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A REVIEW OF RADIOMETRIC MEASUREMENTS OF ATMOSPHERIC ATTENUATION AT WAVELENGTHS FROM 75 CENTIMETERS TO 2 MILLIMETERS

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ABSTRACT

Published values of vertical attenuation resulting from radiometric measurements of absorption and emission of the Earth's atmosphere in the wavelength range from 75 cm (0.4 GHz) to 2 mm (150 GHz) are presented. The literature search included a review of several hundred publications. These data emphasize the need for further theoretical and experimental work in the calculation and measurement of attenuation in this portion of the spectrum.

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SUMMARY

The results of an extensive literature search into the attenuation characteristics of the Earth's atmosphere under clear weather conditions are presented. The frequency range of interest was from 0.4 through 150 GHz.

Plots of the vertical attenuation measured by many researchers versus frequency are presented. Several theoretical curves of zenith attenuation versus frequency are also presented.

It is concluded that there is a need for further theoretical and experimental work in the calculation and measurement of attenuation in this portion of the electromagnetic spectrum.

INTRODUCTION

This paper presents the experimental results of radiometric absorption measurements obtained by previous investigators at wavelengths from 75 cm to 2 mm. In many communication applications, atmospheric absorption is a limiting factor. In other applications, atmospheric absorption can provide a means of obtaining information of scientific interest (ref. 1). The application of the millimeter wave spectrum by passive Earth resource-sensing satellites and the planned exploitation of the millimeter spectrum for future communication systems have directed increased attention to the atmospheric characteristic of absorption. A considerable amount of analytical research and related measurement data, leading to a clear estimation of the mean values of attenuation that one might anticipate, has been reported on the subject. The authors, therefore, considered it important enough to undertake a detailed analytical investigation to compile and present absorption data obtained by radiometric measurements so that they could determine which of those areas of the microwave and millimeter wave spectrum might require further experimentation.

More data are needed to plan space communications and should be collected at existing or prospective locations for future microwave and millimeter wave receiving stations utilizing radiometric techniques. The experimental determinations of absorption through the entire atmosphere have typically utilized radiometric techniques to measure signals received either from thermal sources in the atmosphere or from exo-atmospheric sources, such as the sun, under various conditions of "clear weather".* Using such data to predict attenuation under other meteorological conditions suffers from converting attenuation made under given conditions to some standard conditions for comparison with other data. Moreover, the spectral characteristics of the emitting source must be assumed or determined separately. Furthermore, the composition of the atmosphere as function of altitude must likewise be assumed or measured. The separation of attenuation into water vapor and oxygen components then depends on these factors, the effects of which depend, in turn, on the details of the theory used.

THEORETICAL AND EXPERIMENTAL CONSIDERATIONS

The theoretical aspects of the physical mechanisms which cause the absorption of electromagnetic radiation in the atmosphere are well known (refs. 2-5) and are more elegantly presented in the literature. Thus they will not be discussed in this report. Several hundred publications were reviewed and analyzed to separate absorption data measured along a ray path through the atmosphere from absorption data measured between a point-to-point path over the surface of the Earth. A radiometric measurement utilizing the sun as an exo-atmospheric source of electromagnetic radiation closely simulates the communication path that might exist between a satellite and the Earth. To be rigorously correct during analysis of the experimental data, only the attenuation values measured along a ray path through the atmosphere were considered. Reported attenuations have been included in this survey only if a specific value were stated.

In cases where an attenuation coefficient was given, the measurement values have been included only if the model atmosphere and the assumptions that were used to derive the absorption coefficient from an emission measurement were specifically stated. The results of work done in simulated atmospheres have not been included.

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*Clear weather is defined as a state in which there are no atmospheric hydrometeors present in the main beam of the observing antenna.

DATA PRESENTATION

Presentation of the data was accomplished by dividing the frequency spectrum into two regions: the first, from 0.4 to 10 GHz, and the second, from 10 to 150 GHz. A frequency separation was achieved in this manner because the spectrum between 10 and 100 GHz affords the opportunity for the experimental investigation of those portions of the spectrum considered the most likely candidates for future Earth-space communication links. At these higher frequencies, relatively high gain antennas are achieved with modest aperture diameter; broad channel capability allows high information capacity and the total available bandwidth, even in the restricted atmospheric "windows," exceeds the entire spectrum below 3 cm or 10 GHz. The windows considered for communication are located at 35 and 95 GHz. Additional windows are available at wavelengths shorter than 3 mm. These are at 140 and 240 GHz. In the wavelength region from 3 cm to 3 mm, the windows are located between water vapor and oxygen resonant lines centered at 22.3 and 60 GHz, respectively. Total atmospheric attenuation along a vertical ray path through the atmosphere at a frequency of 60 GHz is on the order of 300 dB. The "wells" or "windows" between oxygen lines in the 58- to 62-GHz region provides a total vertical attenuation along the ray path of approximately 150 dB. This strong atmospheric attenuation precludes consideration of this frequency band for Earth-space communication. The resonant line at 22.3 GHz is not opaque either and its efficacy for the determination of the atmospheric water vapor distribution on a global scale may be limited to ocean areas only. Thus, though 60 and 22.3 GHz are not suited to communication requirements and needs, their importance cannot be overlooked in terms of benefits to the meteorologist who is attempting to obtain a global picture of water vapor and temperature distributions combined with air mass circulations under "clear weather" conditions. Remote sensors housed in a satellite at this frequency offer the potential to synoptically predict in advance the formation of storm clouds and their motions by probing those parameters most significant in the formulation of the physical processes that cause global weather conditions (ref. 6).

THE SPECTRUM FROM 0.4 TO 10 GHz

Figure 1 is a plot of the theoretical attenuation curves of Hogg (ref. 7) and Croom (ref. 8) as a function of frequency. The difference between these curves is due to the differences in the choice of the line-broadening constant in the Van Vleck-Weisskopf equation (ref. 2). Hogg used 0.75 GHz per atmosphere and Croom used 0.54 GHz per atmosphere. The value of 0.54 GHz per atmosphere is in agreement with the laboratory measurement of the line-broadening constant by Maryott and Birnbaum (ref. 9),

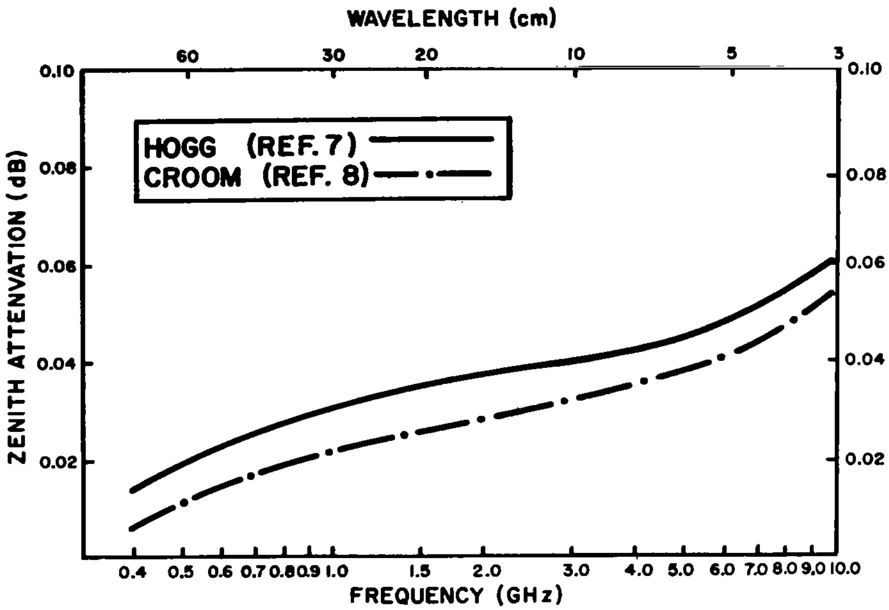

Figure 1. - Theoretical clear sky zenith atmospheric attenuation values in the frequency range 0.4 to 10 GHz

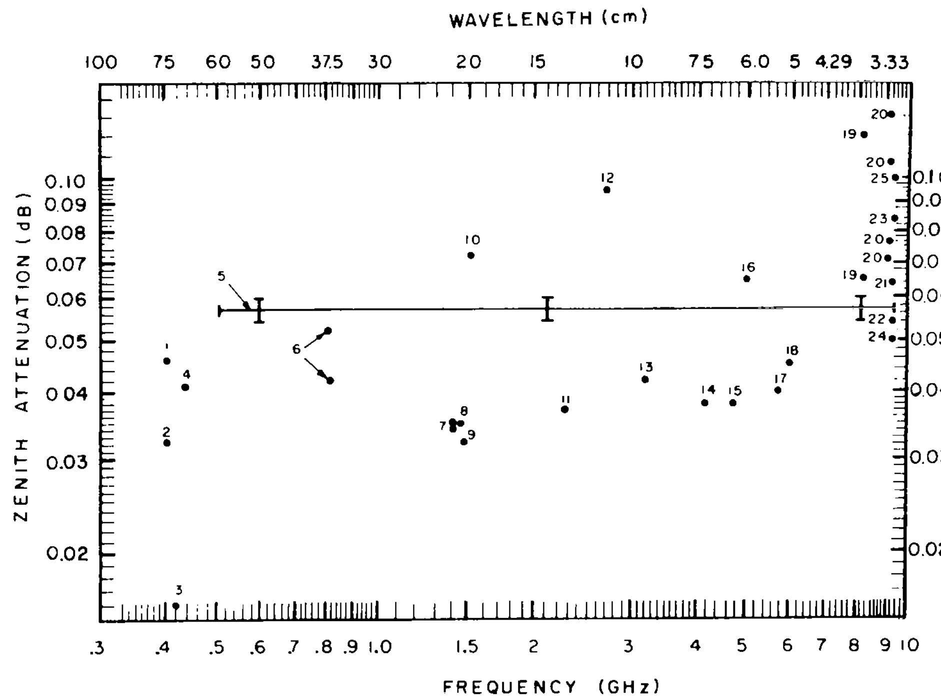

Figure 2. - Measured clear sky zenith atmospheric attenuation values in the frequency range 0.4 to 10 GHz

suggesting that Croom's theoretical curve may be more accurate than that of Hogg. A discussion of the data and theoretical relationships is given in reference 10.

The attenuation characteristics in this range were also reviewed by Medd and Fort (ref. 11) as well as Howell and Shakeshaft (ref. 10). Figure 2 presents the data available to date and Table I lists pertinent information on each of the data points. Howell and Shakeshaft (ref. 10) considered a refraction correction which they believe was previously overlooked or made in the wrong sense. Use of this correction for previous experimental work resulted in a closer agreement between theoretical and experimental values of the attenuation over this frequency range.

THE SPECTRUM FROM 10 TO 150 GHz

The attenuation characteristics in the 10- to 150-GHz frequency region were reviewed by Rosenblum (ref. 32) in 1961 and by Hayes (ref. 33) in 1964. Rosenblum discussed the theoretical predictions of Theissing and Caplan (ref. 34) and Hogg (ref. 7) and presented a summary of the available data. Hayes (ref. 33) presented original work at 10 frequencies (Figure 3) and a discussion of the predictions of Meeks (ref. 35) and Schmelzer (ref. 36) as well as those of Theissing and Caplan (ref. 34). The lack of regularity in the relationship between attenuation and water vapor content may be seen from Hayes' data points. It is pointed out that the frequency-attenuation curves between 65 and 400 GHz by Theissing and Caplan (ref. 34) are derived from the Van Vleck-Weisskopf equation using different meteorological data and integrating with respect to altitude because of the pressure, temperature, and water vapor content dependence with altitude. Hayes used meteorological data taken by a radiosonde at intervals from 0 to 45 km which were grouped under the general classifications of dry, medium, and humid conditions before integration. Hayes also found that by revising the oxygen linewidth parameter, the work of Theissing and Caplan would be appropriate for frequencies down to 40 GHz. Hayes (ref. 33) and Theissing and Caplan (ref. 34) pointed out that the Van Vleck-Weisskopf equation properly describes the general shape of the relation of atmospheric attenuation as a function of frequency, but fails to give the proper absolute magnitude of attenuation in frequency regions between resonant absorption lines except near 110 GHz. In the spectrum region from 10 to 140 GHz, curves drawn through data of Hayes are lower and flatter than those of Theissing and Caplan. Hayes found that Schmelzer's values in agreement with his own in the frequency range from 40 to 80 GHz, but are higher than his data in the 80- to 140-GHz region, apparently because

TABLE I

SUMMARY OF CLEAR SKY ZENITH ATMOSPHERIC ATTENUATION MEASUREMENTS IN THE FREQUENCY RANGE 0.4 to 10 GHz

Frequency (GHz)	Wavelength (cm)	Zenith Attenuation (dB)	Fig. 2 References	Source
0.4	75.0	0.046±0.002	1	Seeger et al. (ref. 12)
0.4	75.0	0.0345±0.001	2	Seeger et al. (ref. 12)
0.408	73.5	0.016±0.007	3	Howell and Shakeshaft (ref. 10)
0.43	69.8	0.041±0.006	4	Dimitrenko (ref. 13)
0.5-9.4	60.0-3.19	0.057±10%	5	Stankevich (ref. 14)
0.82	36.6	0.051±0.001	6	Berkhuijson (Howell and
		0.042±0.002	6	Shakeshaft (ref. 10)
1.407	21.4	0.034±0.008	7	Howell and Shakeshaft,
		0.035±0.010	7	(ref. 10)
1.415	21.3	0.035	8	Penzias and Wilson (Howell and Shakeshaft (ref.10)
1.42	21.1	0.032	9	Mainka (ref. 15) Shakeshaft (ref. 10)
1.50	20.0	0.072	10	Fürstenberg (ref. 16)
2.39	12.6	0.037	11	Ohm (ref. 17)
2.70	11.1	0.095	12	Altenhoff et al. (ref. 18)
3.2	9.37	0.042±0.004	13	Medd and Fort (ref. 11)
4.08	7.35	0.038	14	Penzias and Wilson (ref. 19)
4.70	6.37	0.038	15	Castelli et al. (ref. 20)
4.995	6.0	0.065	16	Baars, Mezger, and Wendker (ref. 21)
5.65	5.31	0.04	17	DeGrasse et al. (ref. 22)
6.0	5.0	0.045	18	Hogg and Semplak (ref. 23)
8.25	3.64	0.065	19	Allen and Barrett (ref. 24)
9.18	3.27	0.07-0.14	20	Castelli (refs. 25, 26, 27)
		0.11-0.15	20	
		0.05-0.10	20	
		0.05-0.085	20	
9.38	3.2	0.064	21	Aarons, Barron, and Castelli (ref. 28)'
99.38	3.2	0.054	22	Lastochkin, Stankevich, and Strezhneva (ref. 29)
9.40	3.19	0.084	23	Fürstenberg (ref. 16)
9.40	3.19	0.05	24	Roll and Wilkinson (ref. 30)
9.5	3.15	0.1	25	Mayer, McCullough, and Sloanmaker (ref. 31)

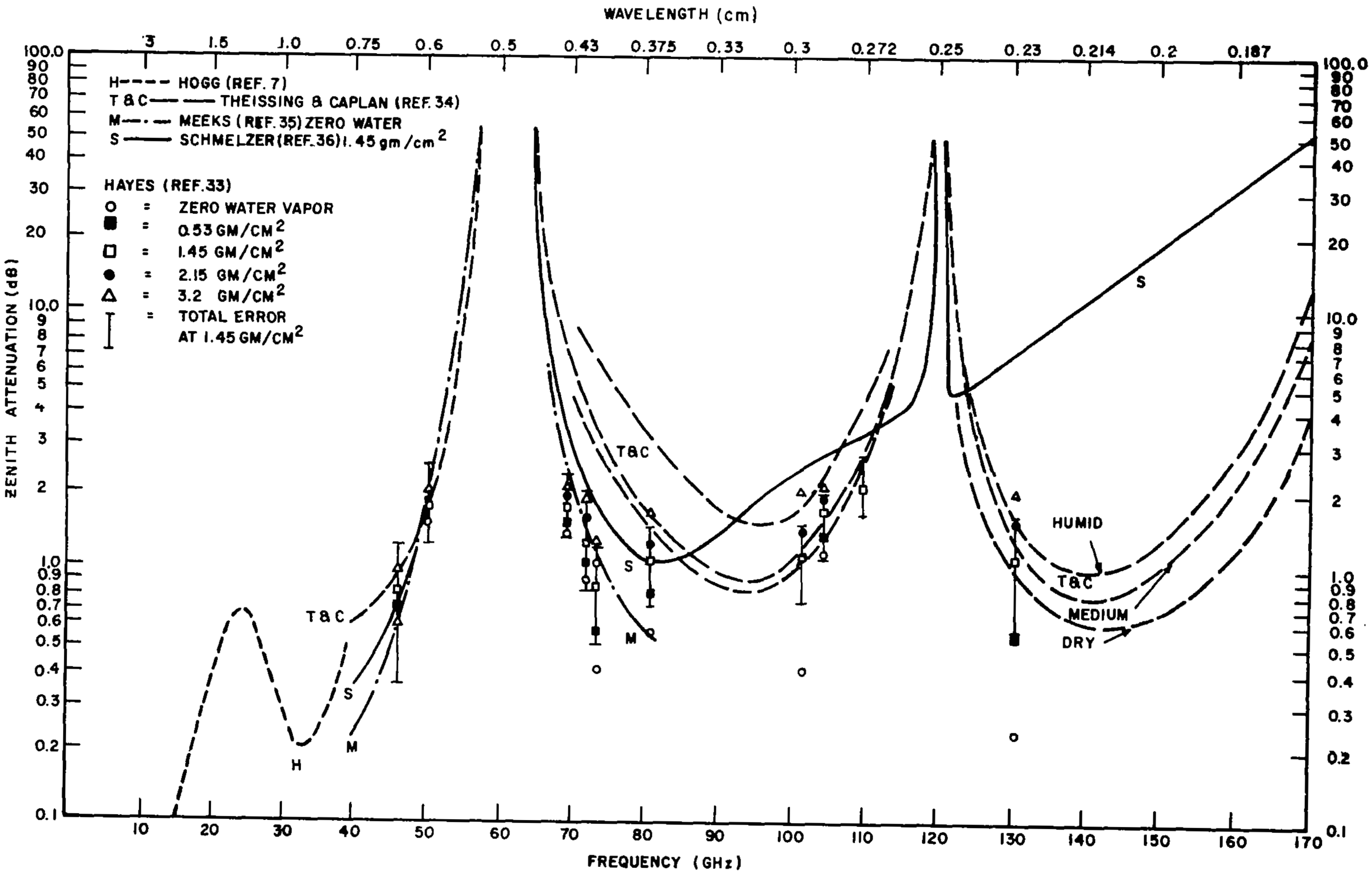

Figure 3.- Theoretical and measured values of zenith atmospheric attenuation in the frequency range 10 to 170 GHz

Schmelzer attributed too large an attenuation coefficient to water vapor at frequencies removed from the water vapor resonances.

Meeks' (ref. 35) theoretical curve is also included in the frequency range from 45 to 75 GHz and is presented here to supplement data presented by Hayes. His oxygen linewidth parameter was based on measurements made in air containing water vapor. This might account for his values being slightly higher than those measured by Hayes.

Experimental attenuation data [except that of Hayes (ref. 33)] in the region from 10 to 150 GHz is plotted in Figure 4. Table II presents pertinent information on the data points as collected from available literature. In the 107- to 121-GHz portion of the spectrum, experimental work by Tolbert, Krause, and Straiton (ref. 63) reveals that a broad resonant absorption line which obscures the separation of the attenuation into water vapor and oxygen does exist. The peak of the water vapor line is prominent enough to be measured at 118 GHz. Its maximum peak is difficult to distinguish accurately, however, in terms of amplitude.

CONCLUSIONS

The wide spread in attenuation values in the frequency range from 0.4 to 150 GHz indicates the variability of the atmosphere even under "clear sky" conditions. Measurements of transatmospheric attenuation under conditions of precipitation (rain, snow, sleet, etc.) are extremely scanty over the frequency range of interest and do not exist for most frequencies. Further theoretical work is needed to extend the present theory on line shape broadening to higher frequencies. In addition, more experimental work is needed to verify the empirical relationships for absorption values as a function of frequency obtained at low elevation angles along a ray through the atmosphere under conditions of heavy precipitation.

In Figure 4 the error bars on lines associated with some attenuation values indicate that one of the following conditions may have existed during the experimental measurement programs: (1) The error may be difficult to measure because of lack of sensitivity of the radiometric instrument, and because it is a small systematic error introduced by horizontal inhomogeneities in the atmosphere as well as time variations in its composition, or (2) the error is based upon the calculation of absorption from emission measurements because of an assumption concerning the mean temperature of the atmosphere which enters the calculation. Absorption data resulting from the measurement of an exoatmospheric source, such as the sun, provides, however, a more

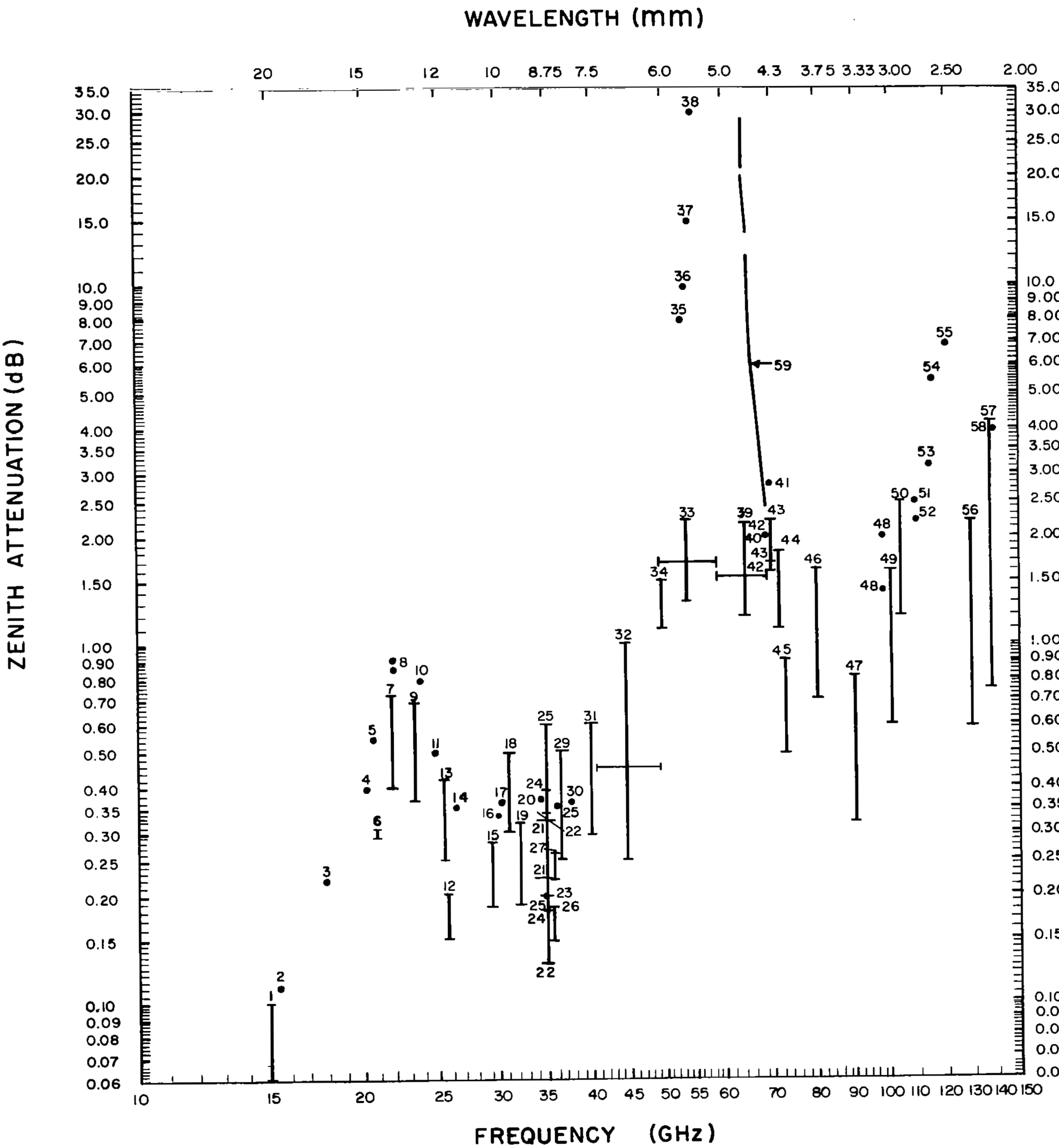

Figure 4. - Measured clear sky zenith atmospheric attenuation values in the frequency range 10 to 150 GHz

TABLE II

SUMMARY OF CLEAR SKY ZENITH ATMOSPHERIC ATTENUATION MEASUREMENTS IN THE FREQUENCY RANGE 10 to 150 GHz

Frequency (GHz)	Wavelength	Zenith Attenuation (dB)	Fig. 4 Refer-ences	Source
15.0	2.0 cm	0.06-0.1	1	Wulfsberg (ref. 37)
15.5	1.94 cm	0.112	2	Allen and Barrett (ref. 24)
18.15	1.62 cm	0.22	3	Griffith, Thornton, and Welch (ref. 38)
20.0	1.5 cm	0.398	4	Dicke et al. (ref. 39)
20.6	1.45 cm	0.55	5	Griffith, Thornton, and Welch (ref. 38)
21.0	1.43 cm	0.291-0.309	6	Staelin (ref. 40)
21.9	1.37 cm	0.396-0.725	7	Staelin (ref. 40)
22.2	1.35 cm	0.85 0.9	8 8	Griffith, Thornton, and Welch (ref. 38)
23.5	1.28 cm	0.368-0.687	9	Staelin (ref. 40)
24.0	1.25 cm	0.799	10	Dicke et al (ref. 39)
24.14	1.24 cm	0.5	11	Griffith, Thornton, and Welch (ref. 38)
25.4	1.18 cm	0.15-0.20	12	Staelin, Barrett, and Kusse, (ref. 41)
25.5	1.17 cm	0.247-0.409	13	Staelin (ref. 40)
26.0	1.15 cm	0.35	14	Griffith, Thornton, and Welch (ref. 38)
29.5	1.02 cm	0.184-0.282	15	Staelin (ref. 40)
30.0	1.0 cm	0.336	16	Dicke et al. (ref. 39)
30.9	9.7 mm	0.36	17	Griffith, Thornton, and Welch (ref. 38)
31.4	9.55 mm	0.3-0.5	18	Hobbs, Corbett, and Santini (ref. 42)
32.4	9.2 mm	0.190-0.318	19	Staelin (ref. 40)
34.4	8.7 mm	0.363	20	Aarons, Barron, and Castelli (ref. 28)
35.0	8.6 mm	0.22-0.32	21	Wulfsberg (ref. 37)
35.0	8.6 mm	0.13-0.34	22	Kalaghan and Albertini (ref. 43)
35.0	8.6 mm	0.2	23	Copeland and Tyler (ref. 44)
35.0	8.6 mm	0.18-0.39	24	Gibson (ref. 45)
35.0	8.6 mm	0.2-0.6	25	Gibson (ref. 46)
35.3	8.5 mm	0.15-0.18	26	Lynn, Meeks, and Sohigian (ref. 47)
35.9	8.35 mm	0.22-0.26	27	Thornton and Welch (ref. 48)
36.06	8.23 mm	0.35	28	Griffith, Thornton and Welch (ref. 38)
36.6	8.2 mm	0.25-0.5	29	Nicoll (ref. 49)
37.5	8.0 mm	0.36	30	Nicoll (Ref. 49)
40.0	7.5 mm	0.3-0.6	31	Whitehurst, Mitchell, and Copeland (ref. 50), Whitehurst, Mitchell (ref. 51)
40.4 49.6	7.4 mm 6.0 mm	0.25-1.0	32	Hayes, (ref. 33)

TABLE II (concl'd)

Frequency (GHz)	Wavelength	Zenith Attenuation (dB)	Fig. 4 References	Source
49.6	6.0 mm	1.3-2.2	33	Hayes, (ref. 33)
59.7	5.0 mm			
50.0	6.0 mm	1.1-1.5	34	Whitehurst, Copeland, and Mitchell (ref. 52)
53.5	5.61 mm	8.0	35	Carter, Mitchell, and Reber (ref. 53)
53.8	5.58 mm	10.0	36	Carter, Mitchell, and Reber (ref. 53)
54.4	5.51 mm	15.0	37	Carter, Mitchell, and Reber (ref. 53)
55.4	5.41 mm	30.0	38	Carter, Mitchell, and Reber (ref. 53)
65.0	4.62 mm	2.8-4.0	59	Tolbert and Straiton, (refs. 54, 55)
69.0	4.35 mm			
69.75	4.3 mm	2.0	40	Tolbert, Straiton, and Walker (ref. 56)
59.0 } 69.0	50.8 mm } 4.35 mm	1.2-2.2	39	Hayes (ref. 33)
70.0	4.3 mm	2.8	41	Tolbert, Britt, and Bahn (ref. 57)
70.0	4.3 mm	1.6-2.2	42	Coates (refs. 58, 59)
70.0	4.3 mm	1.7-2.2	43	Grant, Corbett, and Gibson (ref. 60)
72.0	4.18 mm	1.1-1.8	44	Hayes (ref. 33)
73.0	4.1 mm	0.5-0.9	45	Hayes (ref. 33)
80.0	3.75 mm	0.7-1.6	46	Hayes (ref. 33)
91.0	3.3 mm	0.31-0.80	47	Shimabukuro (refs. 61, 62)
100.0	3.0 mm	2.0, 1.4	48	Tolbert, Krause, and Straiton (ref. 63)
101.0	2.97 mm	0.6-1.6	49	Hayes (ref. 33)
104	2.88 mm	1.2-2.5	50	Hayes (ref. 33)
110	2.72 mm	2.5	51	Tolbert, Krause, and Straiton (ref. 63)
110	2.72 mm	2.2	52	Hayes (ref. 33)
114	2.63 mm	3.2	53	Tolbert, Krause, and Straiton (ref. 63)
116.8	2.56 mm	5.5	54	Tolbert, Krause, and Straiton (ref. 63)
120.2	2.48 mm	7.0	55	Tolbert, Krause, and Straiton (ref. 63)
130	2.30 mm	0.6-2.2	56	Hayes (ref. 33)
139	2.15 mm	0.75-4.2	57	Tolbert, Krause, and Bahn (ref. 64)
140	2.14 mm	4.0	58	Tolbert, Krause, and Straiton (ref. 63)

reliable measure of attenuation since it does not require knowledge of (a) the gain characteristics of the antenna, (b) the loss factor between the antenna feed and receiver, and (c) the absolute temperature of the sun for a "clear weather" condition.

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