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WHITE SANDS MISSILE RANGE, NEW MEXICO

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FOREWORD

In addition the authors of this report, other members of the Laser Study Group are James T. Hall, Richard Hall, James Veilleux, and Ted L. Barber.

ABSTRACT

Potential atmospheric effects on the propagation of electromagnetic radiation at 1.54 micron wavelength are examined. The results of transmission measurements by various investigators, as reported in the literature, coupled with theoretical calculations are applied to estimate the transmission characteristics for erbium ion (Er^{+++}) laser radiation in this region. The output of the Er^{+++} laser at 1.54 μ is discussed in some detail. Predominant attenuation mechanisms are found to be aerosol absorption and aerosol scattering. Contributions from five investigations of atmospheric transmission in this region are summarized. Nonlinear effects are not considered.

CONTENTS

	Page
ABSTRACT -----	iii
INTRODUCTION -----	3
PARAMETERS AFFECTING PROPAGATION -----	6
DATA ON 1.54 μ WAVELENGTH LASER -----	8
MOHLER'S SOLAR SPECTRUM STUDY -----	8
GATES AND HARROP SOLAR STUDY -----	8
BERLINGUETTE AND TATE FIXED RANGE MEASUREMENTS ---	16
TAYLOR AND YATES FIXED RANGE MEASUREMENTS -----	21
ELTERMAN'S SCATTERING COEFFICIENT -----	21
CONCLUSIONS -----	25
REFERENCES -----	27

INTRODUCTION

A study of the atmospheric propagation characteristics of 1.54 micron wavelength laser energy has been undertaken. To evaluate accurately the effect of the atmosphere on the performance of this system, it is necessary to study the attenuating elements and mechanisms, the laser itself, and to relate the results to current theory and data. This report examines the chief sources of attenuation to 1.54 micron radiation, i.e., absorption and scattering. Nonlinear effects will not be considered as they are important only at high beam intensities.

The primary attenuating elements to be encountered in atmospheric transmission are the constituent gases and the aerosols present in the beam path. These will reduce the effective transmitted energy through mechanisms that are wavelength dependent. The reduction can come about through absorption and scattering of the beam energy by the materials present in the beam path.

Radiation will be attenuated by the constituent gases and by aerosol components. Attenuation by gases will arise through (1) Selective line absorption, (2) Continuum absorption, and (3) Rayleigh scattering. Selective line absorption occurs when the radiation energy corresponds very closely to an energy level difference in one of the atmospheric components. Continuum absorption may be thought of as being composed of the wings of many absorption lines whose centers are remote from the wavelength of absorption. (At higher photon energies photo-dissociation and photo-ionization processes contribute strongly to the continuum absorption.) Aerosol contributions are in the form of selective absorption and scattering. The absorption is dependent on the chemical composition and mass density of the aerosol. Scattering, in addition to depending on chemical composition and mass density, is also a function of the shape. The intensity of all of these mechanisms is strongly wavelength dependent.

In view of the wavelength dependence of the absorption and scattering mechanisms the exact spectral response of the laser must be determined. At present the output wavelength and the spectral width are not known with certainty. Therefore, these characteristics will have to be determined, most probably as each absorption measurement is made. These measurements will have to be made with at least the accuracy of the absorption measurements, which are to be high resolution.

Currently available data indicate approximately 12 weak absorption bands in the 1.5 to 1.6 micron region. These bands are shown in Fig. 1.

LOCATION OF ATMOSPHERIC ABSORPTION BANDS IN 1.5 μ TO 1.6 μ RANGE

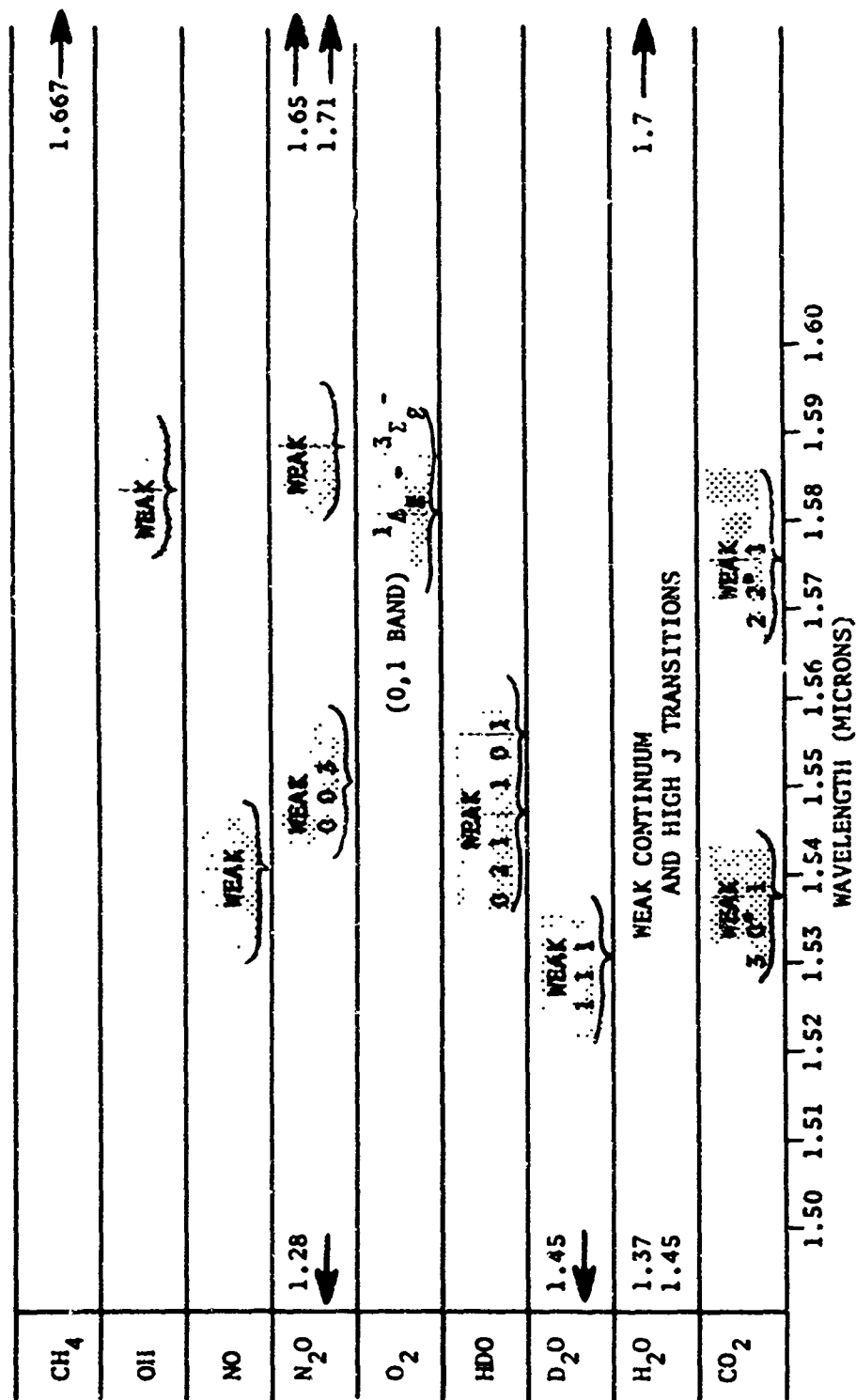


Figure 1. Location and identification of some of the more important atmospheric absorption bands in the 1.5 to 1.6 micron region.

Some of these will certainly be negligible: OH, NO, D₂O. At this point it is difficult to attach much importance to the N₂O band at 1.55 micron and the O₂ electronic band at 1.58 micron. Certainly the CO₂ bands will be important. Water vapor absorption will be primarily continuum absorption and weak selective line absorption due to the higher transitions for bands centered out of the region. There is a possibility that deuterated water vapor may contribute to the atmospheric absorption since 101 and 021 bands are located in the 1.54 region.

The published data indicate that the atmospheric gas absorption contribution to the attenuation coefficient at 1.54 μ will be on the order of 10⁻² km⁻¹. Depending on the laser characteristics and the water vapor content, this number may increase by almost an order of magnitude. Aerosol absorption and scattering will be the predominant attenuation mechanism in the 1.54 μ region. Based on Elterman's calculations, the scattering component alone should be approximately 10⁻¹ km⁻¹ (approximately a 10% reduction per km of path.)

PARAMETERS AFFECTING PROPAGATION

Electromagnetic energy (hereafter referred to as "radiation") may be attenuated by any of the following processes:

- a. molecular and atomic absorption and scattering;
- b. aerosol absorption and scattering;
- c. nonlinear effects.

This report concerns only the first two loss mechanisms. Nonlinear effects are only important at very high beam intensities; only low to moderate beam intensities are contemplated (on the order of or less than 10⁸ watts/cm² for 10⁻⁸ second pulses at low repetition rates). The propagation of monochromatic radiation satisfies the radiation transfer equation which is of the form

$$\frac{dI_{\lambda}}{dx} = k_{\lambda}(-I_{\lambda} + J_{\lambda}) \quad (1)$$

where k_{λ} is the monochromatic attenuation coefficient, J_{λ} is the monochromatic source function, I_{λ} is the specific monochromatic intensity defined as energy per unit time, per unit area, per unit solid angle, per unit wavelength (λ) interval. In general, k_{λ} and J_{λ} are functions of position. In the atmosphere, with relatively low temperature, the primary contribution to J_{λ} is the reradiated energy and scattered energy which is generally negligibly small in the incident

beam direction. Assuming all scattered and reradiated energy is lost to the beam* one may define the transmission, T , by the simpler Beer's Law:

$$T = \frac{I_{\lambda}}{I_{\lambda_0}} = \exp \left[- \int_0^{\ell} k_{\lambda} dx \right] \quad (2)$$

where

I_{λ_0} = Transmitted specific intensity,

I_{λ} = Received specific intensity,

k_{λ} = Total attenuation coefficient (a function of position along the path),

ℓ = Length of path.

The spacial dependence of equation 2 is more clearly seen by replacing $\int k_{\lambda} dx$ with $\int k'_{\lambda} \rho dx$ where k'_{λ} is the mass attenuation coefficient and ρ is mass density. In these cases the integral $\int k'_{\lambda} \rho dx$ is replaced with $k'_{\lambda} w$, where $w = \int \rho dx$ and k'_{λ} is considered constant. The usual units used are $k' = \text{cm}^2/\text{gm}$ and $w = \text{gm}/\text{cm}^2$.

When energy is transmitted over a finite wavelength interval, the transmission is given by

$$T = \frac{\int_{\lambda_1}^{\lambda_2} I_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda_0} d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} I_{\lambda_0} e^{-\int_0^{\ell} k_{\lambda} dx} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda_0} d\lambda} \quad (3)$$

It is apparent that the validity of the simpler Beer's Law approximation where the I 's and k 's are replaced by average values depends

* This creates an overestimate of losses since forward scattering in small angles about the initial beam is considered as loss. For certain applications this scattered component will not reduce the efficiency.

not only upon the attenuation characteristics of the medium but also upon the wavelength distribution of energy in the transmitted beam. This point is brought to light because there is some uncertainty concerning the exact distribution of the energy emitted by the 1.54 μ laser. This will be discussed in greater detail later.

The total attenuation coefficient can be subdivided into components as follows

$$k_{\lambda} = \alpha_{\lambda_T} + \sigma_{\lambda_T} + S_{\lambda_T} + a_{\lambda_T} + C_T \quad (4)$$

where

α_{λ_T} = atomic and molecular selective line absorption coefficient

σ_{λ_T} = atomic and molecular scattering coefficient

C_T = continuum absorption coefficient

S_{λ_T} = aerosol scattering coefficient

a_{λ_T} = aerosol absorption coefficient.

All of the above coefficients are functions of position along the radiation path. This dependence arises from the spacial variation of composition of the medium, its temperature, pressure, etc. With knowledge of the medium parameters, the individual coefficients may be defined as follows:

$$\alpha_{\lambda_T} = \sum_i \alpha_{\lambda_i} N_i \quad (5)$$

where α_{λ_i} is the monochromatic absorption cross section for the con-

stituent whose number density is N_i . The sum is over all absorbing species in the medium. The atomic and molecular scattering coefficient is generally considered to be the contribution from Rayleigh scattering:

$$\sigma_{\lambda_T} = \sum_i \sigma_{\lambda_i} N_i \quad (6)$$

where σ_{λ_i} is the fraction scattered by a single particle and has the

dimensions of an area. Over small wavelength ranges the continuum coefficient, C_T , is relatively constant. In practical applications the continuum absorption contains contributions from all sources that cannot be easily identified.

The total aerosol scattering coefficient, S_{λ_T} , may be evaluated using Mie theory if one assumes all particles are spherical **.

The total aerosol absorption coefficient, a_{λ_T} , can be determined in the same manner as the gas atomic and molecular absorption coefficient.

To evaluate accurately the performance of any radiation device in the atmosphere, the following must be known:

- a. Intensity distribution of source.
- b. Absorption and scattering cross sections of atmospheric constituents for the wavelength interval under consideration.

The problems associated with obtaining this information for the 1.54 μ laser will be reviewed.

DATA ON 1.54 μ WAVELENGTH LASER

Detailed knowledge of the laser output characteristics is as important as information concerning the atmospheric influence on laser propagation. It is necessary, for example, to know the wavelength, spectral width, stability and other parameters of the laser emission before accurate predictions concerning propagation can be made. In this respect the Er^{+++} laser bears some discussion.

This laser is a solid-state device which, when operated at 1.54 μ , appears comparable to the ruby or neodymium lasers in terms of output power and threshold levels. Stimulated emission from the erbium ion has been achieved in several crystalline host materials as well as in glass.

Stimulated emission at 1.54 μ was first reported by Snitzer (2) in 1965. He used a doped glass host at room temperature and identified the emission as being from the $^4I_{13/2}$ excited state at a wavelength of 1.5426 μ . Previous to this, stimulated emission had been achieved

** Theory has been extended to include some spheroids of revolution. Irregular shaped particles are not tractable in the theory.

with Er^{+++} in crystalline hosts at 1.61, 1.612 and 1.617 microns (3,4,5), all at cryogenic temperatures.

Snitzer's investigations included preliminary spectral observations of relatively high resolution. From these measurements he was able to determine the wavelength and estimate the line width as approximately 10 Å, but the accuracy and repeatability of the measurements were uncertain.

It was found that the emission wavelength shifted to 1.56 μ upon the heating of the rod. Such a thermal effect is suggestive of the temperature dependence of the 6943 Å line of ruby; but the mechanism responsible for the effect is apparently not the same in the two lasers.

The fluorescent spectrum of Er has been studied at John Hopkins, and Dieke (6) has reported on the effects of Stark splitting in various crystalline hosts. It is found that the $^4\text{I}_{13/2}$ level has seven

Stark components, which appear to spread over a relatively wide spectral range depending upon the host material (i.e., the field at the sites of the Er^{+++} ion). If this is taken as representative, one might expect a considerable broadening of the $^4\text{I}_{13/2}$ transition line in a

glass host where the fields vary widely due to the random structure. This has given rise to some speculation that the emission line may be quite broad (tens of Å) and possibly erratic in its spectral location (7).

The foregoing may be summarized as follows. The exact wavelength and width of the emission of the Er^{+++} laser is needed before the effects of the atmospheric absorption lines in the vicinity can be determined. Further, if the output is erratic the absorption effects will not be readily predictable. It appears that the laser may emit anywhere within a ± 100 Å band about 15,426 Å and with a spectral width of as much as possibly 50 Å.

If the pulse is wider than a few angstroms the absorption coefficient should be replaced with an average value, where the average value is defined by equating equations 2 and 3. This will produce a relatively constant absorption coefficient in this region. If the spectral width is of the order of 1 Å or less the absorption coefficient will be subject to considerable variation with wavelength in the region.

This uncertainty creates several experimental problems. Not only must one determine the wavelength of the laser radiation but one

must also determine its spectral width. This requires that high dispersion wavelength measurements be made simultaneously with the absorption measurement.

EXISTING DATA ON 1.54 MICRON TRANSMISSION

Many investigators (1, 8-19) have investigated the terrestrial atmosphere's transmission characteristics in the 1.54 micron region. Only one investigator, Mohler, et al. (8) used high resolution measurements and attempted to identify all absorption lines. One (15) observed six strong atmospheric absorption lines in the 1.54 μ region over an extended path. Two of these investigations were solar radiation studies (8 and 17). Two of the investigations cited are theoretical "Band-Model" studies calculated by Plass, et al. (18, 19). Of these investigations five are summarized below.

Mohler's Solar Spectrum Study (8)

Figures 2, 3, and 4 are facsimiles of plates 91, 92, and 93 from the Mohler Solar Atlas. Table I identifies most terrestrial absorption lines shown on the plates. The absorption intensities indicated in Table I are line equivalent widths (essentially the area of the absorption lines). The equivalent widths may be used to crudely construct the line strengths by considering each line to have a Lorentz shape and a halfwidth of approximately one angstrom. It should be noted that the absorption curves represent the selective line absorption through 1.5 air masses referenced to the transmission through the continuum absorption and scattering.

An upper limit may be obtained for the maximum selective line absorption coefficient by use of these data. Assuming an equivalent 12 km sea level path and a minimum transmission of 0.7 in., Equation 2 yields

$$\alpha_{\lambda \max} \approx 3 \times 10^{-2} \text{ km}^{-1}$$

From a superficial examination of the spectrum it appears that over a 10 Å band the average transmission is on the order of 0.95. This yields an average selective absorption coefficient of

$$\alpha_{\beta} \approx 4.1 \times 10^{-3} \text{ km}^{-1}$$

It seems reasonable to expect the line absorption contribution to the total attenuation coefficient to be between these two limits.

Gates and Harrop Solar Study (17)

Gates and Harrop used a solar spectrum recorded in January 1955 on a very clear day at Denver, Colorado to determine band model

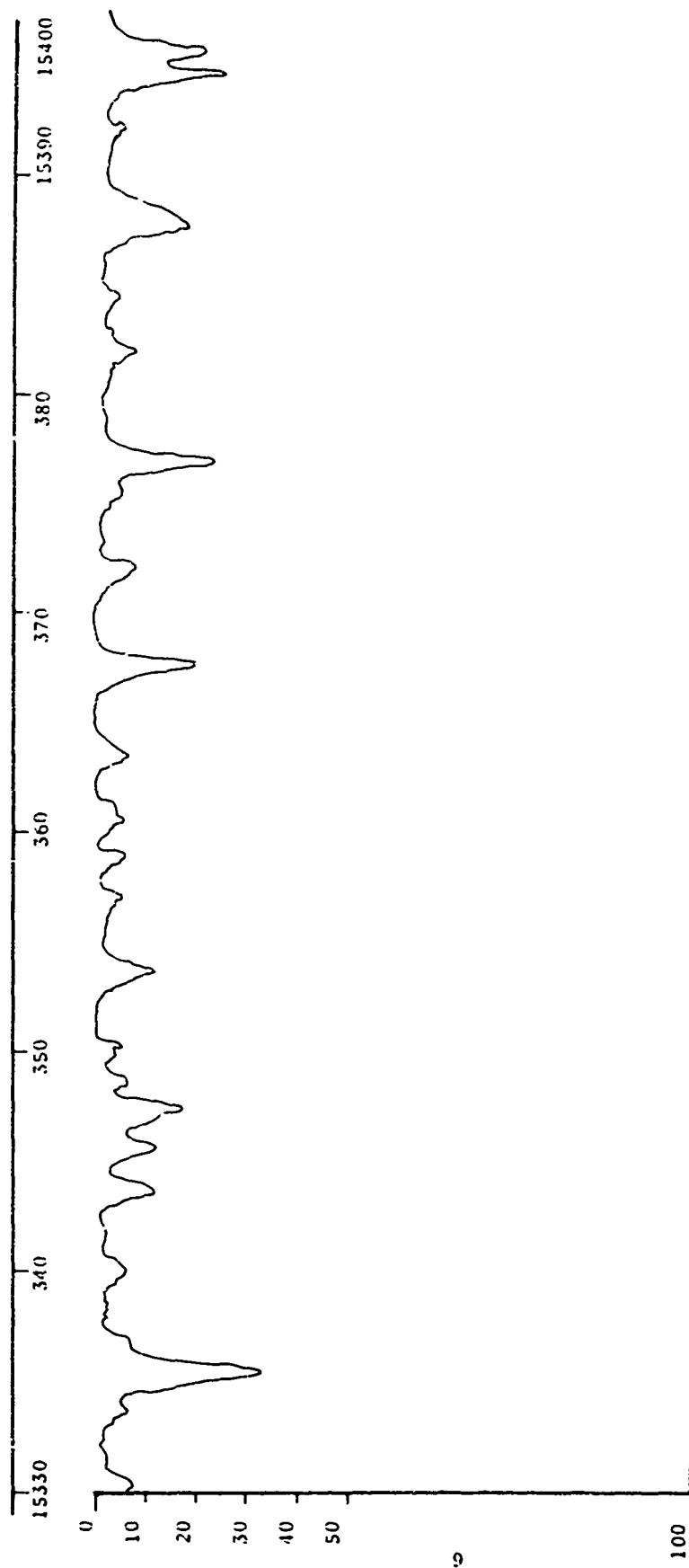


Figure 2. Facsimile of Mohler Plate 91, showing Solar and Atmospheric Absorption lines between 15,330Å and 15,400Å from reference 8.

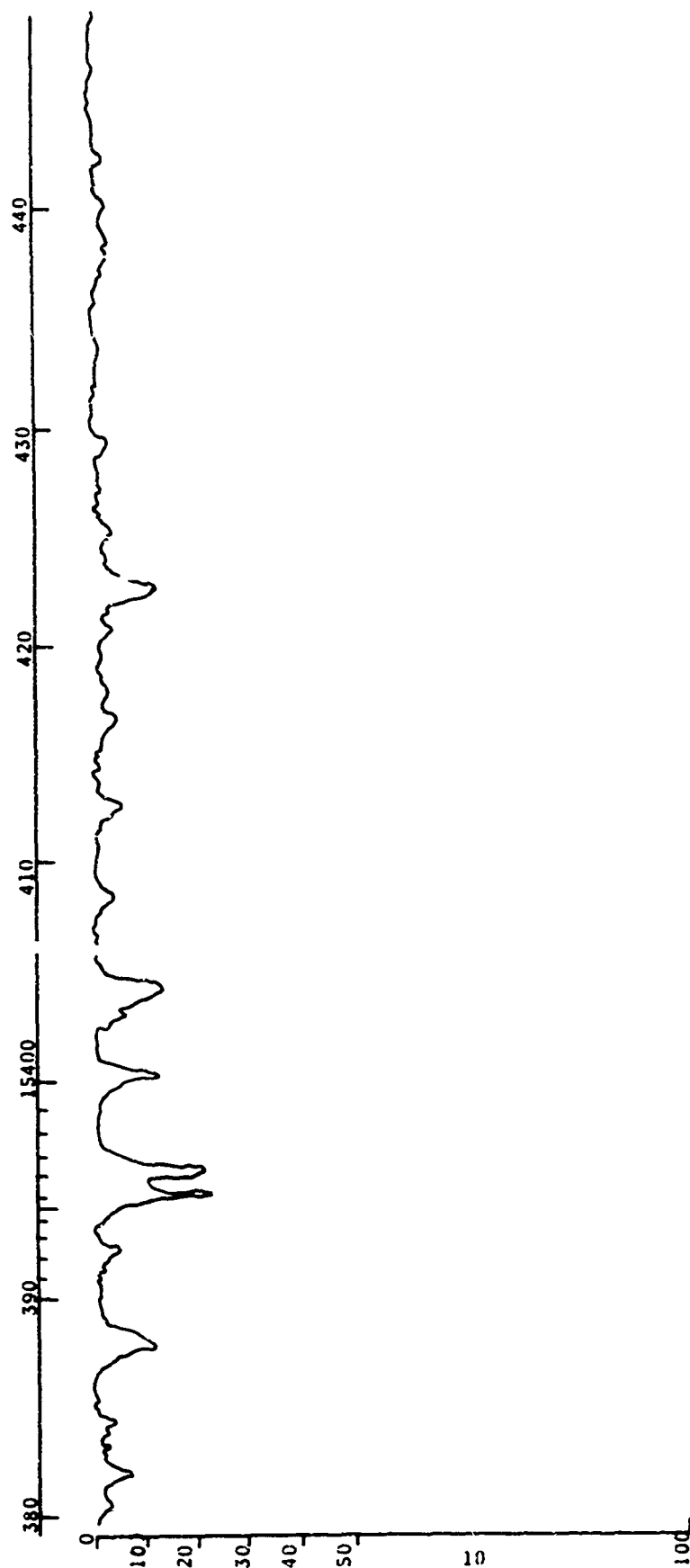


Figure 3. Facsimile of Mohler Plate 92, showing Solar and Atmospheric Absorption lines between 380Å and 440Å from reference 8.

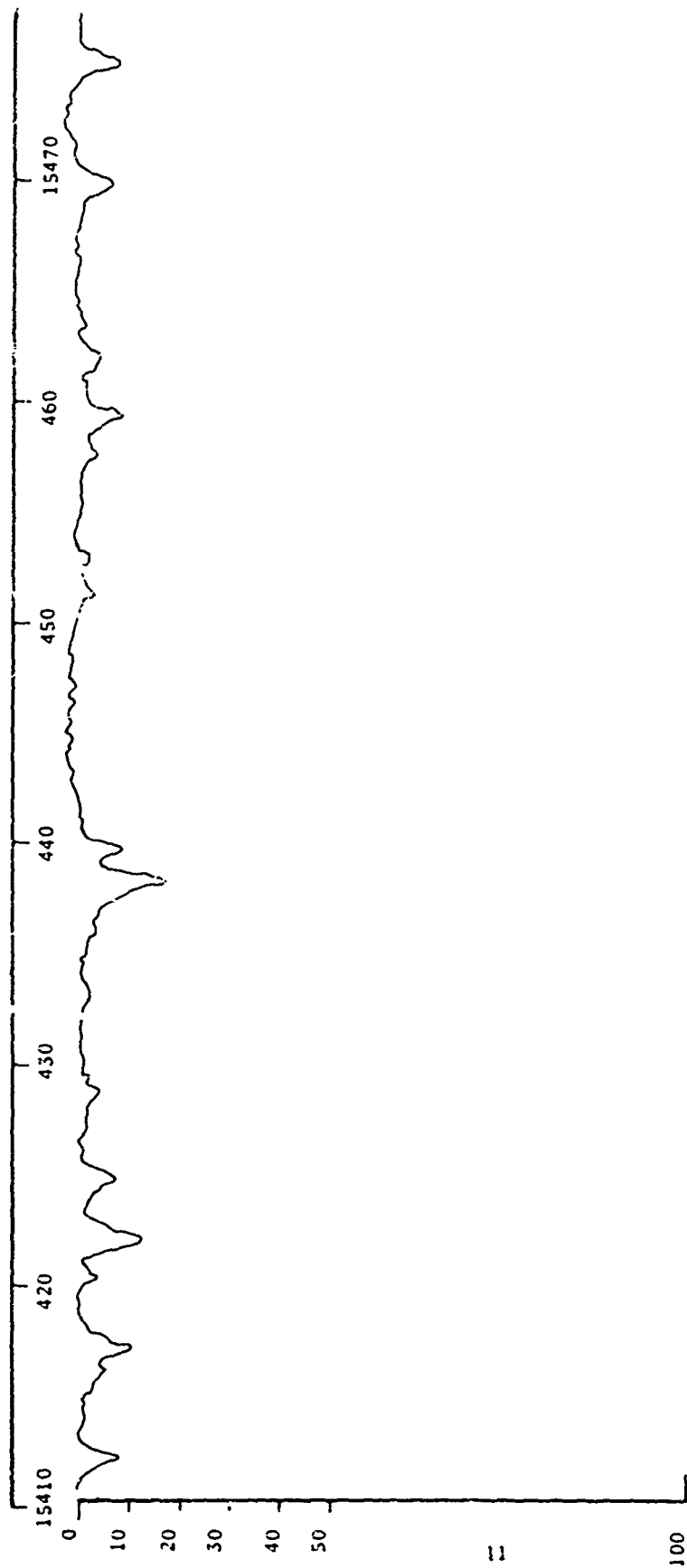


Figure 4. Facsimile of Mohler Plate 93, showing Solar and Atmospheric Absorption lines between 15410 and 15480 from Reference 8.

TABLE I
Summary of Absorption Lines in Region 1.534 μ to 1.554 μ
(Source: Mohler)

Wavelength (microns)	Wavenumber (cm ⁻¹)	Intensity (mA)	Substance	Identification Band	J values
1.535018	6512.8	16	CO ₂	3 0° 1	13-12
1.535373	6511.3	77	CO ₂	3 0° 1	11-10
1.535373 (?)	6511.30 (?)	(?)	H ₂ O	0 2 1	5- 6
1.535716	6509.84	15	CO ₂	3 0° 1	9- 8
1.535889	6509.11	30	(?)	(?)	(?)
1.536059	6508.39	23	CO ₂	3 0° 1	7- 6
1.536366	6507.09	29	(?)	(?)	(?)
1.536426	6506.83	5	CO ₂	3 0° 1	5- 4
1.536759	6505.42	150 (?)	H ₂ O	0 2 1	6- 7
1.536759 (?)	6505.34 (?)	6 (?)	O ₂	3 0° 1	3- 2
1.537097	6503.99	4(a broad line)	CO ₂	3 0° 1	1- 0
1.537218	6503.48	39	H ₂ O	0 2 1	6- 7

TABLE I
(Continued)

Wavelength (microns)	Wavenumber (cm^{-1})	Intensity (mA)	Identification Substance Band	J values
1.537700 (?)	6501.44 (?)	4 (?)	CO ₂	3 0 ⁰ 1 1-2
1.538081	6499.83	12	CO ₂	3 0 ⁰ 1 3-4
1.538435	6498.34	18	CO ₂	3 0 ⁰ 1 5-6
1.538786	6496.80	3 (?)	H ₂ O	0 2 1 6-7
1.538786 (?)	6496.64	14 (?)	CO ₂	3 0 ⁰ 1 7-8
1.538830	6496.67	70	H ₂ O	1 2 0 5-6
1.539219	6495.03	16	CO ₂	3 0 ⁰ 1 9-10
1.539582	6493.50	130	CO ₂	3 0 ⁰ 1 11-12
1.540012 (?)	5491.68 (?)	19 (?)	CO ₂	3 0 ⁰ 1 13-14
1.540399 (?)	6490.05 (?)	20 (?)	CO ₂	3 0 ⁰ 1 15-16
1.540833 (?)	6488.32 (?)	57 *	CO ₂	3 0 ⁰ 1 17-18
1.541258	6486.43	41 (?)	H ₂ O	0 2 1 6-7
1.541260	6486.59 (?)	19 (?)	CO ₂	3 0 ⁰ 1 19-20
1.541449	6485.63	5	H ₂ O	0 2 1 6-7
1.541649	6484.79	10	CO ₂	3 0 ⁰ 1 21-22
1.541757	6484.33	58	H ₂ O	0 2 1 8-9

* Some other source involved.

TABLE I
(Continued)

Wavelength (microns)	Wavenumber (cm^{-1})	Intensity (mA)	Identification Substance Band	J values
1.542068	6483.03	12	CO ₂ 3 0 ⁰ 1	23-24
1.542501	6481.21	11	CO ₂ 3 0 ⁰ 1	25-26
1.542525	6481.11	44 (?)	(?)	(?)
1.542556	6480.98	35	H ₂ O 0 2 1	8- 9
1.5426 -- LASER WAVELENGTH AS REPORTED BY SNITZER				
1.542902	6479.52	15	CO ₂ 3 0 ⁰ 1	27-28
1.543327	6477.74	14	CO ₂ 3 0 ⁰ 1	29-30
1.543768	6475.89	10	CO ₂ 3 0 ⁰ 1	31-32
1.543840	6475.59	60	H ₂ O 0 2 1	7- 8
1.543992	6474.95	45	H ₂ O 0 2 1	7- 8
1.544193	6474.11	9	CO ₂ 3 0 ⁰ 1	33-34
1.545313	6469.41	19	(?)	(?)
1.545776	6467.48	29	(?)	(?)
1.547005	6462.34	58	H ₂ O 0 2 1	7- 8
1.547563	6460.01	60	(?)	(?)

TABLE I
(Continued)

Wavelength (microns)	Wavenumber (cm^{-1})	Intensity (mA)	Substance	Identification Band	J values
1.547680	6459.52	5	H ₂ O	0 2 1	7-8
1.549295	6452.79	3	H ₂ O	1 2 0	7-8
1.540144	6449.25	150 *	(?)	(?)	(?)
1.550692	6446.97	20	H ₂ O	1 2 0	5-6
1.551653	6442.98	70	H ₂ O	0 2 1	7-8
1.552261	6440.46	25	(?)	(?)	(?)
1.553859	6433.83	24	H ₂ O	1 2 0	6-7

* Several sources involved.

atmospheric attenuation coefficients. Their spectrometer resolution was about 70 Å. These investigations attempted to evaluate the continuum attenuation coefficient at 1.542 microns in terms of the estimated precipitable water vapor in the path. Their result was:

$$k'_{\text{cont}} = 1.2 \times 10^{-2} \text{ mm}^{-1} (\text{H}_2\text{O})^{***}$$

Their calculation for the band model specific absorption coefficient, α_β (for the 1.54 μ region), in terms of precipitable water vapor yields

$$k' \alpha_\beta = 2.84 \times 10^{-3} \text{ mm}^{-1} (\text{H}_2\text{O})$$

which may be somewhat higher than that deduced from the Mohler data. These data indicate a continuum absorption coefficient approximately an order of magnitude higher than the specific line absorption coefficient. It should be noted that aerosol scattering and absorption were included in these authors' continuum coefficient. It might also be noted that these coefficients were based upon approximately 6 mm H₂O in the light path.

Berlinguette and Tate Fixed Range Measurements (16)

Spectroscopic measurements, with a resolution of about 65 Å at 1.54 microns were made of atmospheric transmission in the 0.9 μ to 5.9 μ region over fixed outside paths ranging from 7 m to 1.1 km. Absolute transmission measurements were attempted; however, experimental difficulties resulted in calculated transmission greater than 100% as indicated in Table II. Total atmospheric attenuation was determined. Selective window absorption coefficients, in terms of precipitable water vapor, were established for the 1.4 to 1.9 micron window and other windows. The authors state that these values agreed with those established by Taylor and Yates and by Elder and Strong (see Figure 5). Figure 6 indicates that the continuum absorption was rather high, amounting to about a 25% absorption. If the inference is correct, their continuum coefficient should be at least 2 orders of magnitude higher than the selective line absorption coefficient at 1.54 μ . Examination of their experimental results as shown in Figure 7 indicates a total transmission of 0.95 at 1.54 μ for 7.4 mm water vapor in the 1.2 km path. The numbers indicate a total attenuation coefficient of

$$k_T = 6.7 \times 10^{-3} \text{ mm}^{-1} (\text{H}_2\text{O}).$$

*** The product ρl (l in cm) for water vapor is numerically the number of grams of water vapor in a sq. cm. column of length l . It is also the number of precipitable centimeters of H₂O in the path.

TABLE II
Peak Transmissions for Various Conditions
(From Berlinguette and Tat.)

Path → Run →	0.67 km						1.2 km					
	7		10		9		12		11		13	
Wavelength	Trans	H ₂ O	Trans	H ₂ O	Trans	H ₂ O	Trans	H ₂ O	Trans	H ₂ O	Trans	H ₂ O
μ	%	mm	%	mm	%	mm	%	mm	%	mm	%	mm
1.08	87	4.3	95	5.1	85	6.4	85	4.3	82	5.3	88	7.4
1.24	97	"	98	"	86	"	88	"	87	"	88	"
1.65	102	"	99	"	98.5	"	89.5	"	90	"	96	"
2.25	99.5	"	102	"	101	"	94	"	91	"	91	"
3.90	100	4.2	102	5.3	103	6.5	83	4.0	87	5.2	74	7.3
4.62	92.5	3.8	86	5.2	79	"	68	4.0	75	5.1	65	6.7

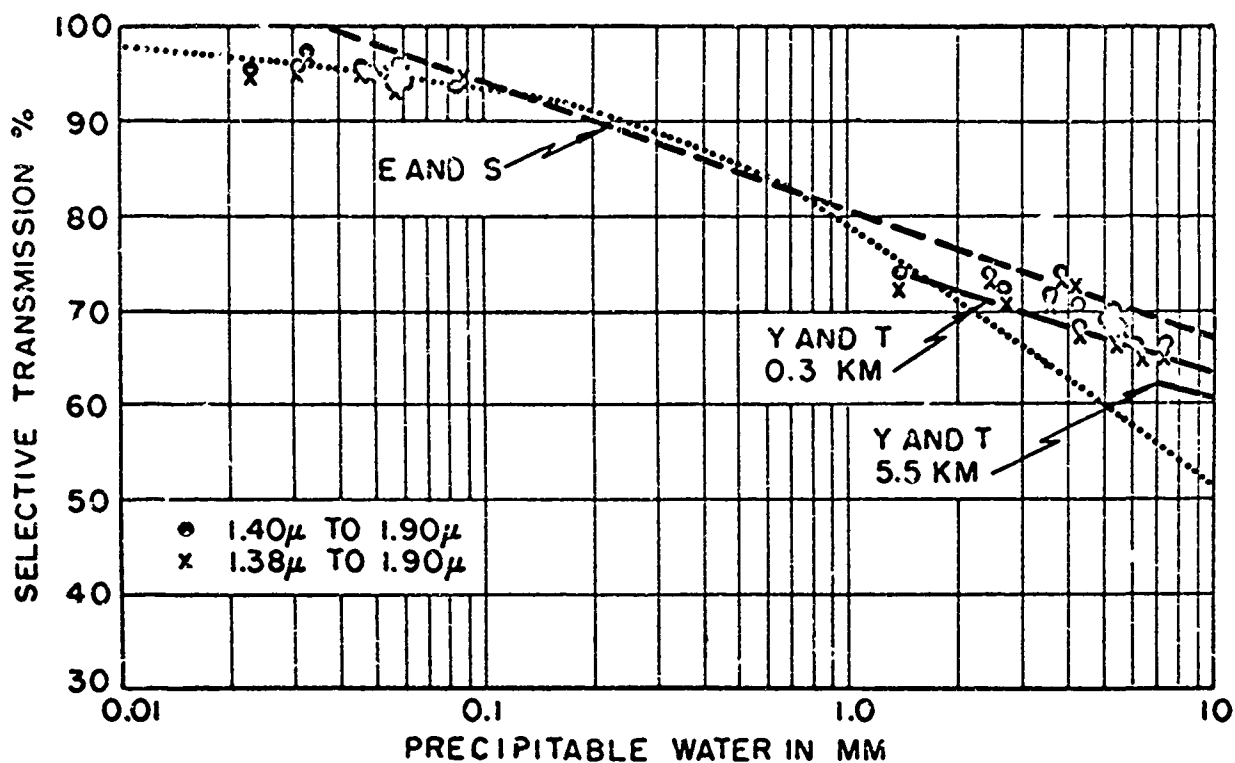


Figure 5. Comparison of Selective Transmission calculated by Berlinguette and Tate (reference 16) to those of Yates and Taylor (Y and T) and Elder and Strong (E and S). Calculations are for total transmission in the band 1.38 to 1.90 microns.

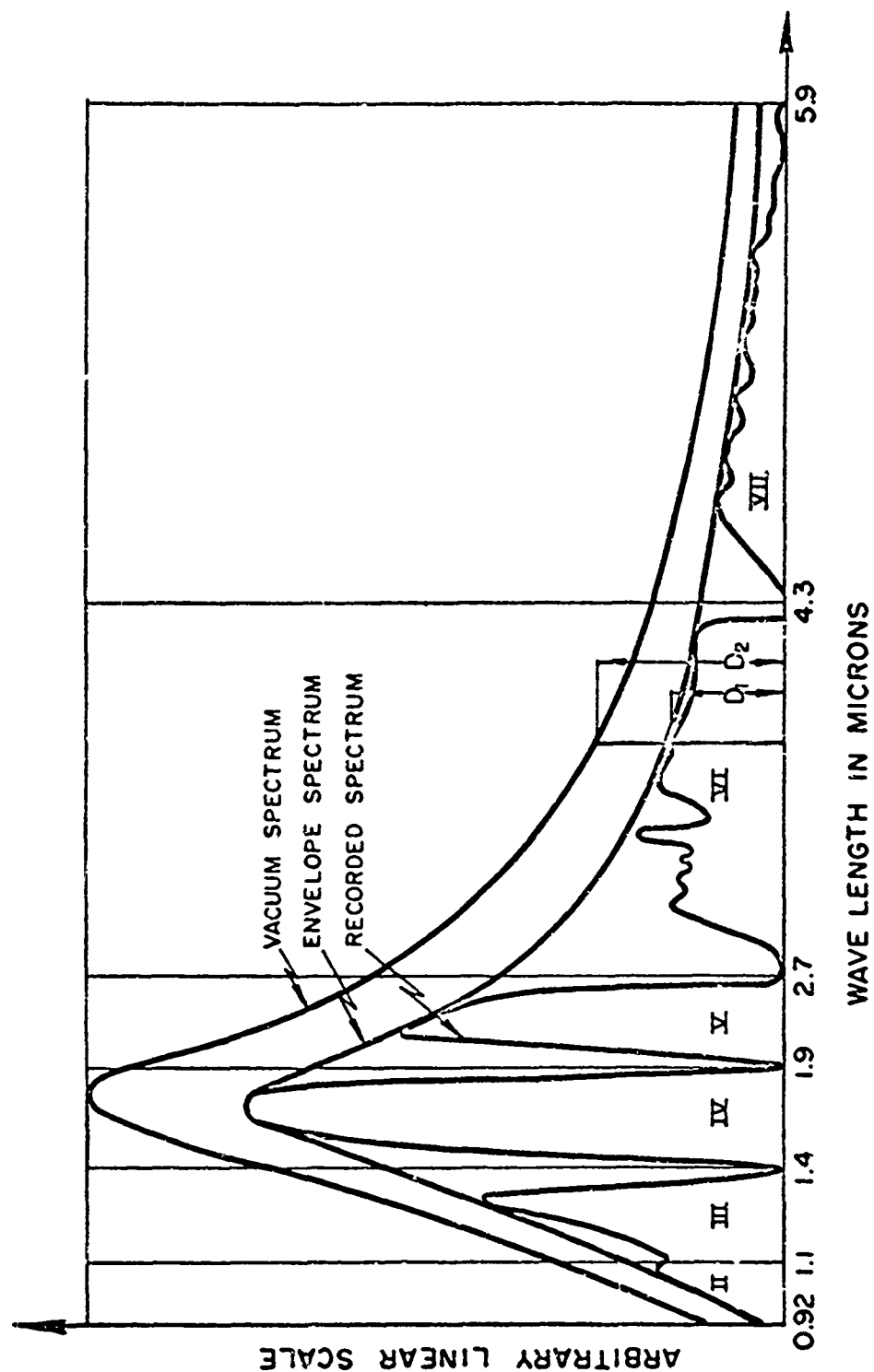


Figure 6. Comparison of emitted spectrum (vacuum spectrum) and spectrum at detector (envelope spectrum) indicating an approximate 25% continuum loss. (From reference 16.)

ABSOLUTE ATMOSPHERIC TRANSMISSION

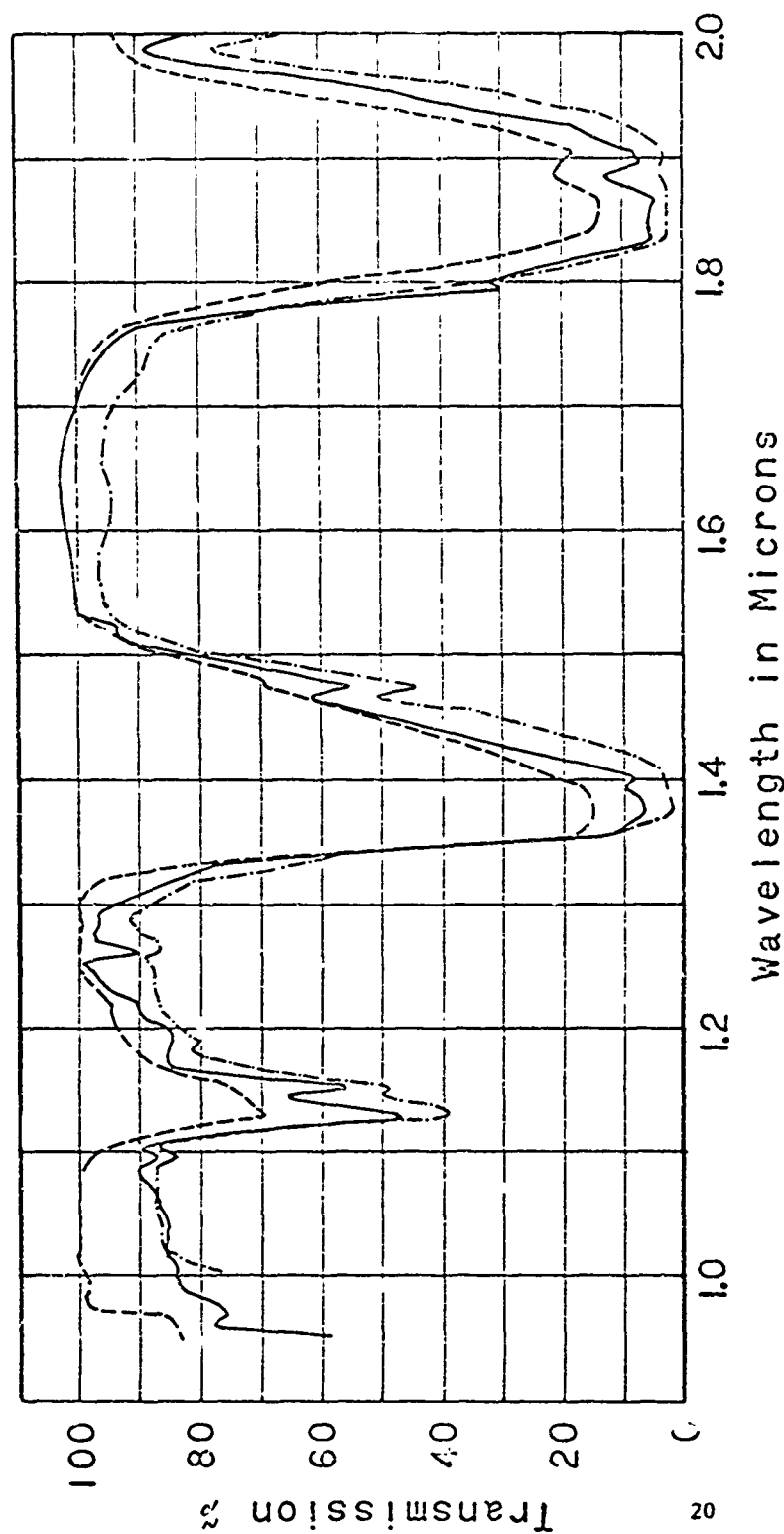


Figure 7. Transmission curves of Herlinguette and Tate (reference 16) indicate a 95% transmission over 1.2 km path at 1.54 μ . The approximate spectral resolution, $\lambda/\Delta\lambda$, at the beginning and end of the spectral region is denoted by "res.," in the legend of the graph.

This value seems unreasonably small for total attenuation. It appears feasible for the selective line absorption at 1.54 microns, which agrees reasonably with the previous values.

Taylor and Yates Fixed Range Measurements (12, 13, 14).

Measurements were made over 5.5 and 16.25 km sea level paths at Chesapeake Bay and over a 27.7 km path at 10,000 feet altitude in Hawaii. Figure 8 displays their results over the two Chesapeake Bay paths. In terms of precipitable water vapor in the path, their approximate attenuation coefficients at 1.54 μ are:

- a) 5.5 km path: $k_{1.54} = 3.15 \times 10^{-2} \text{ mm}^{-1} (\text{H}_2\text{O})$
- b) 16.25 km path: $k_{1.54} = 1.56 \times 10^{-2} \text{ mm}^{-1} (\text{H}_2\text{O})$

Calculations in terms of reciprocal km yield

- a) 5.5 km path: $k_{1.54} = 7.9 \times 10^{-2} \text{ km}^{-1}$
- b) 16.25 km path: $k_{1.54} = 5 \times 10^{-2} \text{ km}^{-1}$

A comparison between these values and those of Berlinguette and Tate indicates a rather large discrepancy. Again aerosol absorption and scattering have not been considered.

Taylor and Yates also give crude measurements of transmission in a snow storm and in fog mixed with rain. The attenuation coefficient during a snow storm at 1.54 μ is estimated to be:

$$k_{\text{snow}} \sim 0.93 \text{ km}^{-1}.$$

The attenuation coefficient for light fog mixed with rain is estimated to be approximately:

$$k_{\text{fog-rain}} \sim 6.91 \text{ km}^{-1}.$$

Elterman's Scattering Coefficient (i)

A clear standard atmosphere model was tabulated for a 25 km meteorological range* based upon the 1964 U. S. Standard Atmosphere. Rayleigh scattering and Mie scattering coefficients were calculated for 22 different wavelengths for various altitudes (assuming 200 particulates per cm^3 at sea level). Figures 9 and 10 are plots of

* The meteorological range, V, is that distance for which the transmittance falls to 2% i.e., $V = 3.1912/\sigma$, where σ is the attenuation coefficient.

CURVE	PATH LENGTH	DATE	TIME	TEMP.	R.H.	PRECIPITABLE WATER	VISUAL RANGE
A	1000'	3-20-56	3PM	37°F	62%	1.1MM	22MI.
B	3.4MI.	3-20-56	10PM	34.5°F	47%	13.7MM	16MI.
C	10.1MI.	3-21-56	12AM	40.5°F	48%	52.0MM	24MI.
WINDOW DEFINITIONS							
I	0.72 TO 0.94 μ	V 1.90 TO 2.70 μ					
II	0.94 TO 1.13 μ	VI 2.70 TO 4.30 μ					
III	1.13 TO 1.38 μ	VII 4.30 TO 6.0 μ					
IV	1.38 TO 1.90 μ	VIII 6.0 TO 15.0 μ					

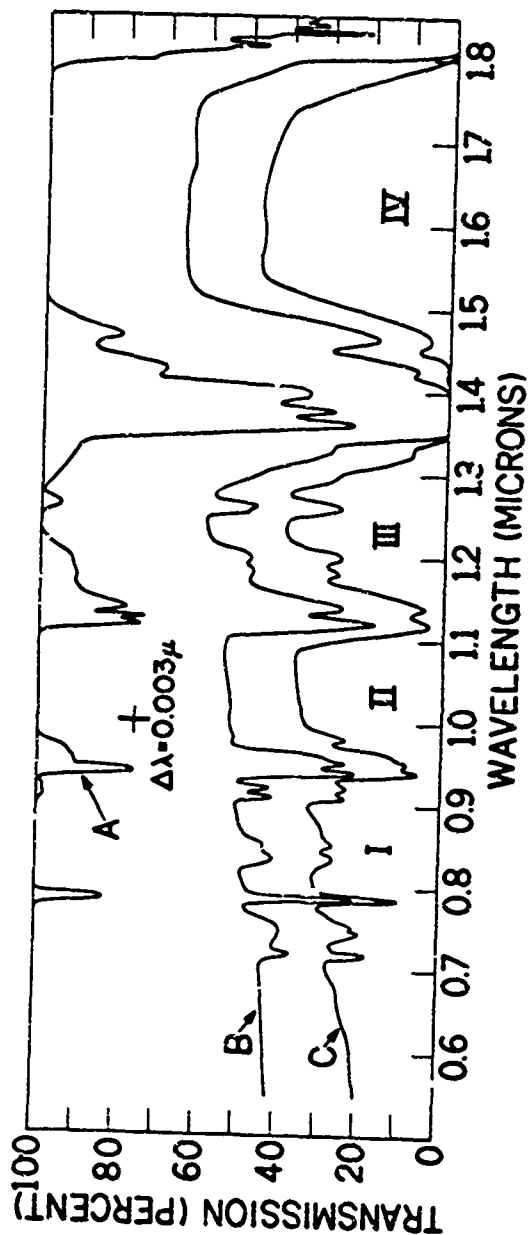


Figure 8. Atmospheric transmission spectra obtained by Taylor and Yates (reference 12).

ATMOSPHERIC SCATTERING COEFFICIENTS VERSUS WAVELENGTH FOR SEA LEVEL ALTITUDE

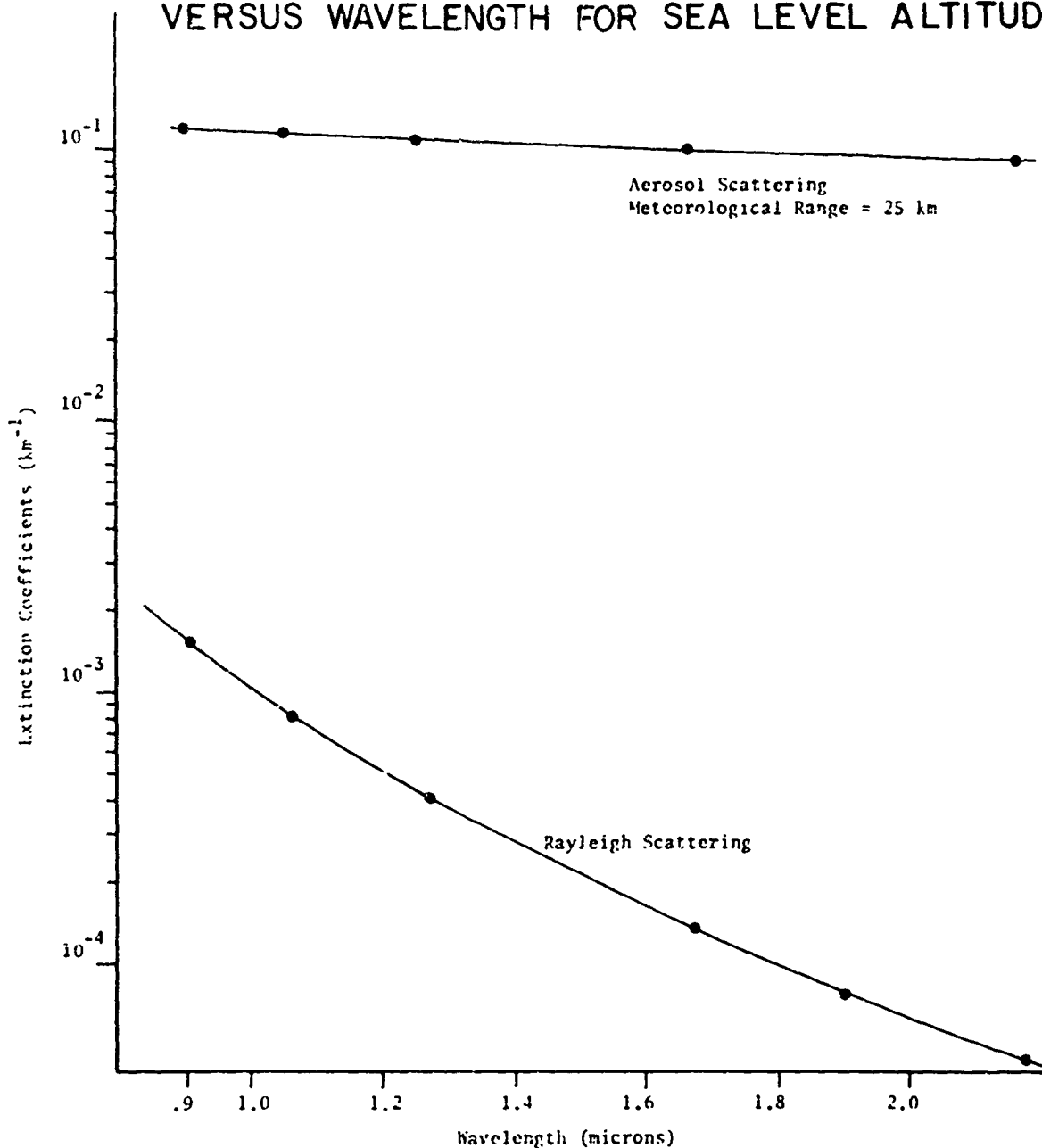


Figure 9. Extinction Coefficients at sea level for aerosol scattering and Rayleigh scattering, from data by Elterman (1).

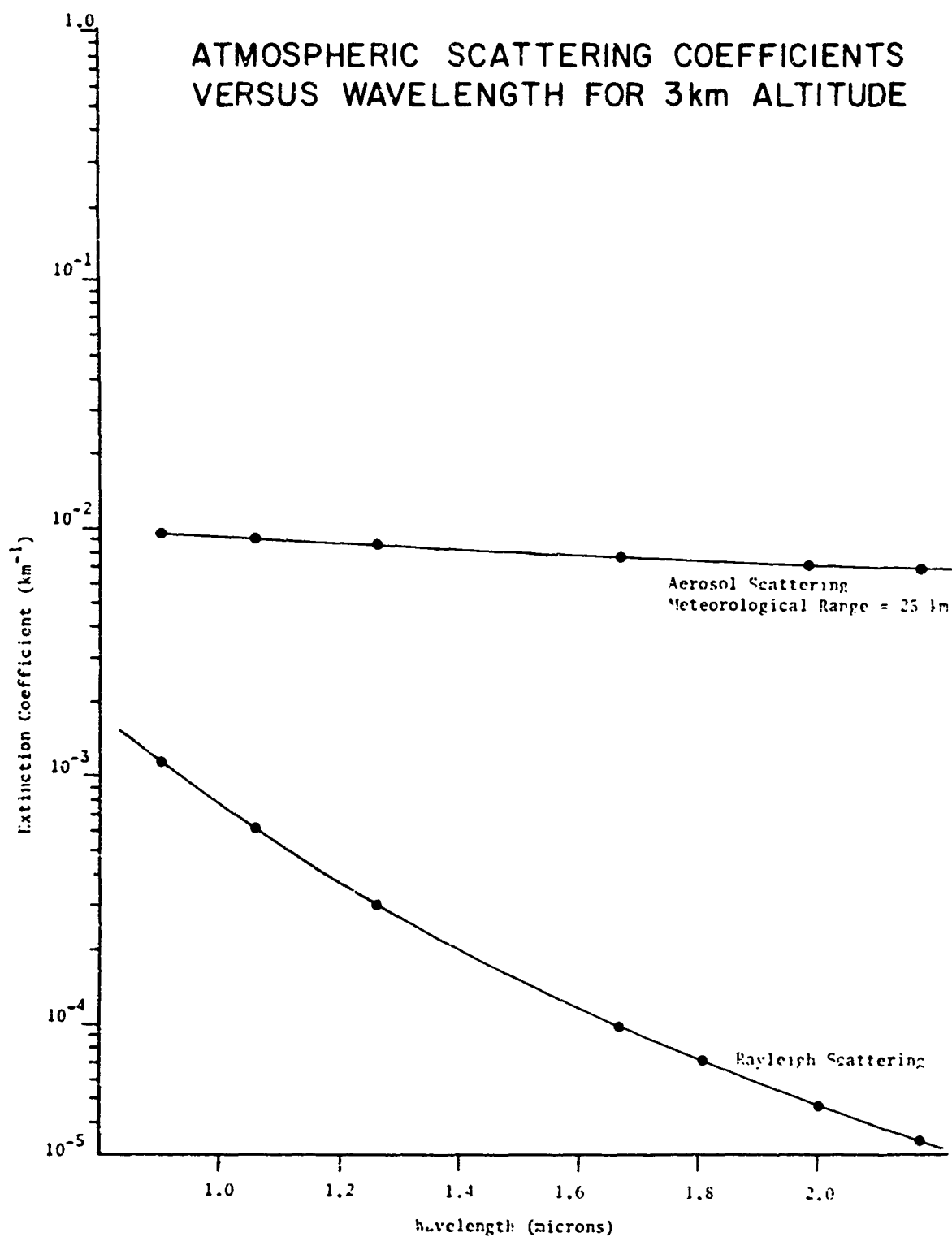


Figure 10. Extinction Coefficients at 3 km for Aerosol Scattering and Rayleigh scattering. From data by Filterman (1).

selected values. Figure 9 shows the sea level curves for both sets of coefficients. In particular these calculations indicate that Rayleigh scattering may be neglected in comparison with Mie scattering. Based upon the reported data, the sea level Mie coefficient should be approximately:

$$S_{\text{sea level}} = 0.1 \text{ km}^{-1}$$

His calculations (See figure 10) also indicate that the Mie scattering coefficient at 3 km for 1.54μ may be an order of magnitude less:

$$S_{3\text{km}} = 8 \times 10^{-3} \text{ km}^{-1}.$$

It should be noted that this author assumed only three attenuation mechanisms: ozone absorption, Rayleigh scattering and aerosol (Mie) scattering.

CONCLUSIONS

In section II of this report five factors were identified that contribute to the atmospheric attenuation. The review in the preceding sections indicates that most investigators have attempted to correlate all absorption to one predominant mechanism: either to water vapor or aerosols, but not both. This leads to difficulty in predicting exact atmospheric attenuation characteristics for various physical conditions (variations in water content, dust content, etc). It appears that a systematic laboratory approach must be undertaken to evaluate the water vapor absorption. Once this is completed, careful determination of the aerosol attenuation must be attempted. The attenuation due to water vapor and aerosol should then be correlated with actual field measurements in which both the water vapor and aerosol content are measured.

In the absence of such data, approximate values may be obtained using the published data. There appears to be little doubt that particulate scattering will probably be the most important loss mechanism for continental sea level paths. The relative importance of atmospheric gas absorption processes (excluding water vapor) will depend to a great extent upon the wavelength band width of the laser. At higher altitudes and for exceptional clear atmosphere conditions gas absorption will be relatively more important.

Based upon the Elterman data, the particulate scattering coefficient $S_{1.54}$ should be within the range (for 25 miles visibility)

$$8 \times 10^{-3} \text{ km}^{-1} \leq S_{1.54} \leq 1.0 \times 10^{-1} \text{ km}^{-1}$$

The increased number of smoke particulates encountered in military uses may increase this upper limit by a factor of 10; however the effect of forward scattering increasing the beam efficiency will tend to reduce this upper limit somewhat. The exact effective value for the upper limit for $S_{1.54}$ is quite uncertain.

The atmospheric selective line absorption coefficient, based upon Mohler's data, should vary between the limits

$$3 \times 10^{-3} \text{ km}^{-1} \leq \alpha_{1.54} \leq 3 \times 10^{-2} \text{ km}^{-1}$$

(It should be noted that the effect of water vapor absorption is not completely accounted for in this coefficient.)

There is considerable uncertainty in the continuum contribution due to water vapor. The various experimental results indicate a very wide spread of values. An estimate of this contribution is probably within the range

$$1 \times 10^{-3} \text{ mm}^{-1} (\text{H}_2\text{O}) \leq k_T' \leq 1 \times 10^{-2} \text{ mm}^{-1} (\text{H}_2\text{O}).$$

For a warm humid day (70°F and 70% relative humidity) these coefficients become

$$1.6 \times 10^{-2} \text{ km}^{-1} \leq C_T \leq 1.6 \times 10^{-1} \text{ km}^{-1}$$

This would effectively double the attenuation coefficient.

Based upon the preceding, the expected value of the total attenuation coefficient should be within

$$0.02 \text{ km}^{-1} \leq k_{T_{1.54}} \leq 0.29 \text{ km}^{-1}$$

Battlefield attenuation will probably be near the upper limit. For adverse conditions such as rain or fog, the total attenuation coefficient will be approximately

$$k_{T_{1.54}} \approx 0.9 \text{ km}^{-1}$$

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13. ABSTRACT Potential atmospheric effects on the propagation of electromagnetic radiation at 1.54 micron wavelength are examined. The results of transmission measurements by various investigators, as reported in the literature, coupled with theoretical calculations are applied to estimate the transmission characteristics for erbium ion (Er ⁺⁺⁺) laser radiation in this region. The output of the Er ⁺⁺⁺ laser at 1.54μ is discussed in some detail. Predominant attenuation mechanisms are found to be aerosol absorption and aerosol scattering. Contributions from five investigations of atmospheric transmission in this region are summarized. Nonlinear effects are not considered.		

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