF LASER WAVELENGTHS PRODUCED IN THE CAVITY

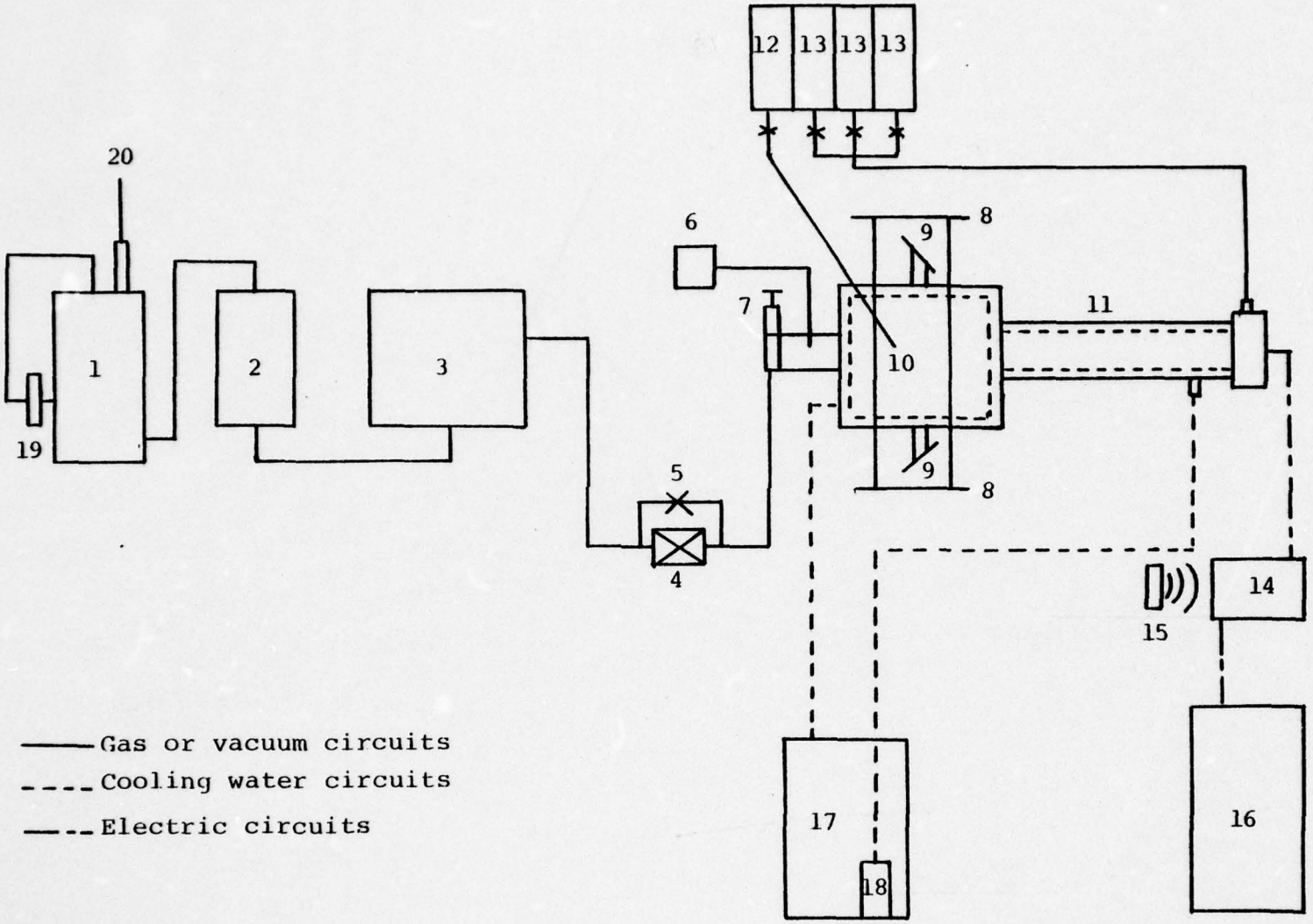


FIGURE 5. HF/DF LASER SYSTEM BLOCK DIAGRAM

1 Vacuum pump

2 Charcoal filter

3 Scrubber

4 Scrubber-vacuum valve

5 By-pass valve

6 Cavity pressure gauge

7 Cavity vacuum valve

8 Optical resonator mirrors

9 Brewster windows

10 Cavity

11 Electric discharge tube

12 H_2 or D_2 gas tank

13 SF_6, O_2, He gas tanks

14 Ballast resistors

15 Ballast resistor cooling fans

16 D.C. power supply

17 Water tank

18 Cooling water pump

19 Oil filter

20 Gas outlet to atmosphere

FIGURE 5. HF/DF LASER SYSTEM BLOCK DIAGRAM (Continued)

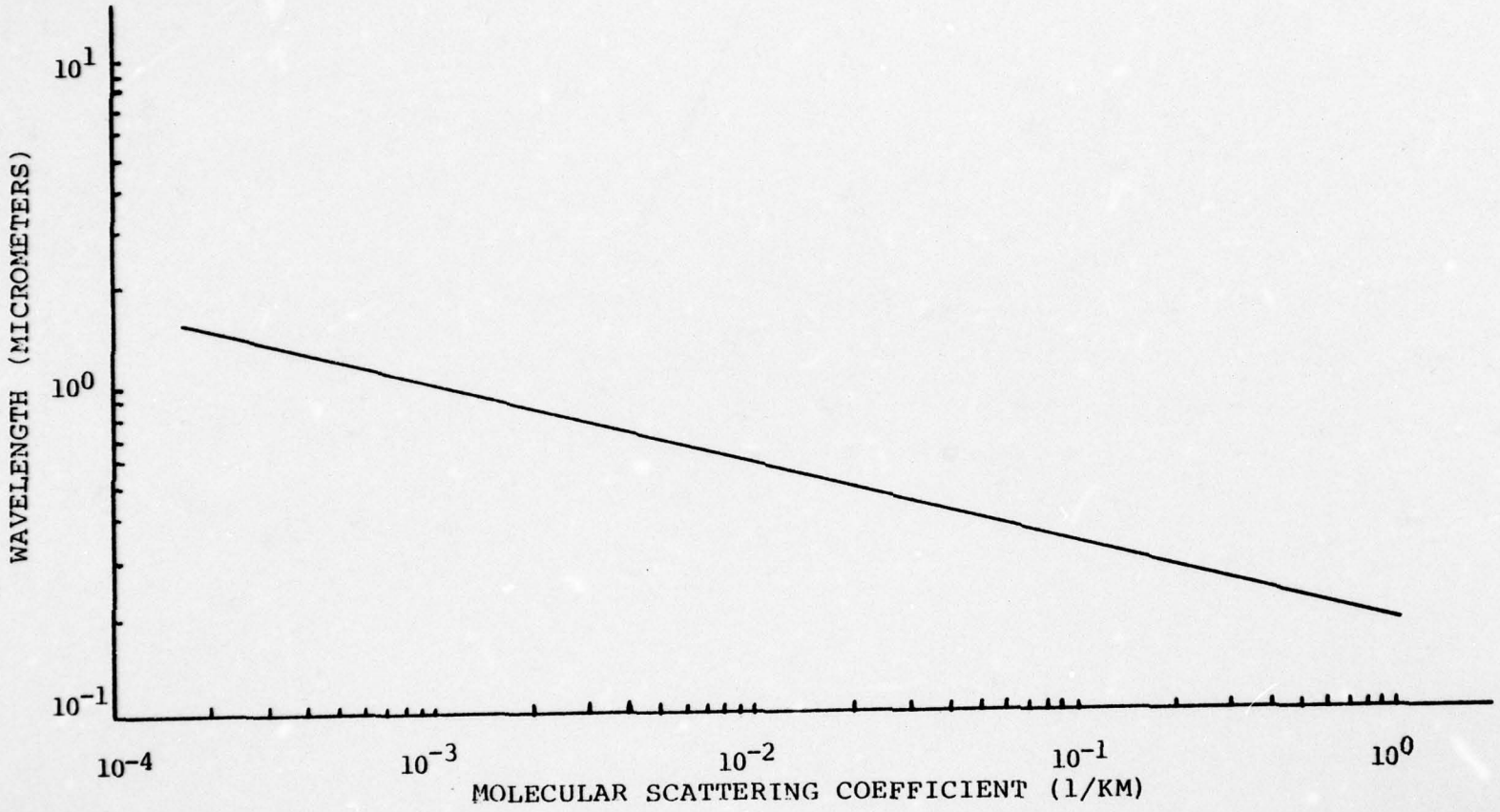


FIGURE 6. MIDLATITUDE WINTER MODEL MOLECULAR SCATTERING COEFFICIENTS

AD-A066 360 NAVAL POSTGRADUATE SCHOOL MONTEREY CALIF F/G 4/1
HIGH RESOLUTION COMPUTER CALCULATION OF OPTICAL TRANSMITTANCE A--ETC(U)
DEC 78 N GUNER

UNCLASSIFIED NL

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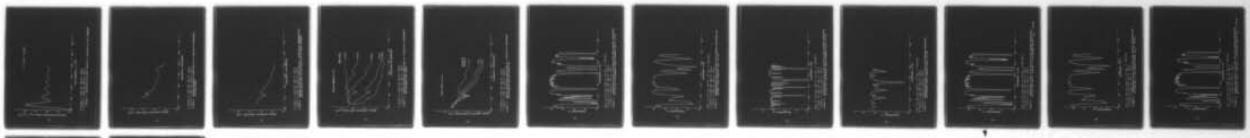

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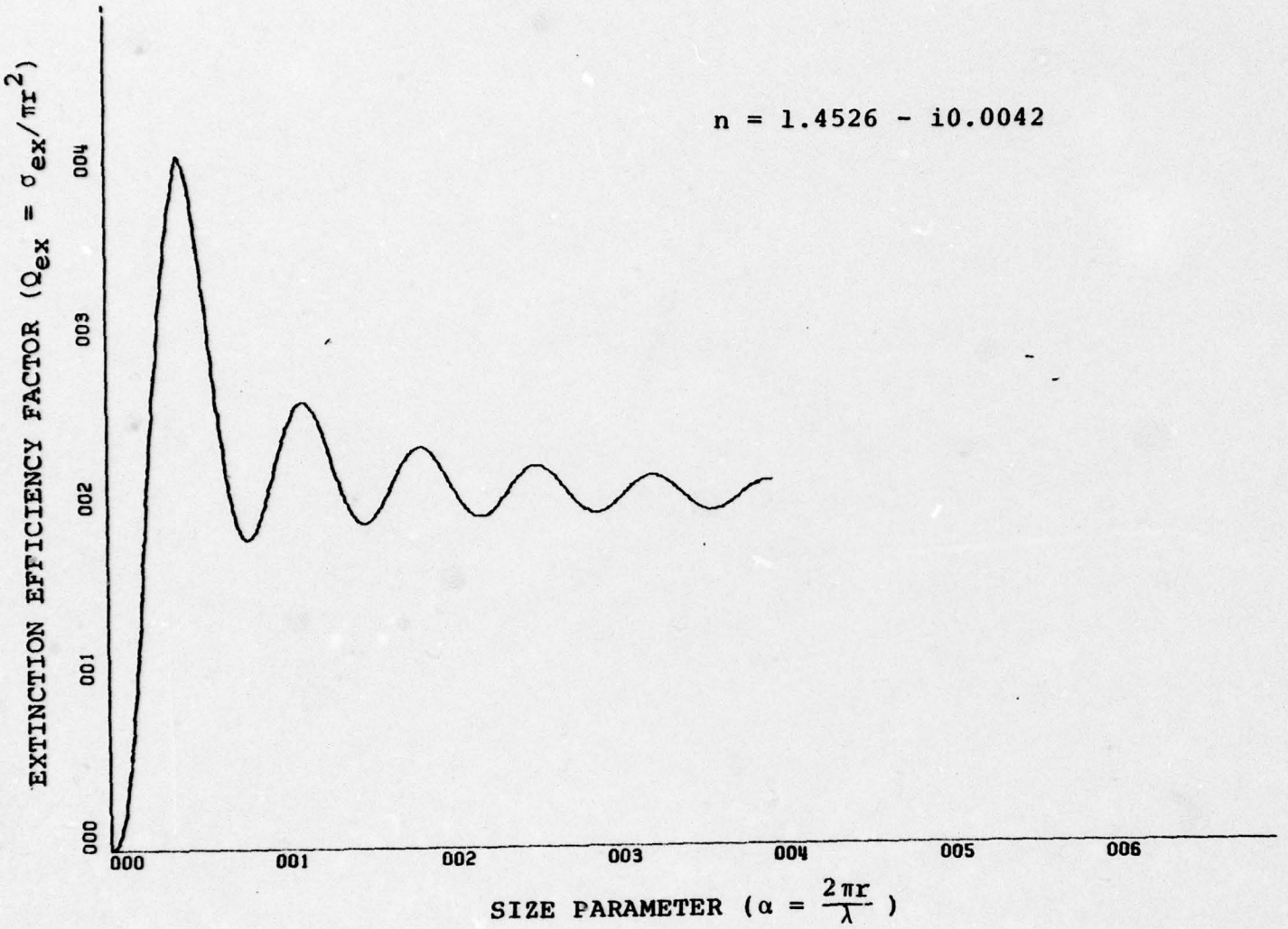
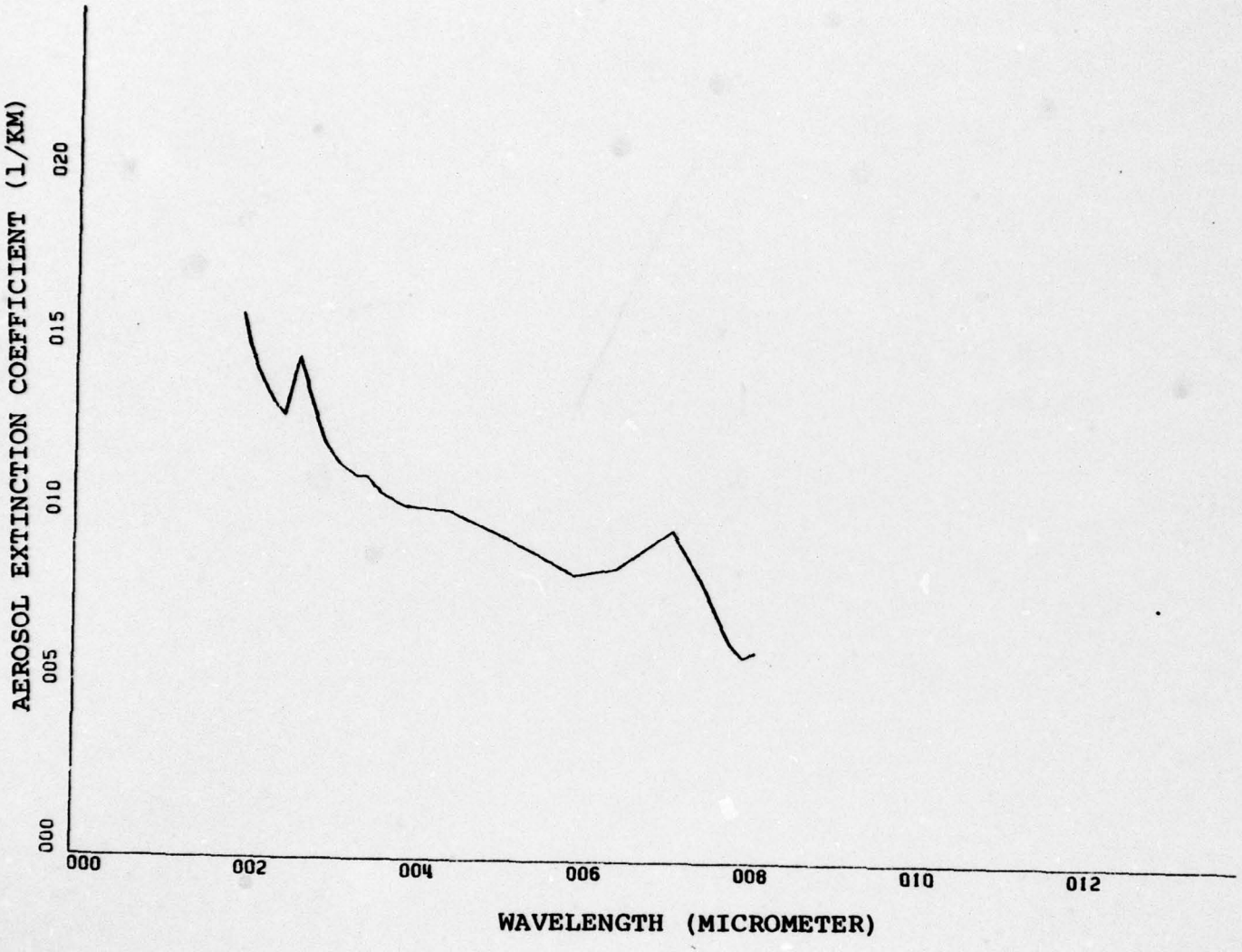


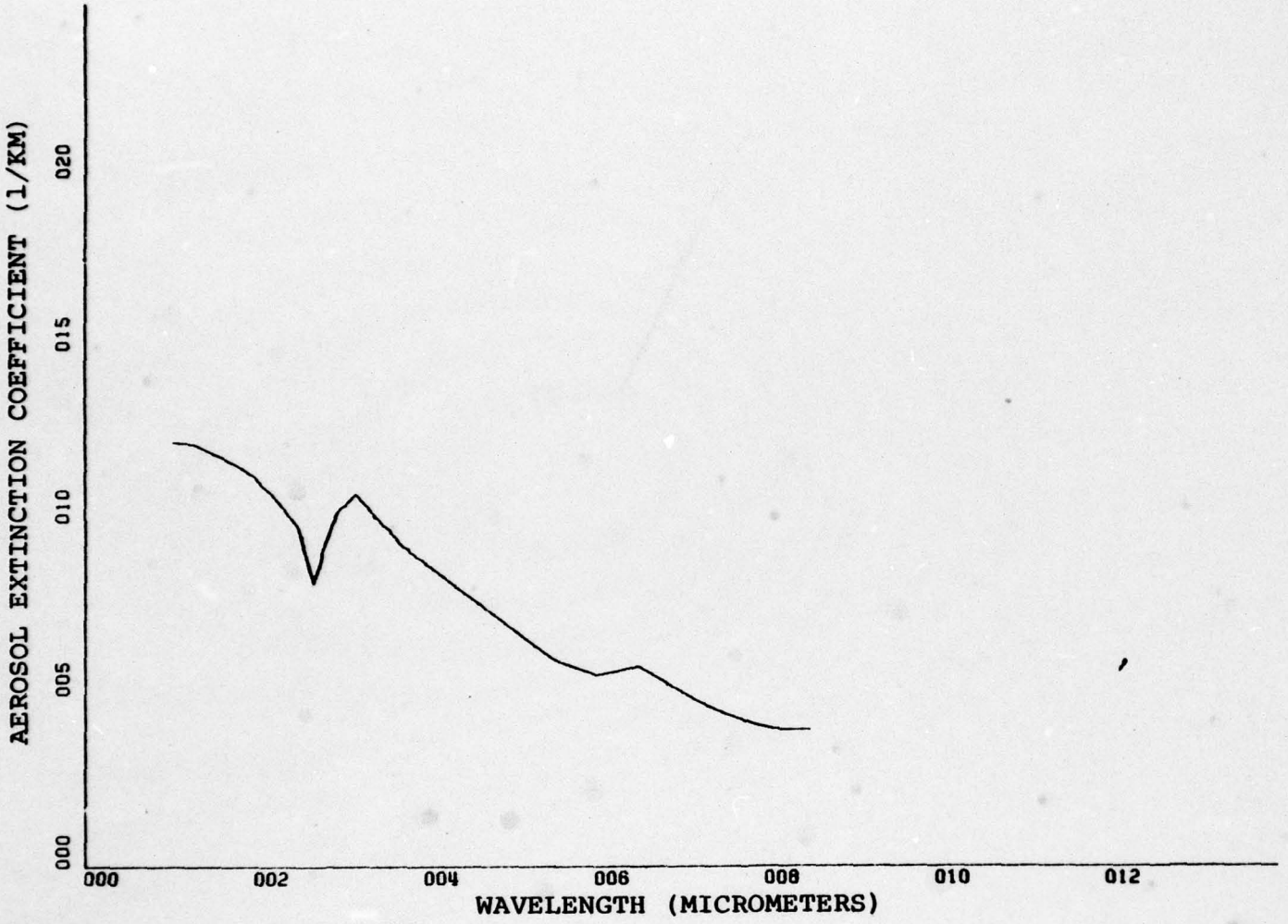
X-SCALE=1.00E+01 UNITS INCH.
Y-SCALE=1.00E+00 UNITS INCH.

FIGURE 7. EXTINCTION EFFICIENCY FACTOR AS A FUNCTION OF SIZE PARAMETER



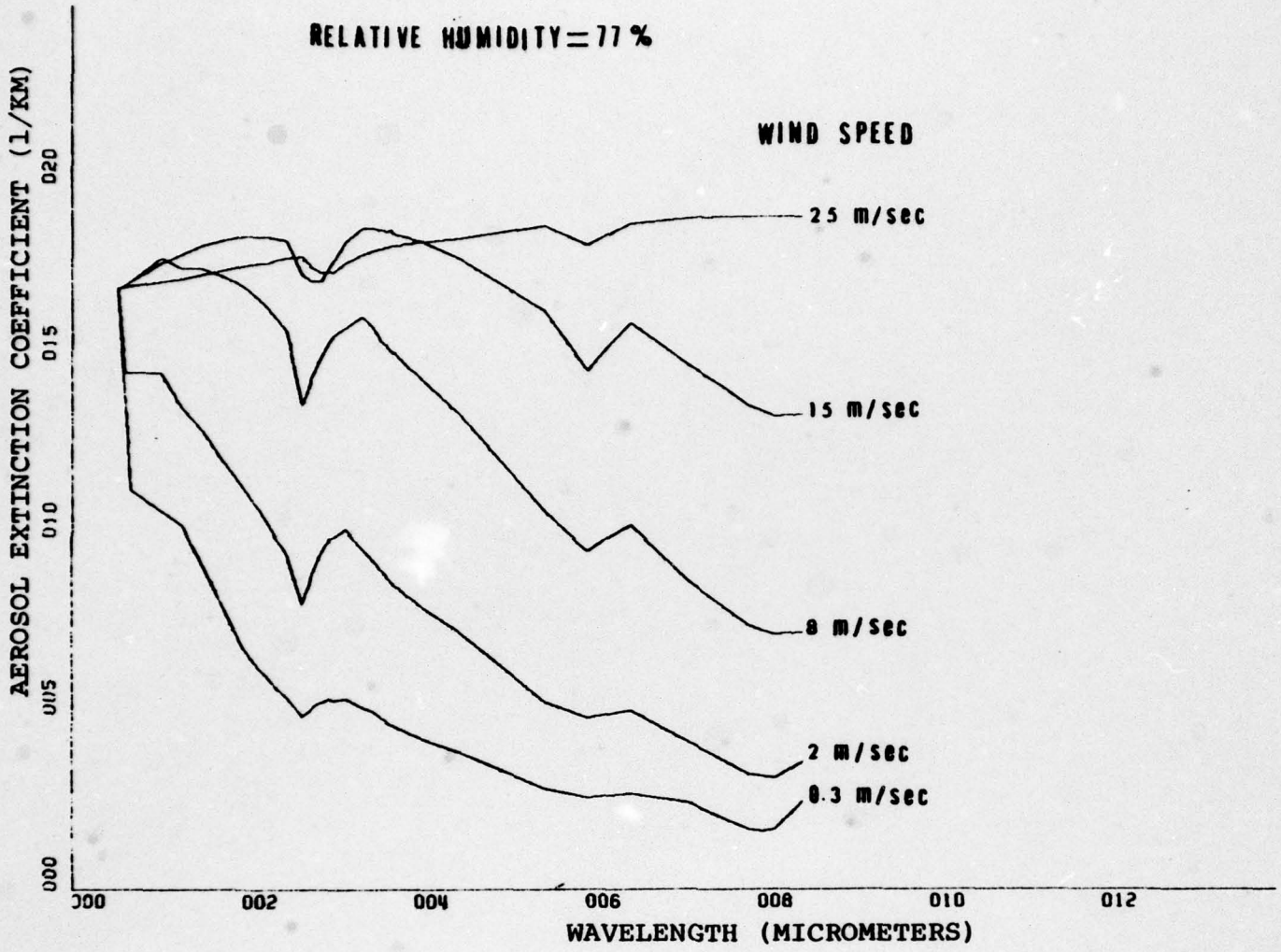
X-SCALE=2.00E+00 UNITS INCH.
Y-SCALE=5.00E-02 UNITS INCH.

FIGURE 8. AEROSOL EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH FOR RURAL MODEL



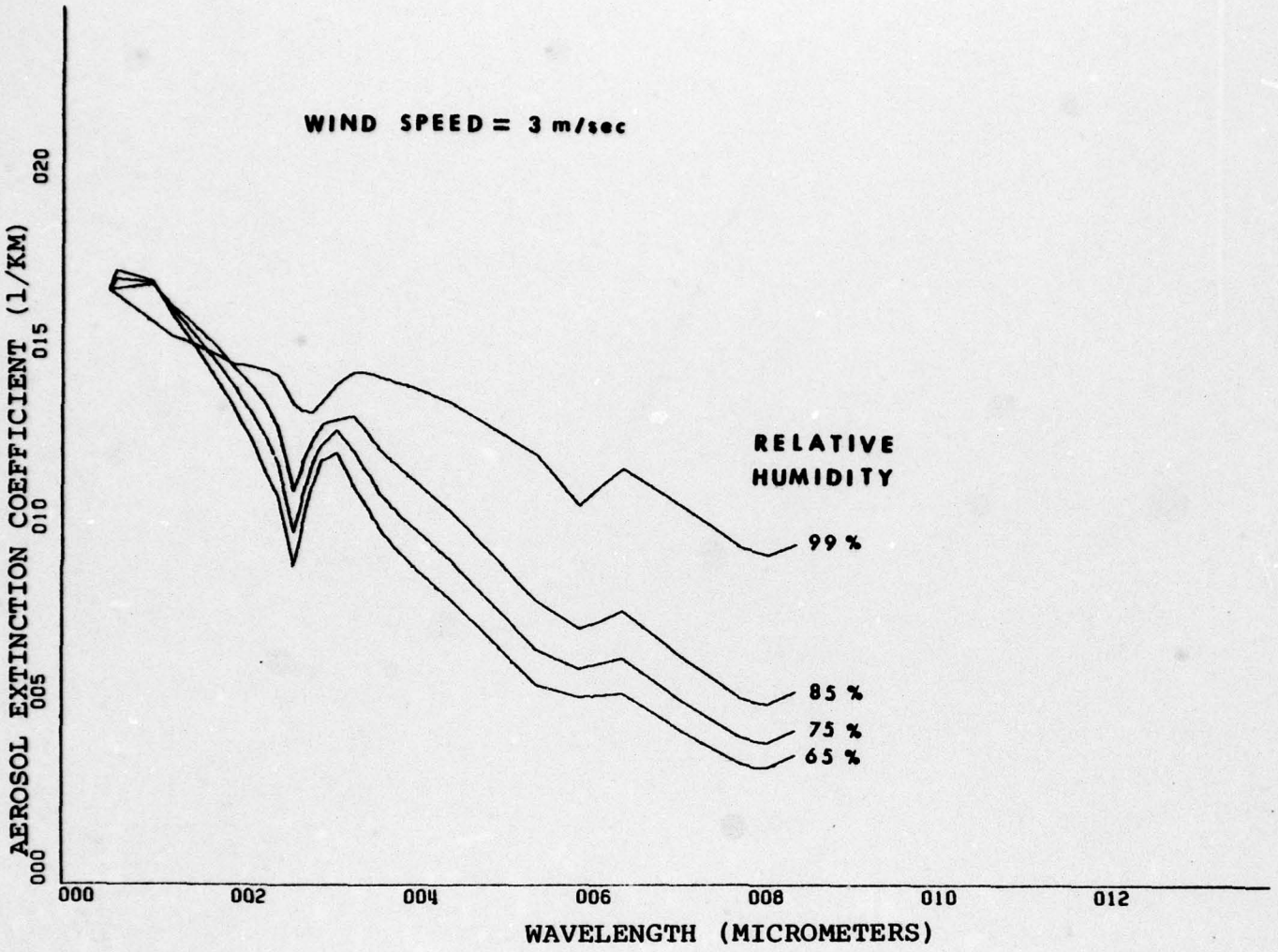
X-SCALE=2.00E+00 UNITS INCH.
Y-SCALE=5.00E-02 UNITS INCH.

FIGURE 9. AEROSOL EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH FOR MARITIME MODEL WITH 75% SEA SPRAY AND 25% RURAL AEROSOLS



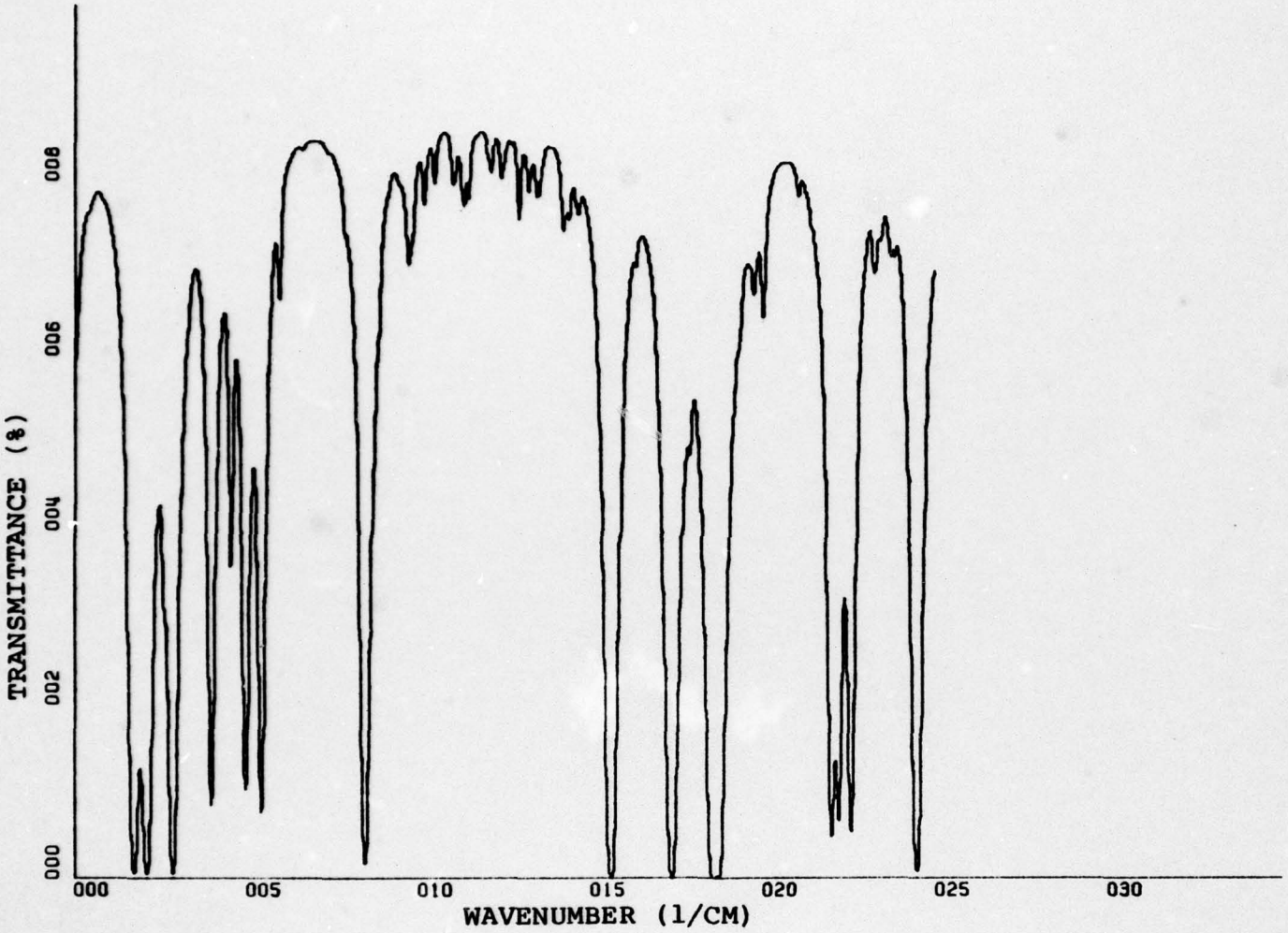
X-SCALE=2.00E+00 UNITS INCH.
Y-SCALE=5.00E-02 UNITS INCH.

FIGURE 10. AEROSOL EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH FOR DIFFERENT WIND SPEEDS



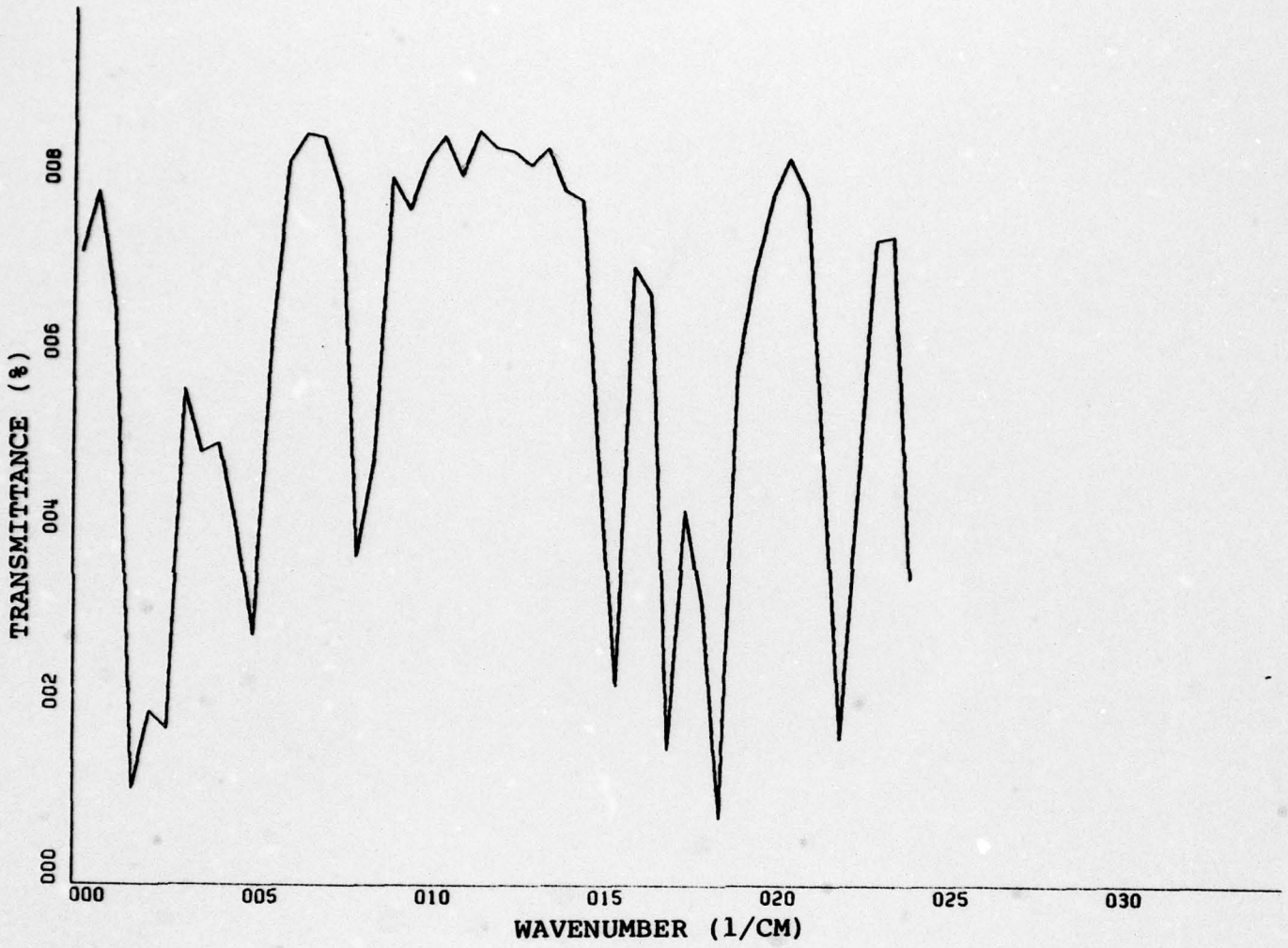
X-SCALE=2.00E+00 UNITS INCH.
Y-SCALE=5.00E-02 UNITS INCH.

FIGURE 11. AEROSOL EXTINCTION COEFFICIENT AS A FUNCTION OF WAVELENGTH FOR DIFFERENT RELATIVE HUMIDITIES



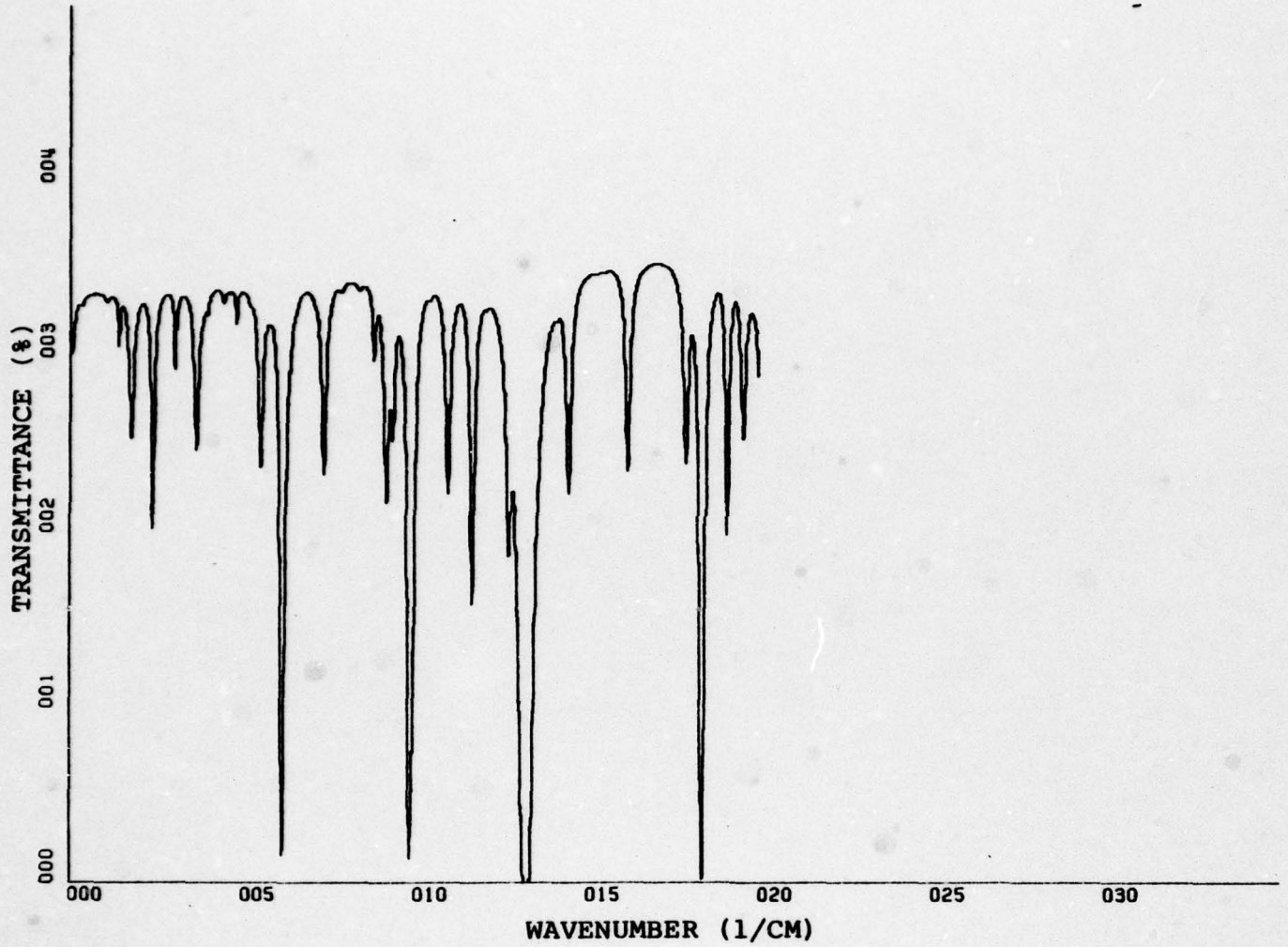
ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 12. TRANSMITTANCE ALONG 10 KM PATH WITH HIGH SPECTRAL RESOLUTION OF 0.01 CM^{-1} FOR MONTEREY YEARLY AVERAGES (Near 3.8 μm)



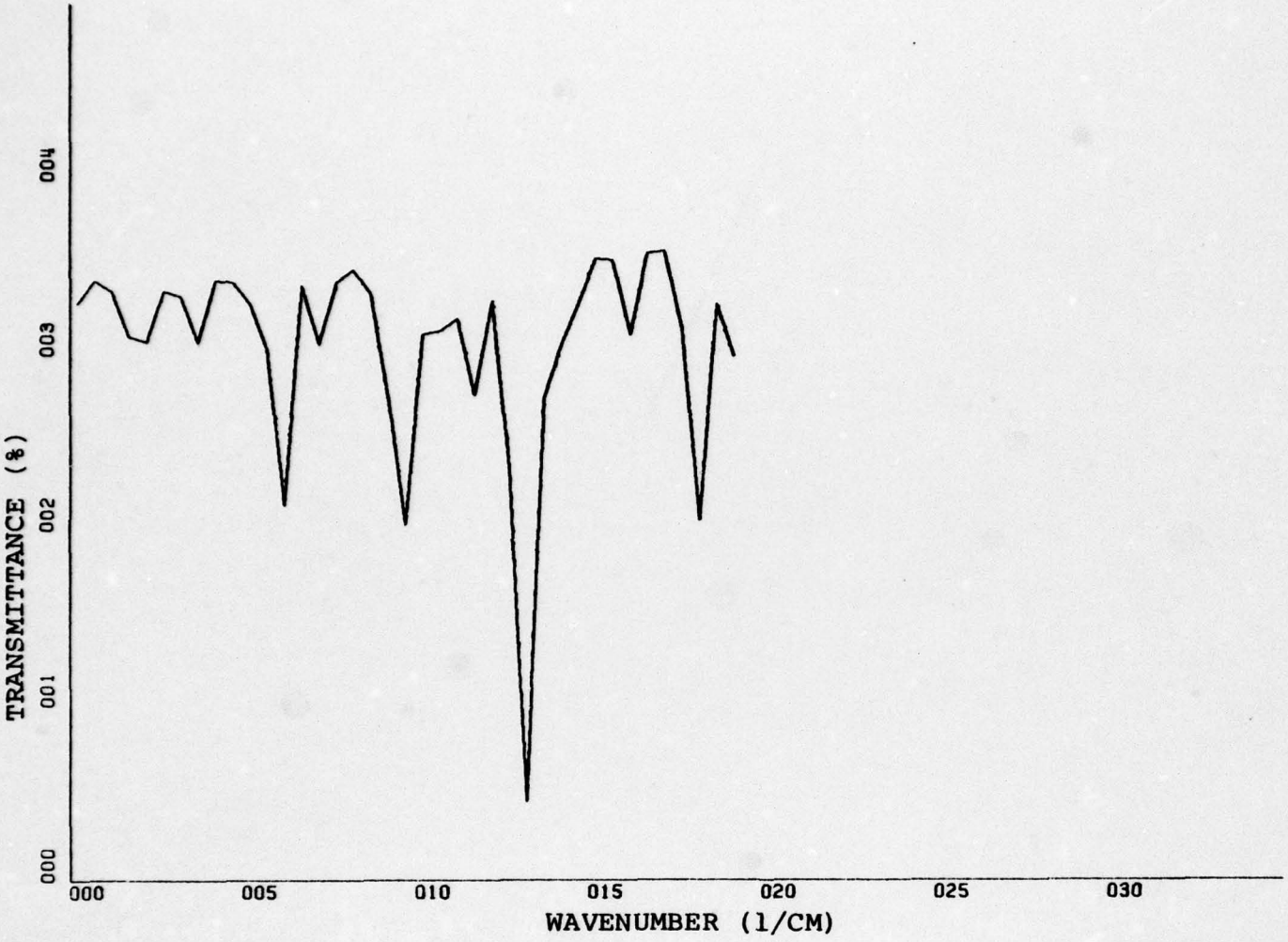
ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 13. TRANSMITTANCE ALONG 10 KM PATH WITH DEGRADED RESOLUTION FOR MONTEREY YEARLY AVERAGES (Near 3.8 μm)



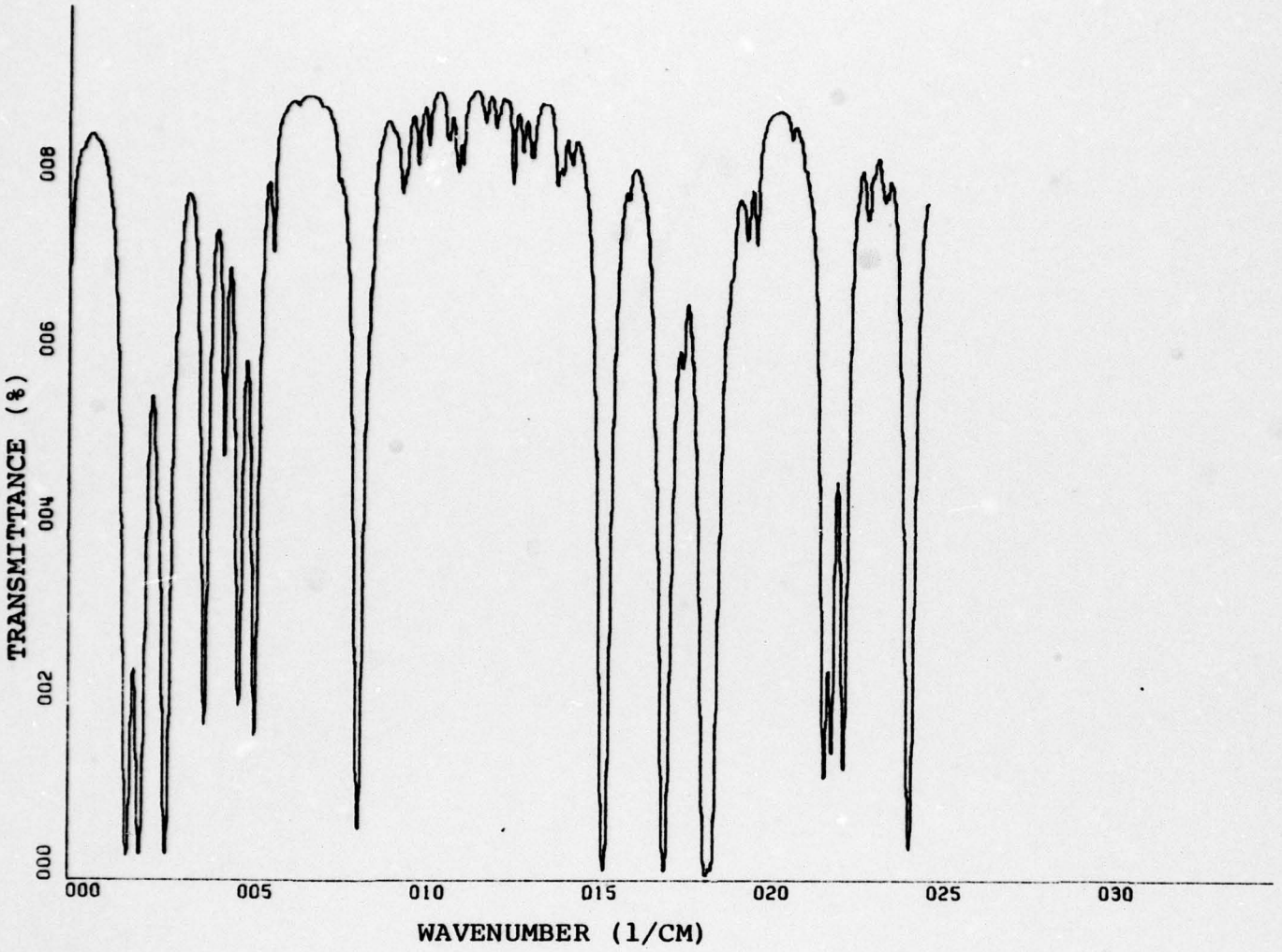
ADD +9.35E+02 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+01 UNITS INCH.

FIGURE 14. TRANSMITTANCE ALONG 10 KM PATH WITH HIGH SPECTRAL RESOLUTION OF 0.01 CM^{-1} FOR MONTEREY YEARLY AVERAGES (Near 10.6 μm)



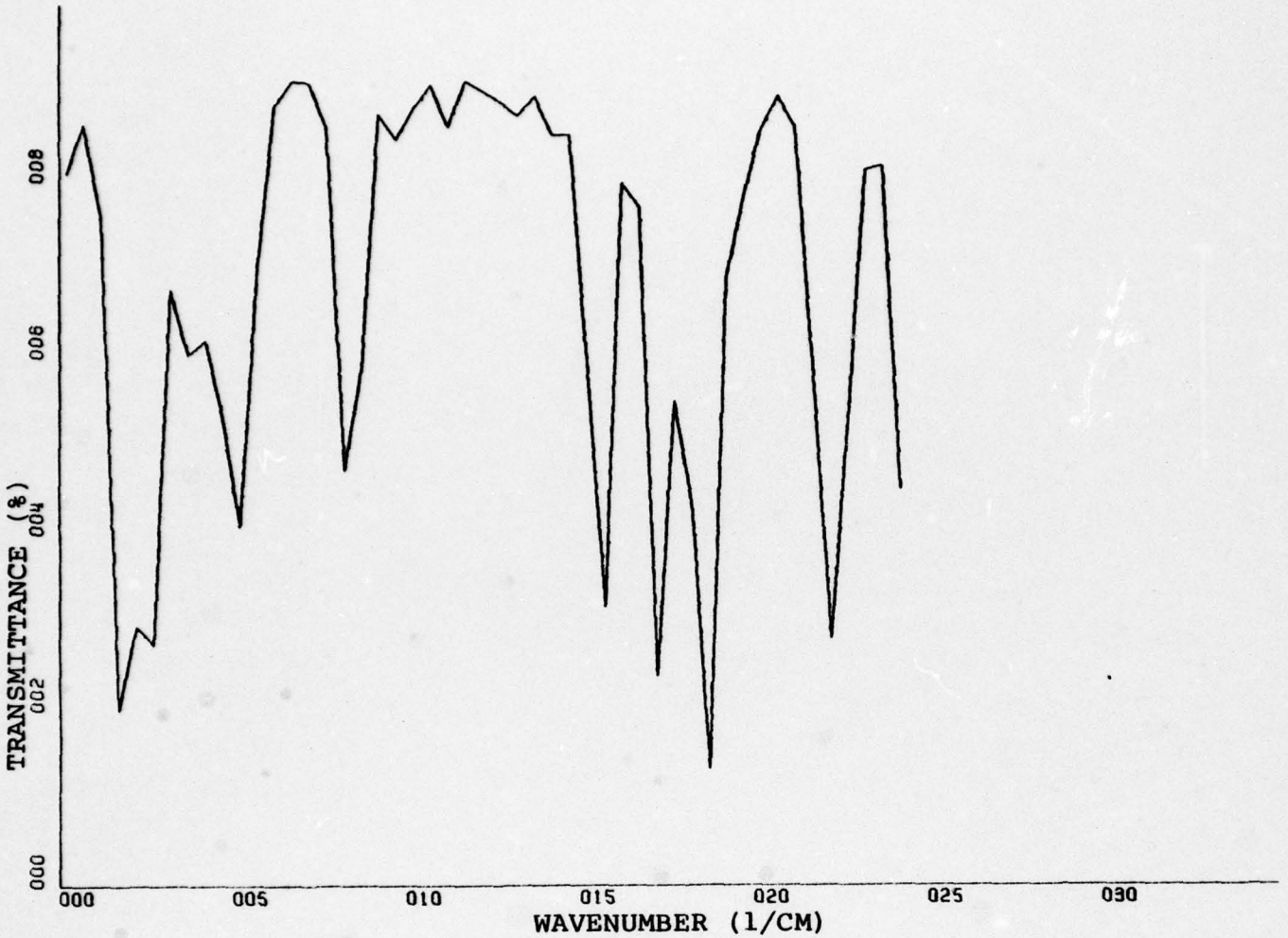
ADD +9.35E+02 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=1.00E+01 UNITS INCH.

FIGURE 15. TRANSMITTANCE ALONG 10 KM PATH WITH DEGRADED RESOLUTION FOR MONTEREY YEARLY AVERAGES (Near 10.6 μm)



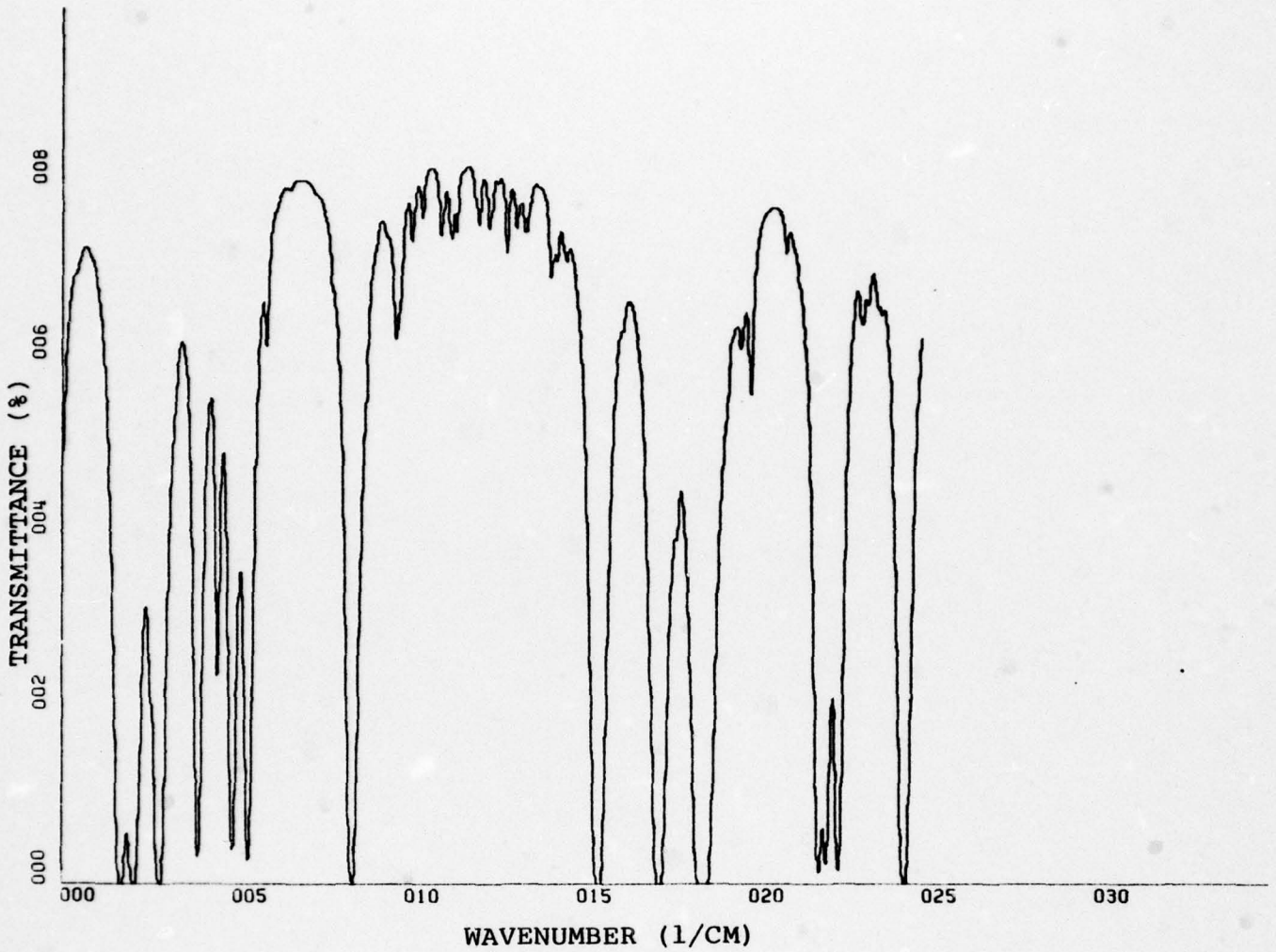
ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 16. TRANSMITTANCE ALONG 10 KM PATH WITH HIGH SPECTRAL RESOLUTION OF 0.01 CM^{-1} FOR P = 1018 MB, T = 290 DEGREES KELVIN, P_{H_2O} = 7.48 MB



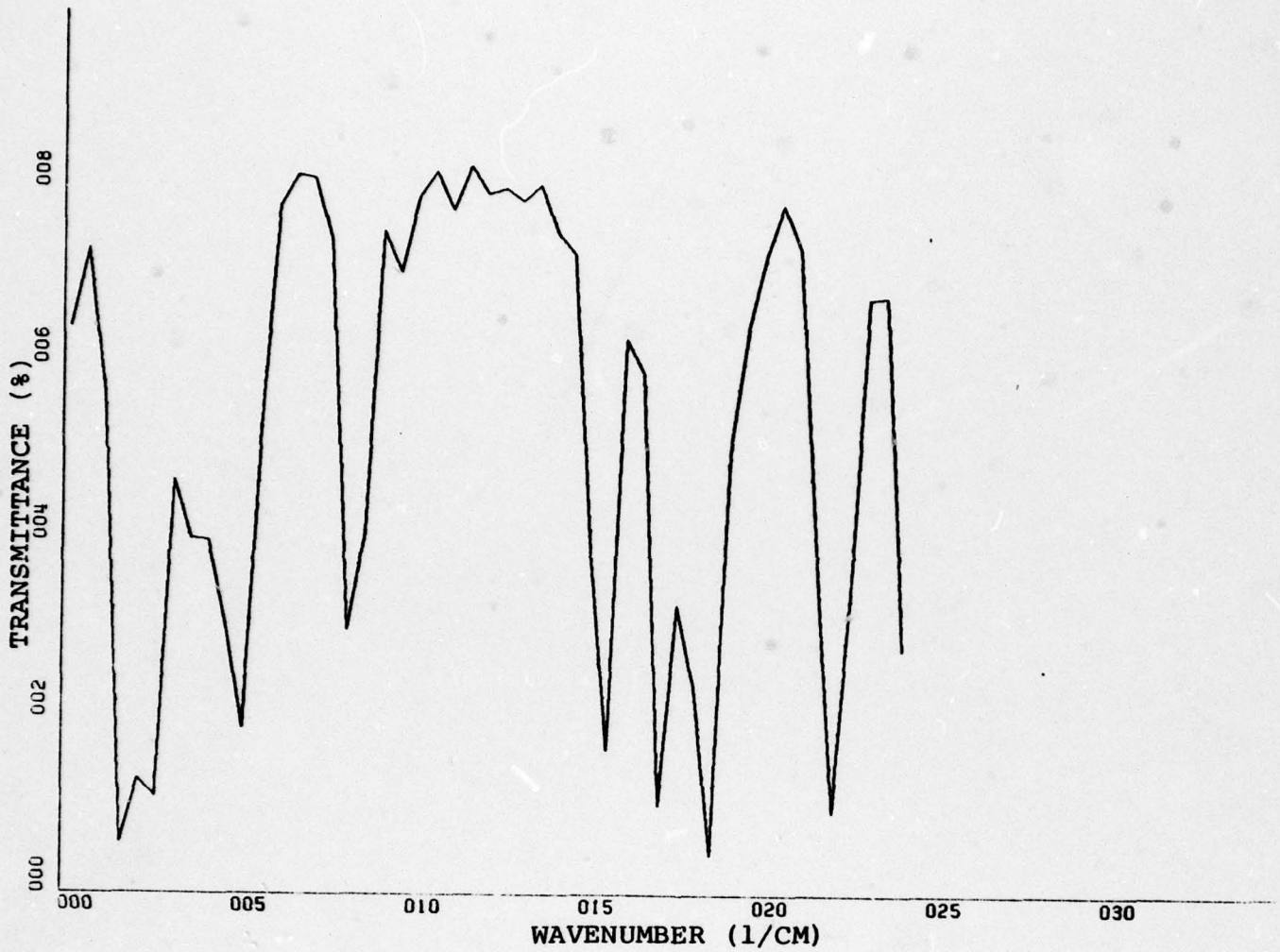
ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 17. TRANSMITTANCE ALONG 10 KM PATH WITH DEGRADED RESOLUTION FOR P = 1018 MB, T = 290 DEGREES KELVIN, P_{H_2O} = 7.48 MB



ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 18. TRANSMITTANCE ALONG 10 KM PATH WITH HIGH SPECTRAL RESOLUTION OF 0.01 CM^{-1} FOR P = 1018 MB, T = 290 DEGREES KELVIN, P_{H_2O} = 15.48 MB



ADD +2.62E+03 UNITS TO ALL X VALUES.
X-SCALE=5.00E+00 UNITS INCH.
Y-SCALE=2.00E+01 UNITS INCH.

FIGURE 19. TRANSMITTANCE ALONG 10 KM PATH WITH DEGRADED RESOLUTION FOR P = 1018 MB, T = 290 DEGREES KELVIN, P_{H_2O} = 15.48 MB

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