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ATMOSPHERIC ABSORPTION IN THE RANGE OF WAVELENGTH BETWEEN 10 CMS AND 1 MICRON

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I. Introduction

The recent rapid development of receiver technology in the mm, sub-mm, and infrared part of the electromagnetic spectrum is making possible the exploitation of this part of the spectrum for astronomical observations. A thorough understanding of the absorption characteristics of the earth's atmosphere at the above wavelengths is of great importance for the effective planning of astronomical observations.

The basic theoretical work on microwave absorption by atmospheric gases was done by Van Vleck towards the end of World War II. Since then numerous theoretical and experimental investigations have been carried out. As a result we are in a position to evaluate the atmospheric absorption characteristics in the range 10 cms to 1 mm with reasonable accuracy for a certain elevation angle and given meteorological conditions. Little reliable information is available at the moment for the wavelength region between 20 microns and 1 mm.

The exploration of the infrared region had been started by extending astronomical observations at optical wavelengths to the near infrared. During the last war and later activity in the medium and far infrared region had been stimulated mainly by military applications. The available literature on this subject is very widespread. A report of Altshuler [1] gives an excellent summary of the work done up to 1961. The information is presented in the form of graphs for an immediate application to practical absorption calculations. Most of the results presented in this report for the infrared region are based on Altshuler's report.

The aim of this report is to give a review of the atmospheric models, to discuss briefly the physical processes connected with the atmospheric absorption and finally to calculate the zenith extinction for the whole wavelength region considered here for different reasonable meteorological conditions and sites of observation. The general trend of extinction with possible windows is presented. The radiation from the atmosphere can be predicted from such extinction data. By extinction is meant the combined effect of scattering and attenuation. Under good observation conditions the scattering can be neglected as compared to absorption, at least in the far infrared and microwave region.

The terminology used in this report is explained here. The transmission of the atmosphere, when the line of sight subtends an angle z ("zenith distance") to the zenith, is given by the equation

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(1)
$$I(z)/I_{\text{Incident}} = p^{F(Z)}$$

L_{Incident} means the radiation intensity of a remote radiation source outside the atmosphere and I(z) means the intensity of this source as measured by an observer at the surface of the earth. For $z < 80^{\circ}$, $F(z) = \sec z$; for larger distances z, the rigorous air mass function has to be used. Also for z = 0, F(z) = 1. Hence p denotes the transmission coefficient of the total atmosphere at zenith. By means of equation (1), it is possible to calculate the transmission of the atmosphere for any zenith distance z if the transmission coefficient p is known.

On the other hand, p can be calculated from experimental extinction values at various zenith distances z. The values of p are presented in different forms by different authors. Sometimes the value -log p is given, which then is a positive number, since $p \leq 1$. Then the loss of the atmosphere, which is defined as (1 - p) can be obtained for small values of p using the relation

(2)
$$1 - p = -\log_{10} p/0.4343$$

Instead of the transmission very often the attenuation of the atmosphere is given, especially for the microwave and sub-mm region. The attenuation is then given in db and is related to the transmission by

(3) zenith attenuation in db =
$$10 \log \frac{1}{p} = -10 \log p$$
.

This makes it convenient to compare -log p and zenith attenuation values given in db.

2. Model Atmospheres

In order to correlate the different experimental conditions and theoretical assumptions, one needs to consider the major models of atmospheres. The physical and chemical properties of the earth's atmosphere vary significantly with altitude. In all models, the vertical structure of atmosphere is considered as consisting of nearly concentric, approximately spherical shells with merging boundaries. Within these systems, the various shells are distinguished from each other by differences in definable and measurable parameters such as temperature, temperature gradient, ionization, predominant chemical processes or a combination of several of these and other factors. One of the accepted systems is due to Chapman (see ref. [2]). In this system the classification is based on dominant physical processes. Troposphere, stratosphere, mesosphere and thermosphere are based on temperature variations. Homosphere and heterosphere are based on composition, ionosphere on ionization, chemosphere depends on chemical reactions and exosphere is based on mechanism of molecular escape.

Troposphere is the region nearest the earth's surface extending to an altitude of about 12 to 14 km depending on the latitude. It has a uniform decrease of temperature with altitude. Temperature inversions happen however in this region as the weather changes. The tropopause is the upper boundary of troposphere extending up to 18 km. These are the regions in which electromagnetic radiation is mainly absorbed by water vapor and oxygen.

Even though there are several tabulations of various parameters describing model atmospheres, ARDC model atmosphere [2], revised at periodic intervals, is the most commonly used. Hogg [3], one of the early workers in this field, used the dependence of temperature and pressure on height based on the international standard atmosphere. The water vapor content was assumed to vary linearly from 10 gm/meter³ at the earth's surface to zero at a height of 5 km. Several authors use various moisture contents, in conjunction with the atmospheric model chosen, depending on geographic location and latitude.

3. Atmospheric Constituents

One has to consider the composition of air in order to estimate the relative importance of various constituents. Air is a mechanical mixture of several gases. The mixing ratio of some gases, as referred to the total amount of gas, is constant and does not depend on altitude, whereas the mixing ratio of other gases varies markedly with time and location, generally showing a rapid decrease in percentage with height. These atmospheric gases are all selective absorbers, that is, they absorb at some wavelengths but are transparent to others. An extraterrestrial radiation at these wavelengths of transparency passes through the atmosphere only slightly attenuated. These windows are therefore of special interest for earthbound observers.

The major constituents in the troposphere are molecular nitrogen $(N_2, 78\%)$, molecular oxygen $(O_2, 21\%)$, and argon (A, 1%). The minor constituents are carbon dioxide (CO_2) , neon (Ne), helium (He), molecular hydrogen (H_2) and variable amounts of carbon monoxide (CO), methane (CH_4) , nitrogen dioxide (NO_2) , nitrous oxide (N_2O) , water vapor (H_2O) and ozone (O_2) . The predominance of these major and minor constituents and variable gases changes with altitude. Although water vapor usually comprises less than 3% of the gases even with moist conditions at sea level, it absorbs in the wavelength region considered here nearly six times as much solar radiation as do all of the other gases combined.

The following gases have approximately constant mixing ratios as referred to the total amount of air at altitudes between 0 to 50 km.

Gas	Concentration (parts per million)	Amount in 1 km path at sea level, atm-cm					
CO2	320	32.0					
N ₂ O	0.27	0.027					
CH4	2.4	0.24					
CO	1. 1	0.11					

Table 1. Concentration of Infrared Absorbing Gases [1]

For example, CO_2 exists in the atmosphere in the proportion of 0.032% by volume (or 320 parts by million), which means that for every km of air at sea level, the light ray traverses 32 atm-cm of CO_2 . The energy transition of these atmospheric components contribute attenuation mainly in the infrared region which will be discussed in section 11.

4. Precipitable Water Vapor

It is customary to express the amount of water vapor concentration, w, in the atmosphere in precipitable cms. There are two notations, denoted by subscripts h and v depending on whether the atmosphere path considered is horizontal or vertical. w_h represents the thickness of the layer of liquid water that would be formed, if all water vapor traversed by a light beam were condensed in a container of cross sectional area equal to that of the parallel beam. The value of precipitable cm of water in a horizontal path, w_h , can be found from water vapor density and path length by an empirical formula [1] as given below.

$$w_{h} = \rho_{w} x/10$$

where w_h = precipitable water content in horizontal path in cms ρ_w = water vapor density (gms m⁻³) x = path length in km

For the zenith attenuation calculations, the more important quantity is the vertical water vapor content of the atmosphere over a given place, in an air column of cross-sectional area of 1 cm^2 . This quantity is called precipitable cm in a vertical path and is denoted by w_v . The total amount of water vapor contained between the height 0 and the height z would be

(5)
$$\mathbf{w}_{\mathbf{v}} = \int_{0}^{\mathbf{z}} \rho_{\mathbf{w}} \, \mathrm{dz}$$

Since by definition the precipitable water is referred to a column of cross section 1 cm^2 , w, can be expressed in either cms or gms/cm².

 w_v can be expressed in different forms, depending on the data available. The hydrostatic equation in the atmosphere is

$$dp = -\rho g \, dz,$$

and the equation of state for water vapor is given by

(7)
$$e = \rho_{w} \frac{R}{m_{w}} T$$

where

- e = partial pressure of water vapor
- $\rho_{\rm m}$ = water vapor density or absolute humidity
- m = gm molecular weight.

The above two equations along with (5) give useful relations to obtain w_v .

Also, at saturation ρ_{ws} is given by equation (7) for corresponding saturation conditions. The values of saturation humidity at different temperatures are available [4] and these are valuable in moisture content conversions. The water vapor content varies with the amount of water vapor in the atmosphere and can change from 3.75 gm/m³ to 15.0 gm/m³ at sea level depending on the season and location. Normally standard values of 7.5 or 10 gm/m³ are used.

5. Line Broadening Parameter

The line broadening parameter denotes the half power width (HPW) of the absorption line and is sometimes expressed in terms of wave number breadth denoted $b\bar{y} \Delta \gamma/c$, frequency width/velocity of light. For example, there are large number of narrow oxygen absorption lines in a band centered at 5 mm, a maxima about 2.5 mm and water vapor maxima near 1.35 cm, 1.63 mm and at very many (600) sub-mm wavelengths. Due to the line broadening effect these lines tend to merge into one diffuse band.

For vertical transmission through the atmosphere, the absorption coefficient in each spectral line varies from a very high value in the center of the line to a much smaller value on the sides. Also the effect on the absorption coefficient due to pressure, temperature and density (known as the broadening of absorption lines) is such that HPW of each line decreases steadily with increasing altitude. Most of the workers have considered only molecular collisions, whereas Meeks and Lilley [5] have included Zeeman effect above 40 km, and Doppler effect above 80 km, to calculate the broadening line widths.

For atmospheric absorption except at high altitudes, the decrease in pressure with height (1/2 atm. in the first 6000 m) is large enough to cause line width to be in the magnitude order of their separation and even of their center frequency. Under such conditions in actual atmosphere, the absorption calculated at any frequency which does not coincide

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with a strong absorption maximum, is greatly effected by the wings of many overlapping lines and can widely vary depending on the broadening assumed for each of them. In spite of this complexity and evidence [6], most attempts to adapt the theory to the absorption measurements used only a single line broadening parameter throughout the absorption spectrum due to the lack of experimental verification and scarcity of information.

6. Variation of Water Vapor Content

The water vapor contained in the vertical atmosphere is described by the equivalent amount of precipitable cm water and this quantity varies depending on the latitude and altitude of a particular site. The data for 29 stations in the United States are taken from Weather Bureau tables [7] and presented graphically in figures 1 and 2 to show the general trend of dependence on latitude and altitude. The Weather Bureau report gives mean values of precipitable water. These mean values are averaged over layers of certain depths ranging between surface and 8 km altitude as well as over periods of one month.

In order to eliminate the altitude differences in the stations referred in the above report, the annual average of precipitable water from 3 to 8 km has been computed and presented as a function of latitude in figure 1. In the same figure the corresponding mean monthly values are plotted. The ratio between the maximum and minimum monthly mean values are about 3:1 (approximately independent of season). However, the ratio of maximum and minimum instantaneous values are considerably larger. Figure 1 reveals the general trend, that the amount of precipitable water decreases with increasing latitude.

Figure 2 shows the variation of annual mean precipitable water from surface to 8 km, with base altitude. The 29 stations are divided into five groups, each group member having approximately the same latitude. A straight line variation is drawn about the average value of each group, even though the individual values are changing at random. (For example, the increasing latitude of stations in two groups is shown by an arrow following a dotted line.)

From this figure one can see the precipitable water decreases with increasing altitude. It shall be noted that the Rocky Mountain area has the minimum amount of precipitable water.

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From these general observations, one can say that profitable experimental work from ground based antennas depends on the quality of the site chosen as much as the design of the instruments and one needs to choose a high mountain in a dry area (suitable geographic latitude) for an observatory site.

7. Methods of Absorption Measurements

The general experimental methods are described here. First, there are the convenient measurements over a chosen absorption path length between a laboratory transmitter and receiver. This has the benefit of ability to control the factors introduced in the absorption path, but in practice is hard to simulate actual atmospheric conditions. Also the path lengths should be quite large in order to obtain measurable attenuation specially in the wings of the absorption lines.

Second, quite a few absorption measurements at longer path lengths in km between ground based transmitter and receiver are available. The results give the horizontal attenuation (db/km) at a known atmospheric pressure but do not account for the vertical variations in the atmosphere. The atmospheric conditions over the entire propagation path are not uniform, as in the first case.

The third method determines the absorption through the entire atmosphere by measuring the radiation from bright extraterrestrial sources, like the sun, at different elevation angles. To compare these spectral results with theory, one has to assume the composition and other properties of the atmosphere as a function of altitude. Even though this procedure has the difficulty of separating the measured attenuation as due to different component contributions, based on theory, it has the benefit of giving the total vertical attenuation in a column of atmosphere (db) rather than attenuation per unit length (db/km). The results from these different measurements agree fairly well at frequencies of principal absorption maxima, for the major absorbants oxygen and water vapor.

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8. Microwave Spectrum of Oxygen

Oxygen gas absorbs energy because the individual molecules behave like dipoles with a permanent magnetic moment. The incident electromagnetic wave passing over these molecules reacts with them, causing them to oscillate and rotate in a variety of ways. According to quantum theory, each of the vibrational states is associated with a certain energy level and is given by " $h\nu$ ". Thus it can be visualized that the incident wave delivers to the gas molecules discrete amounts of energy (in steps of " $nh\nu$ ") during the transition from the lower to the higher energy level. When the molecule returns to the lower level, it reradiates energy in all directions and only a small portion emerges in the propagation direction. The net result is an attenuation in the amplitude of the incident energy.

Figure 3 shows the horizontal oxygen attenuation for various elevations in the earth's atmosphere and is due to Rogers [8]. Thus it represents the gross changes in the absorption spectrum (50-70 kmcs) with increasing height. The various heights are representative of high pressure, transition and low pressure regions. It can also be seen that at the earth's surface the oxygen lines overlap completely to form a continuous region of absorption centered around 60 kmcs. At a height of 8-11 km, the lines continue to overlap, but some lines get clearer. At 30 km and above, the resonances due to individual rotation lines are resolved and the attenuation between the lines becomes quite small.

The oxygen absorption values in the horizontal direction at a given altitude, can be converted to other altitudes by using Van Vleck's [9] empirical relation,

(8)
$$\mathbf{L} = \mathbf{L}_{\mathbf{O}} \left(1 - \frac{\mathbf{h} + \mathbf{h}_{1}}{20} \right)$$

where L and L_O are the horizontal path lengths and h is the height where the absorption has been measured, h, is the height to which this absorption value shall be converted. This formula for altitude correction holds good only in the lower atmosphere (up to 20 km). Using this relation one can see that the horizontal attenuation does not depend much on the altitude of any possible observation site. This is shown in the two lower curves of figure 4. The continuous curve shows the horizontal attenuation at Green Bank (0.83 km) based



Fig. 3 Oxygen Attenuation for Various Elevations in the Earth's Atmosphere.

on Texas [10] sea level values. The dotted curve right below shows the horizontal attenuation at Climax (3.45 km) which is hardly different from the above.

Van Vleck [11] has theoretically estimated a single line broadening parameter, that can best approximate the observed line shape. Hogg [3] and Blake [12] used Van Vleck's theory with their own model atmospheres and measurements and their calculated attenuations are in fair agreement. Meeks and Lilley [5] are the only workers who based their theoretical calculations on a variable (0.01 to 100 mcs) line breadth parameter as a function of height (0 to 100 kms) in conjunction with ARDC model. They also considered the Zeeman (> 40 km) and Doppler (> 80 km) effects on the HPW. Rogers [8] also considered these effects.

The top curve in figure 4 shows the variation of calculated zenith attenuation with frequency (1-400 kmcs) due to Meeks and Lilley. Some measured values for cloudless conditions are shown and the range of values for some frequencies represent the spread in clear weather measurements. These are, however, mainly from astronomical observations and are due to the combined attenuation of water vapor and oxygen (there being no way to separate them). Thus the comparison with the selected experimental values with the theoretical curve shows that oxygen attenuation is predominant at these frequencies.

There is no simple relation between the measured attenuation in a horizontal path and the total absorption of the atmosphere in the entire frequency range. The empirical relation sometimes used, that the zenith attenuation of the atmosphere corresponds to the attenuation of a horizontal path of 5 km sea level length, seems to hold approximately at a few selected frequencies (like 35 and 140 kmcs). Tolbert, et al [13] also provide the calculated oxygen attenuation in the frequency range 20 to 300 kmcs based on $\Delta \nu = 1.9$ mcs per mm of Hg from absorption cell measurements. Their experimental spread of values at a couple of frequencies are in good agreement with the calculated attenuation and are denoted by T in figure 4.

Signal propagation in the vicinity of the line frequencies requires a detailed knowledge of the shape intensity and pressure broadening associated with that line. Also the measured attenuation can give information about the vertical thermal structure of the atmosphere.



(4C) SMEHRROMATA SHT NE NOLTAUNETTA NEBYKO

Fig. 4 Attenuation Due to Oxygen.

9. Water Vapor Attenuation

As pointed out before, even though water vapor comprises less than 3% of all gases, it absorbs nearly six times as much solar radiant energy as do all the other gases combined. Water vapor absorbs energy because the individual molecules behave like dipoles, and in the cm-mm region they have permanent electric dipole moment. These moments interact with incident electromagnetic energy to cause the molecular transitions that are responsible for the absorption.

The zenith attenuation calculations at any altitude are made on the basis of Texas group [10] values with the aid of Altshuler's plots of mixing ratio, relative humidity and precipitable cm, of water vapor variation with altitude. The water vapor mixing ratio is defined as the ratio of gms precipitable water vapor to kgms of dry air. The relative humidity is the ratio of observed mixing ratio to that which would prevail at saturation, at the same temperature. Since the pressure, temperature and density variations with altitude alter the water vapor absorption, the amount of water vapor in the line of sight can be equated to another value at sea level conditions (288 °K temperature and 760 mm pr.). Thus w represents the equivalent precipitable cms of water vapor in a vertical path from altitude h to ∞ and w represents the equivalent precipitable cms of water vapor in one km actual horizontal path length at an altitude h. Both w and w are corrected to sea level conditions and only w, is useful in zenith attenuation calculations.

Figure 5 shows the horizontal water vapor attenuation [10] at sea level, 2, 4, 6, and 8 km elevations and horizontal oxygen attenuation at sea level in the frequency range 10 to 400 kmc. Using this horizontal attenuation (db/km) data for water vapor and oxygen, the attenuation through the entire earth's atmosphere can be determined theoretically by interpolating and extrapolating the attenuation values, to all elevations by use of modified Van Vleck-Weisskopf [14] (VVW) equation and commonly accepted ARDC atmospheric model. The horizontal attenuation values of water vapor in figure 5 are normalized to unit density. Hence, to obtain the total horizontal attenuation at each elevation, one has to know the corresponding density.

According to Altshuler, if the altitude of the tropopause changes, it will be assumed that the relative humidity will remain constant at 100% below the tropopause and the mxing ratio will remain constant above the tropopause. At sea level the water



Fig. 5 Oxygen and Water Vapor Attenuation for Various Elevations in the Earth's Atmosphere.

vapor mixing ratio is 10 decreasing to 4.5×10^{-2} at 11 km, and remaining constant thereafter. From this knowledge of variation of water vapor mixing ratio and ARDC density variation of dry air, one can readily obtain the water vapor density variation with altitude. For an approximate estimate, the atmosphere can be considered to be made up of plane parallel layers of equal thickeness and with the knowledge of water vapor density at each layer. The total zenith attenuation from any altitude can be calculated.

After these calculations were completed a later article by Straiton and Tolbert [15] showed that their attenuation calculations were normalized to water vapor density of one gm m⁻³ at the surface. The total water vapor attenuation through the lower 9 km of the earth's atmosphere for different elevation angles from the earth's surface were given in the same frequency range 10 to 400 kmcs. They have assumed a rate of decrease of water vapor density with height in accordance with $e^{-0.5 z}$, where z is the elevation in km. Thus the losses shown must be multiplied by the ground level water vapor density to obtain the total water vapor loss. With this given variation of water vapor density and altitude, one can obtain the zenith attenuation plots at any altitude. The values obtained from both Altshuler's model and the above empirical relation have been checked and found to agree quite well.

Figure 6 shows the variation of calculated zenith attenuation with frequency for different values of vertical precipitable cm, w_v , of water vapor. The Weather Bureau tables [7] based on monthly mean values, list maximum $w_v = 1.1$ cms and minimum $w_v =$.24 cms at Climax, Colorado. From Altshuler's plot these water vapor values correspond to altitudes of 1 km (1.2 cms) and 3.5 km (.24 cms), respectively. Sea level corresponds to $w_v = 2.1$ cms. Assuming a plane parallel layer atmosphere and using figure 5 with Altshuler's water vapor densities, the zenith attenuation in figure 6 is plotted for 10 to 400 kmcs for $w_v = 2.1$, 1.2 and .24 cms. From Altshuler's transmission data (with w_v as index), the zenith attenuation for a frequency range 150 to 10,000 kmcs is also plotted for $w_v = 1.0$ and .25 cms. One can compare the shifts in the frequency and the magnitude variation of attenuation over the two overlapping window regions, to get an idea of the differences from the two models used. Also from this comparison one can arrive at an approximate factor to match the curves at any w_v value.



Zenith Attenuation Due to Water Vapor (for Different W Values). 9

10. Total Zenith Attenuation

Figure 7 shows the zenith attenuation due to water vapor, oxygen and their sum at Green Bank. A rough measurement at Green Bank showed a variation of w_v from .35 to 2.0 cms over a few days. From Altshuler's model, 2.1 cms corresponds to sea level and 0.35 cms corresponds to 3 km. Again from the plane parallel atmospheric approximation for water vapor is plotted for $w_v = 2.1$ and 0.35 cms (surface up to 8 km) from 10 to 400 kmcs. Also, the zenith oxygen attenuation due to Meeks and Lilley [5] from sea level is plotted on the same figure from 1 to 400 kmcs. It is assumed that zenith oxygen attenuation observed at an altitude of 3 km is not different from zenith attenuation at sea level since measurements or calculations from various elevations in the entire frequency range considered are not available. The total attenuation plots are extended up to 1 kmcs by matching Blake's [12] values at 10 kmcs. This was possible for higher $w_v = 2.1$ cms. For lower w_v , this matching is not accurate, since attenuation due to oxygen very much exceeds water vapor attenuation in 1 to 10 kmcs region.

Two sets of zenith water vapor attenuation are plotted and the same sea level zenith oxygen attenuation is added to them separately to obtain two sets (for $w_v = 2.1$ and .34 cms) of total zenith attenuation. The center frequency, bandwidth, and attenuation values in the window regions are tabulated for the two cases.

	TABLI	E 2a				
Center Frequency (kmcs)	Minimum Attenuation (db)	Bandwidth (kmcs)	Attenuation at Band Limits (db)			
34	.35	30 - 38	(.4)			
85	• 8	70 - 100	(1.0)			
135	1.8	125 - 145	(2)			
260	4.	230 - 290	(5)			
375	7.9	350 - 400	(8.4)			

For $w_{y} = 2.1 \text{ cms}$

For $w_{y} = 0.34$ cms

TABLE 2b										
95	•3	85 - 105	(.38)							
147.5	•24	135 - 160	(.28)							
250	• 2	220 - 285	(.25)							

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Fig. 7 Calculated Zenith Attenuation Due to Oxygen, Water Vapor and Their Sum.

Figure 8 summarizes the presently available calculated and measured total zenith attenuation values and the text explains some of their limitations. The continuous curve is the same calculated one shown in figure 7 (from sea level up to 8 km). Hogg presents the calculated values of total zenith attenuation through the atmosphere (0 to 20 km) from 14 to 40 kmcs. Hogg's curve shown dotted, used a different atmospheric model (described in section 2) and the VVW equation with parameters adjusted to fit the curve for transmission to zenith. Theissing and Caplan [16] give the attenuation values for zenith angle of 45° under the different water vapor conditions (dry, medium, and humid). This data is converted to zenith attenuation using the secant relation (equation (1)) and shown dotted in the figure. They used actual temperature, pressure and water vapor measured values. The source for the experiment was the sun and the detector was sensitive to an extended spectral range covering the sun's spectrum. The calculations were based on the integration of VVW equation over this spectrum, along with the observed parameters. The other available experimental data are also shown in figure 8 with the letters indicating the names of the authors after Rosenblum [17]. It can be seen that the general agreement in the location of windows and the order of attenuation magnitudes (other than at resonances) are comparable.

11. Zenith Attenuation from 1 to 20 Microns

It has been found from quantum mechanical analysis that the far infrared and millimeter wave absorptions are associated with purely rotational states of molecules. The molecular bands in the infrared over the spectral region 1-20 microns arise from vibrational states of the atoms within a gas molecule. A molecule in a given energy state can absorb those wavelengths of radiation which correspond to the allowed quantum transitions to some other energy states. The absorption corresponding to one set of initial and final rotational energy states gives rise to a spectral line, and the entire ensemble of rotational lines associated with the transitions between two vibrational energy states is called a vibration-rotation band. The width of the spectral lines depend on the temperature and pressure in a complex way.

The infrared absorbers are water vapor, CO_2 , O_3 , N_2O , CH_4 , and CO. Near the ground the principal absorbers are H_2O and CO_2 . Ozone is not distributed uniformly



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through the atmosphere, but is mostly concentrated between 10 and 40 km above the earth's surface, with significant peak at about 20-30 km. Ozone shows a large variation with latitude season and weather conditions. The minor constituents CH_4 , N_2O and CO, like CO_2 are found to be uniformly distributed throughout the atmosphere (as shown in Table 1, section 3). Water vapor is the most variable in its concentration in the atmosphere, because the humidity of air fluctuates widely with geography, seasons and the time of day, most of it being near to the ground level.

As a major aid in the calculation of infrared transmission Altshuler [1] has published a detailed procedure for the determination of the infrared line of sight (geometry with respect to earth) and for the evaluation of amount of gases, vapors and haze in the radiation line of sight. Gases and water vapor absorb infrared in regions of their vibration-rotation bands. Temperature and pressure will effect the width of the spectral lines which will then alter the degree of absorption of infrared by the gas. Hence, relative to its infrared absorption, the amount of gas in the line of sight can be equated to another amount under sea level conditions (288 °K temperature and 760 mm · Hg pressure). This sca level amount is termed the "equivalent amount of gas in the line of sight, corrected to sea level conditions".

Thus d denotes the equivalent path length of dry air in the infrared path, corrected to sea level conditions, in km. This is used as an index to specify amounts of CO_2 , N_2O_2 , CH_4 , CO and haze, which have approximately constant mixing ratios with air, from 0 to 50 km altitude. w represents the equivalent precipitable cm of water vapor and z equivalent atmospheric cms of ozone, in the line of sight corrected to sea level conditions. Small lettered subscripts v and h refer to vertical and horizontal paths as used to describe w and w_h. In the present case, as we are mainly interested in the zenith attenuation alone, the line of sight is essentially vertical and d_v, w_v and z_v become d, w and z, respectively. Altshuler gives these equivalent sea level path lengths versus altitude to be used as an index to determine appropriate transmission from the transmission-frequency data.

Figure 9 makes use of the suggested Altshuler's procedure, as outlined above, to obtain zenith attenuation at Climax (3.44 km), Colorado. The attenuation due to water vapor, CO_2 , N_2O , O_3 and scattering are considered as the transmission data for these









constituents only are available. The absorption bands for CH_4 and CO are so weak in comparison with other absorbers that they are not considered to affect the atmospheric transmission sufficiently. Figure 9 thus shows the zenith attenuation for H_2O , CO_2 , N_2O and O, over a wavelength 0 to 20 microns. It can be seen that so far as water vapor is concerned the major windows are in the 8-14 μ , 3.7 to 4.5 μ regions and some narrow ones below 3 microns. There is limited transparency from 14 to 25μ , and from 25 to approximately 1000 μ , the earth's atmosphere is made almost opaque by the pure rotational spectrum of water vapor. CO, is the next major absorber with absorption bands around 15 μ , 4.3 μ and 2.8 μ , contributing fairly large amounts of attenuation. O₃ and NO also have few absorption bands but they contribute a minor loss of order of a db at the peaks. Also CH_4 and CO do have strong absorption bands in the lower 1-6 μ spectral region as evidenced from the infrared solar spectrum. But here it is assumed they do not contribute much to the total attenuation. Scattering varies a little from 1 to 4μ and later remains constant about 0.1 db up to 20 μ . From extinction measurements the common radii for haze are between 0.3 to 0.4 μ and the empirical Rayleigh scattering varies as lower power of λ (order 0 to 1) and hence contributes very little to the attenuation.

According to Altshuler's report the water vapor absorption blocks more or less completely any observation in the wavelength region between 180 to 50 micron (as shown in figure 6). Because of the lack of sensitive detectors for this wavelength region, very few experimental results [18, 19] are available. Figures 10 and 11 show some of this experimental data obtained by Yaroslavsky and Stanevich [18], Gebbie [19] and from these, one may be able to find some more useful observation windows in the sub-mm and far infrared region. Figure 10 gives the optical density (relative transmission) of atmospheric air, in the laboratory, for a layer of thickness 10 meters at a temperature of 20 °C, pressure of 760 mm Hg and absolute humidity 10.5 gm/m³. In Figure 11, the observations were made with a two-beam interferometer of 30 cm aperture and a Golay-type thermal detector. Spectra were obtained from the interferograms by digital computation.

There are some complete review articles [20, 21] on the transmission of the atmosphere in the infrared and a few high resolution spectral [22] measurements. The spectral data usually show the positions and relative intensities of the molecular absorption bands in the atmosphere, whereas figure 9 gives the absolute attenuation values due





FIG. 11. Submillimeter spectrum of solar radiation showing regions of atmospheric transmission and absorption. The calculated positions and intensities of pure rotation lines of H₂O are The numbers in parentheses are calculated half-widths for selected lines. [19] given. 1

to various components and their sum, which provides a better means to compare the losses in the various frequency regions.

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12. Appendix: Van Vleck-Weisskopf Theory

The theory of pressure broadening was first proposed by Lorenz [23]. Lorenz treated resonant absorption, while Debye [24] treated nonresonant absorption. It was anticipated that Debye's theory would turn out to be a special case of Lorenz theory. However, this supposition was not the and the need for further clarification arose. A single integrated absorption theory was put forward by Van Vleck and Weisskopf [14] by combining both the above theories with modified assumptions. For a single absorption line due to any gaseous constituent, the attenuation α , at an angular frequency ω associated with pressure broadening is given by VVW equation

(9)
$$\alpha = \frac{2\pi \mathrm{Ne}^2}{\mathrm{mc}} \left(\frac{\omega}{\omega_{\mathrm{c}}}\right)^2 \left[\frac{1/\tau}{(\omega-\omega_{\mathrm{o}})^2 + (1/\tau)^2} + \frac{1/\tau}{(\omega+\omega_{\mathrm{o}}) + (1/\tau)^2}\right].$$

Here e and m are the charge and mass of an electron, c is the velocity of electromagnetic wave, ω_0 is the angular frequency of the center line, N is the number of molecules per cubic cm and τ is the mean interval between collisions. The term $(1/\tau)$ may be replaced by $\Delta \omega$, the half width of the line at its half power point.

The contributions to the absorption from the various lines may be obtained by adding their individual attenuations. The number of molecules per cubic cm and the line width can be seen approximately proportional to pressure. The line breadth parameter $\Delta \nu = \frac{\Delta \omega}{2 \pi}$ was left as an undetermined factor in this equation. This is best found by actual atmospheric measurements. The more recent work on collision broadening has been directed toward deriving more explicit expressions for $\Delta \nu$. The intensity distribution in a pressure broadened line is represented by Fourier expression, to obtain a formula for the line breadth and the line shift of a spectral line [25]. Van Vleck subsequently modified the VVW equation for the microwave absorption of oxygen and water vapor by adding another term to equation (9) to account for the residual effect of neighboring lines besides the main absorption maximum.

According to Van Vleck [11] the oxygen absorption in the range 0.7 to 10 cms is proportional to the square of the pressure and at shorter wavelengths the absorption is independent of pressure. The attenuation increases gradually with the decrease in temperature. At -40 °C the attenuation is about 78 percent higher than at 20 °C. Schulze and Tolbert [26] have studied the details of the shape, intensity and pressure broadening of 2.53 mm oxygen absorption line wing in detail. There is discrepancy between these measurements and VVW theory, probably due to an inappropriate choice of line shape factor to describe the losses in the wings of absorption lines.

Van Vleck's quantum mechanical calculation for water vapor [27] in the 0.07 to 10 cms range shows that the combined residual attenuation due to neighboring lines around 1.35 cm is inversely proportional to pressure. The attenuation is directly proportional to pressure at other wavelengths. Attenuation increases slowly with decreasing temperature and is 20 to 45 percent greater at -40 °C that at 20 °C. The measured attenuation due to residual effect is found to be four times larger than predicted value. Tolbert, et al [13] made atmospheric measurements in the 100-140 kmcs range. They also found that the actual atmospheric values are four times larger than theoretically anticipated. This discrepancy can either be due to the assumption of Lorenz model of infinitely sharp collisions, or inappropriate line width factors.

VVW theory assumes the period of oscillation of incident energy to be much longer than the mean duration of a molecular collision. This is true for microwaves but becomes worse as the incident radiation frequency increases. Molecular collision broadening is considered for the prediction of effects of pressure and temperature on line broadening. Thus the VVW theory and the modifications have been able to account quite well for the observed maxima of oxygen and water vapor. However, the values of the actual atmospheric attenuation in the wings of the lines do not agree with theoretical values due to the complexities in the pressure broadening effects.

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