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ATMOSPHERIC TRANSMISSION OF CO_2 LASER RADIATION WITH APPLICATION TO LASER DOPPLER SYSTEMS

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November 28, 1975

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16. ABSTRACT

The molecular absorption coefficients of carbon dioxide, water vapor, and nitrous oxide are calculated at the P16, P18, P20, P22, and P24 lines of the CO_2 laser for temperatures from 200 to 300 K and for pressures from 100 to 1100 mb. The temperature variation of the continuum absorption coefficient of water vapor is taken into account semi-empirically from Burch's data. The total absorption coefficient from the present calculations falls within ±20 percent of the results of McClatchey and Selby. The transmission loss which the MSFC CO_2 pulsed laser Doppler system experiences has been calculated for the January 1973 flight-test conditions for the five P-lines. The total transmission loss is approximately 7 percent higher at the P16 line and 10 percent lower at the P24 line compared to the P20 line. Comparison of the CO_2 laser with HF and DF laser transmission reveals that $P_2(8)$ line at 3.8 μm of the DF laser is much better from the transmission point of view for altitudes below 10 km.

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I. INTRODUCTION

Marshall Space Flight Center (MSFC) has been developing laser Doppler systems for remote measurement of wind speed and turbulence for over a decade. Some of these systems designed to operate over long atmospheric paths are affected by the attenuation due to the atmospheric gases, particulate matter, and turbulence. The transmission losses due to the molecular gases and aerosols are considered in this report. The effects of atmospheric turbulence on the performance of the laser Doppler system will be considered in a later publication.

The transmission losses are characterized as linear or nonlinear to distinguish between laser power-independent and power-dependent processes. We consider the linear transmission losses. The infrared 10.6 μm spectral region lies in one of the atmospheric transmission windows and is the wavelength at which CO_2 laser operates efficiently. An atmospheric window is a spectral region over which the absorption by the permanent gases is relatively weak and is usually chosen for atmospheric propagation to keep the absorption losses to a minimum.

The atmospheric windows in the infrared lie between the strong bands of carbon dioxide and water vapor which are the two major absorbing gases in the infrared. Figure 1 shows a low resolution absorption spectrum of solar radiation at ground level from 1 to 15 μm [1] together with the spectra of various atmospheric gases from the laboratory measurements for comparison and the operating wavelength region of HF*, DF**, and CO_2 lasers. Except for ozone and water vapor, the other absorbing gases are generally uniformly mixed.

None of the windows are completely transparent as a result of molecular absorption and scattering by particulate matter. The CO_2 laser lines have a typical line width of 2×10^{-5} μm or 60 mHz while the absorption lines of atmospheric gases are several orders of magnitude wider. McClatchey and Selby [2]

* Hydrogen Fluoride

** Deuterium Fluoride

have calculated the atmospheric transmission in the 10.6 μm region for a set of standard atmospheric conditions. Their results are shown as two-way losses in dB for the AFCRL* Mid-Latitude Summer Hazy Atmosphere for some P-lines and R-lines in Figure 2. The transmission losses for several lines at 3.5 km altitude for a 10 km horizontal path are shown in Table 1.

TABLE 1. TRANSMISSION LOSSES

Laser Line	Loss (dB)	Laser Line	Loss (dB)
P40*	2.15	P4	3.58
P32	5	R0*	2.2
P20	7.85	R12	6.8
P18	10.4	R22	6.3
P14	9.23	R30	4.6
P6	4.64		

*P40 and R0 lines have the least transmission loss.

The atmospheric conditions are variable and deviations from the standard AFCRL models can result in large errors in the absorption coefficient. The purpose of this report is to provide the absorption coefficient of each of the molecules relevant for CO_2 laser radiation for various pressures and temperatures of interest in the lower atmosphere. The transmission may then be calculated at the prevailing atmospheric conditions.

The pulsed laser Doppler system developed by MSFC for the detection and measurement of atmospheric turbulence uses a CO_2 laser beam propagating in the atmosphere over several kilometers. The atmospheric data obtained during the flight tests at Edwards AFB are used to calculate the transmission loss which the system experiences and are compared with the measured signal-to-noise (S/N) ratio. The transmission loss is found to be significant and serves to explain a large part of the losses leading to the $1/R^3$ falloff of the measured S/N values instead of the theoretical $1/R^2$ falloff where R is the range. The transmission loss may be reduced by operating at a different infrared wavelength. The $P_2(8)$ line at 3.8 μm of the DF laser experiences a transmission loss which is much less than that of the CO_2 laser.

*Air Force Cambridge Research Laboratories

II. CALCULATION OF THE ABSORPTION COEFFICIENT

The molecules active in the 10 μm region of the infrared are methane, CH_4; ethylene, C_2H_4; nitrous oxide, N_2O; ammonia, NH_3; Ozone, O_3; nitric acid, HNO_3; carbon dioxide, CO_2; and water, H_2O. Excluding water vapor; nitrogen, oxygen, argon, and carbon dioxide are the four major constituents of the atmospheric gases. The remaining gases constitute less than 0.004 percent of the total by volume. It is assumed that all of the gases except water vapor and ozone are uniformly mixed by volume in the atmosphere.

The absorption coefficient for each line as a function of frequency is assumed to be described by the Lorentz relation

$$k(\nu) = \frac{S\alpha}{\pi[(\nu - \nu_0)^2 + \alpha^2]} \tag{1}$$

where ν_0 (cm^{-1}) is the resonant frequency, S (cm^{-1}/molecules cm^{-2}) is the line intensity per absorbing molecule, and α (cm^{-1}) is the Lorentz line width parameter. The validity of equation (1) to describe the correct line shape in the wings has been in doubt specially for carbon dioxide and water vapor. The Lorentz shape overpredicts the wings for carbon dioxide while underestimating for water vapor.

The line intensity is independent of pressure but is dependent on temperature and is given by

$$S(T) = S(T_s)\,\frac{Q_v(T_s)}{Q_v(T)}\,\frac{Q_r(T_s)}{Q_r(T)}\,\exp\left[\frac{1.439\,E''(T - T_s)}{T\,T_s}\right]$$

where E'' (cm^{-1}) is the energy of the lower state of the transition, Q_v and Q_r are the vibrational and rotational partition functions, respectively, and T_s is standard temperature, 296 K.

The half-width of the line depends on the pressure and temperature as follows:

$$\alpha = \alpha_0 \frac{p}{p_0} \left(\frac{T_0}{T}\right)^n$$

where n is usually assumed equal to 1/2. n = 0.62, suggested by Benedict and Kaplan [3], is used for water vapor. Measurements by Ely and McCubbin [4] at high temperatures and by Tubbs and Williams [5] at temperatures lower than the room value suggest that the half-width variation of carbon dioxide is closer to n = 1 than n = 1/2. The exact dependence is uncertain and appears to depend on the rotational quantum number of the line. In the absence of more accurate information, we use the usual n = 1/2 in this work for carbon dioxide.

The four absorption line parameters ν_0, S, α, and E'' have been listed for the seven molecules H_2O, CO_2, O_3, N_2O, CO, CH_4, and O_2 by McClatchy et al [6] from the existing information and these are used here for the line-by-line calculation of the absorption coefficient at the laser line frequencies.

The atmospheric carbon dioxide and water vapor are the major attenuators at the CO_2 laser line frequencies. The concentrations of the trace gases and pollutants are too low to have any significant effect. A simple estimate may be made as follows. At the line center, the absorption coefficient is $K = S/\pi\alpha$ per molecule. For a concentration of 1 ppm, the number of molecules in 1 km path is approximately 10^{18}. For $S = 10^{-23}$ and $\pi\alpha = 0.1$, one obtains $K = 10^{-4}$ c/km where c is the number of ppm. Most of the trace gases have a concentration c of unity or less. For instance, ozone has a concentration of approximately 0.02 ppm at sea level and 0.2 ppm at 25 km. N_2O has a concentration of 0.28 ppm. The effect of the trace gases is thus very small compared to CO_2 and H_2O. Among the trace gases, N_2O has several lines in the 10 μm region and its effect has been calculated to give an idea of its contribution to the absorption. At altitudes higher than 12 km, ozone absorption may become important specially at the R-lines of CO_2 laser. In addition to the molecular absorption, scattering and absorption due to the aerosols must be included in obtaining the total absorption coefficient.

III. ABSORPTION BY CARBON DIOXIDE

The absorption coefficient at the center of P20 laser line by the atmospheric carbon dioxide has been calculated by Yin and Long [7] and they gave polynomial fits to the absorption coefficient as a function of altitude for two model atmospheres. The wings of neighboring lines also contribute to the absorption at any laser line frequency. In this work, lines within ±20 cm^{-1} are assumed to contribute to the absorption. A concentration of 330 ppm of CO_2 in the atmosphere is assumed. The effect of including the wings of the neighboring lines is approximately an increase of 3 to 5 percent at the P20 line. Since the CO_2 laser operates efficiently around the P20 line, the absorption coefficients for P16, P18, P20, P22, and P24 lines are calculated for temperatures and pressures of interest in the lower atmosphere. The effect of temperature on the absorption coefficient may be seen from Figures 3 and 4. The absorption coefficients for P16, P18, and P20 lines are approximately the same at 300 K and they separate out at 200 K. The absorption coefficients are almost independent of pressure and the slight pressure dependence comes from the line wings as the absorption at the line center is independent of pressure. Figures 5 through 9 give the absorption coefficient at the individual laser lines for pressures from 100 to 1100 mb and temperatures from 200 K to 300 K.

IV. ABSORPTION BY WATER VAPOR

Many weak absorption lines of water vapor occur in the 10 μm region. On the basis of these lines, there should be an almost complete transparency in this region for reasonable atmospheric water vapor content. The measurements of heat radiation of the sky gave higher values of total radiation than would be expected due to the rotational lines of water vapor. To explain the observed higher emissions, the existence of a water vapor continuum in the 8 to 14 μm atmospheric window and beyond due to the wings of strong lines located in the bands on either side of the window was first suggested by Elsasser [8] in 1938. The existence of continuum absorption by water vapor has been well established now due to the several experimental observations on solar spectrum and in the laboratory [9-14]. However, the theory based on the usual line shapes has not been successful in explaining the experimental observations. Thus the calculations have to be based on the available experimental results.

McCoy, Rensch, and Long [14] measured the absorption of the water vapor continuum and suggested the empirical equation,

$$K = 4.32 \times 10^{-6} p(P + 193 p) \text{ km}^{-1} \quad , \tag{2}$$

where p is the partial pressure of water vapor and P is the total pressure, both in Torr. This relation has been widely used to estimate the water vapor absorption. Equation (2) takes care of the pressure dependence and is valid at the room temperature. The continuum absorption has been observed to decrease with increasing temperature and vice versa.

Burch [15] measured the continuum absorption coefficient for pure water vapor at three temperatures and his results are shown in Figure 10. The points marked are the revised values and are 10 to 15 percent less than the solid curves obtained in the earlier measurements [16]. The rapid decrease in the absorption coefficient with increasing temperature is a prominant feature of these results. The association of water molecules due to hydrogen bonding (dimerization) proposed by Varanasi, Chow, and Penner [17] predicts the trend of observed temperature dependence of the continuum absorption coefficient.

For atmospheric transmission studies, we are interested in temperatures less than 296 K. Since no data are available at low temperatures, an empirical extrapolation suggested by Burch is used in this work:

$$C_s^\circ (T) = C_s^\circ (296) \left(\frac{296}{T}\right)^{\tau} \qquad (3)$$

where C_s° is the absorption coefficient, molecule^{-1} cm^2 atm^{-1}, and τ is to be determined from the experimental values. At 10.6 μm, we find that $\tau = 5.300$ for $T = 358$ K and $\tau = 5.25$ for $T = 392$ K. τ appears to decrease slightly with temperature. These τ values are for temperatures above room temperature; no laboratory measurements are available for temperatures below room temperature. One value of the absorption coefficient at $T = 283$ K is 10 g^{-1} cm^2 atm^{-1} from Figure 8 of Bignell's [13] paper from the solar spectrum observations. The magnitude of the error is unknown here. This value corresponds to $\tau = 5.1$ at $T = 283$ K. Thus the value of τ appears to remain close to 5 even below $T = 296$ K. We assume $\tau = 5.25$ in this work.

There is also the effect of foreign gas broadening on the continuum absorption. The results of McCoy, Rensch, and Long give $C_B^\circ \approx 0.005\, C_s^\circ$ at room temperature. The continuum absorption coefficient is given by $K = Cu$ where u is the absorber thickness expressed in molecules cm^{-2} and C is given by

$$C = C_s^\circ p + C_B^\circ P \qquad (4)$$

where p is the partial pressure of water vapor and P is the total pressure, both in atmospheres. The partial pressure of water vapor may be obtained from

$$p = 4.56 \times 10^{-5}\, w\, T \tag{5}$$

where w is the number of gm-cm^{-2}/km of water vapor. The water vapor is usually expressed in units of precipitable centimeters which is the same as gm-cm^{-2}. The absorber thickness u is given by

$$u = 3.34 \times 10^{22}\, w = \frac{7.18 \times 10^{26}\, p}{T} \text{ molecules/cm}^2 \quad . \tag{6}$$

The continuum absorption may be written as follows after combining equation (3) to equation (6):

$$K = \frac{1.58 \times 10^{5}}{T} \left(\frac{296}{T}\right)^{5.25} p(p + 0.005\, P) \text{ km}^{-1} \quad . \tag{7}$$

We used $C_s^\circ = 2.2 \times 10^{-22}$ molecules^{-1} cm^2 atm^{-1} at 10.6 μm. Equation (7) is used in this work to calculate the water vapor continuum absorption coefficient for all CO_2 laser lines shown in Figure 11.

In addition to the continuum, rotational lines of water vapor absorb in the 10.6 μm region. Line-by-line calculation is performed for lines which are within ±20 cm^{-1} from the laser line. The line parameters tabulated by McClatchy et al are used in these calculations. The effects of varying the pressure and the temperature are shown in Figures 12 to 18.

V. ABSORPTION BY NITROUS OXIDE

Nitrous oxide has several lines in the 10 μm region. The absorption due to these lines at the laser line frequencies is obtained by a line-to-line calculation assuming that lines within ±20 cm^{-1} contribute. The concentration of N_2O

is assumed to be 0.28 ppm. The results are shown in Figures 19 to 25 for various pressures and temperatures. It may be seen that the absorption of N_2O is approximately two orders of magnitude less than that of CO_2.

VI. COMPARISON WITH AFCRL CALCULATIONS

The present calculations are compared in Table 2 with those of McClatchey and Selby [2] for the AFCRL Standard Atmospheric Models at sea level. Our results have been within ±20 percent of AFCRL numbers.

TABLE 2. COMPARISON WITH THE RESULTS OF McCLATCHEY AND SELBY

	Tropical		Midlatitude Summer		Midlatitude Winter		Subarctic Summer	
	AFCRL	Present	AFCRL	Present	AFCRL	Present	AFCRL	Present
P16	0.5722	0.5481	0.3527	0.3728	0.07466	0.09775	0.1953	0.2274
P18	0.6346	0.4972	0.4146	0.3377	0.1223	0.0907	0.2548	0.2065
P20	0.6094	0.5051	0.3852	0.3419	0.09575	0.08964	0.2238	0.2078
P22	0.6058	0.4842	0.3867	0.3266	0.1021	0.084	0.229	0.1973
P24	0.6029	0.4796	0.3815	0.3216	0.09554	0.0795	0.2223	0.1921

VII. APPLICATION TO PULSED LASER DOPPLER SYSTEM

Huffaker [18, 19, 20, 21] discussed the various laser Doppler systems which are being developed at NASA/MSFC. The pulsed laser Doppler system utilizes the natural particulate matter of the air for long range atmospheric applications. It consists of a coherent CO_2 laser operating at 10.6 μm and transmits 140 pps adjustable in width from 2 to 10 μs through a modified Cassegrain telescope. A homodyne receiver collects the back scattered laser radiation which is detected by a cooled infrared detector and processed in signal processing electronics. This system was carried aboard Ame's Convair 990 airplane and has been flight-tested at Edwards AFB. The atmospheric temperature, dew point, and altitude are measured along the flight path in addition to the S/N value, particle concentrations, etc. The values obtained during the descent of the airplane against the uniform target of Rogers Dry Lake are used to calculate the transmission loss for five P lines and the effect on the S/N ratio.

The S/N ratio for the pulsed laser heterodyne system is given by [19]

$$\frac{S}{N} = \frac{E\ \sigma' \eta_d \eta_s \eta_a\ d^2}{16\ h\ \nu \left[R^2 + \left(\frac{\pi d^2}{4\lambda} \right)^2 \right]} \tag{8}$$

for reflection against a target filling the beam which is focused to infinity. The symbols and their values are as follows:

Parameter	Symbol	Value
Signal-to-Noise Power Ratio	S/N	
Laser Pulse Energy	E	12 mJ
Modified Target Cross-section	σ'	0.05 $ster^{-1}$
Target Range	R	
Aperture Diameter	d	10 in.
System Efficiency	η_s	0.05
Detector Quantum Efficiency	η_d	0.25
Atmospheric Transmission	η_a	
Wavelength	λ	1.06×10^{-5} m
Energy per Photon	$h\nu$	1.9×10^{-20} J.

The atmospheric transmission loss η_a is calculated from

$$\eta_a = \exp \int_0^R 2\,K\,(R)\,dR\ . \tag{9}$$

The range is converted into altitude by the relation

$$H = 1.97\ \text{kft} + R \sin 7° \tag{10}$$

for the flight data of January 1973.

The loss in S/N ratio due to atmospheric absorption at any range is calculated from

$$\left(\frac{S}{N}\right)_{\text{Atm. Loss}} = 8.68 \int_{1.97}^{H} K(H) \frac{dH}{\sin 7^\circ} \cdot \text{db} \qquad (11)$$

The measured values of the static temperature (T_S) and the dew-point temperature (T_D) along the flight path at various altitudes for flight B8, Run 18, 1/19/1973, at Edwards AFB are given in Table 3. The individual molecular absorption coefficients corresponding to these atmospheric conditions are calculated from the data of this report and are shown in detail for the P20 line. The aerosol attenuation must also be added to obtain the total absorption coefficient. The aerosol absorption and scattering coefficients for the hazy condition are taken from Reference 2 and are shown in Table 4 together with the total molecular absorption coefficients for five P lines. The atmospheric two-way transmission loss is calculated using equation (11) and is shown in Figure 26 for the five P lines. The P22 and P24 lines have lower loss and P16 and P18 lines have higher loss than the P20 line. The magnitude of the difference is approximately 2 dB over a path of 90 kft. Thus the variation from line to line is not significant around the P20 line. The S/N ratio corrected for the transmission loss is shown in Figure 27 together with the measured values. If there were no atmospheric losses, the curve falls off as $1/R^2$ where R is the range. The measurements indicate a fall-off nearly as $1/R^3$. Though the CO_2 laser operates in the atmospheric window, the transmission loss is significant over long paths which may explain a large part of the losses leading to $1/R^3$ dependence of the measured S/N values. Some of the remaining losses may be of instrument origin and some due to the atmospheric turbulence.

The range of the system will improve if the large transmission loss can be reduced. One way to reduce the transmission loss is to operate at a different infrared wavelength having less atmospheric absorption. This possibility is examined in the next section.

TABLE 3. CALCULATION OF ABSORPTION COEFFICIENT FOR FLIGHT B8, RUN 18, 1/19/1973, EDWARDS AFB

H (kft)	T_S °C	T_O °C	$K_{CO_2}^{P20}$	$K_{H_2O}^{P20}$ Continuum	$K_{H_2O}^{P20}$ Lines	$K_{N_2O}^{P20}$	K_{Total}^{P20} km^{-1}
2.39	-0.6	-7.9	0.05187	0.02773	0.000983	5×10^{-5}	0.08063
3.00	-3.6	-9.4	0.04821	0.02633	0.000818	3.9×10^{-5}	0.0754
4.00	-8.6	-9.9	0.0424	0.0309	7.1×10^{-4}	3.5×10^{-5}	0.07405
5.03	-10.5	-11.1	0.0404	0.0291	6.08×10^{-4}	3.3×10^{-5}	0.07014
5.98	-9.9	-13.8	0.04105	0.02016	4.75×10^{-4}	2.9×10^{-5}	0.0617
6.98	-12.3	-15.3	0.03852	0.01877	3.95×10^{-4}	2.6×10^{-5}	0.05771
8.00	-13.5	-16.6	0.03729	0.0168	3.37×10^{-4}	2.4×10^{-5}	0.05445
8.99	-15.0	-19.0	0.03579	0.01346	2.61×10^{-4}	2.1×10^{-5}	0.04953
10.00	-16.4	-20.8	0.03444	0.0115	2.13×10^{-4}	1.9×10^{-5}	0.04617
11.03	-17.3	-25.9	0.03358	0.0068	1.29×10^{-4}	1.8×10^{-5}	0.04053
12.02	-18.5	-27.4	0.03246	0.00568	1.07×10^{-4}	1.6×10^{-5}	0.03826
12.96	-19.5	-34.2	0.03156	0.00267	5×10^{-5}	1.5×10^{-5}	0.0343
14.00	-19.8	-45.0	0.03128	0.00075	2×10^{-5}	1.3×10^{-5}	0.03205
14.99	-20.7	-42.3	0.03048	0.001044	2×10^{-5}	1.2×10^{-5}	0.03156
16.01	-21.3	-40.6	0.02997	0.00127	2.4×10^{-5}	9.5×10^{-6}	0.03127

TABLE 4. MOLECULAR ABSORPTION COEFFICIENT OF P LINES AND AEROSOL ATTENUATION PER KM

H (kft)	K (P16)	K (P18)	K (P20)	K (P22)	K (P24)	$K_a + \sigma_a$ (aerosol)
2.39	0.08803	0.08171	0.08063	0.07512	0.07062	0.0248
3.00	0.08227	0.07658	0.0754	0.07032	0.06603	0.02075
4.00	0.08081	0.07542	0.07405	0.06963	0.06572	0.0153
5.03	0.07634	0.07143	0.07014	0.06585	0.06207	0.0114
5.98	0.06717	0.06303	0.0617	0.05747	0.05363	0.0085
6.98	0.06278	0.05903	0.05771	0.05374	0.05007	0.0057
8.00	0.05894	0.05578	0.05445	0.05062	0.04703	0.0036
8.99	0.05386	0.05087	0.04953	0.04588	0.0442	0.0026
10.00	0.05024	0.04751	0.04617	0.04267	0.0393	0.002
11.03	0.04378	0.04157	0.04053	0.03686	0.03352	0.0017
12.02	0.04167	0.0396	0.03826	0.035	0.03175	0.0013
12.96	0.03736	0.03563	0.0343	0.03125	0.02796	0.001
14.00	0.03487	0.03339	0.03205	0.029	0.02579	0.00072
14.99	0.03438	0.03288	0.03156	0.02854	0.02542	0.00053
16.01	0.03409	0.03258	0.03127	0.02829	0.02521	0.00039

VIII. LASERS WITH LOW TRANSMISSION LOSS

Infrared transmission of HF and DF laser radiation has been calculated by Wang [23]. Spencer, Denault, and Takimoto [24] have given experimental results for several DF laser lines. We will now use this information to calculate the transmission loss for the laser Doppler system using HF and DF laser lines and compare with the CO_2 laser system.

The performances of CO_2, HF, and DF laser Doppler systems looking down at a ground target from 5 km altitude at an inclination of 15° in AFCRL Midlatitude Summer Atmosphere are shown in Figure 28. The curves without atmospheric effects are calculated for the same values of the parameters assuming that the backscatter coefficient varies as $1/\lambda^2$ [25]. The CO_2 laser experiences a loss which is 16 dB higher than that for DF laser for a slant range of 20 km.

The two-way transmission losses for a horizontal transmission over a range of 40 km at altitudes of 5 km and 10 km are given in Table 5.

TABLE 5. TWO-WAY HORIZONTAL TRANSMISSION LOSS FOR INFRARED LASERS OVER 40 km RANGE

Laser, Line and Wavelength	Loss in db	
	H = 5 km	H = 10 km
CO_2, P20, 10.6 μm	19	7
HF, $P_2(8)$, 2.91 μm	4	0.6
DF, $P_2(8)$, 3.8 μm	1	0.45
CO, $P_6(5)$, 5.07 μm	3.5	0.45

The DF laser has the least loss. As the altitude increases, the magnitude of the loss reduces. At 10 km altitude, HF, DF, and CO lasers have approximately the same loss. Figure 29 gives the two-way loss as a function of altitude for these lasers in AFCRL mid-latitude summer atmosphere using data from Reference 23. DF laser is much better than the CO_2 laser for transmission through the atmosphere. But due to the longer wavelength, the CO_2 laser system has a larger coherence diameter than the DF laser system which may be an important consideration for an operating system.

IX. CONCLUSIONS

The atmospheric transmission loss has been calculated for five P lines (P16, P18, P20, P22, and P24) of the CO_2 laser using the January 1973 flight test conditions. It is found that the transmission loss is approximately 7 percent higher for P16 lines and 10 percent lower for P24 line compared to the P20 line. Thus the variation of the transmission loss is not very significant around the P20 line which is the usual range of efficient operation of the CO_2 laser. The P40 line or R0 line have better transmission but it may not be possible to operate on these lines.

Comparison with other infrared lasers reveals that DF laser operating at 3.8 μm on $P_2(8)$ line has the least transmission loss and that the CO_2 laser has higher loss at all altitudes. However for altitudes higher than 10 km, the magnitude of the loss is small, and no significant advantage appears to be gained in choosing one laser or the other.

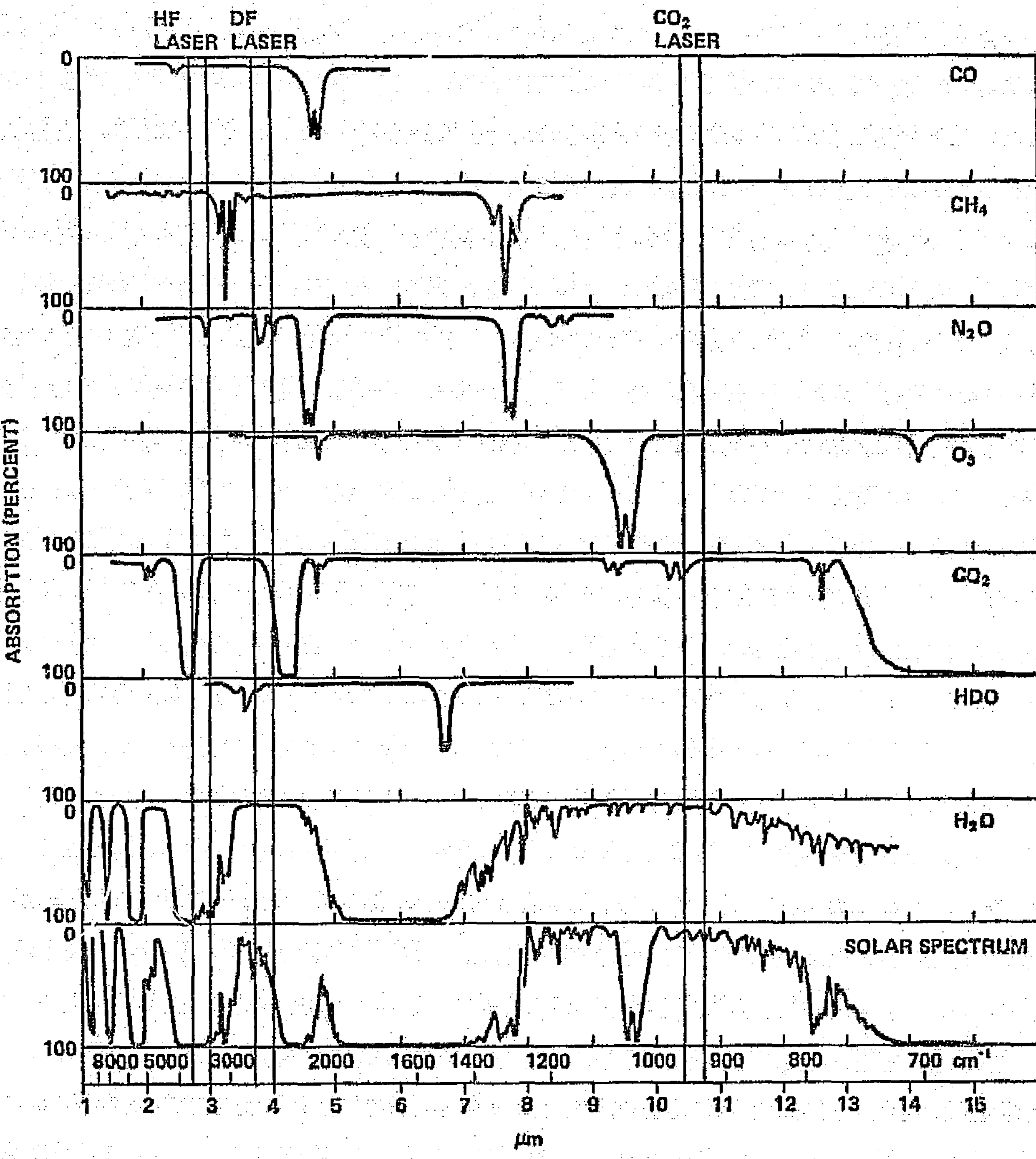

Figure 1. Near-infrared solar spectrum, spectra of various atmospheric gases and operating frequencies of HF, DF, and CO_2 lasers.

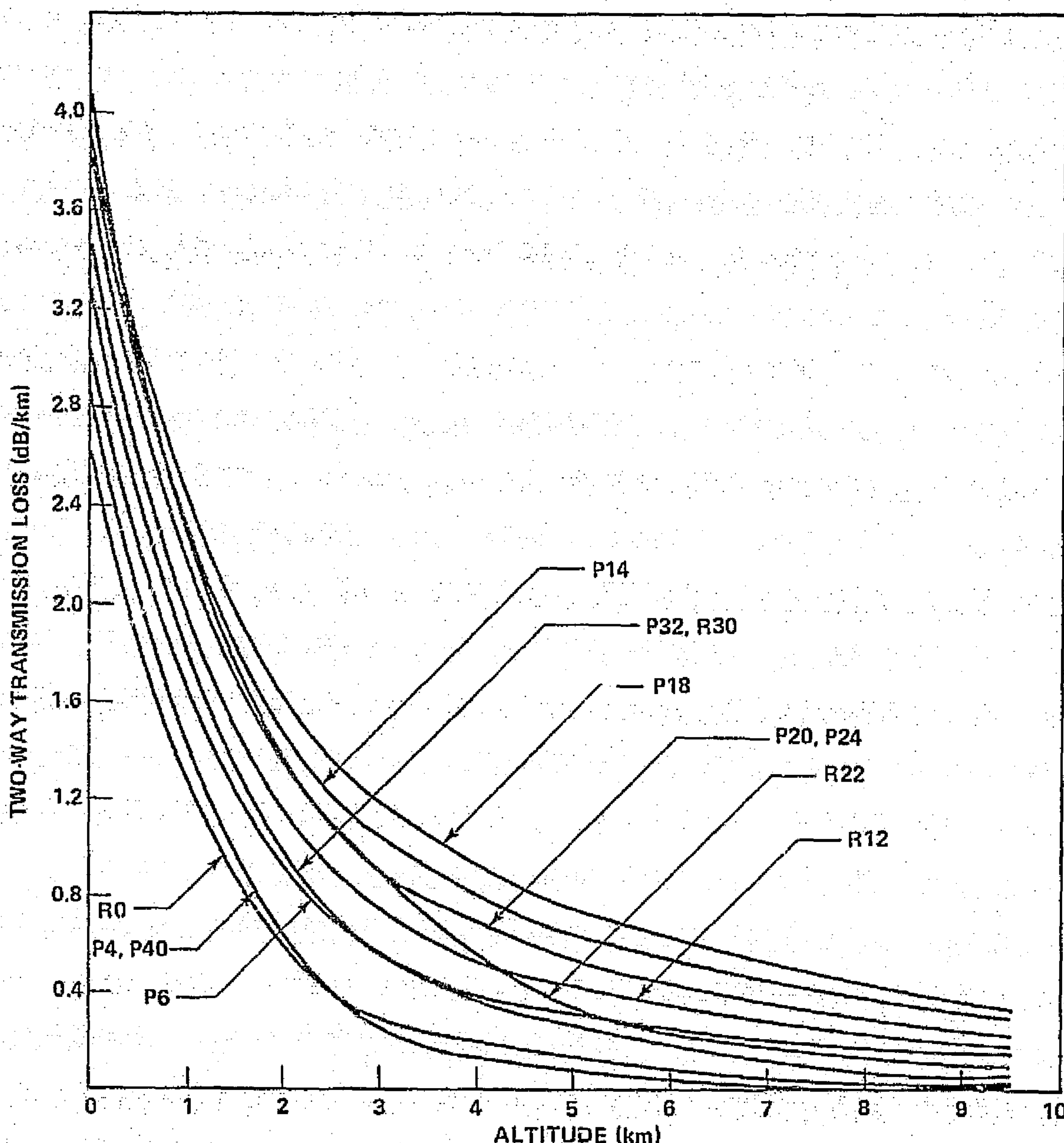

Figure 2. Variation of two-way transmission loss with altitude for P and R lines of CO_2 laser in AFCRL Midlatitude Summer Hazy Atmosphere.

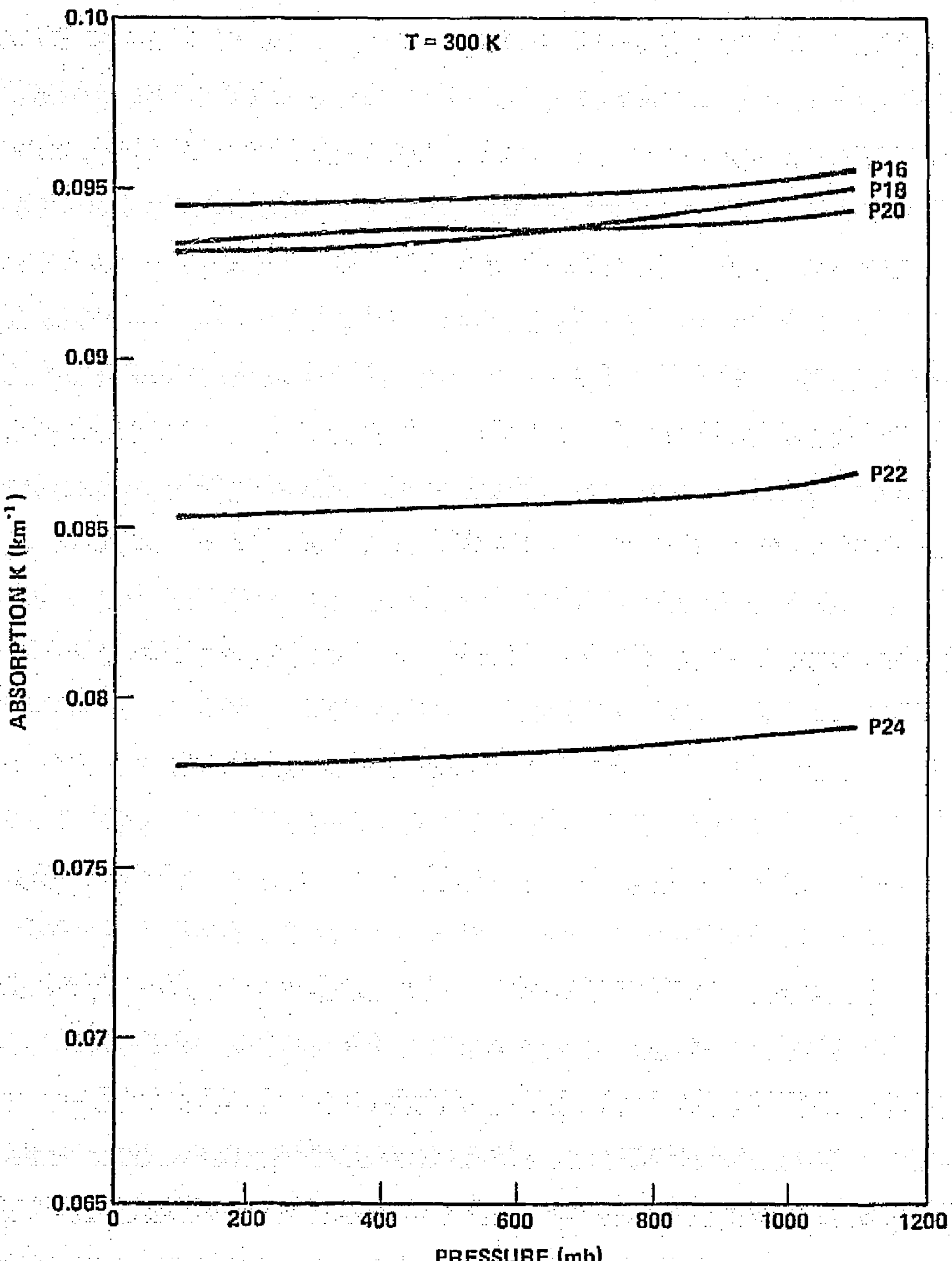

Figure 3. Absorption coefficient of carbon dioxide at T = 300 K.

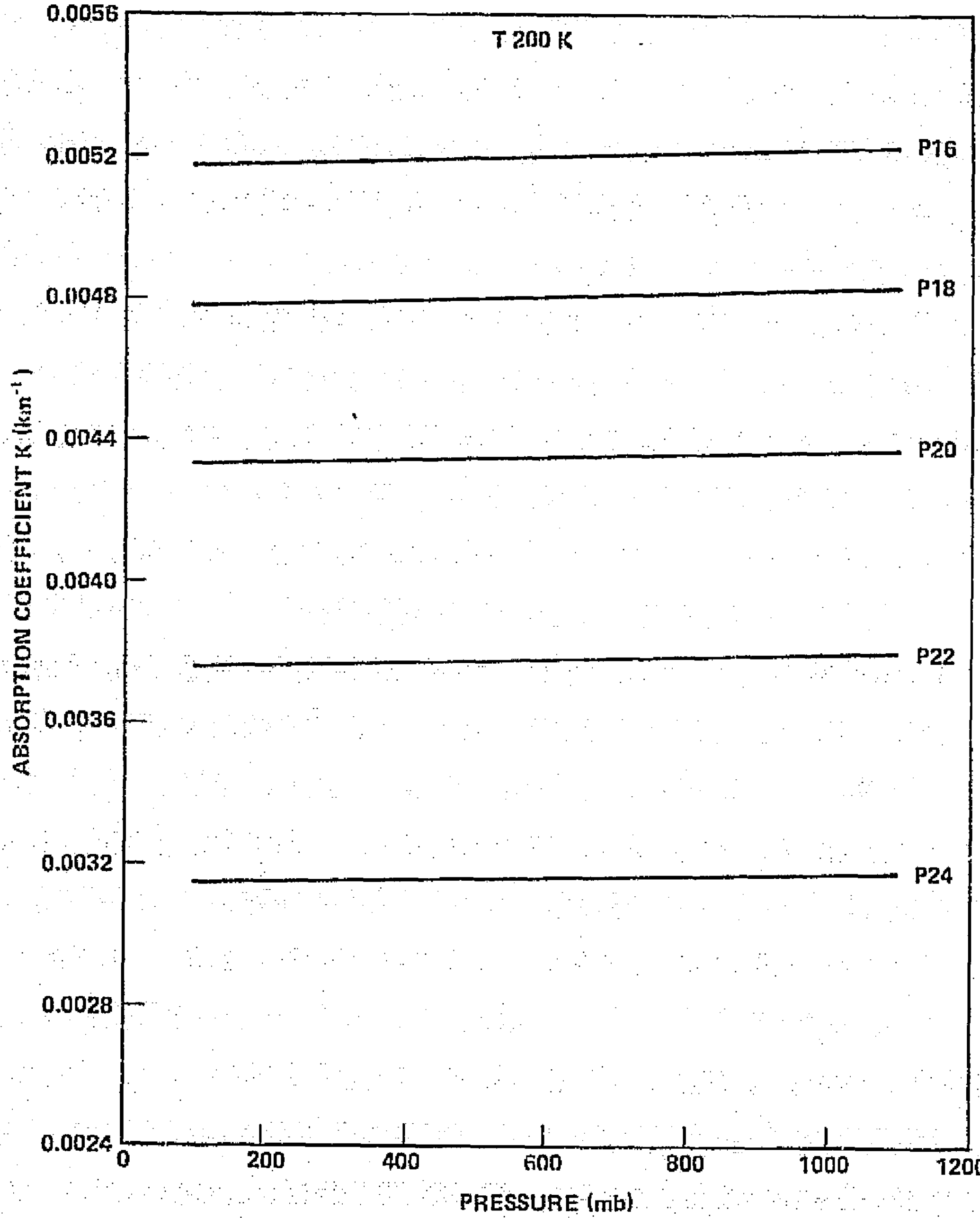

Figure 4. Absorption coefficient of carbon dioxide at T = 200 K.

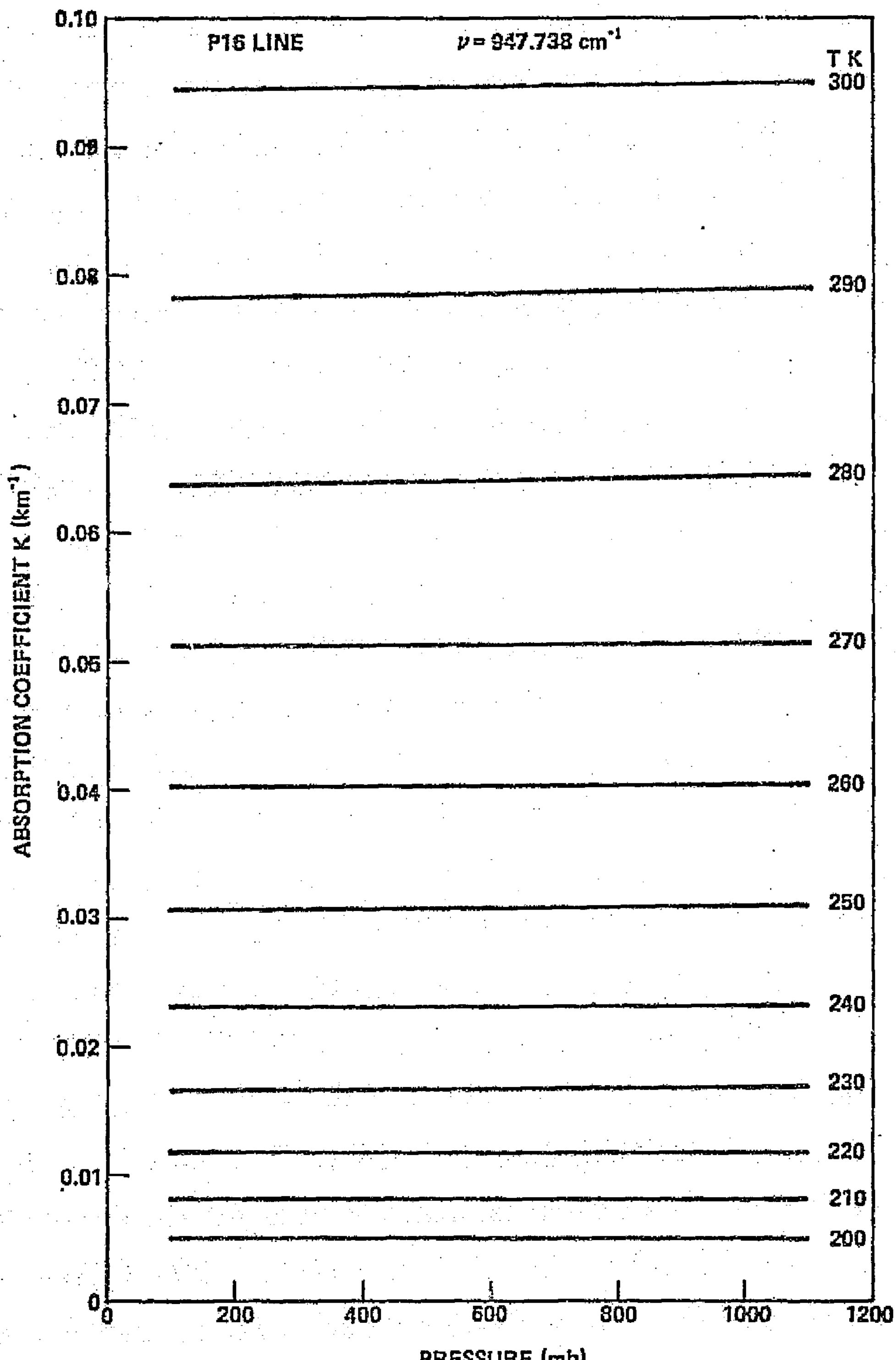

Figure 5. Absorption coefficient of carbon dioxide at $\nu = 947.738\ cm^{-1}$.

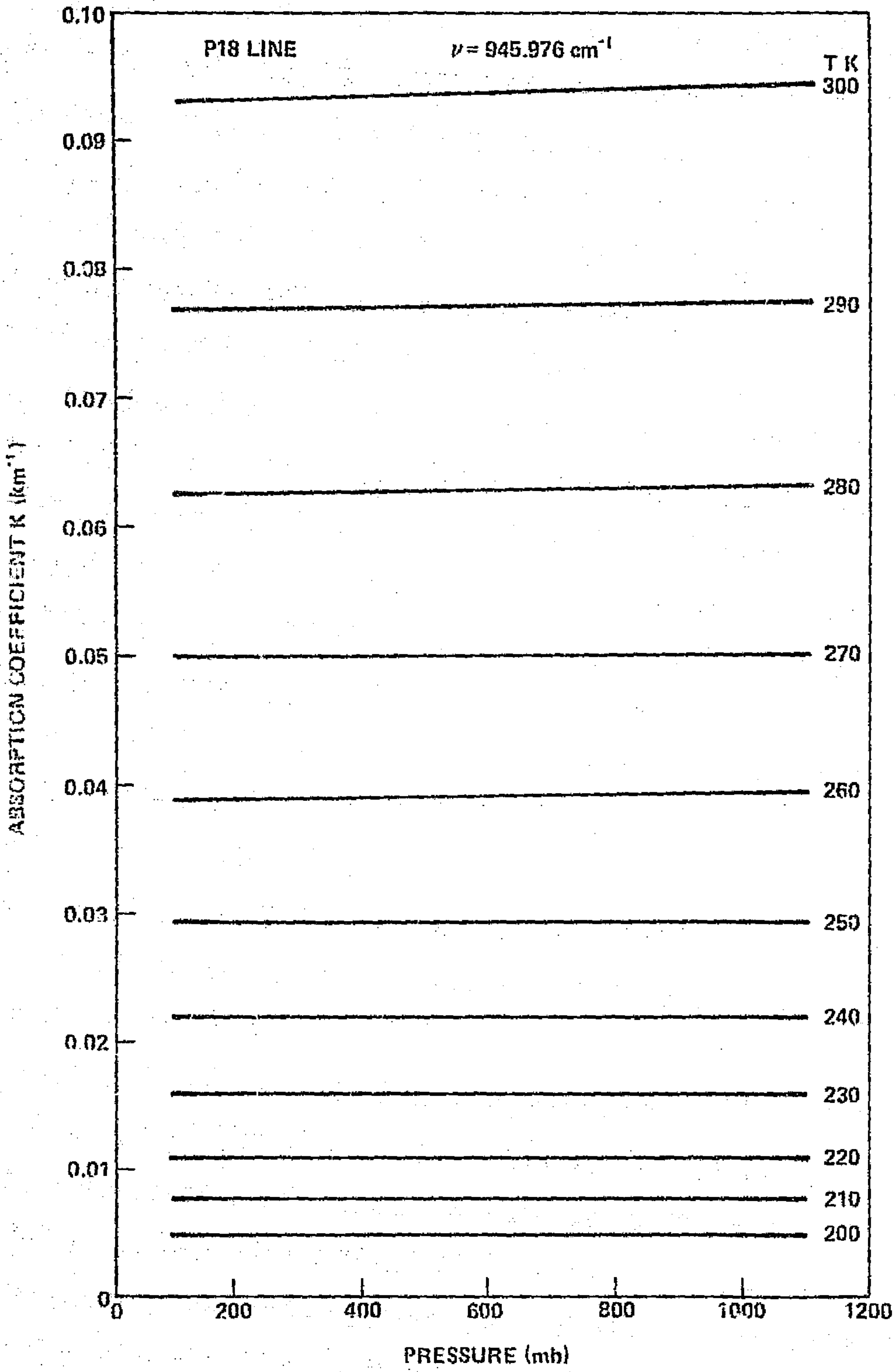

Figure 6 . Absorption coefficient of carbon dioxide at $\nu = 945.976\ cm^{-1}$.

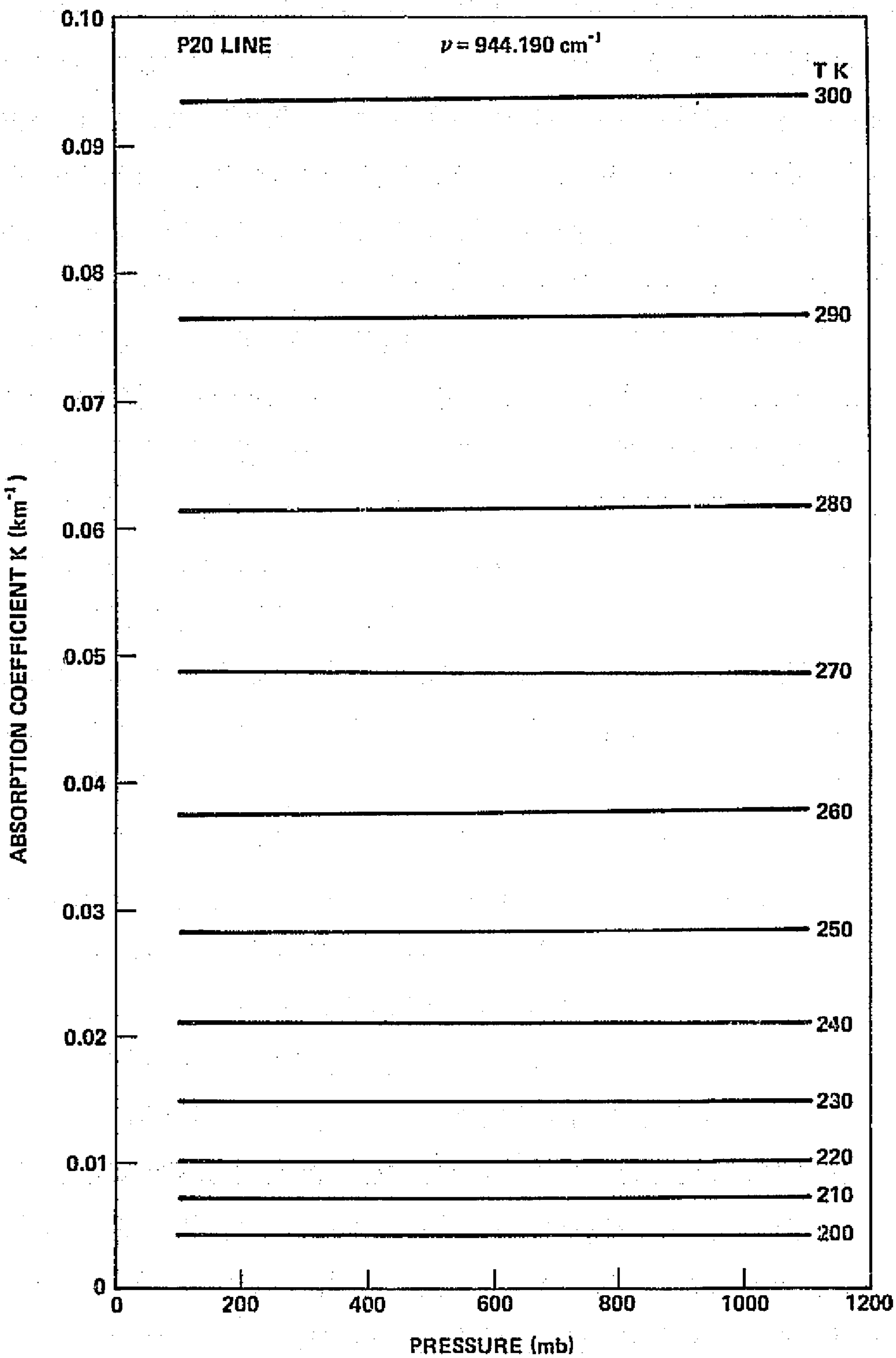

Figure 7. Absorption coefficient of carbon dioxide at $\nu = 944.190\ cm^{-1}$.

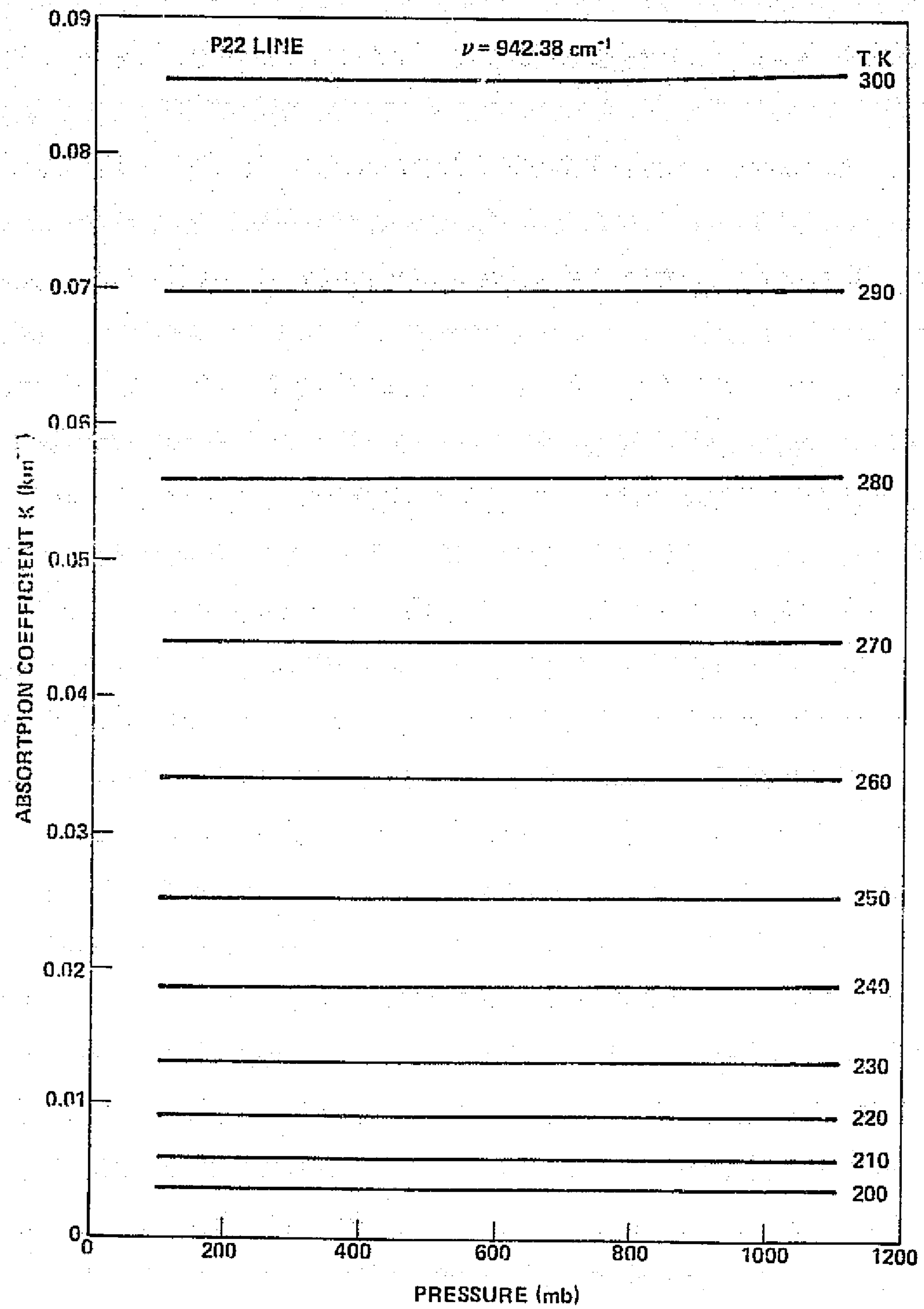

Figure 8. Absorption coefficient of carbon dioxide at $\nu = 942.38\ cm^{-1}$.

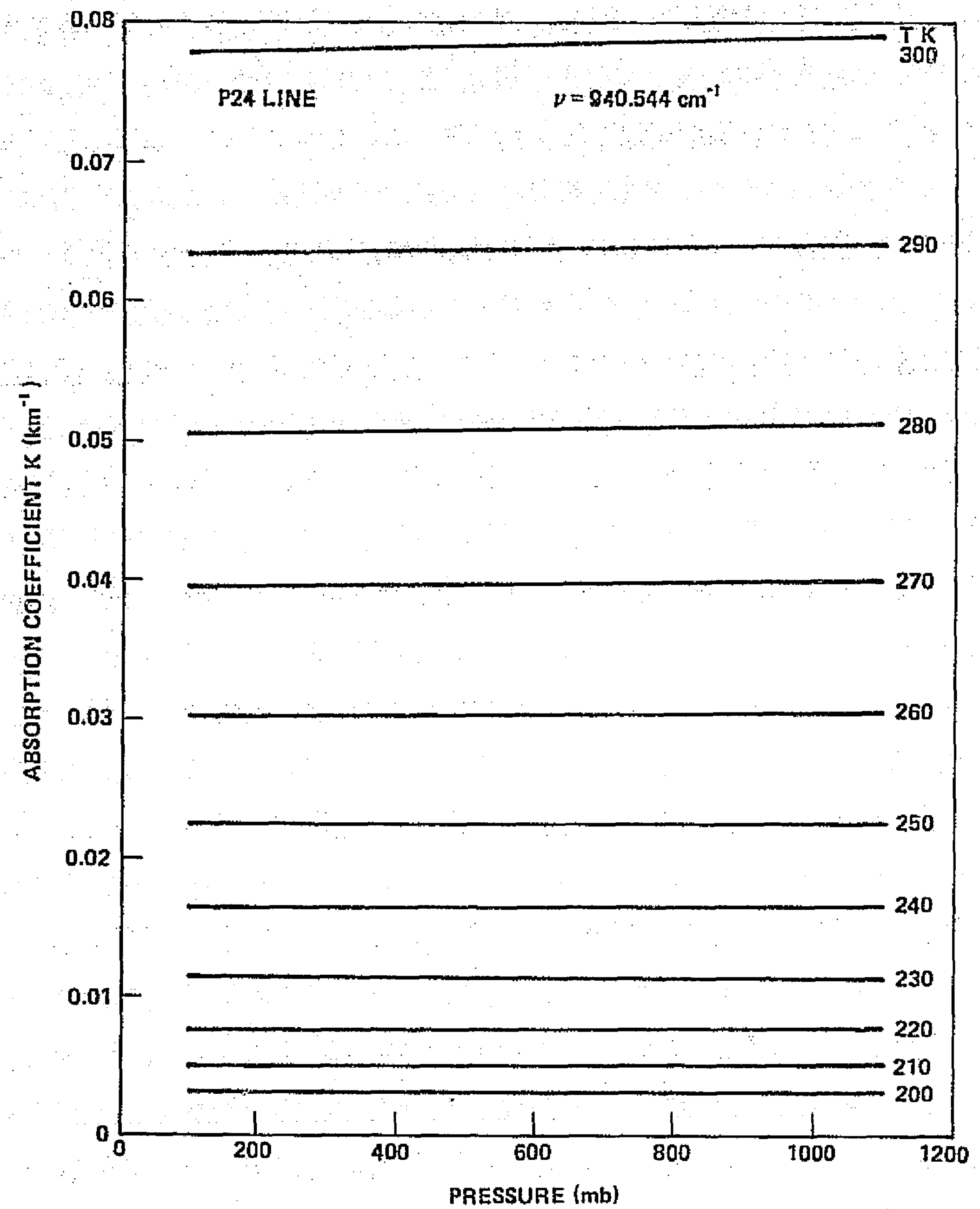

Figure 9. Abs. ·ption coefficient of carbon dioxide at ν = 940.544 cm^{-1}.

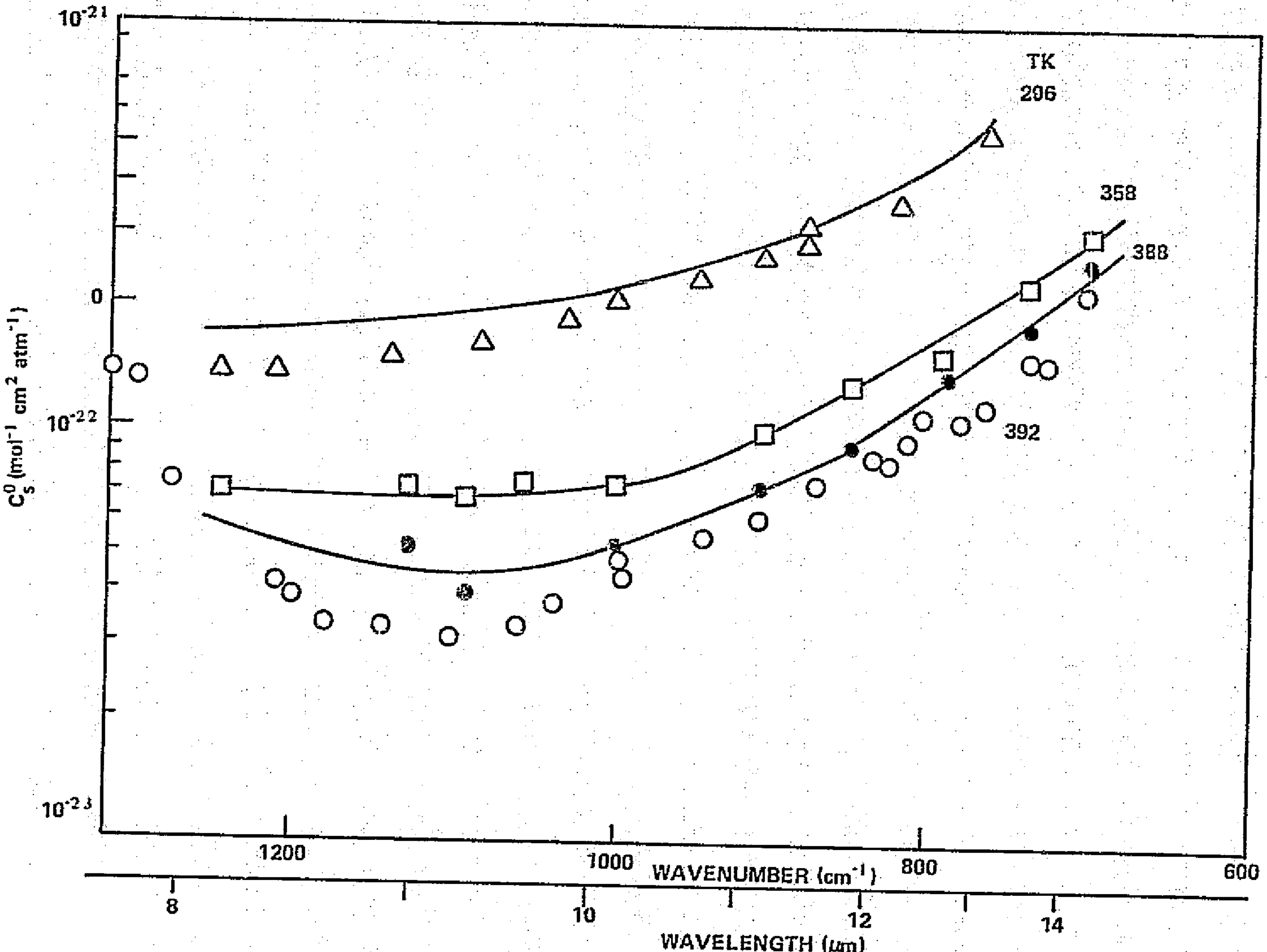

Figure 10. Continuum absorption coefficient of H_2O at different temperatures [15].

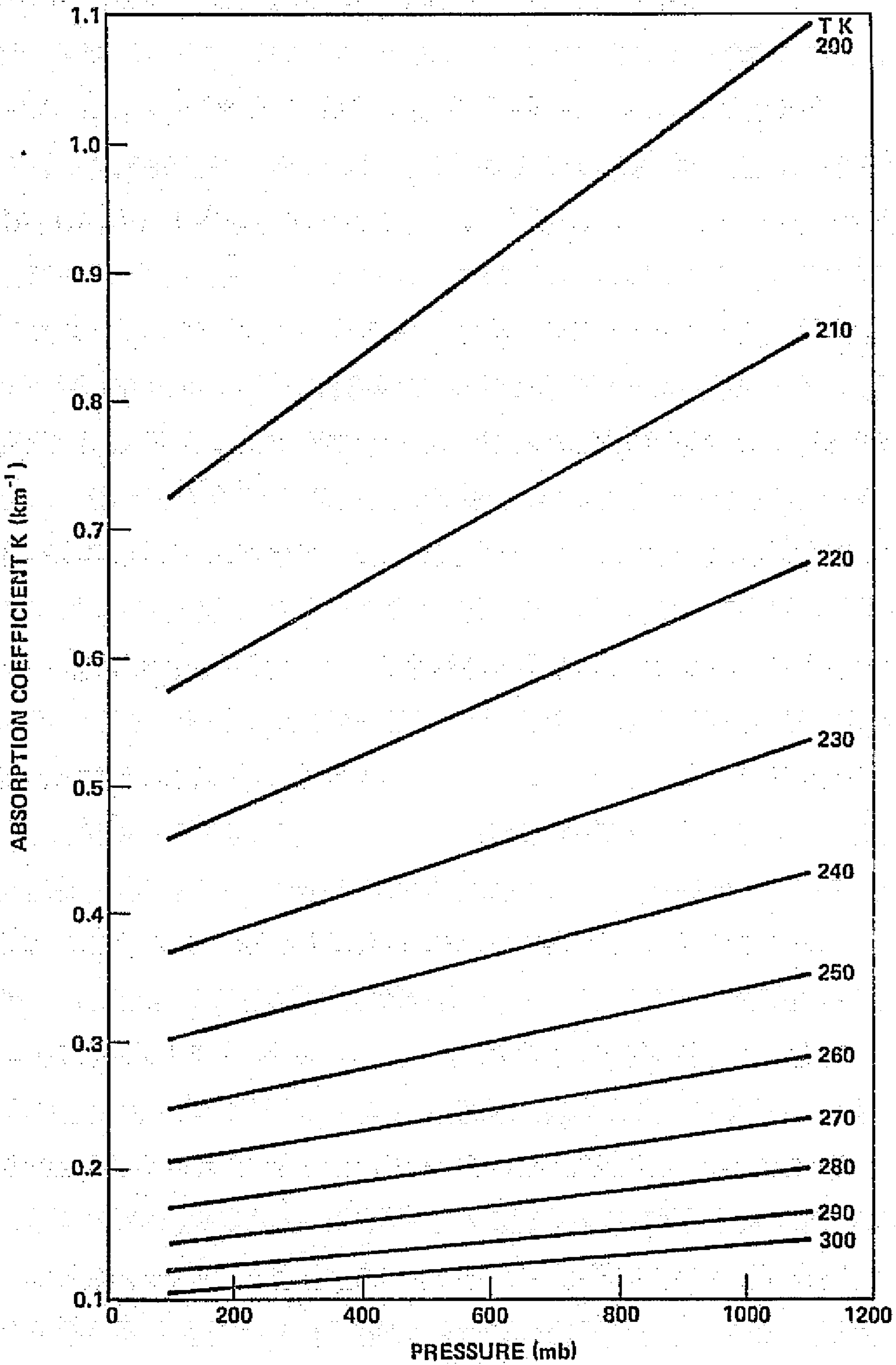

Figure 11. Absorption coefficient of water vapor continuum for 1 PR-CM at 10.6 μm.

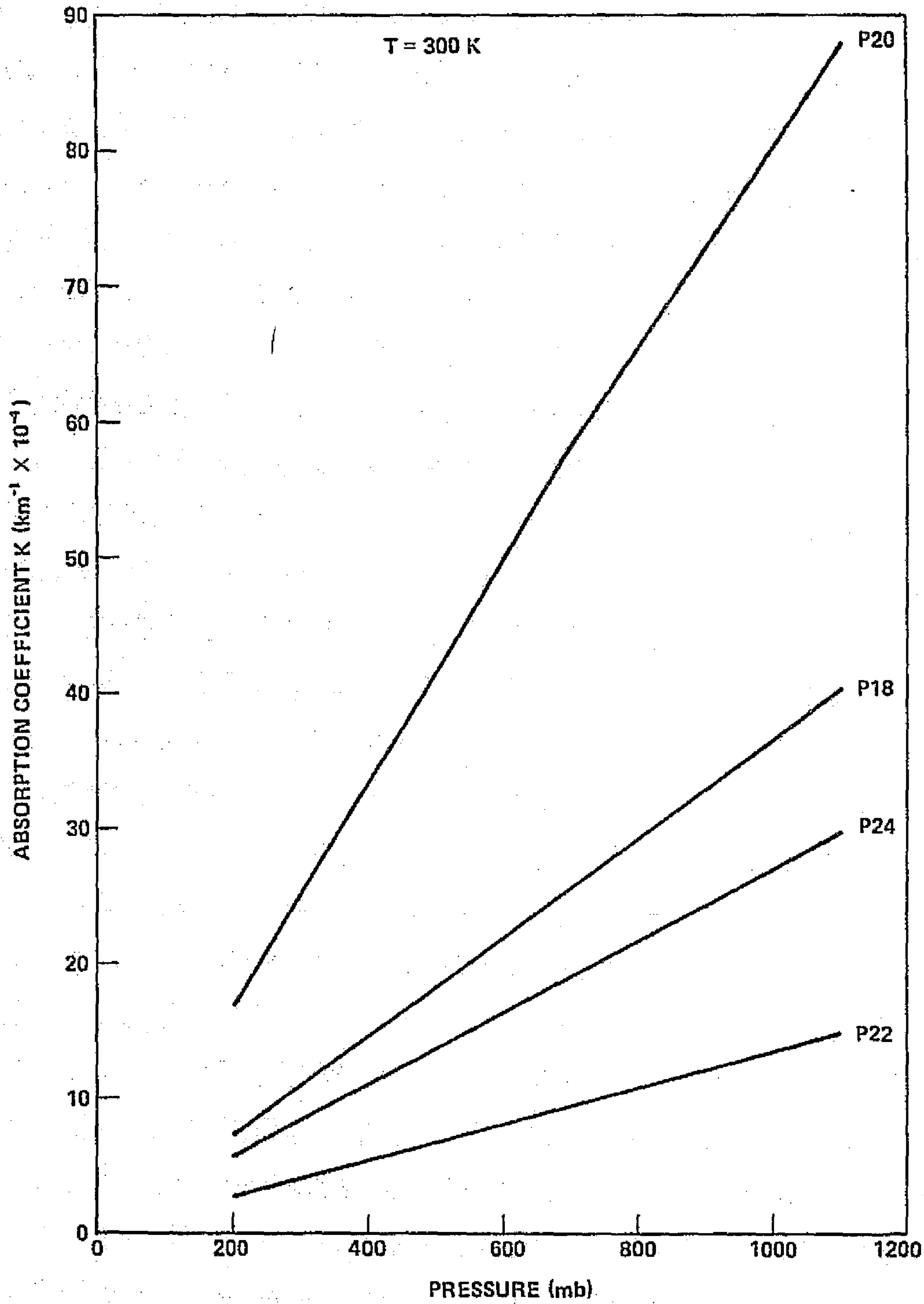

Figure 12. Absorption coefficient of 1 PR-CM of water vapor lines at T = 300 K.

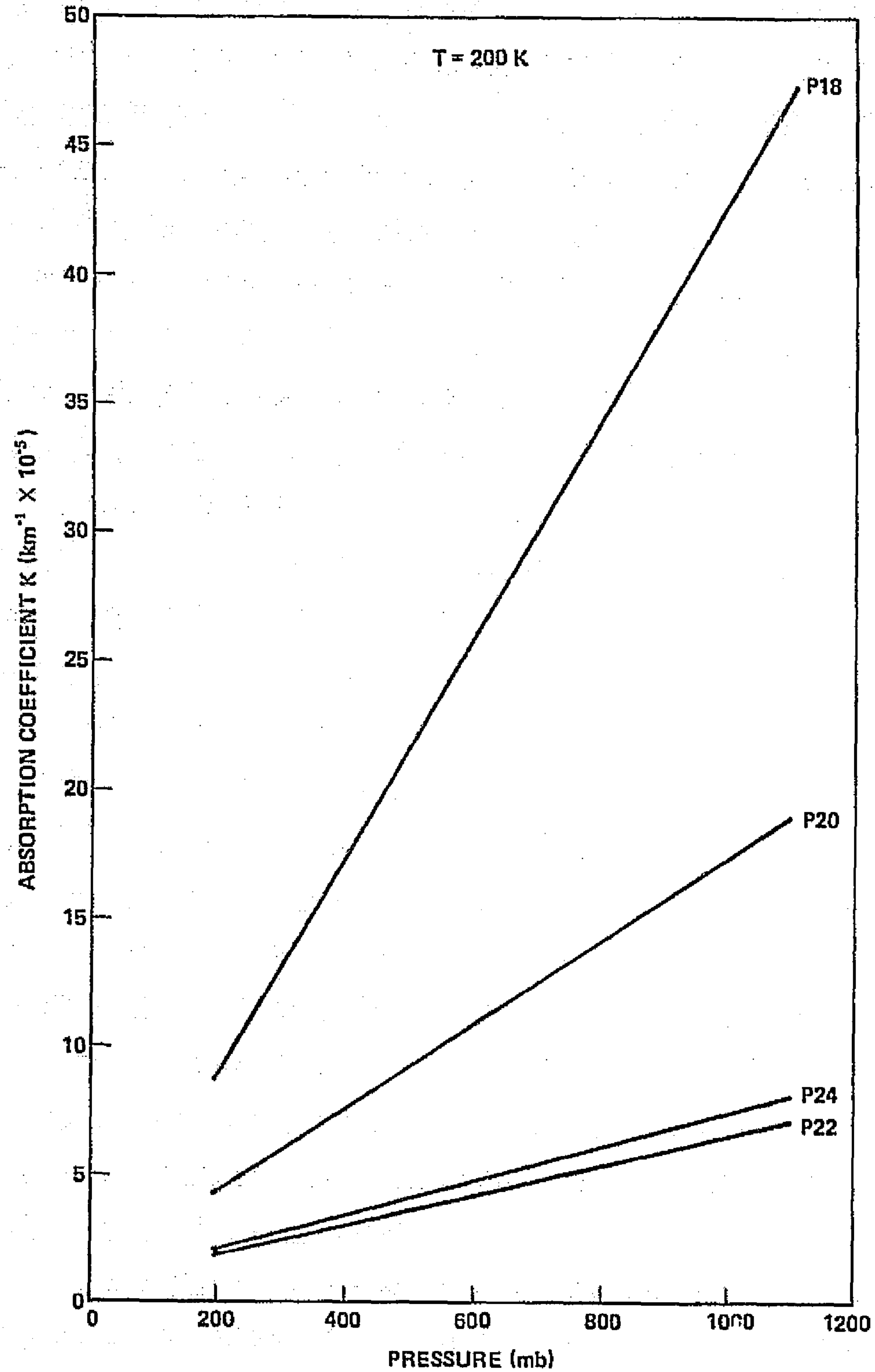

Figure 13. Absorption coefficient of 1 PR-CM of water vapor lines at T = 200 K.

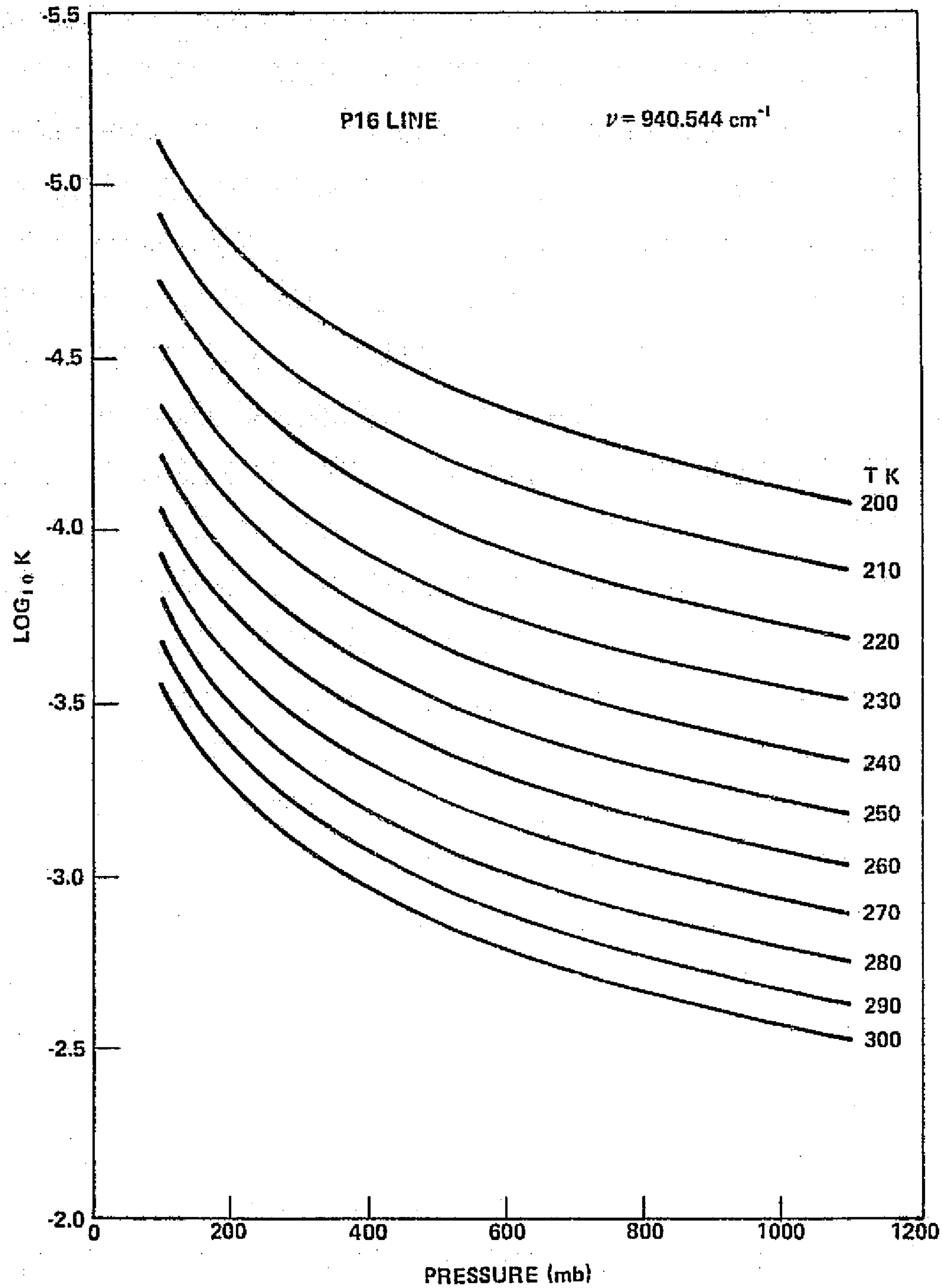

Figure 14. Absorption coefficient of water vapor lines at ν = 940.544 cm^{-1} for 1 PR-CM.

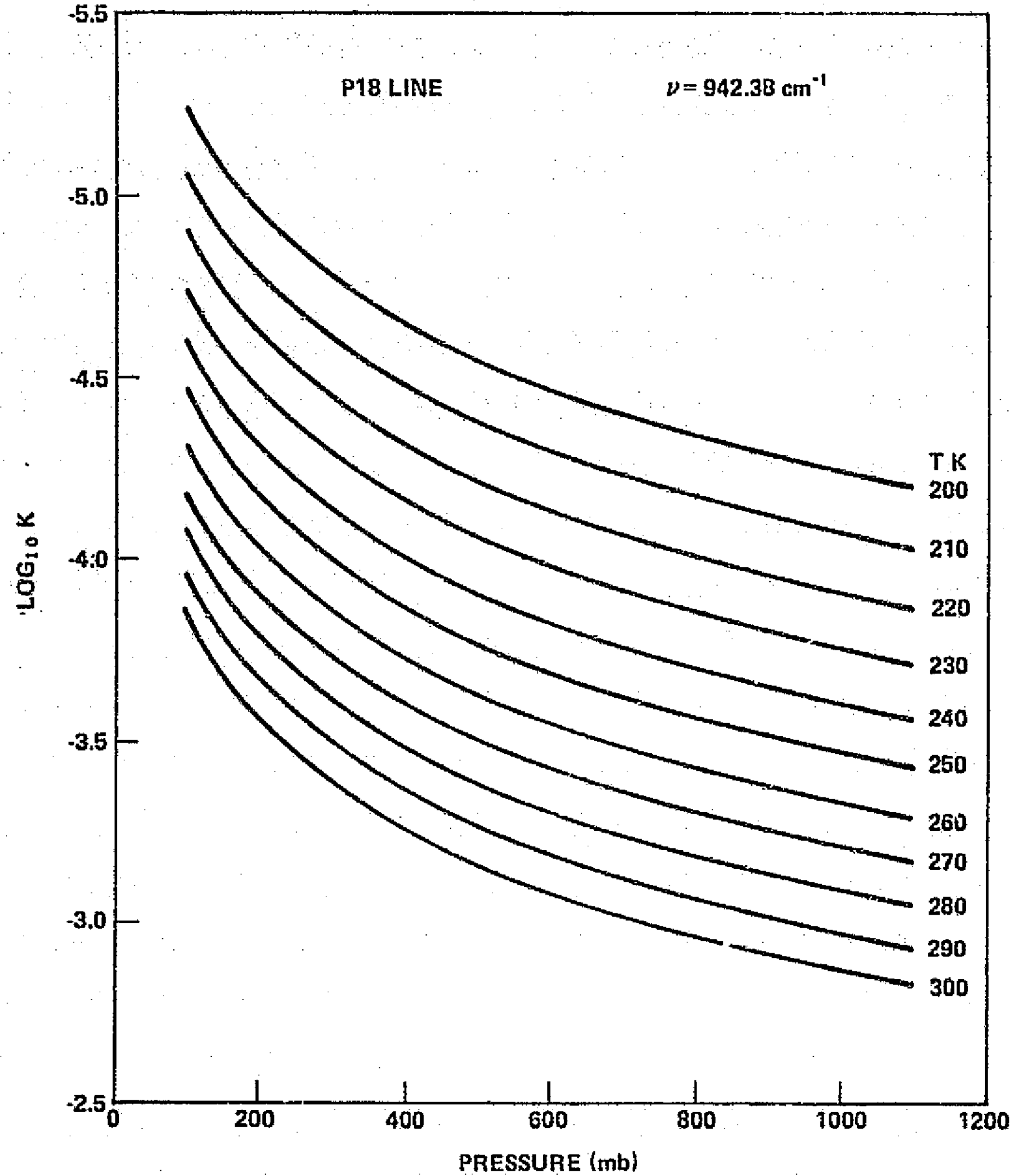

Figure 15. Absorption coefficient of water vapor lines at ν = 942.38 cm^{-1} for 1 PR-CM.

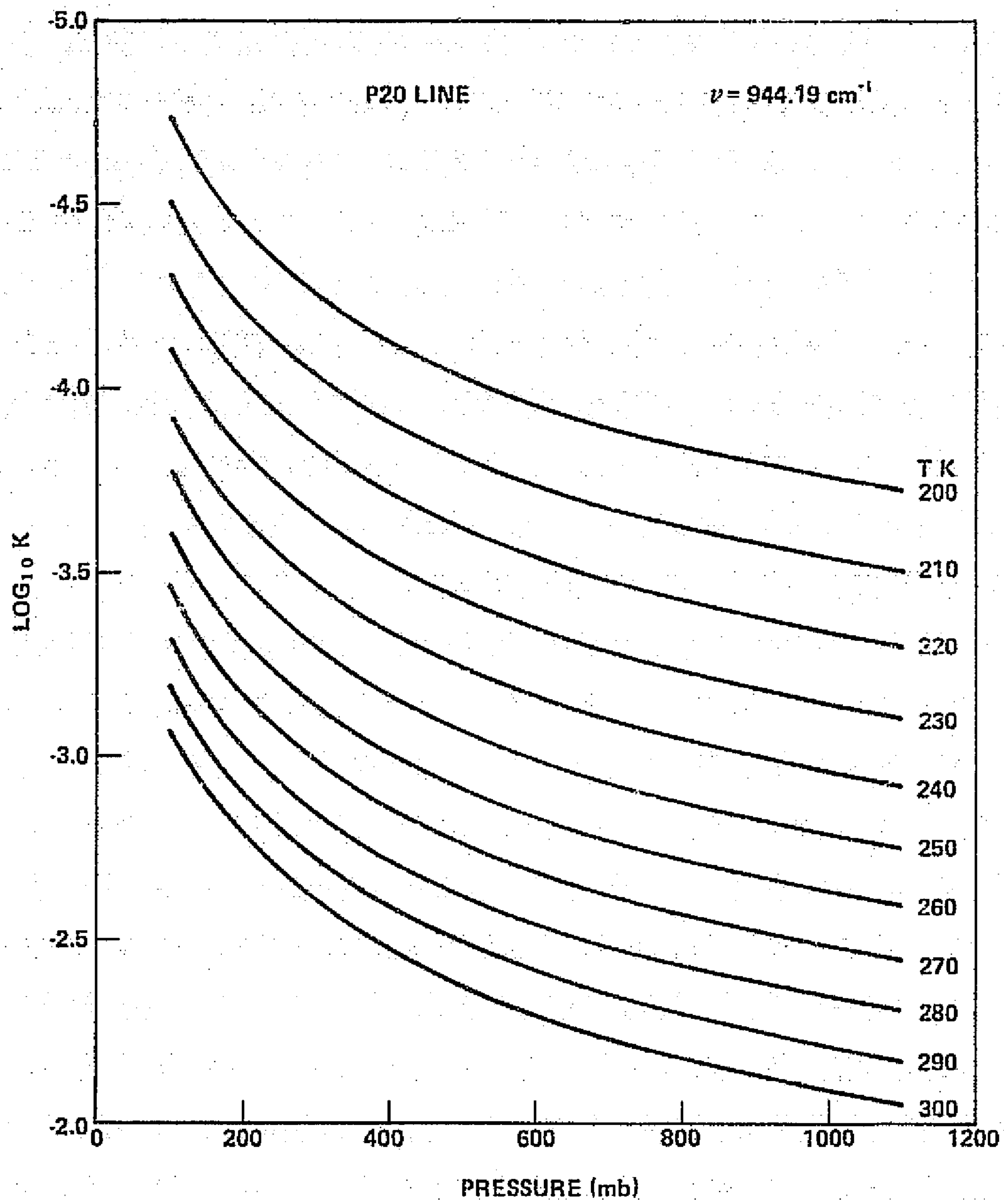

Figure 16. Absorption coefficient of water vapor lines at $\nu = 944.19\ \text{cm}^{-1}$ for 1 PR-CM.

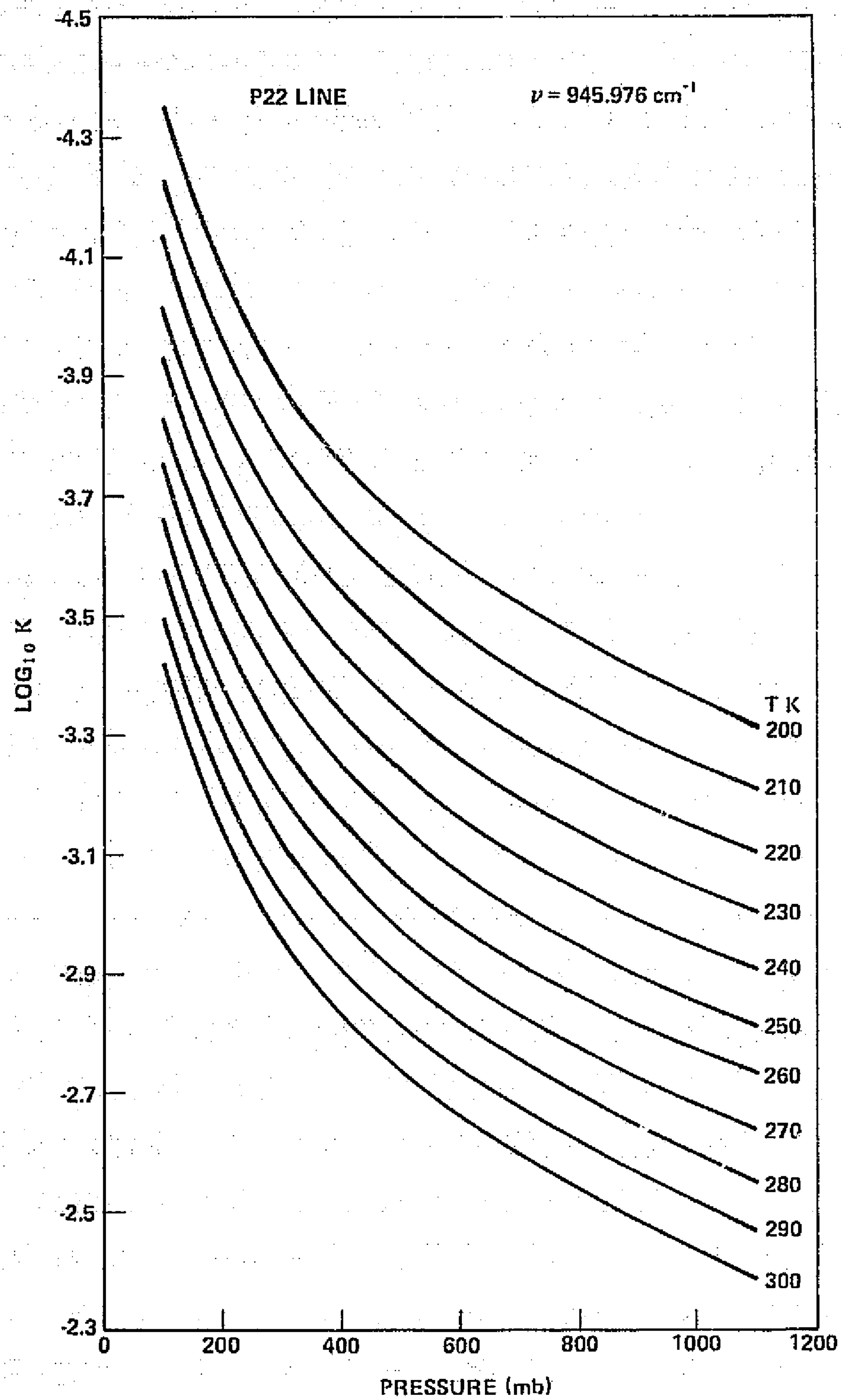

Figure 17. Absorption coefficient of water vapor lines at ν = 945.976 cm^{-1} for 1 PR-CM.

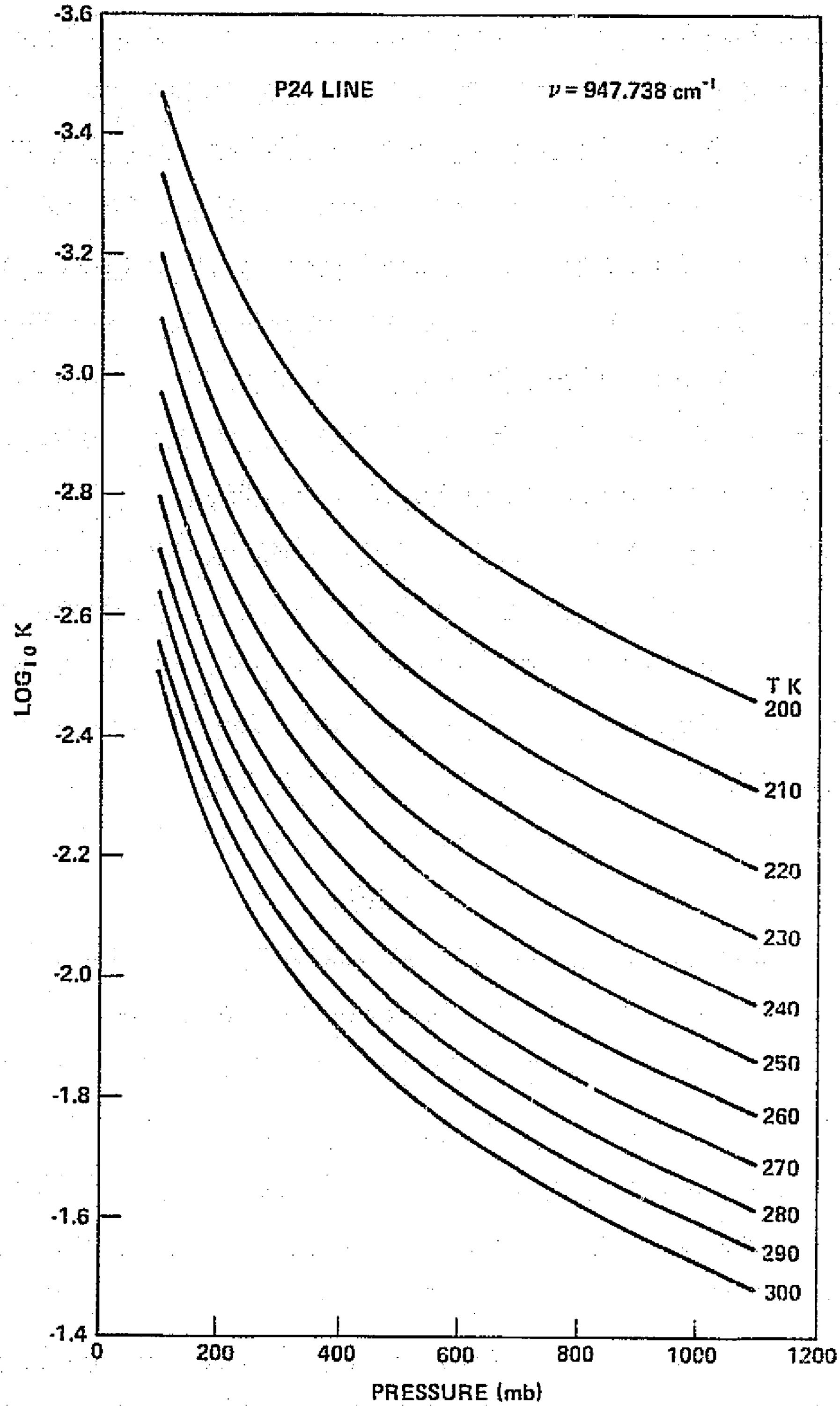

Figure 18. Absorption coefficient of water vapor lines at $\nu = 947.738\ cm^{-1}$ for 1 PR-CM.

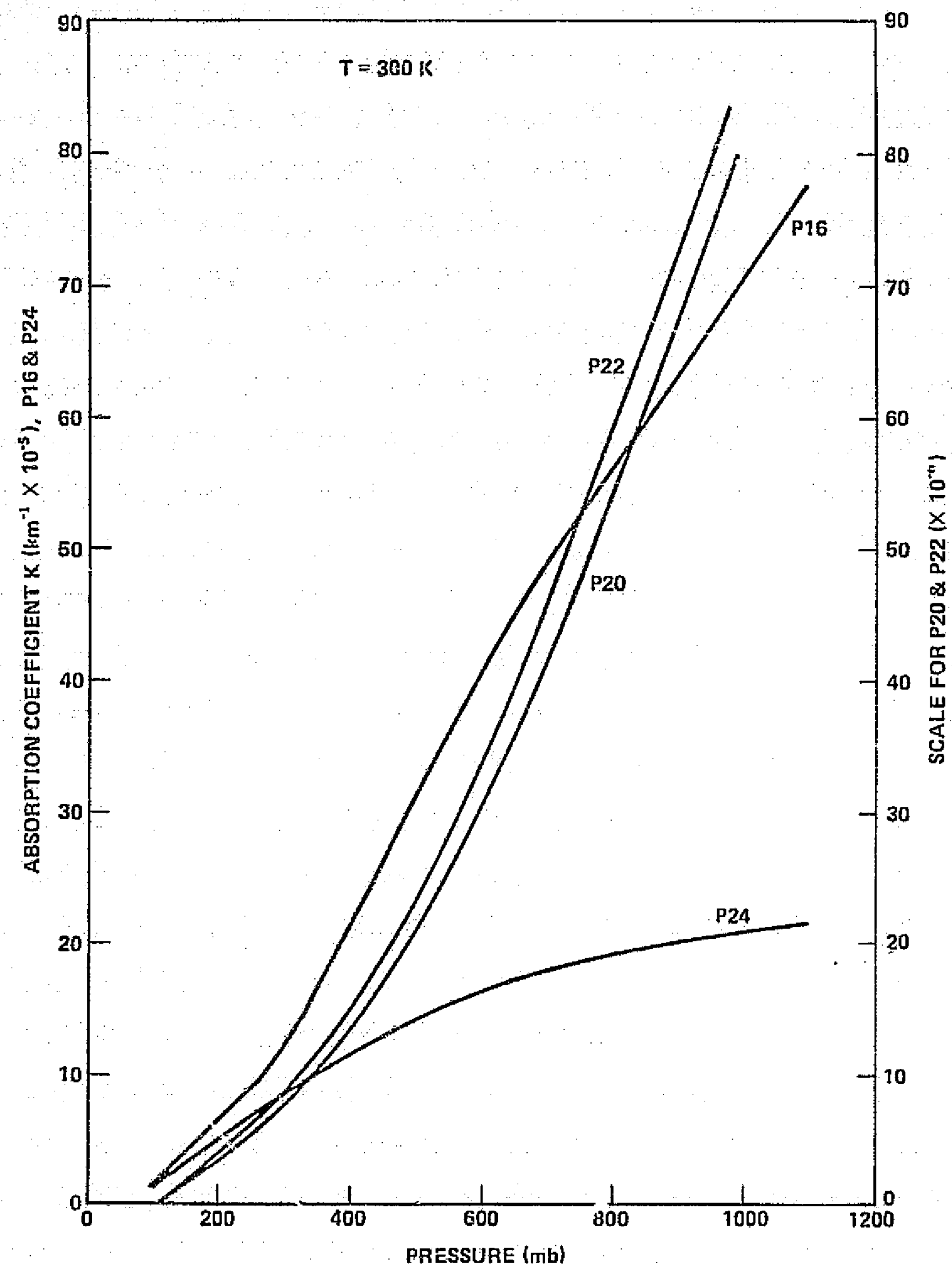

Figure 19. Absorption coefficient of nitrous oxide lines at T = 300 K.

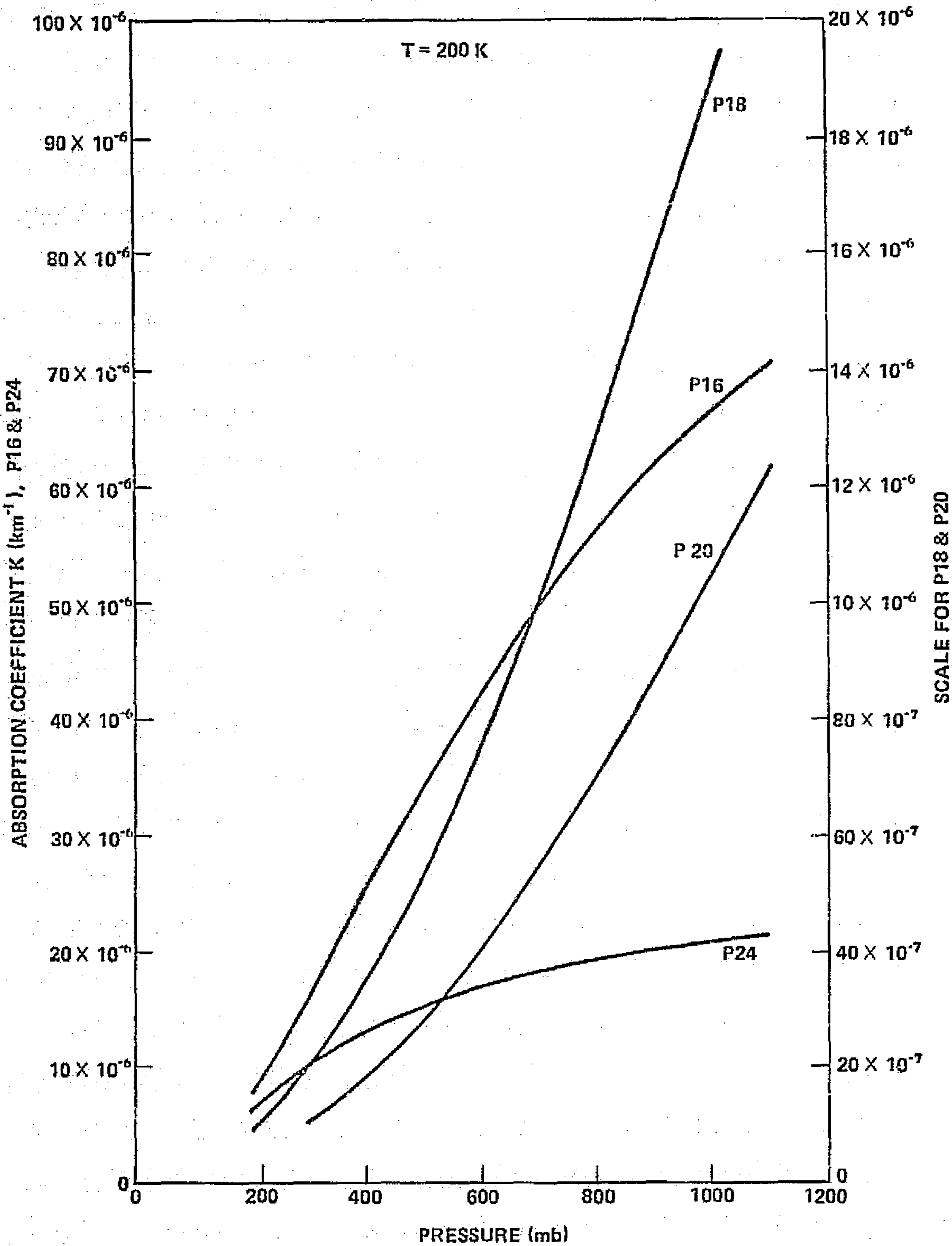

Figure 20. Absorption coefficient of nitrous oxide at T = 200 K.

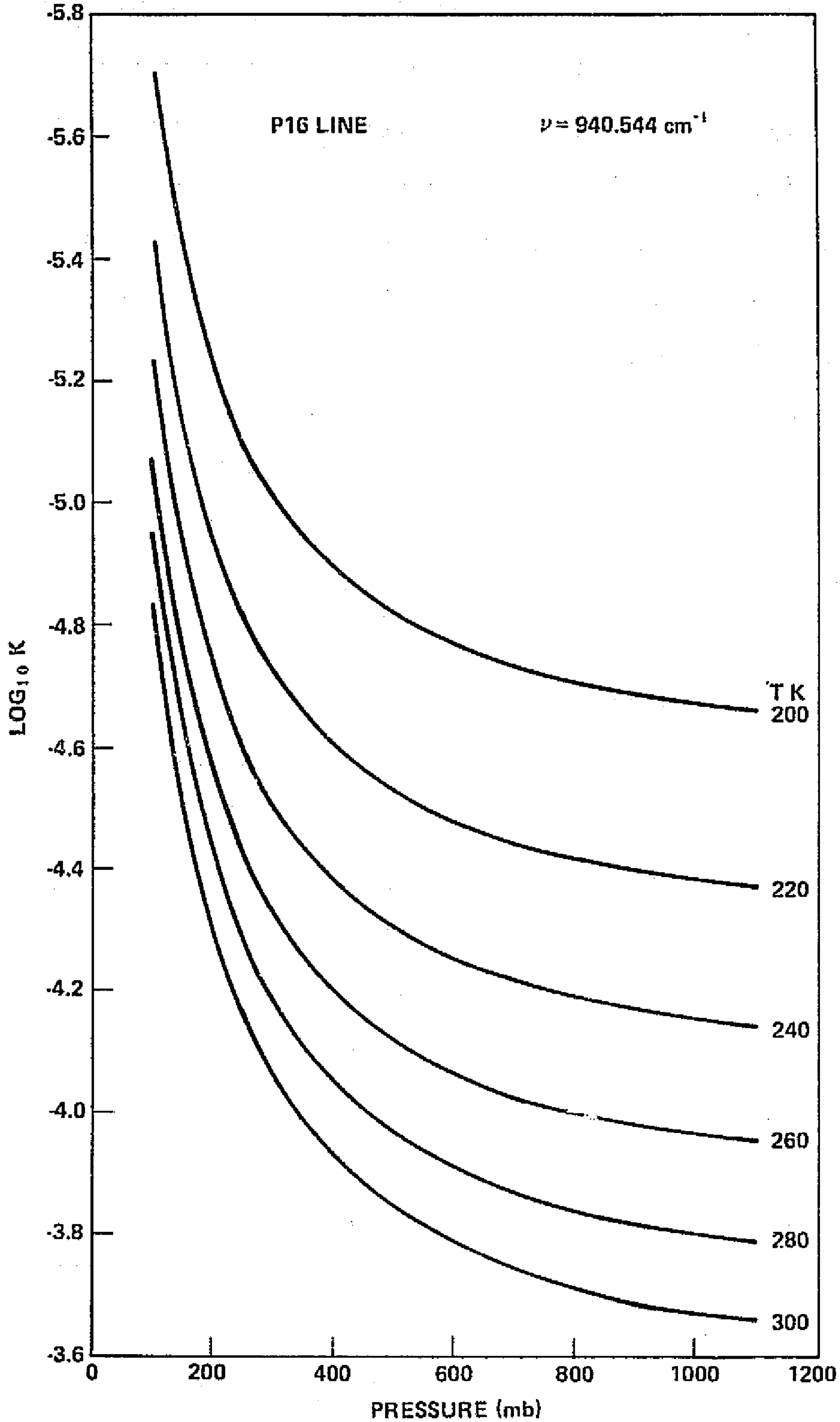

Figure 21. Absorption coefficient of nitrous oxide lines at ν = 940.544 cm^{-1}.

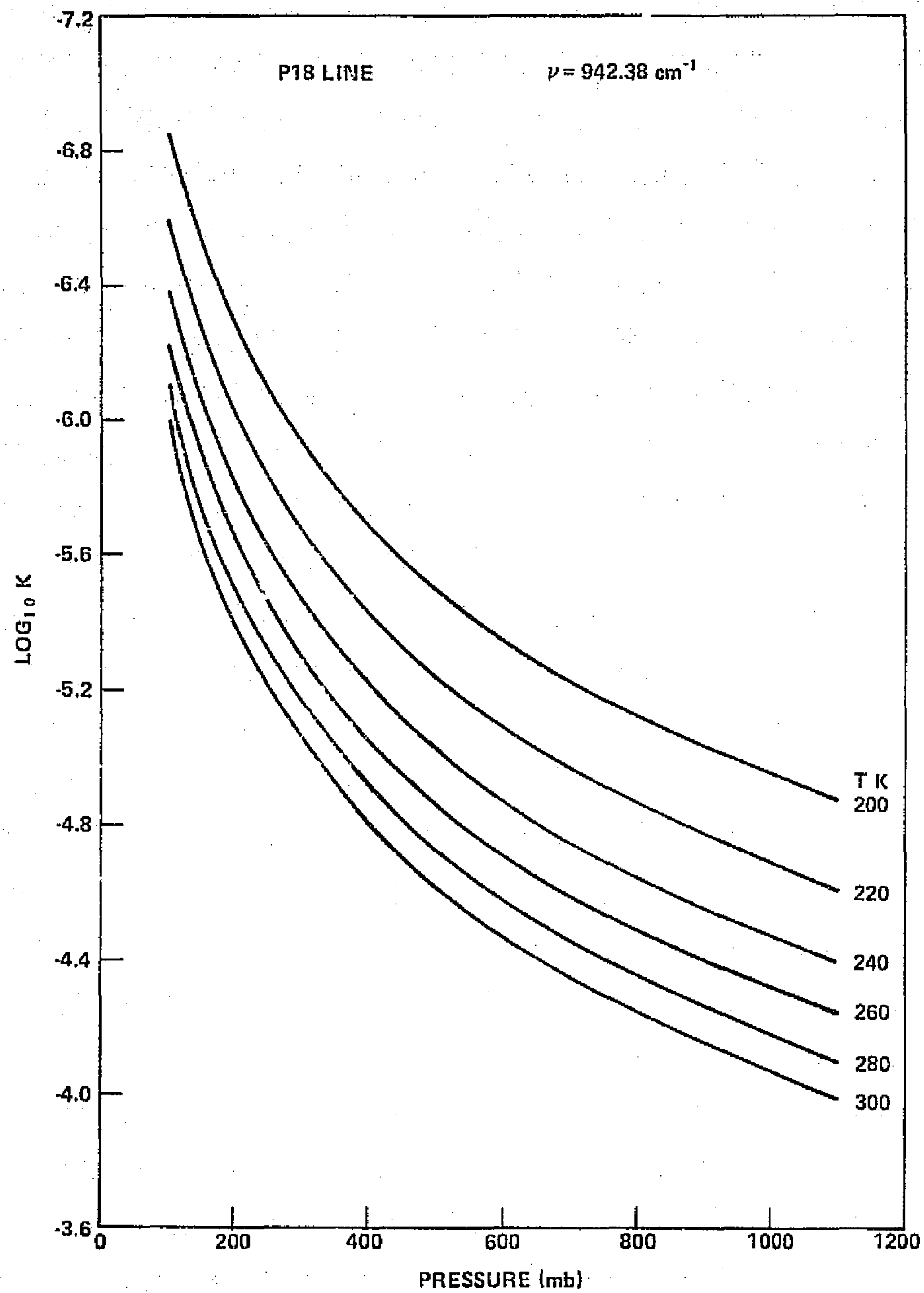

Figure 22. Absorption coefficient of nitrous oxide at ν = 942.38 cm^{-1}.

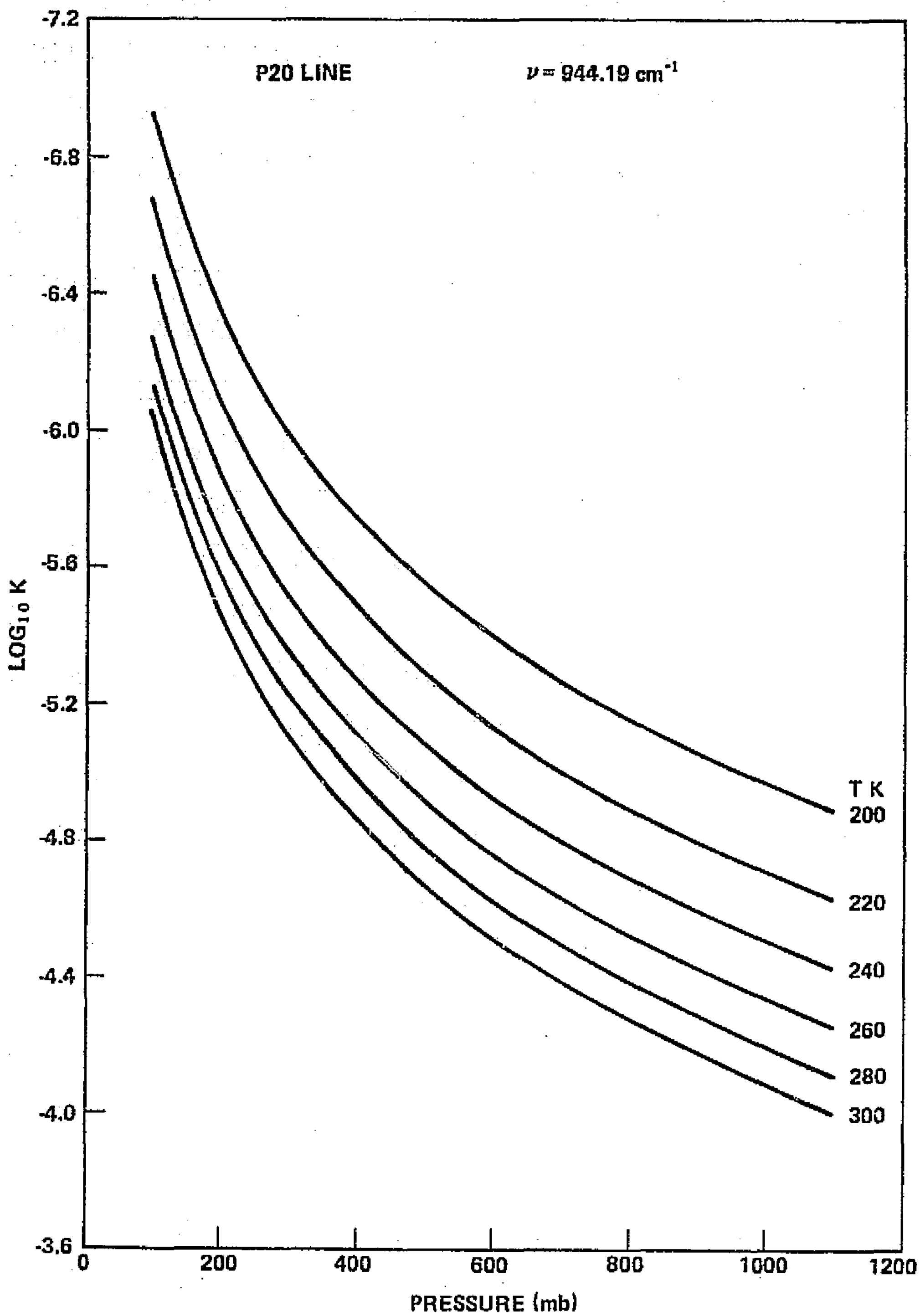

Figure 23. Absorption coefficient of nitrous oxide lines at $\nu = 944.19\ cm^{-1}$.

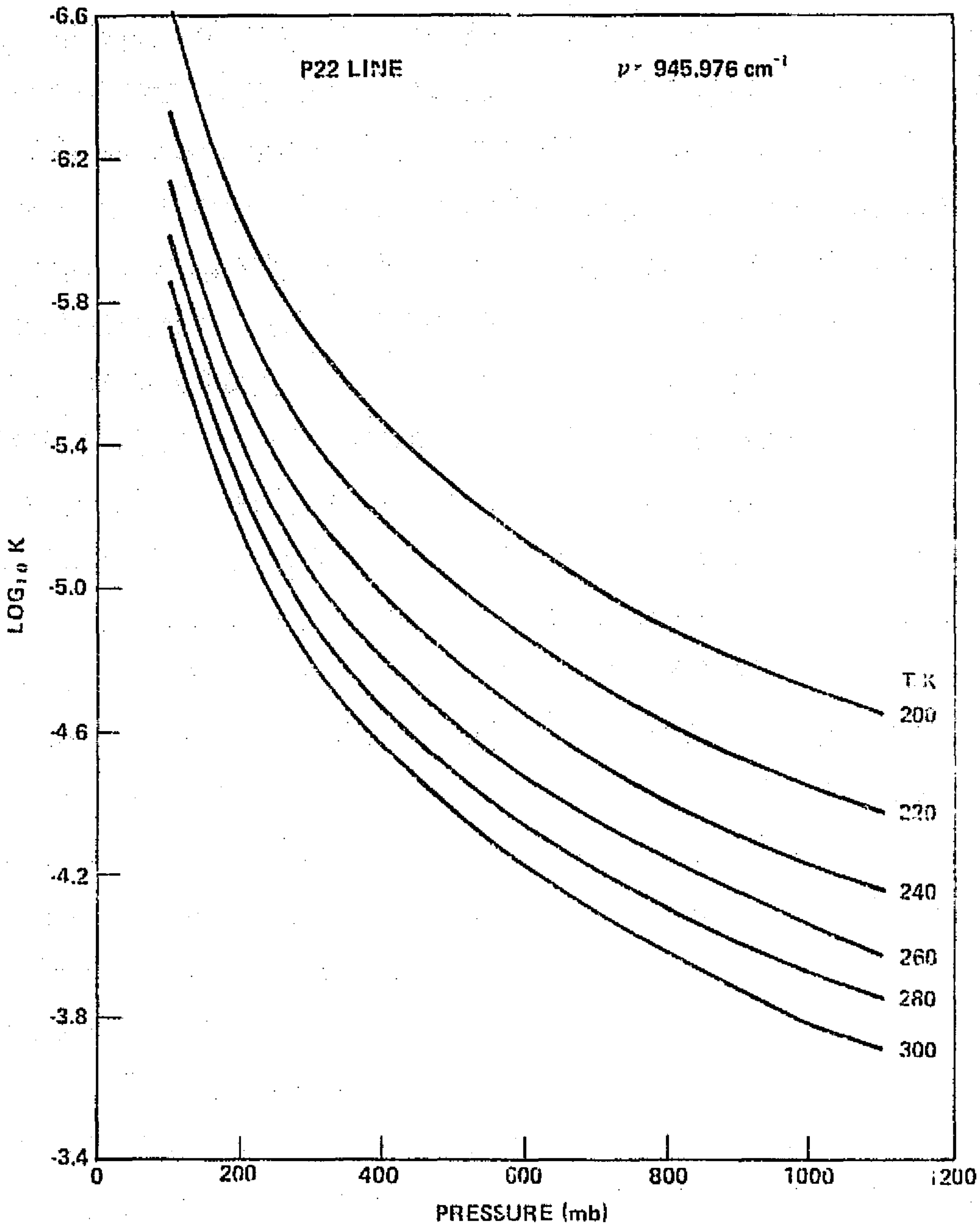

Figure 24. Absorption coefficient of nitrous oxide lines at $\nu = 945.976\ cm^{-1}$.

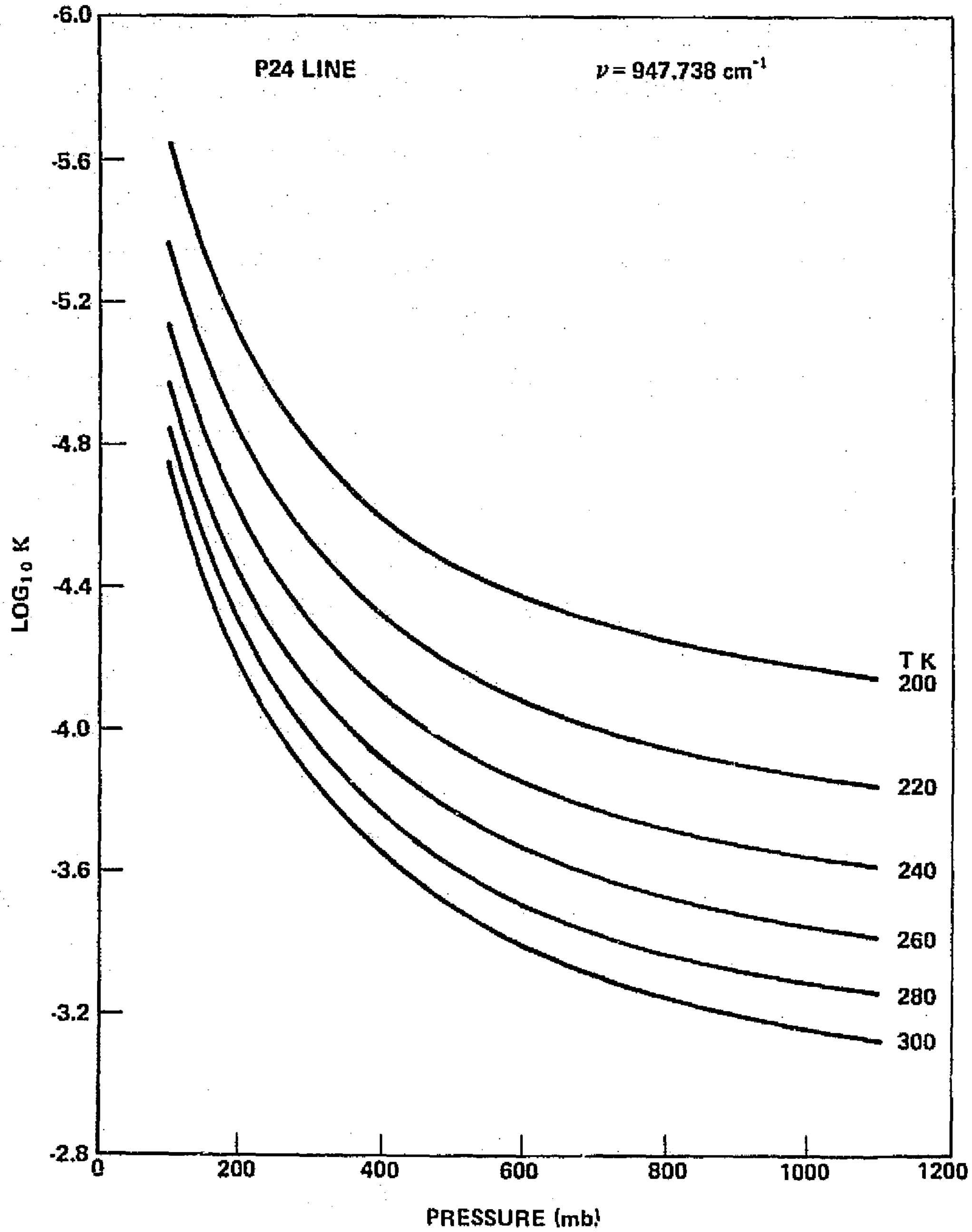

Figure 25. Absorption coefficient of nitrous oxide lines at $\nu = 947.738\ cm^{-1}$.

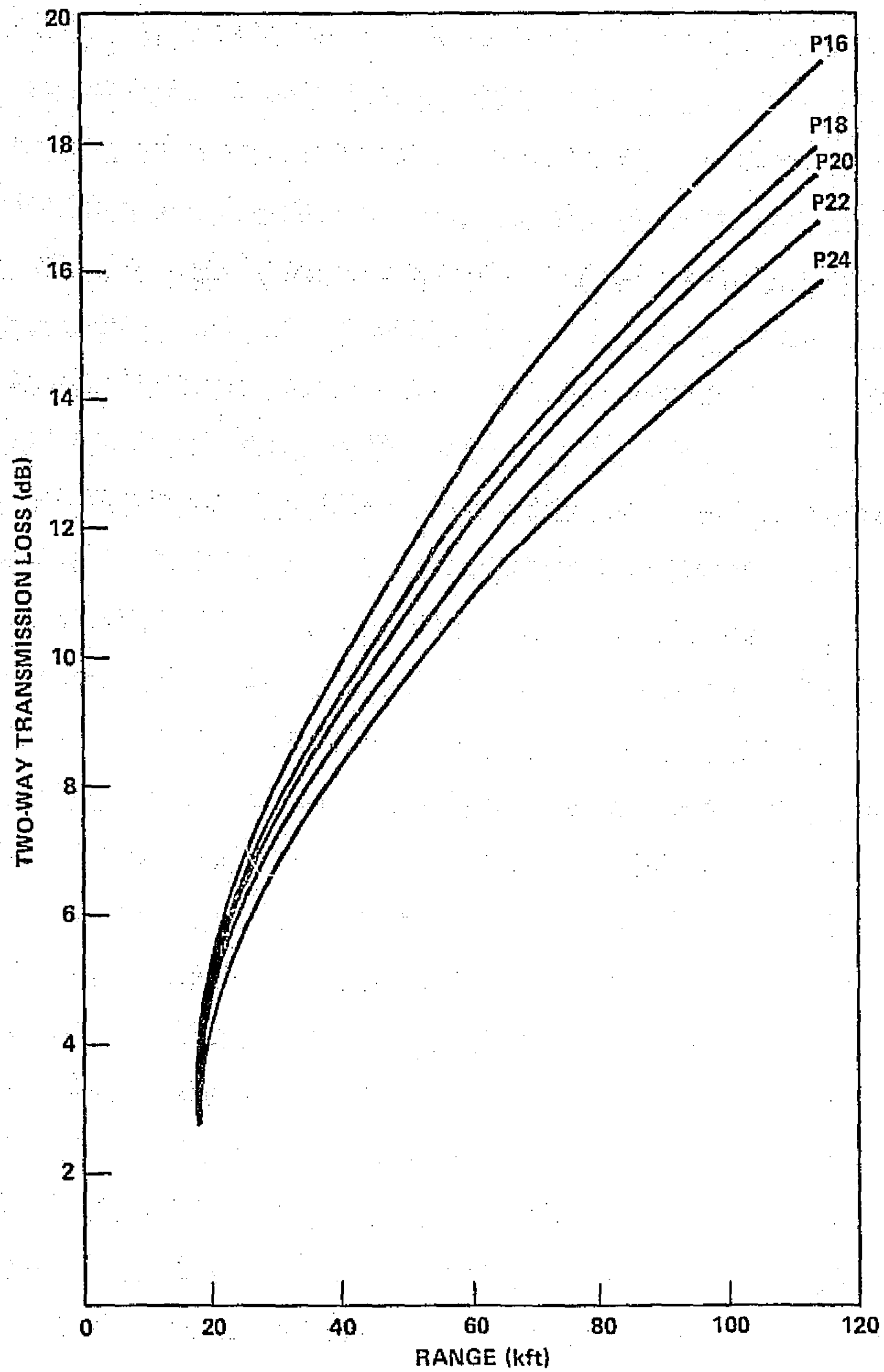

Figure 26. Total transmission loss at the P lines for flight B8, run 18, 1/19/1973 at Edwards AFB.

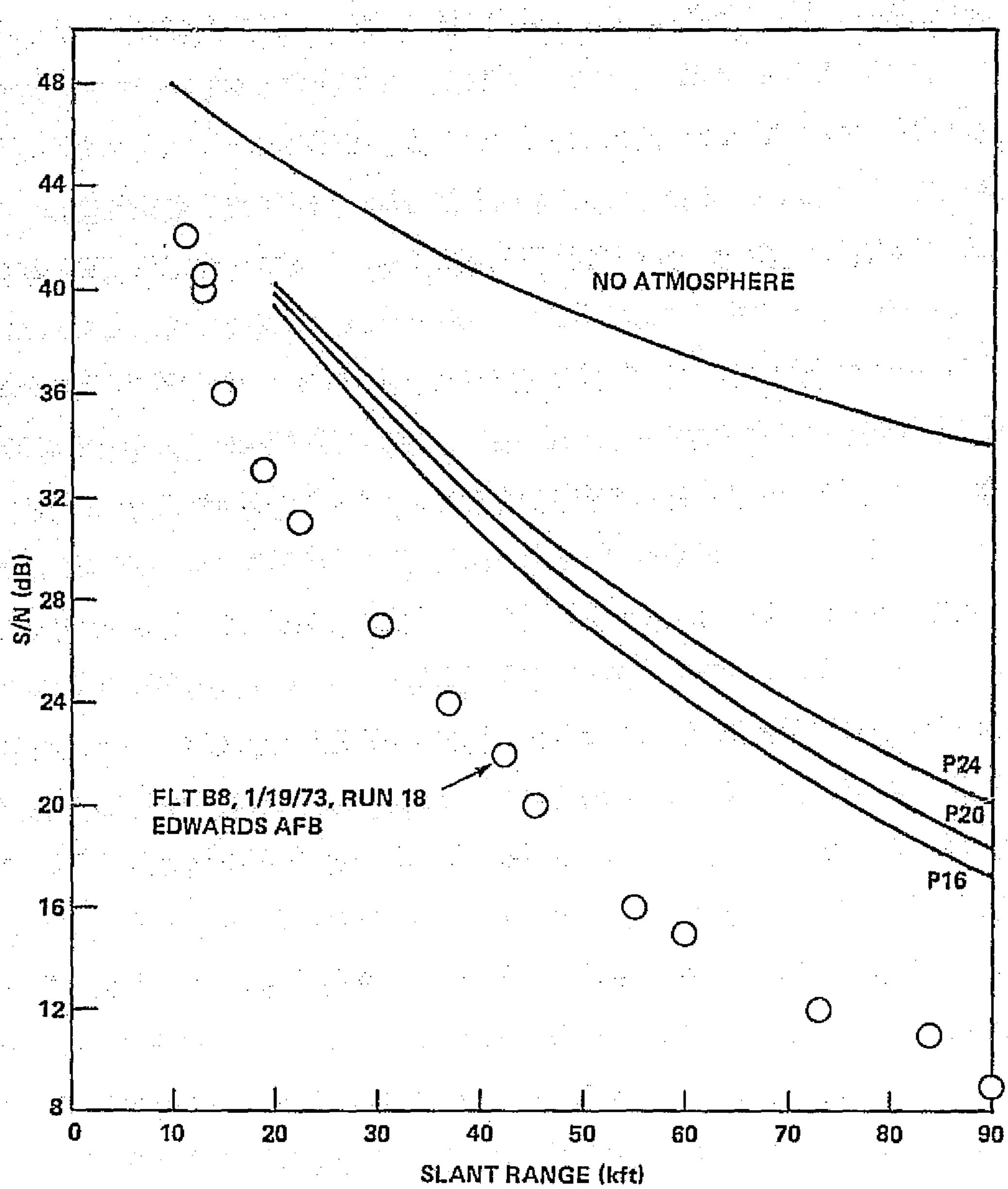

Figure 27. Comparison of measured and theoretical S/N values.

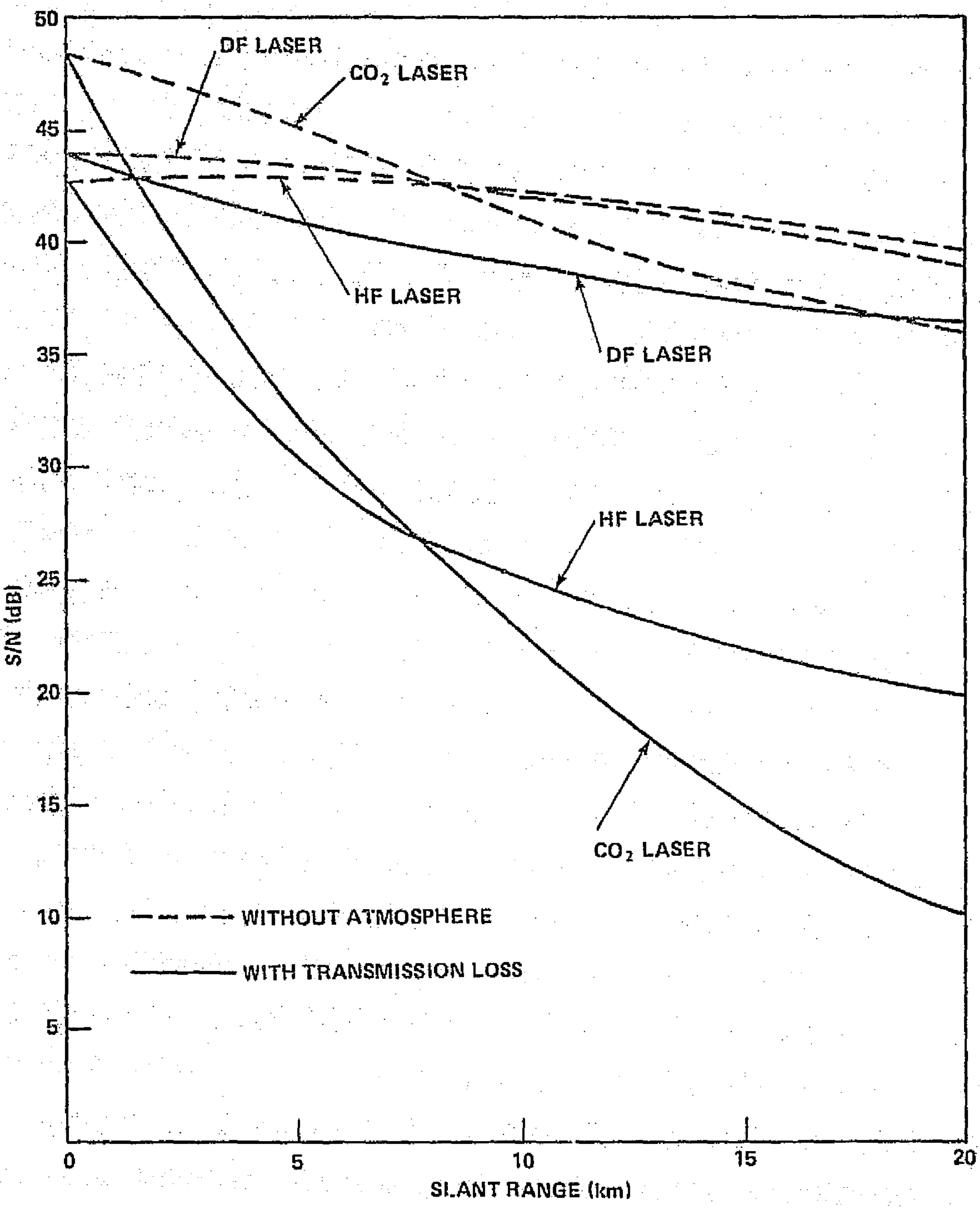

Figure 28. Performance of CO_2, HF and DF laser Doppler systems against ground target at 15° inclination in AFCRL Midlatitude Summer Atmosphere.

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APPROVAL

ATMOSPHERIC TRANSMISSION OF CO_2 LASER RADIATION WITH APPLICATION TO LASER DOPPLER SYSTEMS

By S. S. R. Murty

The information in this report has been reviewed for security classification. The report, in its entirely, has been determined to be unclassified and contains no information concerning Department of Defense or Atomic Energy Commission programs.

This document has also been reviewed and approved for technical accuracy.

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