A Comparison of Experimental and Theoretical Values of Atmospheric Absorption at the Longer Millimeter Wavelengths

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Abstract—**The main objective of this paper is to compare experimentally determined values of atmospheric absorption at the longer millimeter wavelengths with theoretical absorptions. The difficulties that arise in attempting to obtain accurate theoretical and experimental results are discussed. The experimental absorptions were obtained from a set of low angle slant path measurements at 15 and 35 GHz using the sun as a source. The surface absorption coefficient, zenith absorption and effective height of the absorbing atmosphere were derived from these data. Regressions of both surface absorption coefficient and zenith absorption were performed as a function of surface absolute humidity; the results were compared with theoretical values obtained by several investigators. Zenith absorptions were found to be in good agreement with theory; however, experimental surface absorption coefficients were consistently lower than calculated values.**

I. Introduction

THE PRINCIPAL ATMOSPHERIC gases which absorb electromagnetic energy in the millimeter-wave region of the spectrum are oxygen and water vapor. This absorption is difficult to calculate in the window regions because the total absorption is the summation of contributions from the wings of hundreds of absorption lines throughout the spectrum, and the shapes of these lines are not precisely known. It is also difficult to measure the absorption in the window regions because it is relatively low (only about 0.1 dB/km at the longer millimeter wavelengths).

Since the absorption is a function of temperature, pressure and humidity, it is necessary that these meteorological parameters be known along the propagation path if the results are to be compared with theory. The dilemma that arises is that although a more controlled experiment can be conducted over a short path, the net absorption is very low; higher absorptions are present for longer terrestrial paths, but meteorological data are more difficult to obtain. In addition, multipath effects and earth curvature limit the length of the path. This limitation may be overcome by using a slant path; but since it is not practical to collect meteorological data along the total path, only surface values are used. The surface absorption coefficient is calculated directly from these values. In order to calculate the zenith absorption, vertical temperature, pressure and humidity profiles must be estimated; profiles similar to the U.S. Standard Atmosphere are often used. Fortunately, past results indicate that the zenith absorption is correlated with the surface parameters.

In this paper, results of atmospheric absorption measurements made over very long slant paths at frequencies of 15 and 35 GHz are reported. The absorption was determined from a set of measurements using the sun as a source. Fifty-eight sets of data were collected at sunrise and sunset during clear sky conditions for a set of elevation angles from near the horizon to 20°. For a normal clear atmosphere (free of inversions) the absorption is directly proportional to the length of the propagation path through the absorbing medium. A linear regression of absorption as a function of distance is performed and the surface absorption coefficient and zenith absorption are determined and then compared with theoretical values.

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II. Theoretical Considerations

Atmospheric gases absorb energy from electromagnetic waves if the molecular structure of the gas is such that the individual molecules possess electric or magnetic dipole moments. It is known from quantum theory that at specific wavelengths, energy from the wave is transferred to the molecule, causing it to rise to a higher energy level; if the gas is in thermodynamic equilibrium it will then reradiate this energy isotropically as a random process, thus falling back to its prior energy state. Because the incident wave has a preferred direction and the emitted energy is isotropic, the net result is a loss of energy from the wave. The only atmospheric gases with strong absorption lines at millimeter wavelengths are water vapor and oxygen. The absorption lines of O_3, CO, N_2O, NO_2 and CH_2O are much too weak to affect propagation in the window regions.

The oxygen molecule has a magnetic dipole moment with a cluster of resonances near a wavelength of 5 mm (60 GHz) and a single resonance at 2.53 mm (118.75 GHz). Although the more than 30 lines near a wavelength of 5 mm are resolvable at low pressures (high altitudes), they appear as a single pressure-broadened line near sea level, owing to a large number of molecular collisions. Even though the magnetic dipole moment of oxygen is approximately two orders of magnitude weaker than the electric dipole moment of water vapor, the net absorption due to oxygen is still very high, simply because it is so abundant. The fact that the distribution of oxygen throughout the atmosphere is very stable makes it very easy to model. A plot of the approximate oxygen absorption as a function of frequency is shown in Fig. 1.

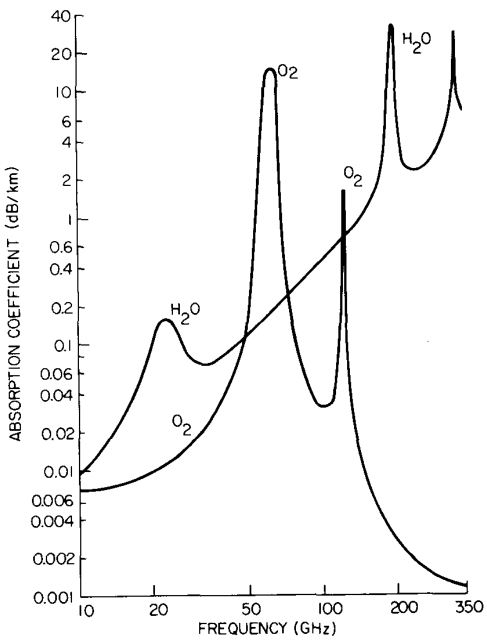

Fig. 1. Absorption coefficients of oxygen and water vapor.

The water vapor molecule has an electric dipole moment with resonances at wavelengths of 13.49, 1.64, and 0.92 mm (22.24, 183.31, and 325.5 GHz) in the millimeter-wave region. In general, the positions of these resonances, their intensities, and their linewidths agree well with experimental data. There are, however, serious discrepancies between theoretical and experimental absorption coefficients in the window regions between these strong lines; experimental attenuations are often a factor of two to three times larger than theoretical values. Although the cause of the discrepancy is not known, indications are that either the line shapes do not predict enough absorption in the wings of the resonance or there is an additional source of absorption that has not yet been identified. It should be mentioned that there are over 1800 water vapor lines in the millimeter wave/infrared spectrum, 28 of which are at wavelengths above 0.3 mm. Because the wings of these lines contribute to the absorption in the window regions, very small errors in the line shapes can significantly affect the overall absorption. In addition to the uncertainty of the absorption coefficient of water vapor, there is also the problem of water vapor concentration. The amount of water vapor in the lower atmosphere is highly variable and has surface densities ranging from a fraction of a gram per cubic meter for very arid climates to more than 30 g/m^3 for hot and humid regions; for this reason it is very difficult to model. A plot of the approximate water vapor absorption as a function of frequency along with that of oxygen is shown in Fig. 1 for a density of 7.5 g/m^3. Because the absorption is assumed to be linearly proportional to the water vapor density, except for very high concentrations, absorptions for other water vapor densities may be calculated.

It is assumed that for clear sky conditions the slant path absorption is proportional to the distance through the absorbing atmosphere. For high elevation angles a flat earth approximation may be used and the distance through the absorbing layer is proportional to the cosecant of the elevation angle. For low elevation angles the following formula, based on a curved earth, has been derived using the law of cosines [1].

$$D(\theta)=[(a_e+h_e)^2-a_e^2\cos^2\theta]^{1/2}-a_e\sin\theta \tag{1}$$

where

- θ elevation angle
- $D(\theta)$ distance through the absorbing layer
- a_e effective earth radius
- h_e effective height of the absorbing layer.

The elevation angle θ, is recorded at the time of each measurement. The effective earth radius a_e is a function of the refractivity profile. Since this profile cannot be readily obtained in practice, the effective earth radius is estimated from the surface refractivity. The effective earth radius factor k is

$$k=\frac{1}{1+\frac{a}{n}\frac{dn}{dh}\cos\theta} \tag{2}$$

where

- a earth radius
- n index of refraction
- dn/dh gradient of index of refraction with height.

For θ close to the horizon and $n \doteq 1$

$$\frac{dn}{dh}=\frac{1-k}{ak}. \tag{3}$$

Based on a large sample of refractivity data, it has been shown [2]

$$-\Delta N=7.32e^{.005577N_s} \tag{4}$$

where the surface refractivity $N_s=(n-1)\cdot 10^6$ and ΔN = refractivity gradient

$$\frac{dn}{dh}\approx\frac{\Delta n}{\Delta h}=\frac{\Delta N\times 10^{-6}}{\Delta h}$$

$$k=\frac{1}{1-0.04665e^{.005577N_s}}. \tag{5}$$

The effective earth radius is

$$a_e=ka. \tag{6}$$

The effective height of the absorbing atmosphere h_e is defined as follows. If all of the oxygen and water vapor in the atmosphere were compressed into a uniform layer having a weighted density equal to that of the oxygen and water vapor at the earth's surface, then the height of that layer is designated as the effective height of the absorbing medium. Since h_e is a function of the vertical distributions of oxygen and water vapor and since these are not known, a method for estimating h_e must be devised. We have assumed that the absorption $A(\theta)$ is proportional to the distance through the lower atmosphere $D(\theta)$.

$$A(\theta) = \alpha_0 + \alpha_1 D(\theta) \tag{7}$$

where α_0 and α_1 are the regression line coefficients. But as the distance $D(\theta)$ approaches zero, the absorption $A(\theta)$ also approaches zero; therefore α_0 should approach zero.

Thus for $\alpha_0 = 0$ we would like to determine a value for α_1 which produces a best fit for the regression line. Since the set of $D(\theta)$ values is a function of h_e, we select a value of h_e which produces a set of distances that result in a minimum standard error of estimate S_e. To obtain an expression for S_e we define the following statistical parameters.

$$\bar{D} = \frac{\sum_{i=1}^{N} D(\theta_i)}{N} \tag{8}$$

$$\bar{A} = \frac{\sum_{i=1}^{N} A(\theta_i)}{N} \tag{9}$$

$$\hat{A}(\theta_i) = \alpha_1 D(\theta_i) \tag{10}$$

$$S_e = \sqrt{\frac{1}{N-2} \sum_{i=1}^{N} [A(\theta_i) - \hat{A}(\theta_i)]^2}\,. \tag{11}$$

(Note that N is the sample size, not to be confused with the refractivity.)

The value of h_e which minimizes S_e is selected as the effective height of the absorbing layer.

III. Measurement Program

A brief description of the experimental system and the measurement procedure that was used to obtain the absorption data is described in this paper; more details have been provided in a previous paper [3]. All measurements were made at Prospect Hill, Waltham, MA, during sunrise and sunset at elevation angles from 1.0°, in increments of 0.5°, up to 10°, and then in increments of 1° up to 20°. An 8.8 m paraboloidal antenna having beamwidths of approximately 4 and 9 arcmin at 35 and 15 GHz, respectively, was used. Conventional Dicke-switched radiometers with state-of-the-art components were used.

The antenna beam was positioned ahead of the sun and the intensity of the received signal (antenna temperature) was observed as the sun drifted through the beam. The apparent sky temperature, due to atmospheric emission was compensated for by moving the antenna off the sun at each elevation angle to obtain a background reading which was subtracted out. In addition, calibrated noise diodes were turned on at each elevation angle to compensate for radiometer gain changes. The data were thus derived from a series of repeated drift measurements. With this system attenuations of up to approximately 25 dB could be measured. Errors were estimated to be about 0.1 dB for low attenuations but approached 2 dB for attenuations above 20 dB. Since data were collected during a sunspot minimum, solar activity was minimal. The measurement time for each set of data was only about two hours so errors due to solar instability were insignificant. All data were recorded on magnetic tape. The surface temperature, pressure and dew point temperature were recorded at the start and completion of each set of data and then averaged. For the period during which absorption data were collected, 58 sets of data were designated as "clear sky." This meant that the sun could be clearly viewed during the course of the measurements.

IV. Analysis of Data

The surface absolute humidity and surface refractivity were computed from the surface temperature, dew point and pressure. The effective earth radius was then computed from the surface refractivity using (5) and (6). A linear regression of absorption versus distance through the absorbing layer was conducted for a set of effective heights of the absorbing atmosphere ranging from 0.1 to 8 km in 0.1 km intervals. For each set of data the standard error was calculated and plotted as a function of effective height; the effective height which produced the minimum standard error was selected as the effective height of the absorbing atmosphere. With a_e and h_e determined, $A(\theta)$ was then plotted as a function of $D(\theta)$. With (7) a regression line with slope α_1 was computed. The corresponding set of zenith absorptions was computed by multiplying the absorption coefficients by the effective heights.

A. 35 GHz Data

Using the procedure described above an effective earth radius was computed from each surface refractivity. The corresponding k-factors ranged from 1.30 to 1.48, not too different from the often used $k = 4/3$ factor. With the effective earth radius specified, an optimum effective height was determined for each set of data. Plots of the dependence of the standard error of estimate of the regression line on the effective height are shown in Fig. 2 for low, average and high humidity days. It is seen that the standard error, although not too sensitive a function of the effective height, has a minimum value for each set of effective heights.

With the optimum effective heights specified, a linear regression is then performed for each set of data. Typical regression lines for low, average and high humidity days are shown in Fig. 3. It is seen that the correlation coefficients are very high indicating that the absorption is indeed proportional to the distance through an absorbing layer. The slope of the regression line α_1 is the surface absorption coefficient in dB/km. Since the absorbing layer is assumed to consist of a uniform distribution of oxygen and water vapor, the zenith absorption is simply the product of the surface absorption coefficient times the effective height.

The main objective of this experiment was to attempt to establish the dependence of the surface absorption coefficient α_1 and the zenith absorption A_z on surface meterological parameters for clear sky conditions. We have 58 sets of

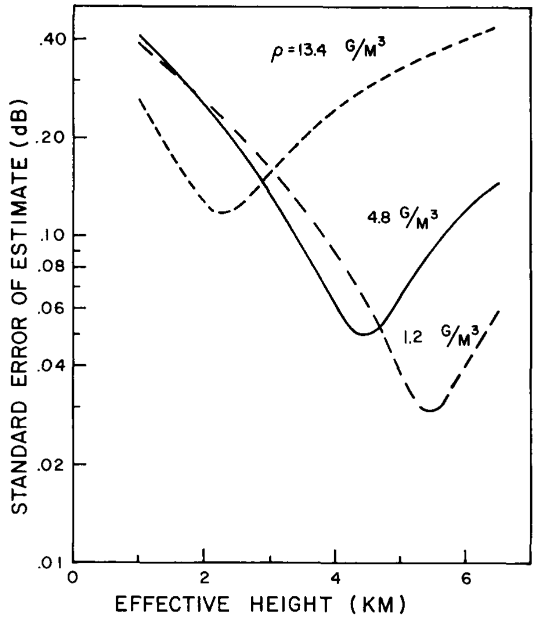

Fig. 2. Optimum effective heights for dry, average and humid days.

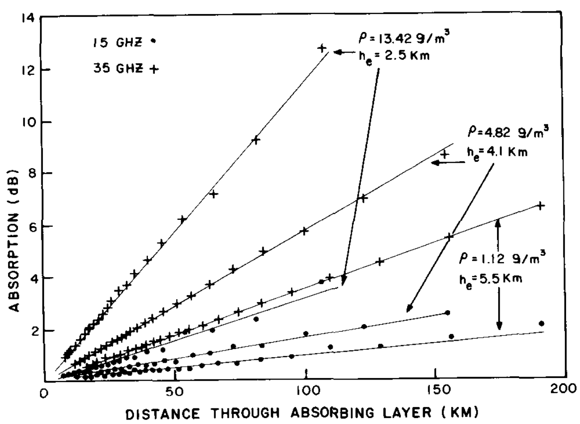

Fig. 3. Atmospheric absorption as a function of distance through an absorbing layer.

surface absorption coefficients, zenith absorptions, surface humidities and temperatures. A multiple linear regression of zenith absorption A_z versus surface absolute humidity ρ and temperature t was performed. The resulting regression line is

$$A_z(\rho, t) = 0.271 + 0.0114\rho - 3.554 \times 10^{-4} t$$

where A_z is in dB, ρ is in g/m^3 and t is in Kelvin units.

The corresponding correlation coefficients are

$$r(A_z; \rho) = 0.8346$$

$$r(A_z; t) = 0.5197$$

$$r(A_z; \rho, t) = 0.8365.$$

It is seen that $r(A_z, \rho)$ is significantly larger than $r(A_z; t)$. Also, the range of temperatures for clear sky conditions was about 30 K; since this corresponds to an absorption range of

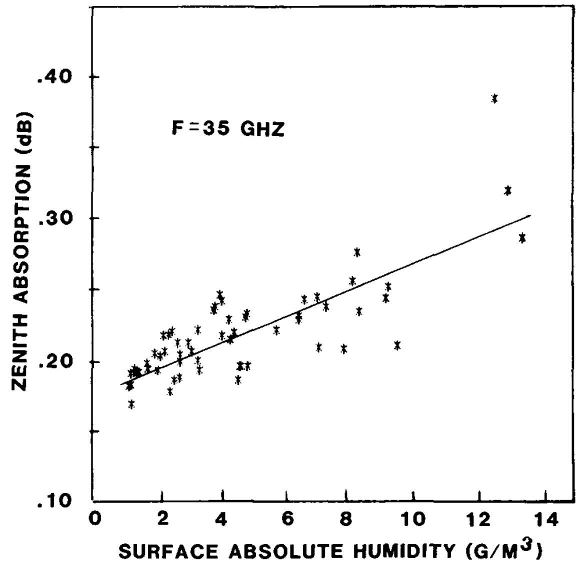

Fig. 4. Zenith absorption versus surface absolute humidity, F = 35 GHz.

only about 0.01 dB it was concluded that the surface temperature is not a significant parameter for this study. The regression analysis was repeated again for ρ only and $A_z(\rho) = 0.177 + 0.0093\rho$ with a standard error of estimate $S_e(A; \rho) = 9.46 \times 10^{-4}$. A plot of $A_z(\rho)$ versus ρ is shown in Fig. 4. A correlation coefficient of 0.794 indicates that there is indeed a linear dependence of absorption on surface absolute humidity.

A linear regression of the surface absorption coefficient α_1 as a function of surface absolute humidity was also conducted for the same 58 sets of data. This analysis led to the following result.

$$\alpha_1(\rho) = 0.018 + 0.0068\rho$$

$$S_e(\alpha_1; \rho) = 5.13 \times 10^{-4}$$

$$r(\alpha_1, \rho) = 0.872.$$

We note that the correlation coefficient and standard error are comparable to those obtained for zenith absorption. A plot of $\alpha_1(\rho)$ versus ρ is shown in Fig. 5.

There are several reasons why the correlation of absorption with surface absolute humidity is perhaps not higher. We have made the assumption that the surface humidity is representative of the vertical humidity profile. The total precipitable water which is a measure of all of the water vapor along a vertical path through the atmosphere is a more meaningful indicator of humidity than the surface value alone. The correlation of total precipitable water with surface absolute humidity has been studied by several investigators and unfortunately their conclusions are not in agreement. Reber and Swope [4] report correlation coefficients of only about 0.5 based on annual statistics for several regions near Los Angeles. Monthly correlation in some cases dropped below zero. Bolsenga [5] on the other hand reported correlation coefficients of about 0.80 and Reitan [6] has reported correlation coefficients as high at 0.99. Thus there is sufficient

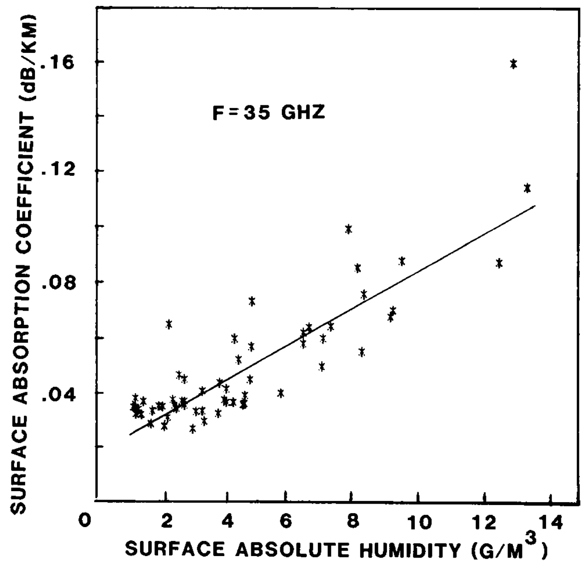

Fig. 5. Surface absorption coefficient versus surface absolute humidity, F = 35 GHz.

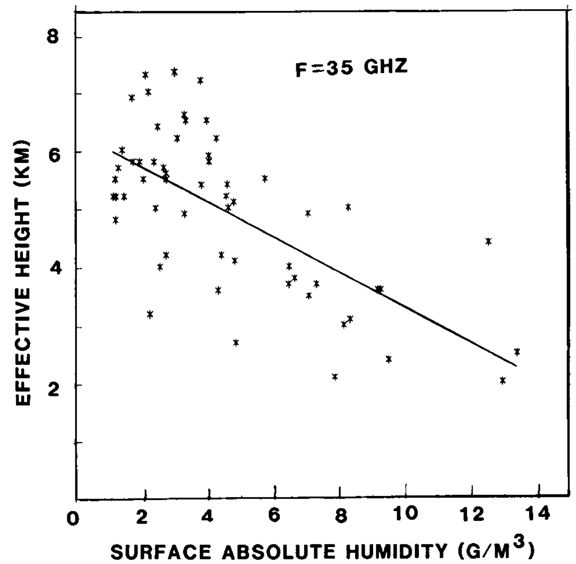

Fig. 6. Effective height versus surface absolute humidity, F = 35 GHz.

uncertainty to conclude that the surface absolute humidity is only a fair indicator of the water vapor aloft. Unfortunately it is very difficult to measure the total precipitable water; surface absolute humidity is the best alternate parameter.

However, even if it were possible to obtain an accurate humidity profile at the location of the radiometer, it would still be necessary to assume that the atmosphere is horizontally stratified in order to infer the humidity over 100 km down range for very low elevation angles. Thus it is not possible from a practical standpoint to determine the humidity along a slant path. Fortunately, the surface absolute humidity is an unbiased estimator of the humidity aloft so the resulting regression should be a good indicator of the approximately linear relationship of absorption as a function of humidity.

Since the effective height of the absorbing layer is a function of the vertical distributions of oxygen and water vapor and since the water vapor is related to the surface absolute humidity, then the effective height should also be a function of the surface absolute humidity. A regression of effective height as a function of the surface absolute humidity was performed, and the results are shown in Fig. 6. For a linear regression the correlation coefficient was 0.668. Only a very slight increase in the correlation resulted when a higher degree polynomial regression was tried. The regression line is

$$h_e = 6.35 - 0.302\rho.$$

The standard errors for the intercept and slope are 0.23 and 0.043, respectively. It is seen that there is only a fair correlation of the effective height with surface absolute humidity. This is not too suprising considering once again the variability of the humidity aloft.

The behavior of the surface absorption coefficient with the effective height was also examined. A plot of these parameters is shown in Fig. 7. Polynomial regressions for absorption as a function of height were performed, and it was found that a second degree polynomial provided a rather good fit ($r = -0.916$). This result indicates that high absorptions are typically associated with low effective heights; this is consistent with that which would have been expected since a high absorption is produced by a high water vapor density which in turn lowers the effective height of the combined densities of oxygen and water vapor.

B. 15 GHz Data

The 15 GHz absorption data were not as consistent as those measured at 35 GHz. This was due primarily to the fact that the 15 GHz radiometer was noisier than the 35 GHz radiometer. In addition, the absorption at 15 GHz was significantly lower than that at 35 GHz which resulted in a larger percent error. Whereas the 35 GHz absorption decreased monotonically with increasing elevation angle, this was not typically the behavior of the 15 GHz data, particularly at the higher elevation angles for which the absorptions were only a fraction of a dB. Thus it was not possible to use the same procedure as was used with the 35 GHz data for obtaining an optimum effective height for the equivalent absorbing layer.

The effective height of the absorbing layer is a weighted average of the individual oxygen and water vapor absorptions. Since the percent contribution to the absorption is approximately the same for these gases at both 15 and 35 GHz, particularly for surface absolute humidities below about 15g/m^3, the effective heights which were derived from the 35 GHz data were also used for 15 GHz.

As before, the measured absorptions were plotted as a function of distance through the equivalent absorbing layer. Typical plots of $A(\theta)$ versus $D(\theta)$ for the same low, average and high humidity days as for 35 GHz are also plotted in Fig. 3. Note the irregular behavior of the data for distances corresponding to the higher elevation angles.

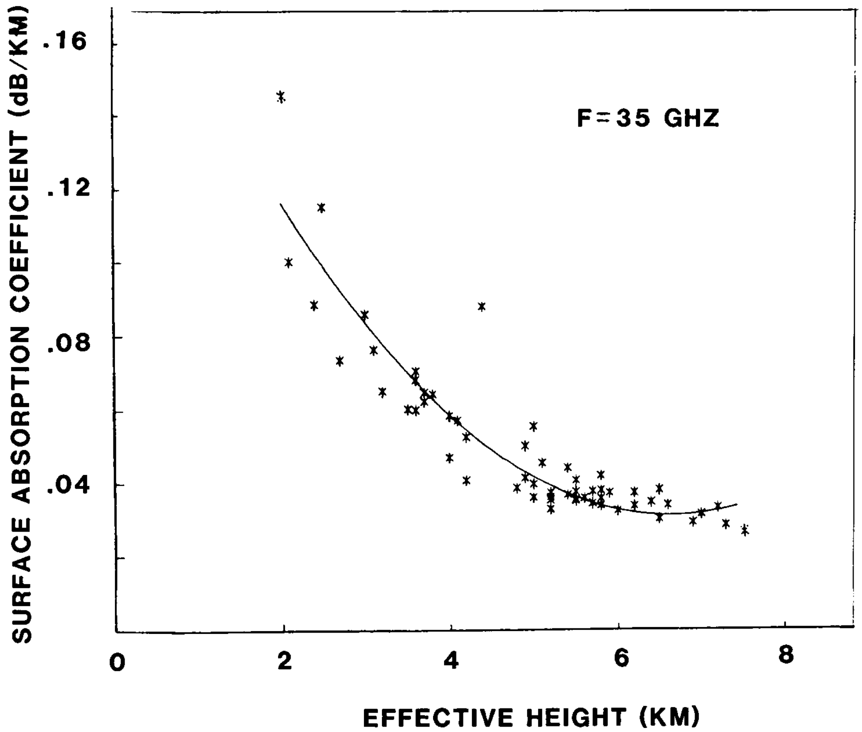

Fig. 7. Surface absorption coefficient versus effective height, F = 35 GHz.

Zenith absorptions for 15 GHz were calculated for the same 58 days as was done for the 35 GHz absorptions, and a regression of zenith absorption as a function of surface absolute humidity was performed. The result is

$$A_z(\rho)=0.048+0.0035\rho$$

$$S_e(A_z;\ \rho)=4.51\times 10^{-4}$$

and

$$r(A_z,\ \rho)=0.717.$$

As would be expected the correlation coefficients for the 15 GHz data are poorer than those for the 35 GHz data. A plot of $A_z(\rho)$ versus ρ is shown in Fig. 8.

A regression of the surface absorption coefficient vs surface absolute humidity was done for the same 58 sets of data, and the resulting equation was obtained.

$$\alpha(\rho)=0.0042+0.0023\rho$$

$$S_e(\alpha_1;\ \rho)=2.45\times 10^{-4}$$

and

$$r(\alpha_1,\ \rho)=0.780.$$

A plot of $\alpha_1(\rho)$ versus ρ is shown in Fig. 9.

V. Comparison of Experiment with Theory

Theoretical absorption results have been obtained from four sources; Liebe [7], Clough *et al.* [8], Gibbins [9], and CCIR

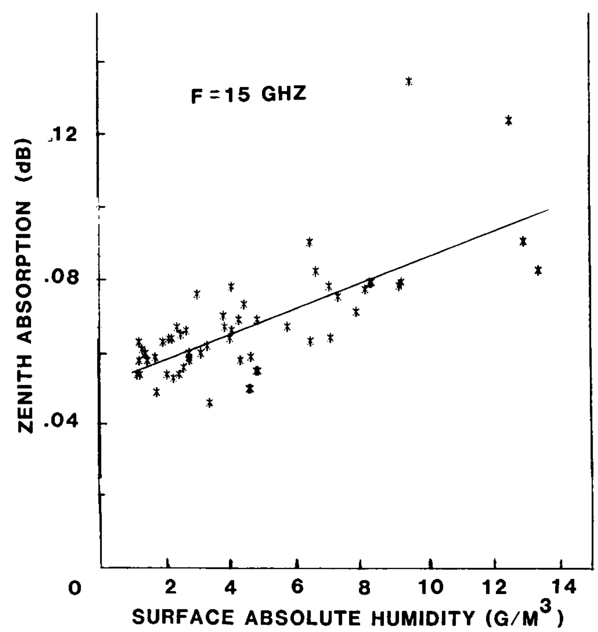

Fig. 8. Zenith absorption versus surface absolute humidity, F = 15 GHz.

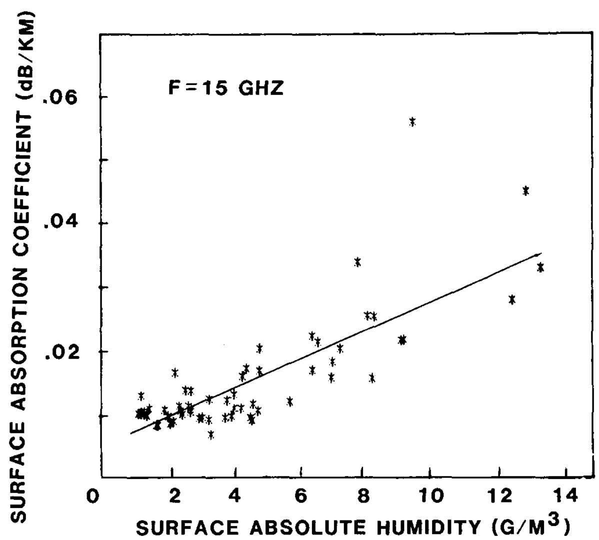

Fig. 9. Surface absorption coefficient versus surface absolute humidity, F = 35 GHz.

TABLE I
REGRESSION COEFFICIENTS FOR ABSORPTION VERSUS SURFACE ABSOLUTE HUMIDITY

	Absorption Coefficient (dB/KM) $\alpha_1 = \alpha_{10} + \alpha_{11}\rho + \alpha_{12}\rho^2$					Zenith Absorption (dB) $A_z = A_{z0} + A_{z1}\rho + A_{z2}\rho^2\rho$ in g/m^3				
					F = 15 GHz					
	Experiment	Liebe	Gibbins	Clough	CCIR		Experiment	Liebe	Clough	CCIR
α_{10}	0.0045	0.0094	0.0083	0.0082	0.0083	A_{z0}	0.0477	0.0470	0.0400	0.0499
α_{11}	0.0027	0.0020	0.0025	0.0024	0.0026	A_{z1}	0.0035	0.0039	0.0044	0.0059
α_{11}		5.62×10^{-5}	4.72×10^{-5}	1.91×10^{-5}		A_{z2}		6.56×10^{-5}	3.63×10^{-5}	
					F = 35 GHz					
α_{10}	.0182	0.0304	0.0270	0.0279	0.0270	A_{z0}	0.1774	0.1530	0.1522	0.1622
α_{11}	.0068	0.0068	0.0088	0.0091	0.0104	A_{z1}	0.0093	0.0130	0.0171	0.0232
α_{12}		2.99×10^{-4}	2.57×10^{-4}	4.78×10^{-5}		A_{z2}		3.68×10^{-4}	5.56×10^{-5}	

[10]. Liebe and Clough specially calculated absorptions at 15 and 35 GHz for a range of humidities so that we could make a direct comparison. Gibbins and CCIR results were computed from their respective equations. It was found that the zenith absorptions and surface absorption coefficients of Liebe and Clough could be accurately represented by second degree polynomials of the surface absolute humidity. Gibbins' result was expressed as a second degree polynomial of the surface absolute humidity; he did not, however, provide an algorithm for the calculation of zenith absorption. The CCIR expressions for zenith absorption and surface absorption coefficient were expressed as linear functions of surface absolute humidity. In Table I the regression coefficients for the calculated and measured absorptions are summarized. In Figs. 10–13 the regression lines for zenith absorption and surface absorption coefficient are plotted as a function of surface absolute humidity for frequencies of 15 and 35 GHz, respectively.

It is seen that the experimental zenith absorption at 15 GHz agrees very well with calculations by Clough *et al.* and Liebe. The CCIR result is slightly higher for the higher humidities. At 35 GHz the experimental values are in good agreement with those of Liebe and Clough except for the high humidities. The CCIR results are higher, particularly at the higher humidities. The experimental surface absorption coefficients at 15 GHz are lower than four sets of theoretical values; however, the slopes of experimental and theoretical regression lines are about the same. At 35 GHz the experimental absorption coefficients are also lower than the theoretical values particularly for higher humidities.

The experimental and theoretical effective heights are shown in Fig. 14 as a function of surface absolute humidity. The experimental regression line is that of Fig. 6. The theoretical values were calculated for both 15 and 35 GHz and found to be approximately the same. The Clough values were slightly higher than those of CCIR and Liebe. The experimental values were found to be slightly higher than the theoretical values, particularly for the lower humidities.

Finally, in Fig. 15 the calculated and experimental ratios of the 35 GHz to 15 GHz absorptions are compared. There is a distinct difference in the humidity dependence of the ratios.

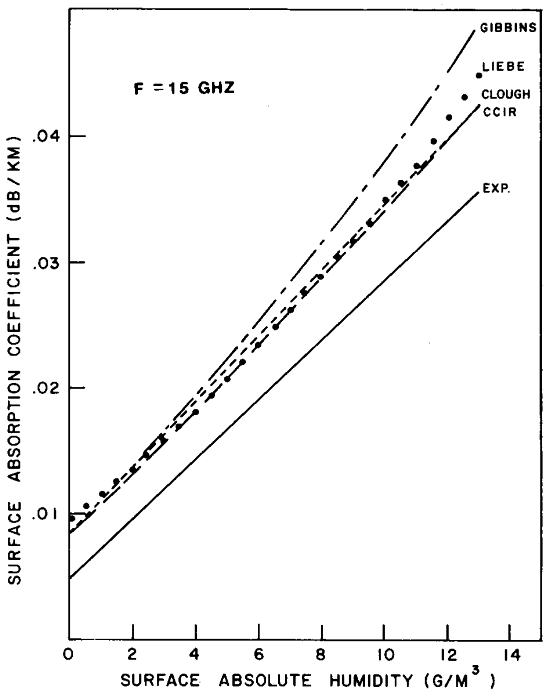

Fig. 10. Calculated and experimental surface absorption coefficients, F = 15 GHz.

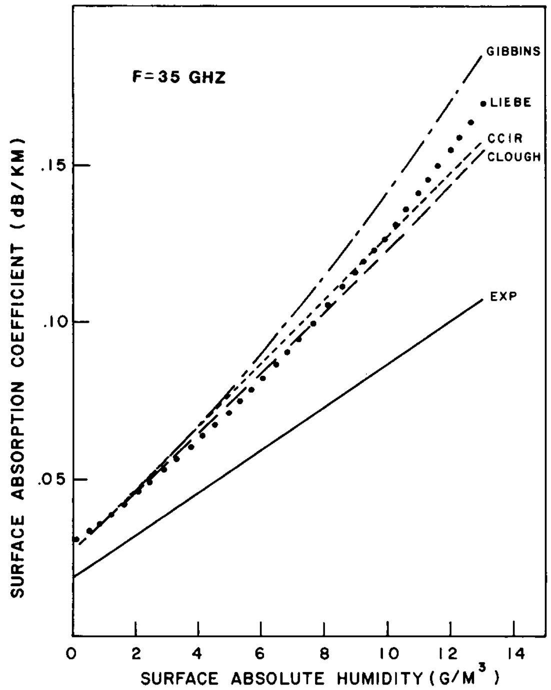

Fig. 12. Calculated and experimental, surface absorption coefficients, F = 35 GHz.

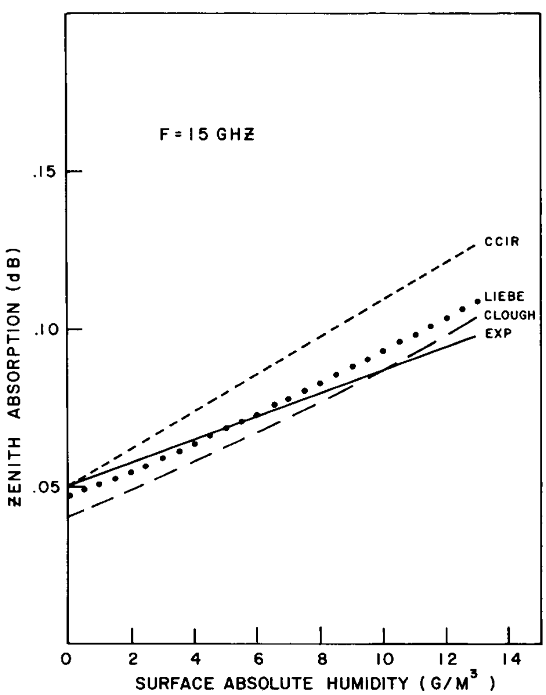

Fig. 11. Calculated and experimental zenith absorptions, F = 15 GHz.

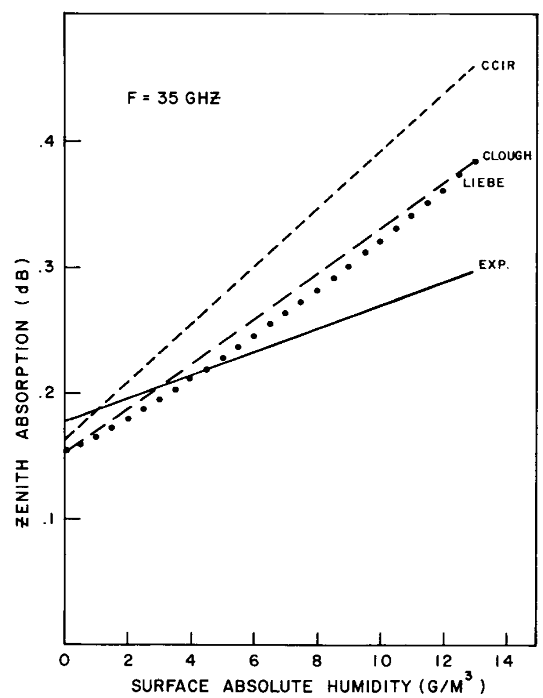

Fig. 13. Calculated and experimental zenith absorptions, F = 35 GHz.

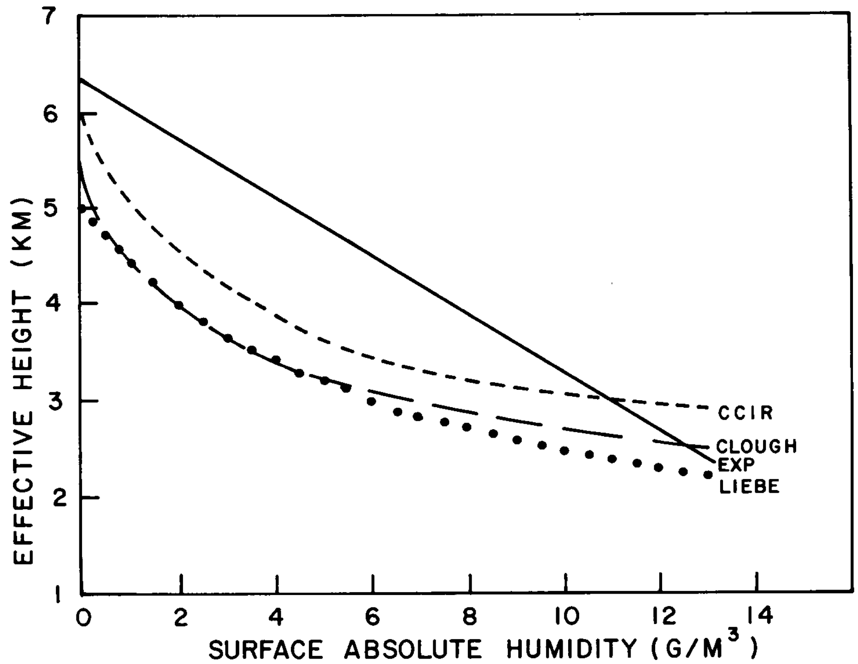

Fig. 14. Calculated and experimental effective heights.

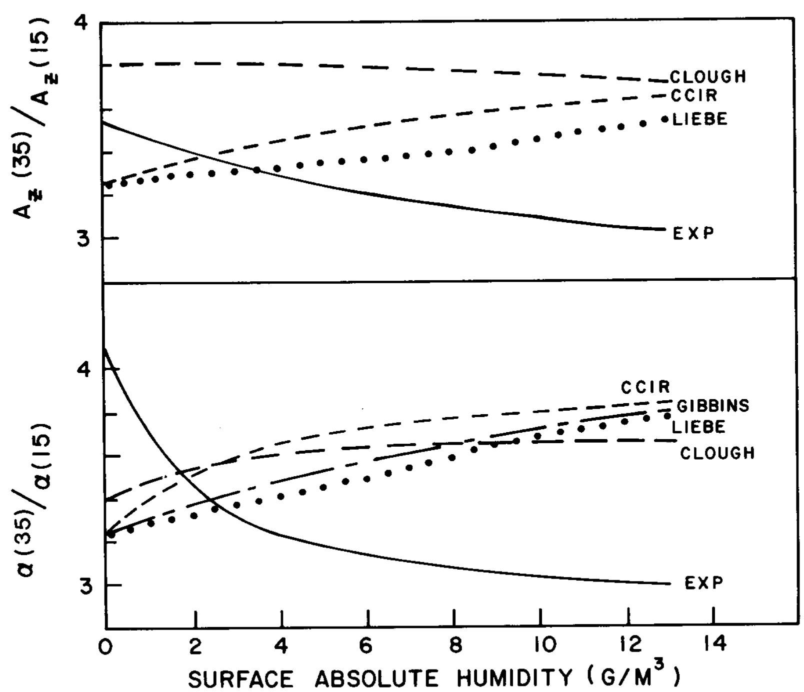

Fig. 15. Calculated and experimental frequency ratios of absorption.

The experimental ratios generally decrease as the surface absolute humidity increases. Only the Clough ratio of zenith absorptions shows a slight decrease with increasing humidity.

VI. Conclusion

An effort has been made to conduct accurate measurements under clear sky conditions of atmospheric absorption at the longer millimeter wavelengths. The absorption was correlated with meteorological data and then compared with the theoretical values. It has been shown experimentally that the absorption is indeed directly proportional to the distance through the absorbing atmosphere. The correlation of absorption with surface absolute humidity has been examined and found to be fair. However, since the water vapor along the propagation path is not expected to be highly correlated with the surface absolute humidity, it is understandable that the correlation of the absorption with the surface absolute humidity would only be moderate. It would appear, however, that the surface absolute humidity should be an unbiased estimator of the water vapor aloft; that is, there is no reason to believe that the surface absolute humidity should consistently underestimate or overestimate the amount of water vapor aloft. Therefore, from a statistical standpoint, the correlation of absorption with surface absolute humidity should be meaningful.

The theoretical zenith absorptions of Liebe [7] and Clough *et al.* [8], are in good agreement at both 15 and 35 GHz; the CCIR [10] results are significantly higher for the higher humidities. The experimental zenith absorptions agree very well with those of Liebe and Clough *et al.* at 15 GHz; at 35 GHz the agreement is poorer for higher humidities.

Calculated surface absorption coefficients as a function of surface absolute humidity show good agreement at both 15 and 35 GHz; Gibbins' [9] values are slightly higher than the others. The experimental surface absorption coefficients are consistently lower than the theoretical values.

The calculated effective heights as a function of surface absolute humidity are in good agreement with one another. The experimental effective heights are somewhat higher than the corresponding calculated values, particularly for the lower humidities. Since the zenith absorption is the product of the surface absorption coefficient and the effective height, the typically lower experimental surface absorption coefficients combine with typically higher effective heights to produce zenith absorptions which are in good agreement with calculated values.

The calculated ratios of the 35 GHz to 15 GHz zenith absorptions of Liebe and CCIR are in good agreement with one another; corresponding values of Clough *et al.* are somewhat higher. The experimental ratios are higher for the lower humidities and lower for the higher humidities. The calculated ratios of the surface absorption coefficients as a function of surface absolute humidity show good agreement. Once again the experimental values are somewhat higher than the calculated values for low humidities and somewhat lower for high humidities. The most significant difference in the humidity dependence of the absorption ratios is that the calculated ratios generally increase with increasing humidity whereas the experimental ratios decrease with increasing humidity.

In conclusion, we feel that the experimental results that have been presented are very important, since to the best of our knowledge they are the only measured absorption data that have been directly compared with calculated values at the longer millimeter wavelengths. In general, the experimental and theoretical zenith absorptions are in good agreement; the experiment surface absorption coefficients on the other hand, are consistently lower than the calculated values. An explanation for this behavior is not available at this time. Further controlled experiments of absorption as a function of meteorological parameters would be valuable.

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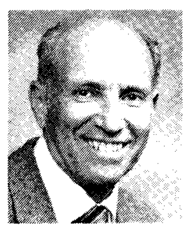

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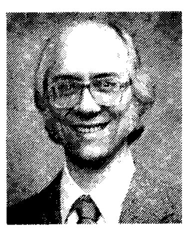

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