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Final Report

INVESTIGATION OF ATMOSPHERIC ABSORPTION
for REMOTE SENSING APPLICATIONS

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ABSTRACT

The report discusses the need for an understanding of atmospheric absorption processes in the interpretation of remote radiance measurements. Specifically included are absorption by the 15 μm carbon dioxide bands, the 14 μm ozone band and the oxygen A-band.

1. Introduction

In order to make the fullest use of meteorological satellite radiation data it is essential to have an accurate quantitative knowledge of the absorption and emission of radiant energy by atmospheric gases. This is particularly critical for the remote sensing of the atmospheric temperature field where the effect of small errors in both measurements and calculations can dominate the temperature solution. The primary purpose of the work described in this report is to improve the accuracy of atmospheric transmittance calculations and to compare results with laboratory and atmospheric measurements. The work is a continuation of contracts CWB 11106 and CWB 11376.

Investigation of the carbon dioxide absorption bands in the 15μ spectral region is contained in Chapter 2 of this report. Weak absorption by other bands near 15μ is discussed in Chapter 3. Chapter 4 is concerned with atmospheric absorption by the oxygen A-band.

In addition to work reported here, two papers concerning results obtained under the current and preceeding contracts were given at meetings: S. R. Drayson, "Methods for calculating atmospheric transmission functions" presented at Specialists Conference on Molecular Radiation and Its Applications to Diagnostic Techniques, Huntsville, Alabama, October 5-6, 1967.

S. R. Drayson, "Absorption by the 15μ m bands of CO_2 ". Paper presented at IUGG/WMO Symposium on Radiation, Including Satellite Techniques, Bergen, Norway, 22-28 August, 1968.

During the time period covered by the present contract, the Principal Investigator obtained the degree of Doctor of Philosophy in Meteorology from the University of Michigan. Research for the thesis (Drayson, 1967) was funded by a Grant from the National Science Foundation. However, much of

the background material was obtained from this contract and its predecessors, including information on the $15\ \mu\text{m}$ CO_2 bands and computer programs that were adapted from those used to calculate atmospheric transmittances. The author gratefully acknowledges this important contribution.

In July 1968 the University of Michigan Computing Center removed its IBM 7090 computer and enlarged the IBM System 360 which had already been in use for almost a year. Most of the programs for computing transmittances had been written in MAD language, with some subroutines in assembly language. Neither of these could be used with the new computing system so that the programs had to be completely rewritten. Fortran was chosen as the new language for two reasons:

1. At the present time it is the easiest and most economical language to use on the IBM 360 System.
2. It is widely used by other installations. In particular programs were supplied and run on the sponsor's CDC 6600 in Washington.

The programs were altered slightly to take advantage of some of the features available on the new computing system, including the virtually unlimited fast access storage and the availability of semi-permanent storage in disc files for storage of programs and line parameters of absorption bands. Some programs were generalised, e. g. the inclusion of line-to-line variation of Lorentz half-width in the slant path programs.

A considerable proportion of the total effort under the present contract was consumed by these programming changes. However, the resulting Fortran programs can be applied to a wide variety of transmittance problems, with only minor programming modifications, and by a wide variety of users.

It had originally been anticipated that satellite data from SIRS and IRIS would become available during the contract, but the launching failure of Nimbus prevented this. It is hoped that such data will be obtained during the period of the next contract.

2. The 15 μ m Bands of Carbon Dioxide

Carbon dioxide is the most important atmospheric absorber of long-wave radiation between about 600 and 800 cm^{-1} . Our earlier studies of the carbon dioxide absorption bands between 12 and 18 μm enabled us to theoretically calculate spectra which were in generally good agreement with experimental laboratory data. The methods of calculating the various band parameters for all the significant absorption bands and different isotopic molecules of carbon dioxide have already been described in detail (Drayson, Li and Young, 1968) and will not be repeated in this report. A listing of line positions and intensities has also been prepared (Drayson and Young, 1967).

Except for minor changes the parameters remain the same. A comparison was made between experimental spectra obtained from a spectrometer flown on a balloon by the University of Denver (Murcrary & Kyle, 1968). The sun was used as a source and many of the individual absorption lines of carbon dioxide were resolved, the resolution of the instrument being a few tenths of a wavenumber. Theoretical slant path spectra were calculated for conditions similar to the experimental ones, and plotted on the same scale. The general structure and relative intensities of the lines in the spectra showed close agreement, except for a feature at 665.1 cm^{-1} on the experimental spectra. The theoretical spectra showed a much smaller absorption at this wavenumber, but a relatively large feature near 664.26 cm^{-1} , the wavenumber of the R(4) line of the fundamental of $^{12}\text{C}^{16}\text{O}^{16}\text{O}$. The listing of the theoretically calculated lines shows the Q-branch of the fundamental of $^{12}\text{C}^{16}\text{O}^{17}\text{O}$ to be in this region also. It was therefore concluded that the vibrational energy of the upper state of this isotopic molecule should be increased from 664.72 to about 665.1 cm^{-1} . The abundance of $^{12}\text{C}^{16}\text{O}^{17}\text{O}$ is small, and the fundamental of this molecule falls in a region dominated by the fundamental of $^{12}\text{C}^{16}\text{O}^{16}\text{O}$, so that the small error in wavenumber is of little consequence. Indeed, its contribution to the absorption

is so small that it has apparently not been previously observed.

Unfortunately, a quantitative comparison of the absorption of the experimental spectra with the theoretical calculations was not possible. Such a comparison would be useful in estimating the accuracy of the calculations applied to atmospheric slant paths, and perhaps shed some light on the distribution of carbon dioxide in the stratosphere.

Atmospheric transmittances may be used to theoretically calculate radiances reaching a satellite by means of an integral equation of the form

$$I_{\nu} = B(\nu, T_0) \tau_{\nu}(p_0) + \int_{p_0}^0 B(\nu, T) \frac{d\tau_{\nu}^{(d)}}{dp} dp$$

where

I_{ν} is the radiance at wavenumber ν

$B(\nu, T)$ is the Planck function

$\tau_{\nu}(p)$ is the transmittance for a vertical path starting outside the atmosphere down to pressure p at wavenumber ν

p_0, T_0 surface pressure and temperature

Temperature profiles are obtained by inverting this equation of radiative transfer, using measurements of radiance in a spectral region in which the principal absorber has a known (preferably constant) mixing ratio. The inversion procedure is made easier if it can be assumed that $\tau_{\nu}(p)$ is not a function of temperature. In particular, the solution is often expressed as a deviation from a climatological mean profile, frequently expanded in terms of empirical orthogonal functions. It would be helpful if difference between the transmittances calculated from the mean and actual profiles were small enough to justify the use of the mean profile transmittances in all calculations.

Temperature changes affect atmospheric transmittances in several ways. Both the Lorentz and Doppler half-widths are functions of temperature, leading to a weak dependence of transmittance on temperature. However,

the greatest change in transmittance occurs because of the sometimes rapid change of line intensity with temperature.

To illustrate the effect of temperature variations, transmittance calculations were made for the U. S. Standard Atmosphere (1962), and the same atmosphere 10K warmer at all levels. Tables 1 and 2 show the transmittances for a vertical path down to the indicated pressure levels, at wavenumbers at resolutions corresponding to those used by the SIRS instrument.

Near the peak of the R-branch (677.1 cm^{-1}) the temperature influence is seen to be remarkably small. In this region most of the absorption is due to lines of R-branch of the fundamental, whose intensities decrease slightly with increasing temperature.

However, lines of the strongest overtone band (010:1 - 020:2) also contribute and these line intensities increase with temperature, just enough to compensate for the fundamental's decrease, with very little net change in absorption.

Further away from the band center the intensities of the lines of the fundamental, i. e. lines with a high J-number (rotational quantum number), increase with increasing temperature, reinforcing the effect of the overtone bands. Beyond this, only lines of overtone bands contribute significant absorption so that increased absorption is observed at the higher temperature. Fig. 1 shows the transmittance plotted as a function of pressure for the two profiles for three wavenumbers. The weighting functions $dt/d \log_{10} p$ has been plotted in Fig. 2 for 705.8 cm^{-1} . Not only does the maximum occur at a lower pressure for the lower temperatures, but the maximum has a higher value.

Calculations were made of radiances for the U. S. Standard Atmosphere (1962) using the correct transmittance functions and using those for the warmer atmosphere. Comparison showed the correct values to be as much as 2-3%

Wavenumber (cm ⁻¹)	668.7	677.1	691.6	698.7	705.8	713.7	748.5
Resolution (cm ⁻¹)	4.6	4.7	5.0	5.1	5.2	5.4	6.0
Pressure (MB)							
.1	.976	.996	.997	.998	.998	.999	1.000
.4	.952	.991	.994	.995	.996	.998	.999
.7	.928	.987	.990	.993	.995	.997	.999
1.0	.906	.982	.987	.991	.994	.996	.999
1.3	.885	.978	.984	.989	.993	.995	.998
1.6	.865	.974	.981	.988	.992	.995	.998
2.0	.840	.969	.978	.986	.990	.994	.998
2.5	.812	.962	.973	.983	.989	.993	.998
3.0	.787	.955	.969	.980	.987	.992	.997
4.0	.745	.942	.961	.976	.984	.990	.997
5.0	.710	.929	.953	.971	.982	.989	.996
6.5	.668	.909	.941	.964	.978	.987	.996
8.0	.633	.889	.930	.957	.974	.984	.995
10.0	.592	.863	.915	.948	.969	.982	.994
13.0	.538	.824	.892	.935	.961	.977	.993
16.0	.490	.785	.870	.922	.954	.973	.992
20.0	.436	.735	.841	.904	.944	.967	.990
25.0	.377	.675	.806	.882	.932	.961	.988
30.0	.328	.618	.772	.860	.920	.954	.986
40.0	.251	.515	.705	.818	.896	.940	.983
50.0	.192	.426	.642	.776	.872	.926	.979
65.0	.129	.317	.555	.716	.837	.906	.973
80.0	.085	.232	.475	.658	.802	.886	.967
100.0	.047	.149	.381	.584	.755	.858	.959
130.0	.017	.069	.267	.483	.687	.816	.947
160.0	.006	.028	.182	.394	.621	.774	.935
200.0	.001	.007	.104	.294	.537	.719	.918
250.0	.000	.001	.048	.195	.440	.649	.895
300.0		.000	.020	.122	.347	.576	.869
400.0			.003	.037	.190	.425	.807
500.0			.000	.008	.088	.289	.734
650.0				.000	.020	.142	.617
800.0					.003	.060	.500
1000.0					.000	.016	.375

Table 1
Vertical Path Transmittances from Outside the Atmosphere at Indicated
Wavenumbers and Spectral Resolutions, Calculated for the U. S. Standard
Atmosphere (1962).

Wavenumber (cm ⁻¹)	668.7	677.1	691.6	698.7	705.8	713.7	748.5
Resolution (cm ⁻¹)	4.6	4.7	5.0	5.1	5.2	5.4	6.0
Pressure (MB)							
.1	.974	.995	.997	.998	.998	.999	1.000
.4	.950	.991	.993	.995	.996	.997	.999
.7	.962	.986	.990	.993	.995	.996	.999
1.0	.904	.982	.986	.991	.993	.995	.998
1.3	.882	.978	.983	.989	.992	.995	.998
1.6	.862	.974	.980	.987	.991	.994	.998
2.0	.837	.969	.977	.985	.989	.993	.998
2.5	.809	.962	.972	.982	.988	.992	.997
3.0	.784	.955	.968	.979	.986	.991	.997
4.0	.741	.952	.959	.974	.983	.989	.996
5.0	.706	.929	.951	.969	.980	.988	.996
6.5	.663	.909	.939	.962	.976	.985	.995
8.0	.627	.889	.927	.954	.971	.983	.995
10.0	.586	.863	.911	.945	.966	.979	.994
13.0	.532	.824	.888	.930	.957	.975	.992
16.0	.484	.786	.865	.916	.949	.970	.991
20.0	.430	.736	.835	.897	.938	.963	.989
25.0	.372	.677	.798	.873	.925	.956	.987
30.0	.324	.620	.762	.850	.911	.948	.984
40.0	.248	.517	.694	.805	.885	.932	.980
50.0	.191	.429	.629	.760	.859	.917	.975
65.0	.128	.320	.540	.697	.820	.895	.969
85.0	.085	.236	.459	.635	.782	.872	.962
100.0	.047	.153	.365	.558	.731	.841	.953
130.0	.018	.073	.252	.454	.656	.795	.939
100.0	.006	.031	.169	.364	.586	.749	.924
200.0	.001	.008	.094	.265	.498	.689	.905
250.0	.000	.001	.042	.170	.398	.614	.879
300.0		.000	.017	.101	.306	.537	.850
400.0			.002	.028	.157	.383	.782
500.0			.000	.006	.067	.251	.704
650.0				.000	.014	.116	.582
800.0					.002	.046	.462
1000.0					.000	.011	.321

Table 2

Vertical Path Transmittances from Outside the Atmosphere at Indicated Wavenumbers and Spectral Resolutions Calculated for an Atmosphere Everywhere Warmer by 10K than U. S. Standard Atmosphere (1962).

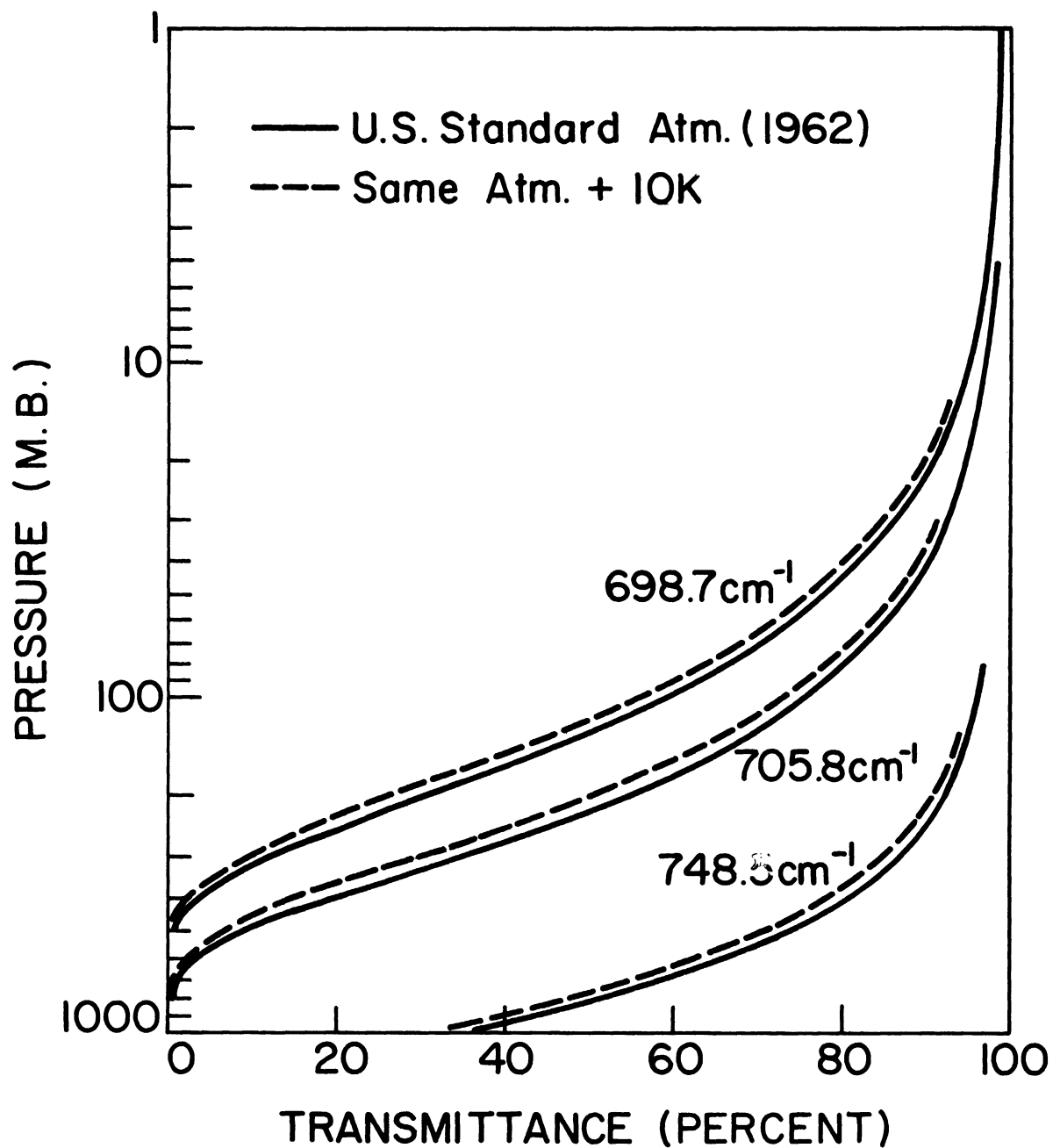


Figure 1. Atmospheric Transmittances as a Function of Pressure Calculated for Two Temperature Profiles.

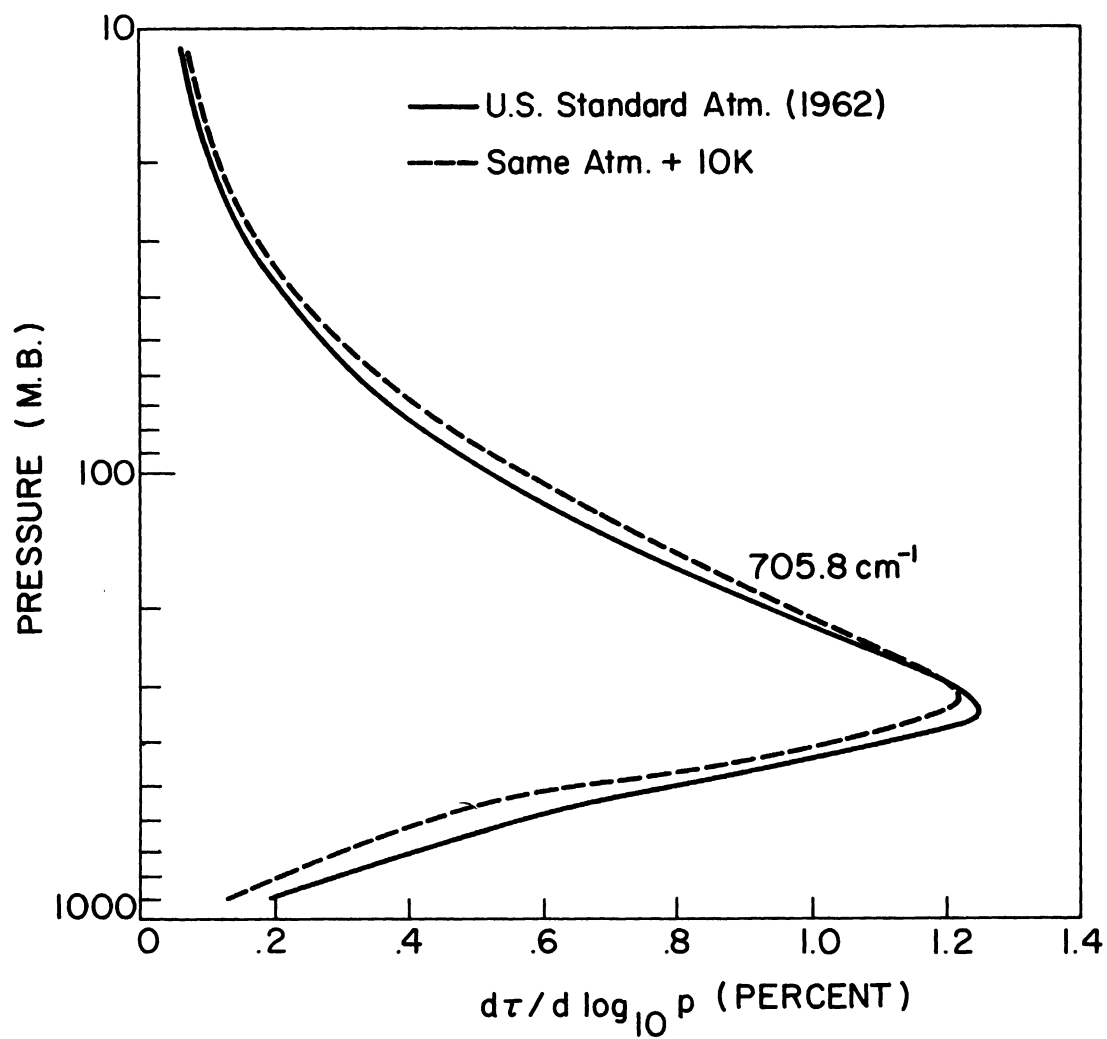


Figure 2. Comparison of Weighting Functions at 705.8 cm^{-1}
 Calculated for Two Temperature Profiles.

higher, an amount much larger than the SIRS instrument error, and outside the range of errors that can be tolerated in a successful temperature sounding experiment. Thus it is essential to allow for the variations of atmospheric transmittances with temperature, a factor which offers no fundamental physical difficulty but which complicates the inversion procedure. This is just one of many minor but critical details that cannot be neglected in the process of obtaining atmospheric temperature profiles from satellite radiance measurements.

The most important difficulty which prevents the more accurate evaluation of the absorption due to carbon dioxide in the $15\text{ }\mu\text{m}$ spectral region is the lack of precise knowledge of some of the band parameters. While the wavenumbers of all lines are sufficiently well known, the band intensities and the line Lorentz half-widths have a larger degree of uncertainty.

The total intensity of all CO_2 bands in the $15\text{ }\mu\text{m}$ region has been frequently estimated experimentally (see Drayson et al., 1968) and is probably known to an accuracy of better than five percent. The same error limits apply to the intensity of the ν_2 fundamental of $^{12}\text{C }^{16}\text{O}_2$ and of the minor isotopic molecules of carbon dioxide. However, the intensities of the overtone bands remain uncertain, particularly those bands whose lines are overlapped by the much stronger lines of the fundamental. Only careful experimental measurements can remedy the situation.

Our knowledge of pressure broadened half-widths remains essentially the same as reported last year. Most of the line half-widths that have been experimentally determined are for self-broadened carbon dioxide. Some progress has been made in foreign broadening, particularly with the use of the CO_2 laser in the $10.6\text{ }\mu\text{m}$ region. However, the range of rotational quantum numbers of lines that can be measured in this way is limited by the laser modes and it is not obvious that results in this region can be carried over without any modification into the $15\text{ }\mu\text{m}$ region. Direct measurement of line half-widths

in the $15\text{ }\mu\text{m}$ region remain inadequate for self-broadened lines and are virtually missing for nitrogen and air broadened lines.

Yamamoto et al. (1969) have applied the Anderson theory to theoretically calculate the half-width of CO_2 lines in the $15\text{ }\mu\text{m}$ bands, both for self-broadened and nitrogen-broadened lines. Their results show that values are controlled by two parameters:

- a) for low J-numbers the half-width is a function of the product of the quadrupole moments of CO_2 and of the broadening gas. For large J-numbers this parameter has a smaller effect and is entirely absent in the self-broadened case.
- b) for high J-numbers, a parameter corresponding to the classical collision diameter largely controls the half-width but is ineffective for low J-numbers.

Since the correct values for both of these parameters are not well known, Yamamoto et al. present results using a variety of reasonable values. In particular they have fitted their parameters to the few experimentally determined values of half-width that are available in the $15\text{ }\mu\text{m}$ region. Further measurements, particularly with nitrogen and air broadening could help to verify the theory and obtain good estimates for the two parameters needed, leading to reliable values for half-widths.

The deviation of pressure broadened lines from the Lorentz line shape is still not well understood. Indeed, it is not known if there are deviations for air-broadened carbon dioxide in the $15\text{ }\mu\text{m}$ region, yet alone any quantitative measurements. Whatever the deviations they are probably considerably less important than the uncertainty in line intensities and half-widths in atmospheric applications.

3. Absorption by Other Atmospheric Constituents Near $15\ \mu\text{m}$

Although carbon dioxide is the major atmospheric molecular absorber near $15\ \mu\text{m}$, there are two other constituents whose absorption cannot be neglected if high accuracy is required. They are water vapor and ozone. Unlike carbon dioxide their mixing ratios are not constant, but vary with height, geographical location and time. Thus the problem of calculating atmospheric transmittance involves both the distribution of the absorber and its spectral characteristics. The discussion that follows is chiefly concerned with the latter aspect.

Our understanding of the absorption by water vapor is hampered by two difficulties:

- i) Uncertainty in the intensities and half-widths of those absorption lines lying within the spectral region of interest.
- ii) Uncertainty in the shapes of the far wings of lines lying outside the $15\ \mu\text{m}$ spectral region, which contribute to the atmospheric water vapor continuum.

Experimental studies to eliminate these uncertainties are being carried out by a number of workers, and it seems likely their combined efforts will improve the situation shortly.

The atmospheric absorption by the $14\ \mu\text{m}$ band of ozone has been largely ignored in the radiative transfer literature. Atmospheric spectra are dominated by carbon dioxide near $14\ \mu\text{m}$ and this effectively masks the absorption by ozone. However, since the wavenumbers best suited for measurements of atmospheric radiances for use in a temperature inversion scheme fall near the peak of the ozone absorption, an investigation was made of the importance of the ozone contribution. Before embarking on a detailed study of the atmospheric absorption by ozone, it was decided to make a crude estimate of its importance, and to continue with more sophisticated techniques if these could be justified.

Until recently no quantitative measurements of the $14\ \mu\text{m}$ (ν_2) band of ozone were available, a limitation that certainly discouraged earlier workers. Careful measurements have been reported by McCaa and Shaw (1967), and these form the basis for the estimates of atmospheric absorption that follow.

Because of various experimental limitations, the laboratory data cannot easily be applied directly to atmospheric conditions. In particular almost all the optical masses used in the measurement program are greater than the amount of ozone in a vertical atmospheric path, which is typically in the range 0.2 to 0.5 atm. cm. Thus, in order to apply the laboratory absorptions measurements to atmospheric conditions it is necessary to extrapolate the absorption down towards zero optical mass, a procedure which can introduce large uncertainties. Nevertheless, to obtain a preliminary estimate of the absorption for typical ozone distributions, this procedure was adopted.

The calculation was based on the ozonesonde measurement from New Mexico, 9th September 1964. This measurement is the nearest available in time and location to the balloon flight at Palestine Texas in September 1964 of the SIRS instrument by the National Environmental Satellite Laboratory. The total ozone was 0.261 atm. cm. which is well below the maximum amount that can be present in the atmosphere. The amount in a vertical path down to several pressure levels is shown in Table 3.

The Curtis-Godson approximation was used to reduce the atmosphere to a number of 'equivalent' homogeneous paths, neglecting any temperature effects. It was found that for the optical masses and equivalent pressures of these homogeneous paths, the absorption was close to that given by the weak line approximation. In view of the uncertainties already introduced by the extrapolation

Pressure (mb)	Ozone (atm cm x 10 ³)	Absorption (%) at wavenumber:				
		677.5	691.0	697.0	703.0	709.0
0.0	0	0.0	0.0	0.0	0.0	0.0
12.9	74	1.3	1.1	0.7	0.6	1.1
20.0	112	2.3	1.7	1.1	1.0	1.7
23.7	134	2.5	2.1	1.3	1.2	2.1
31.6	171	3.2	2.6	1.7	1.5	2.6
50.0	215	4.0	3.3	2.1	1.9	3.3
89.1	243	4.5	3.7	2.4	2.1	3.7
141	245	4.6	3.8	2.4	2.2	3.8
355	245	4.6	3.8	2.4	2.2	3.8
708	254	4.7	3.9	2.5	2.2	3.9
1000	261	4.9	4.0	2.6	2.3	4.0

Table 3

Ozone amounts and estimates of absorption for a vertical path down to the listed pressures at selected wavenumbers in the 14 μ m ozone band.

procedure, the slight modification to the absorptance introduced by departure from the weak line approximation could not be justified and the approximation was adopted. In addition, the calculations were greatly simplified by this procedure and it did not compromise the aim of the investigation, to obtain a rough estimate of the atmospheric absorption by the ozone. For larger atmospheric ozone amounts a different method would be required.

The calculated absorptions are shown in Table 3. The wavenumbers are the same as those of the SIRS instrument used in the balloon flight. The maximum absorption is seen to be about 5% at 677.5 cm^{-1} , with absorptions of greater than 2% on each of the other channels, and hence ozone is a minor but significant contributor to atmospheric absorption in this spectral region.

Absorption by the $14 \mu\text{m}$ ozone has two broad absorption peaks, at about 680 cm^{-1} , and 720 cm^{-1} . The former falls near the maximum of the R-branch of the carbon dioxide fundamental, while the latter is in a region where weaker overtone bands of carbon dioxide are dominant. Thus the ozone absorption is relatively more important at wavenumber greater than about 700 cm^{-1} where it is essential to incorporate the ozone influence.

Having established the importance of the $14 \mu\text{m}$ ozone band a more accurate method calculation is required. A deck of line positions and intensities has been obtained from Dr. S. A. Clough (AFCRL) and these will be used in atmospheric slant path transmittance calculations. Before such calculations can be made, the ozone distribution is required, data that may not be readily available for locations corresponding to satellite radiance measurements. Since the ozone contribution is small compared with the carbon dioxide, it may be possible to use climatology, at least in some cases. Alternately, measurements in the $9.6 \mu\text{m}$ ozone band such as obtained from IRIS for example, may provide the required information.

4. Atmosphere Absorption by the Oxygen A-Band

The intensities and half-widths of lines in the oxygen A-band, centered near 7600 Å, were discussed in a previous report (Drayson et al., 1968). It was shown that the parameters derived by Burch and Gryvnak (1967) from laboratory measurements gave excellent agreement with their measurements for both the shape of the spectra and the total absorption over a wide range of optical masses and pressures.

A further investigation of the A-band was recently reported by Adiks and Dianov-Klokov (1968). The band intensity of $4.0 \text{ gm}^{-1} \text{ cm}^2 \text{ cm}^{-1}$ obtained by them is close to the value of Burch and Gryvnak ($4.09 \text{ gm}^{-1} \text{ cm}^2 \text{ cm}^{-1}$). However, the measured values of pressure broadened half-width are considerably different, some 30% below the values of Burch and Gryvnak, for self-broadened oxygen. Surprisingly the half-widths of air-broadened oxygen were reported as being about 10% less than those of the self-broadened gas, whereas Burch and Gryvnak found them to be about 5% higher.

Faced with this discrepancy in the values of the pressure broadened half widths, the values of Burch and Gryvnak have been retained for the following reasons:

- a) Our previous experience in using these values gave us great confidence in the accuracy and reliability of the measurements.
- b) The products of line intensity and half-widths give values close to those of Wark and Mercer (1965), whose measurements were for conditions closely approximating those for strong line absorption. The products from the data of Adiks and Dianov-Klokov are considerably lower.
- c) Accurate measurements of pressure broadened half-widths are not easy to make. The initial values obtained by Burch et al (1964) and were similar to those of Adiks and Dianov-Klokov. However improvement in experimental techniques provided the more accurate values of Burch and Gryvnak.

The band parameters were used to make calculations of atmospheric slant path transmittance, for comparison with cloud-top reflectance measurements made from an aircraft (Wark, 1968). The transmittance calculations were made using the same techniques and programs as used for the carbon dioxide slant path computations. The Voigt profile was used throughout the atmosphere since the Doppler and Lorentz half-widths are equal at about 250 mb. Since the aircraft measurements were all made for conditions under which the temperature was close to that of the U. S. Standard Atmosphere (1962), this temperature profile was used in the calculations.

Figure 3 shows the comparison of the experimental and theoretical transmittances for a zenith angle θ , with $\sec\theta = 2$. The experimental transmittances at pressures lower than 600 mb were obtained by an extrapolation from those at higher pressures (Wark, 1968). The wavenumber is 13102.7 cm^{-1} (corresponding to a wavelength of 7632 Å) and the resolution is 13.7 cm^{-1} . Although the agreement between the two curves is good near 500-600 mb, the differences become much larger near the surface. Small shifts in the central wavenumber and the resolution of the theoretical computations (to allow for uncertainties in the wavenumber, resolution and slit function of the instrument) did not change the transmittances. Similarly the use of the Lorentz profile at pressures higher than 10mb changed the calculated transmittances only slightly between 100 and 1000 mb. (maximum change .002 at 100 mb.), showing that Lorentz profile only need be considered for this application at this wavenumber. In other parts of the band, where the atmospheric absorption is weaker, the Voigt profile may still have to be used.

To understand how the differences between the experimental and calculated transmittances arise, it is necessary to observe that the slopes of the two curves are different. This implies that uncertainties in the band intensity or half-widths, such as discussed earlier, cannot be solely responsible, since

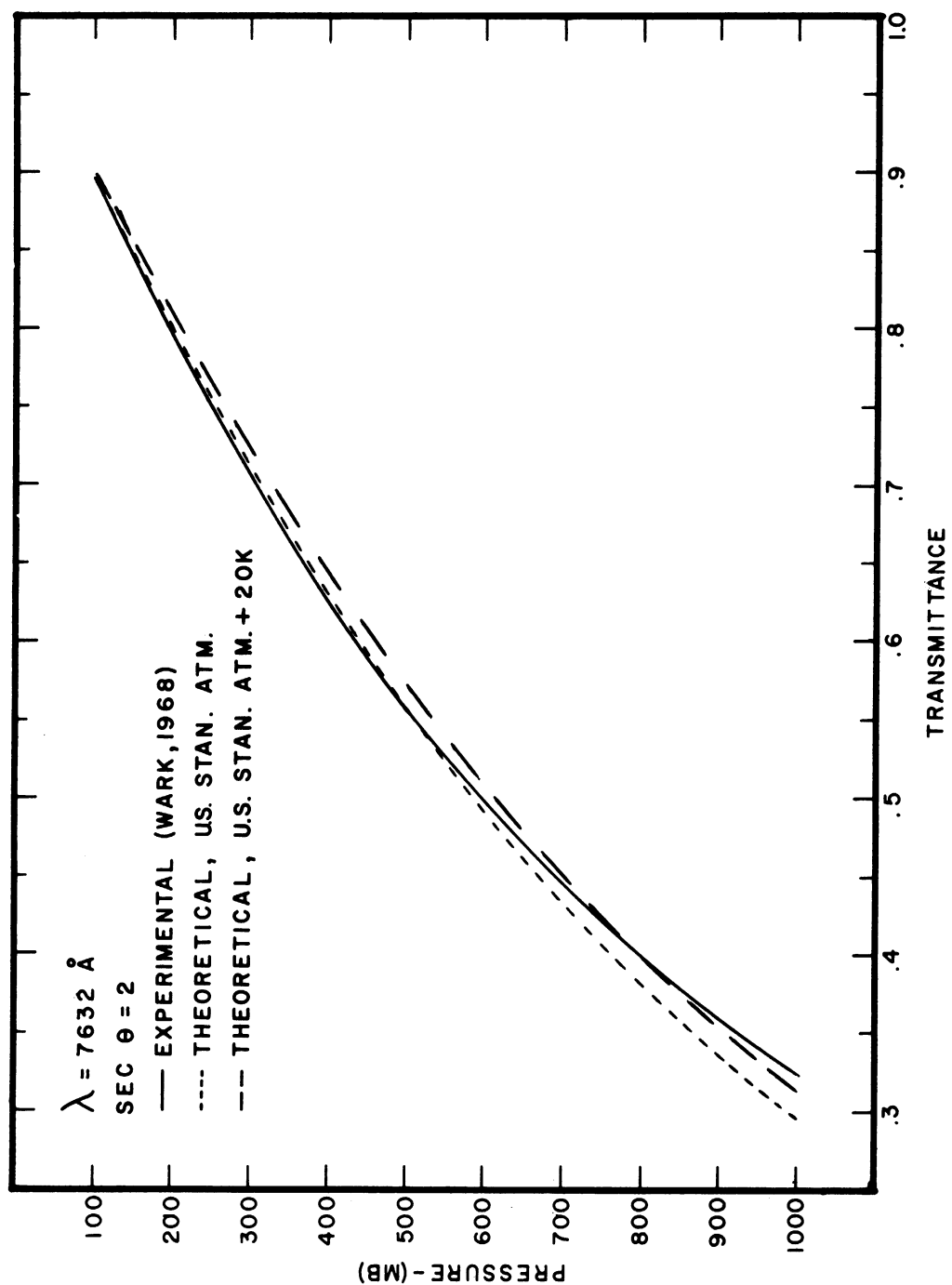


Figure 3. Comparison of Experimental and Calculated Transmittances in the Oxygen A-Band at 7632 \AA .

changes in these parameters will shift the curve over, but alter the slope only slightly.

One possible explanation is that the transmittance curve is sensitive to changes in the temperature profile. This idea was investigated by Wark and Mercer (1965), who found only a small temperature dependence. Nevertheless, a further calculation was made for an atmosphere everywhere 20K warmer than the U. S. Standard Atmosphere, and the result is also shown in Figure 1. The agreement with the experimental is much better near the surface, but since the slope has changed little with the increased temperature, the overall agreement has not been greatly improved. It would presumably be possible to adjust the temperature profile to produce agreement with the experimental transmittances, but the profile would not be representative of the conditions under which the experimental data were obtained.

Temperature affects the transmittances in two ways. The temperature dependence of the line half-widths (Lorentz and Doppler) will slightly change the transmittance. As noted, the Doppler broadening is relatively unimportant in this application, so only the Lorentz need be considered. Increasing temperature decreases the half-width and leads to higher transmittances. A similar but more marked effect occurs due to the change of line intensity with temperature. In the spectral region under consideration the intensities of the lines decrease with increasing temperature, which in turn increases the transmittance. No adequate explanation has been found of the differences between the experimental and theoretical transmittances. None of the more usual and more obvious possibilities help to produce agreement. The investigation will continue until a satisfactory explanation is obtained.

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