Computed Transmission Through Rain at Microwave and Visible Frequencies

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In this paper we present tables which contain the Mie scattering coefficient, absorption coefficient, extinction coefficient, equivalent medium index of refraction and phase delay for rains conforming to the Laws and Parsons drop-size distribution. These transmission characteristics have been calculated for microwave frequencies of interest in common carrier radio relay systems, 300 to 1.43 GHz, that is, 0.1 to 21.0 cm, at rain rates from 0.25 to 150.0 mm/hr. We also include the extinction coefficients for the visible wavelength 0.6328 μ.

The microwave tables were generated by using a Mie scattering computer program similar to that designed and previously reported by Deirmendjian. The calculations at 0.6328 μ were made separately by employing the usual assumptions for droplets with very large circumference to wavelength ratios.

I. INTRODUCTION

The Mie extinction properties are of basic importance to those interested in developing an understanding of the influence of rainfall on open air communication systems. In this connection we have generated a rather extensive set of tables of extinction properties of rain. The tables have been used within Bell Laboratories to study a variety of transmission problems, examples of which are the investigation of satellite ground station interference by Gusler and Hogg (1970),* the study of microwave transit time variations by Gray (1970), Pierce's (1969) investigation of the problems associated with the synchronization of digital networks and Setzer's (1969) study of the extinction properties of atmospheric aerosols.[1–4] A set of tables with similar results was published by Medhurst (1965); however, his presentation only includes

* The attenuation constants used by Gusler and Hogg were based on empirical data. The calculated values presented in this paper were used for comparison purposes only.

total attenuation.[5] Our tables include the Mie scattering coefficient, absorption coefficient, extinction coefficient, the van de Hulst equivalent medium index of refraction and the van de Hulst phase delay for rains conforming to the Laws and Parsons drop-size distribution. These transmission characteristics have been calculated for incident microwave wavelengths of 0.1, 0.2, 0.3, 0.5, 1.0, 1.62, 1.88, 2.73, 5.0, 7.5, 10.0, 15.0 and 21.0 cm (corresponding to 300, 150, 100, 60, 30, 18.5, 16, 11, 6, 4, 3, 2 and 1.43 GHz) at rain rates of 0.25, 1.25, 2.5, 5.0, 12.5, 50.0, 100.0 and 150.0 mm/hr. Also included are the extinction coefficients for the visible wavelength 0.6328 μ at the above rain rates.

The calculations in the microwave region were performed on a GE 635 computer using a scattering program similar to that previously presented by Deirmendgian (1963).[6] Since the raindrop circumference-to-wavelength ratio ($\pi d/\lambda$), that is, size parameter, for the visible wavelength, is outside the range of validity of the computer program, approximate characteristics were calculated for 0.6328 μ. The usual assumptions for spheres with very large parameters were employed.

The indices of refraction used in this report and shown in Table I are for a rain temperature of 20°C. They were obtained by cross checking many of the standard optical and microwave references and are thought to be reliable.

II. DROPLET SIZE DISTRIBUTION

All computations in this paper are based on the assumption that raindrops are spherical and the distribution of rain is as was measured by Laws and Parsons and quoted by Kerr (1951).[7] The Laws and Parsons distribution is presented in Table II as the percentage of total water volume within specific size ranges. In order to use the computer program, it is necessary to express the distribution in terms of the number of droplets per unit volume within specific size ranges. If the droplets are assumed to fall at the terminal velocity V_0, that is, up and down drafts are neglected, then the conversion is

$$D(d_{i+1}, d_1) \approx R_f \cdot P(d_{i+1}, d_i)/[V(\bar{d})V_0(\bar{d})], \tag{1}$$

where $D(d_{i+1}, d_1)$ represents the size distribution in units of droplets per unit volume in the droplet diameter range d_{i+1} to d_i. Henceforth, the diameter range d_{i+1} to d_i will be called Δd_i. R_f is the total rainfall rate which is typically specified in mm/hr; $P(d_{i+1}, d_i)$ is the volume percentage rainfall in the diameter range Δd_i as measured by Laws and Parsons; $\bar{d}$ is the average diameter in the range Δd_i; and $V(\bar{d})$

is the volume of a sphere of diameter $\bar{d}$. The terminal velocities of raindrops $V_0(\bar{d})$ are presented in Table III.[7]

For an example of the function $D(d_{i+1}, d_i)$ resulting from the use of equation (1), refer to Fig. 1.

III. TRANSMISSION PARAMETERS FOR MICROWAVE FREQUENCIES

The Mie coefficients and the equivalent index of refraction of the rain medium are defined by van de Hulst (1957).[8] For a detailed description of these parameters, please refer to his work. Essentially, the scattering coefficient $\beta_{scat}(\lambda)$ and the absorption coefficient $\beta_{abs}(\lambda)$ are measures of the total energy scattered and absorbed by a unit volume of rainfall. In the simple case of a single scattering aerosol the ratio of intensity of the transmitted beam $I_T(\lambda)$ to that of the incident beam $I_0(\lambda)$ is

$$I_T(\lambda)/I_0(\lambda) = \exp[-\beta_{ext}(\lambda) \cdot l], \tag{2}$$

where l is the length of the propagation path through the rain and the extinction coefficient $\beta_{ext}(\lambda)$ is

$$\beta_{ext}(\lambda) = \beta_{scat}(\lambda) + \beta_{abs}(\lambda). \tag{3}$$

A plane-parallel medium containing many scattering particles can be represented by a slab of homogeneous material having a complex refractive index $\tilde{m}$. Carefully note that this sort of representation can

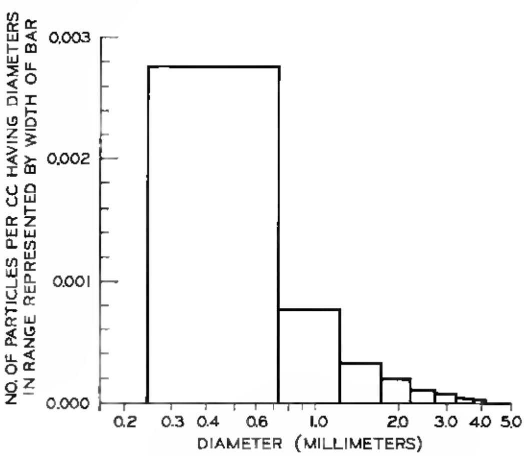

Fig. 1—Laws and Parsons drop-size distribution for 150 mm/hr rain.

be designed, by selecting the appropriate value of $\tilde{m}$, to preserve the input-output relationships but all detail of the scattering process within the medium is lost. According to the van de Hulst (1957) definition of $\tilde{m}$, the amplitude and phase of the incident wave are changed by the slab in the proportion

$$\exp[-(2\pi l/\lambda)\mathrm{Im}(1 - \tilde{m})]\cdot \exp[-(2\pi li/\lambda)\mathrm{Re}(\tilde{m} - 1)], \qquad (4)$$

where the first term is recognized as defining the amplitude ratio and the second the phase.[8] The values of β_{ext}, β_{abs}, β_{scat}, $\tilde{m}$ and the phase angle described above have been calculated for the specified microwave frequencies. The results appear in Tables IV through XVI. The reader is advised to use special care when attempting to apply the van de Hulst phase angle and medium index $\tilde{m}$. It is recommended that van de Hulst's derivation be studied carefully so that the meaning and limitations of these functions are well understood. For example, light reflected from the slab cannot be derived by using the refractive index $\tilde{m}$, but should be computed by means of the actual scattering functions.

Also, it should be noted that although $\tilde{m}$ is calculated, $(\tilde{m} - 1)$ is used to determine the phase angle. Since $\tilde{m}$ is very close to one, cancellation of the leading terms reduces the significant places in the numerical value of the phase angle to one or two at most. Consequently the values given in the phase change column of Tables IV through XVI exhibit noticeable discontinuous jumps.

IV. TRANSMISSION PARAMETERS FOR 0.6328 μ

The Mie coefficients β_i are defined as

$$\beta_i(\lambda) = \int_0^\infty \gamma_i(\lambda, r)n(r)\,dr, \qquad i = 1, 2, 3, \qquad (5)$$

where r is the droplet radius; $n(r)$ is the continuous size distribution, and $\gamma_i(\lambda, r)$, $i = 1, 2, 3$ are the extinction, scattering and absorption cross sections, respectively for droplets of radius r. The smallest ratio of raindrop circumference to wavelength for the combination of a Laws and Parsons rain and 0.6328 μ is approximately 1500. For most purposes, the laws of geometric optics can be applied in such cases and therefore

$$\gamma_{ext}(\lambda, r) \approx 2\pi r^2. \qquad (6)$$

Also, since the index of refraction of water at 0.6328 μ is a real number, 1.33, the absorption coefficient will be zero. It follows from equations (3), (5) and (6) that

$$\beta_{ext}(0.6328\mu) = \beta_{scat}(0.6328\mu), \qquad (7)$$

$$\approx 2\pi \int_0^\infty r^2 n(r)\, dr. \tag{8}$$

This expression and the Laws and Parsons distribution were used to generate Table XVII. In this connection the Laws and Parsons distribution $D(d_{i+1}, d_i)$ was used to approximate the continuous function $n(r)$.

V. GRAPHICAL REPRESENTATION

For the purpose of illustration, a graph of extinction coefficients versus total water content and rain rate is included (see Fig. 2). Not all wavelengths are represented because some of the curves are too closely grouped in the neighhorhood of those shown. Those that were excluded, were excluded for reasons of clarity only. One point of some interest is the location of the attenuation curve for 0.6328 μ in Fig. 2. Note that it represents a reversal of the trend exhihited as wavelength

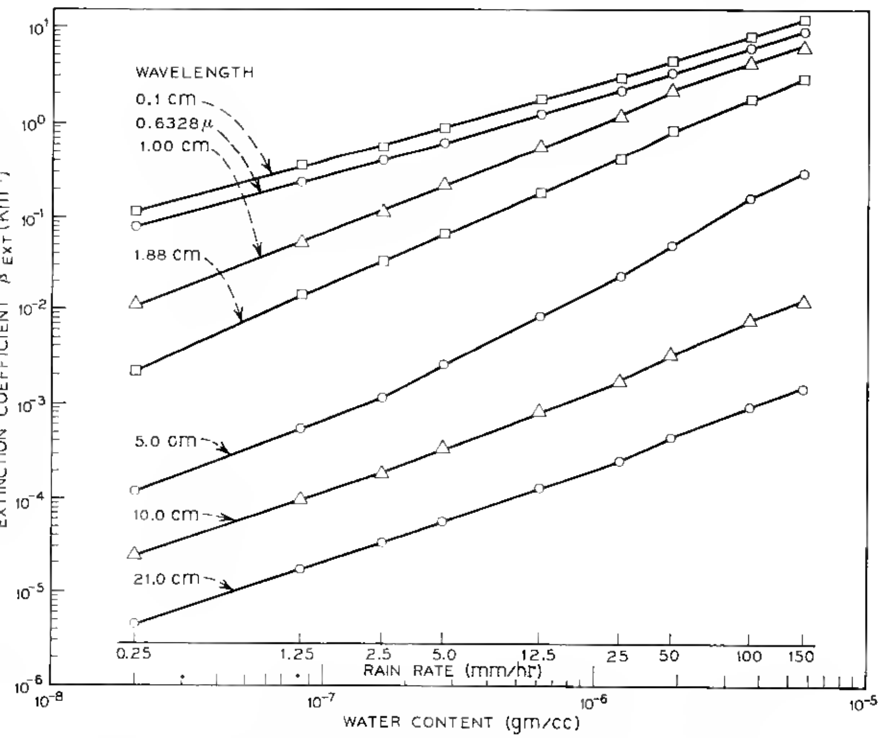

Fig. 2—Rainfall water content and rain rate versus extinction coefficient β_{ext}.

TABLE I—INDEX OF REFRACTION OF WATER AT 20°C

Wavelength (cm)	Index of Refraction
0.10	2.587 - 0.937(i)
0.20	3.039 - 1.575(i)
0.30	3.505 - 2.007(i)
0.50	4.364 - 2.521(i)
1.00	5.900 - 2.900(i)
1.62	7.001 - 2.544(i)
1.88	7.500 - 2.500(i)
2.73	8.070 - 1.990(i)
5.00	8.670 - 1.202(i)
7.50	8.770 - 0.915(i)
10.00	8.871 - 0.628(i)
15.00	8.916 - 0.422(i)
21.00	9.000 - 0.275(i)
0.6328 μ	1.33 - 0.0(i)

TABLE II— LAWS AND PARSONS DROP-SIZE DISTRIBUTIONS FOR VARIOUS PRECIPITATION RATES

Drop Diameter (cm)	Rain Rate (mm/hour)								
	0.25	1.25	2.5	5	12.5	25	50	100	150
	Percent of Total Volume								
0.05	28.0	10.9	7.3	4.7	2.6	1.7	1.2	1.0	1.0
0.1	50.1	37.1	27.8	20.3	11.5	7.6	5.4	4.6	4.1
0.15	18.2	31.3	32.8	31.0	24.5	18.4	12.5	8.8	7.6
0.2	3.0	13.5	19.0	22.2	25.4	23.9	19.9	13.9	11.7
0.25	0.7	4.9	7.9	11.8	17.3	19.9	20.9	17.1	13.9
0.3		1.5	3.3	5.7	10.1	12.8	15.6	18.4	17.7
0.35		0.6	1.1	2.5	4.3	8.2	10.9	15.0	16.1
0.4		0.2	0.6	1.0	2.3	3.5	6.7	9.0	11.9
0.45			0.2	0.5	1.2	2.1	3.3	5.8	7.7
0.5				0.3	0.6	1.1	1.8	3.0	3.6
0.55					0.2	0.5	1.1	1.7	2.2
0.6						0.3	0.5	1.0	1.2
0.65							0.2	0.7	1.0
0.7									0.3

TABLE III—RAINDROP TERMINAL VELOCITY

Radius, cm	Velocity, m/sec
0.025	2.1
0.05	3.9
0.075	5.3
0.10	6.4
0.125	7.3
0.15	7.9
0.175	8.35
0.2	8.70
0.225	9.0
0.25	9.2
0.275	9.35
0.30	9.5
0.325	9.6

TABLE IV—MIE EXTINCTION PARAMETERS AT 0.1 CM WAVELENGTH (300 GHz), H_2O INDEX OF REFRACTION 2.587—0.937i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(\mathrm{km})^{-1}$	Absorption Coef. $(\mathrm{km})^{-1}$	Extinction Coef. $(\mathrm{km})^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{\mathrm{deg}}{\mathrm{km}}\right)$
				$\mathrm{Re}(\tilde{m} - 1)$	$\mathrm{Im}(1 - \tilde{m})$	
0.25	0.05390	0.05878	0.1127	0.0×10^{-6}	0.1051×10^{-7}	0.0
1.25	0.1705	0.1723	0.3428	0.0×10^{-6}	0.3051×10^{-7}	0.0
2.5	0.2760	0.2693	0.5452	0.0×10^{-6}	0.4763×10^{-7}	0.0
5.0	0.4550	0.4306	0.8856	0.0×10^{-6}	0.7630×10^{-7}	0.0
12.5	0.8913	0.8133	1.705	0.0×10^{-6}	1.451×10^{-7}	0.0
25.0	1.452	1.284	2.736	0.0×10^{-6}	2.305×10^{-7}	0.0
50.0	2.270	1.914	4.187	0.0×10^{-6}	3.471×10^{-7}	0.0
100.0	3.993	3.354	7.347	0.0×10^{-6}	6.109×10^{-7}	0.0
150.0	5.636	4.730	10.37	0.0×10^{-6}	8.636×10^{-7}	0.0

TABLE V—MIE EXTINCTION PARAMETERS AT 0.2 CM WAVELENGTH (150 GHz), H_2O INDEX OF REFRACTION 3.039—1.575i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.05581	0.05445	0.1103	0.0×10^{-6}	0.2276×10^{-7}	0.0
1.25	0.1828	0.1685	0.3514	0.0×10^{-6}	0.6657×10^{-7}	0.0
2.5	0.2991	0.2686	0.5677	0.0×10^{-6}	1.042×10^{-7}	0.0
5.0	0.4965	0.4349	0.9314	0.0×10^{-6}	1.671×10^{-7}	0.0
12.5	0.9766	0.8283	1.805	0.0×10^{-6}	3.176×10^{-7}	0.0
25.0	1.596	1.315	2.911	0.0×10^{-6}	5.044×10^{-7}	0.0
50.0	2.512	1.988	4.500	0.0×10^{-6}	7.592×10^{-7}	0.0
100.0	4.403	3.449	7.856	0.1×10^{-6}	13.33×10^{-7}	18.0
150.0	6.212	4.846	11.06	0.1×10^{-6}	18.83×10^{-7}	18.0

TABLE VI—MIE EXTINCTION PARAMETERS AT 0.3 CM WAVELENGTH (100 GHz), H_2O INDEX OF REFRACTION 3.505—2.007i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.04252	0.04991	0.09243	0.0×10^{-6}	0.2886×10^{-7}	0.0
1.25	0.1544	0.1586	0.3130	0.0×10^{-6}	0.8927×10^{-7}	0.0
2.5	0.2634	0.2555	0.5189	0.1×10^{-6}	1.432×10^{-7}	12.0
5.0	0.4520	0.4175	0.8695	0.1×10^{-6}	2.342×10^{-7}	12.0
12.5	0.9211	0.8026	1.723	0.1×10^{-6}	4.542×10^{-7}	12.0
25.0	1.542	1.283	2.825	0.2×10^{-6}	7.320×10^{-7}	24.0
50.0	2.502	1.957	4.459	0.2×10^{-6}	11.27×10^{-7}	24.0
100.0	4.382	3.389	7.770	0.4×10^{-6}	19.72×10^{-7}	48.0
150.0	6.153	4.751	10.90	0.6×10^{-6}	27.76×10^{-7}	72.0

TABLE VII—MIE EXTINCTION PARAMETERS AT 0.5 CM WAVELENGTH (60 GHz), H_2O INDEX OF REFRACTION 4.364—2.521i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.01638	0.02856	0.04493	0.0×10^{-6}	0.2281×10^{-7}	0.0
1.25	0.08590	0.1085	0.1945	0.1×10^{-6}	0.9094×10^{-7}	7.2
2.5	0.1667	0.1876	0.3544	0.1×10^{-6}	1.608×10^{-7}	7.2
5.0	0.3157	0.3236	0.6393	0.2×10^{-6}	2.832×10^{-7}	14.4
12.5	0.7145	0.6574	1.372	0.4×10^{-6}	5.924×10^{-7}	28.8
25.0	1.279	1.089	2.368	0.6×10^{-6}	10.06×10^{-7}	43.3
50.0	2.233	1.743	3.977	0.8×10^{-6}	16.59×10^{-7}	57.6
100.0	3.934	2.999	6.933	1.3×10^{-6}	28.89×10^{-7}	93.6
150.0	5.505	4.165	9.670	1.8×10^{-6}	41.65×10^{-7}	129.6

TABLE VIII—MIE EXTINCTION PARAMETERS AT 1.0 CM WAVELENGTH (30 GHz), H_2O INDEX OF REFRACTION 5.9—2.9i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.001459	0.009006	0.01046	0.0×10^{-6}	0.01046×10^{-7}	0.0
1.25	0.01303	0.04392	0.05695	0.1×10^{-6}	0.5248×10^{-7}	3.6
2.5	0.03112	0.08465	0.1158	0.2×10^{-6}	1.038×10^{-7}	7.2
5.0	0.07387	0.1617	0.2355	0.4×10^{-6}	2.066×10^{-7}	14.4
12.5	0.2210	0.3751	0.5961	0.8×10^{-6}	5.106×10^{-7}	28.8
25.0	0.4939	0.6890	1.183	1.4×10^{-6}	9.978×10^{-7}	50.5
50.0	1.071	1.234	2.305	2.1×10^{-6}	19.16×10^{-7}	75.6
100.0	2.184	2.207	4.397	3.6×10^{-6}	36.26×10^{-7}	130.0
150.0	3.280	3.106	6.386	4.9×10^{-6}	52.58×10^{-7}	177.0

TABLE IX—MIE EXTINCTION PARAMETERS AT 1.62 CM WAVELENGTH (18.5 GHz), H_2O INDEX OF REFRACTION 7.001—2.544i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.0001932	0.002970	0.003162	0.0×10^{-6}	0.05064×10^{-7}	0.0
1.25	0.002003	0.01814	0.02015	0.1×10^{-6}	0.2982×10^{-7}	2.2
2.5	0.005166	0.03855	0.04372	0.3×10^{-6}	0.6316×10^{-7}	6.6
5.0	0.01373	0.08067	0.09440	0.5×10^{-6}	1.336×10^{-7}	11.1
12.5	0.04672	0.2093	0.2560	1.0×10^{-6}	3.544×10^{-7}	22.2
25.0	0.1198	0.4172	0.5370	1.7×10^{-6}	7.320×10^{-7}	37.8
50.0	0.3051	0.8111	1.116	2.9×10^{-6}	15.01×10^{-7}	64.5
100.0	0.7365	1.525	2.262	5.2×10^{-6}	30.19×10^{-7}	115.5
150.0	1.209	2.210	3.420	7.4×10^{-6}	45.49×10^{-7}	164.4

TABLE X—MIE EXTINCTION PARAMETERS AT 1.88 CM WAVELENGTH (16 GHz), H_2O INDEX OF REFRACTION 7.5—2.5i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.0001035	0.002018	0.002121	0.0×10^{-6}	0.03934×10^{-7}	0.0
1.25	0.001083	0.01299	0.01407	0.1×10^{-6}	0.2410×10^{-7}	1.91
2.5	0.002821	0.02836	0.03118	0.3×10^{-6}	0.5216×10^{-7}	5.74
5.0	0.007659	0.06135	0.06901	0.5×10^{-6}	1.131×10^{-7}	9.56
12.5	0.02667	0.1661	0.1928	1.0×10^{-6}	3.094×10^{-7}	19.1
25.0	0.07037	0.3422	0.4126	1.8×10^{-6}	6.524×10^{-7}	34.4
50.0	0.1853	0.6849	0.8702	3.1×10^{-6}	13.58×10^{-7}	59.2
100.0	0.4643	1.308	1.773	5.5×10^{-6}	27.44×10^{-7}	105.5
150.0	0.7701	1.907	2.678	7.9×10^{-6}	41.31×10^{-7}	151.0

Table XI—Mie Extinction Parameters at 2.73 Wavelength (11 GHz), H_2O Index of Refraction 8.07—1.99i, for Laws and Parsons Rain

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\tilde{m} - 1)$	$Im(1 - \tilde{m})$	
0.25	0.00002176	0.0006630	0.0006630	0.0×10^{-6}	0.01786×10^{-7}	0.0
1.25	0.0002257	0.004325	0.004550	0.1×10^{-6}	0.1123×10^{-7}	1.3
2.5	0.0005954	0.009876	0.01047	0.3×10^{-6}	0.2525×10^{-7}	4.0
5.0	0.001664	0.02377	0.02543	0.5×10^{-6}	0.6008×10^{-7}	6.6
12.5	0.005980	0.07349	0.07947	1.1×10^{-6}	1.844×10^{-7}	14.5
25.0	0.01652	0.1725	0.1890	1.9×10^{-6}	4.330×10^{-7}	25.0
50.0	0.04603	0.3936	0.4396	3.4×10^{-6}	9.956×10^{-7}	44.8
100.0	0.1227	0.8482	0.9710	6.3×10^{-6}	21.80×10^{-7}	83.0
150.0	0.2057	1.303	1.508	8.9×10^{-6}	33.72×10^{-7}	118.7

TABLE XII—MIE EXTINCTION PARAMETERS AT 5.0 CM WAVELENGTH (6 GHz), H_2O INDEX OF REFRACTION 8.670—1.202i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\bar{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\bar{m} - 1)$	$Im(1 - \bar{m})$	
0.25	0.000001855	0.0001138	0.0001156	0.0×10^{-6}	0.05728×10^{-8}	0.0
1.25	0.00001769	0.0005516	0.0005692	0.1×10^{-6}	0.2604×10^{-8}	0.7
2.5	0.00004546	0.001138	0.001183	0.3×10^{-6}	0.5262×10^{-8}	2.2
5.0	0.0001254	0.002589	0.002714	0.5×10^{-6}	1.177×10^{-8}	3.6
12.5	0.0004493	0.007932	0.008380	1.0×10^{-6}	3.554×10^{-8}	7.2
25.0	0.001290	0.02076	0.02205	1.9×10^{-6}	9.200×10^{-8}	13.7
50.0	0.003760	0.05599	0.05975	3.5×10^{-6}	24.63×10^{-8}	25.2
100.0	0.01065	0.1509	0.1615	6.8×10^{-6}	66.19×10^{-8}	49.0
150.0	0.01777	0.2542	0.2720	10.1×10^{-6}	111.4×10^{-8}	80.0

TABLE XIII—MIE EXTINCTION PARAMETERS AT 7.5 CM WAVELENGTH (4 GHz), H_2O INDEX OF REFRACTION 8.77—0.915i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(\text{km})^{-1}$	Absorption Coef. $(\text{km})^{-1}$	Extinction Coef. $(\text{km})^{-1}$	Medium Index of Refraction $\tilde{m}$		Phase Change $\left(\frac{\text{deg}}{\text{km}}\right)$
				$\text{Re}(\tilde{m} - 1)$	$\text{Im}(1 - \tilde{m})$	
0.25	0.0000003639	0.00004853	0.00004889	0.0×10^{-6}	0.03631×10^{-8}	0.0
1.25	0.000003433	0.0002078	0.0002112	0.1×10^{-6}	0.1456×10^{-8}	0.5
2.5	0.000008733	0.0003957	0.0004044	0.3×10^{-6}	0.2712×10^{-8}	1.4
5.0	0.00002337	0.0007859	0.0008092	0.4×10^{-6}	0.5307×10^{-8}	1.9
12.5	0.00008091	0.002002	0.002083	1.0×10^{-6}	1.335×10^{-8}	4.8
25.0	0.0002185	0.004256	0.004474	1.8×10^{-6}	2.823×10^{-8}	8.6
50.0	0.0006030	0.009508	0.01011	3.3×10^{-6}	6.285×10^{-8}	15.8
100.0	0.001629	0.02251	0.02414	6.4×10^{-6}	14.90×10^{-8}	30.7
150.0	0.002705	0.03549	0.03820	9.5×10^{-6}	23.54×10^{-8}	45.6

TABLE XIV—MIE EXTINCTION PARAMETERS AT 10.0 CM WAVELENGTH (3 GHz), H_2O INDEX OF REFRACTION 8.871—0.6280i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\bar{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\bar{m} - 1)$	$Im(1 - \bar{m})$	
0.25	0.0000001149	0.00002309	0.00002320	0.0×10^{-6}	0.02296×10^{-8}	0.0
1.25	0.000001081	0.00009474	0.00009582	0.1×10^{-6}	0.08815×10^{-8}	0.36
2.5	0.000002746	0.0001758	0.0001786	0.2×10^{-6}	0.1599×10^{-8}	0.72
5.0	0.000007326	0.0003369	0.0003443	0.4×10^{-6}	0.3017×10^{-8}	1.44
12.5	0.00002528	0.0008147	0.0008400	1.0×10^{-6}	0.7200×10^{-8}	3.6
25.0	0.00006790	0.001627	0.001696	1.8×10^{-6}	1.430×10^{-8}	6.5
50.0	0.0001857	0.003336	0.003521	3.3×10^{-6}	2.924×10^{-8}	11.9
100.0	0.0004946	0.007142	0.007637	6.2×10^{-6}	6.302×10^{-8}	22.3
150.0	0.0008220	0.01099	0.01181	9.2×10^{-6}	9.729×10^{-8}	33.2

TABLE XV—MIE EXTINCTION PARAMETERS AT 15.0 CM WAVELENGTH (2 GHz), H_2O INDEX OF REFRACTION 8.916—0.4220i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(\mathrm{km})^{-1}$	Absorption Coef. $(\mathrm{km})^{-1}$	Extinction Coef. $(\mathrm{km})^{-1}$	Medium Index of Refraction $\bar{m}$		Phase Change $\left(\frac{\mathrm{deg}}{\mathrm{km}}\right)$
				$\mathrm{Re}(\bar{m} - 1)$	$\mathrm{Im}(1 - \bar{m})$	
0.25	0.002267×10^{-5}	0.9807×10^{-5}	0.9830×10^{-5}	0.0×10^{-6}	0.01459×10^{-8}	0.00
1.25	0.02129×10^{-5}	3.894×10^{-5}	3.916×10^{-5}	0.1×10^{-6}	0.05408×10^{-8}	0.24
2.5	0.05403×10^{-5}	7.087×10^{-5}	7.141×10^{-5}	0.2×10^{-6}	0.09604×10^{-8}	0.48
5.0	0.1439×10^{-5}	13.22×10^{-5}	13.37×10^{-5}	0.4×10^{-6}	0.1760×10^{-8}	0.96
12.5	0.4957×10^{-5}	30.73×10^{-5}	31.23×10^{-5}	1.0×10^{-6}	0.4022×10^{-8}	2.40
25.0	1.328×10^{-5}	58.70×10^{-5}	60.03×10^{-5}	1.8×10^{-6}	0.7612×10^{-8}	4.32
50.0	3.622×10^{-5}	113.2×10^{-5}	116.8×10^{-5}	3.2×10^{-6}	1.456×10^{-8}	7.68
100.0	9.608×10^{-5}	227.4×10^{-5}	237.0×10^{-5}	6.1×10^{-6}	2.941×10^{-8}	14.64
150.0	15.96×10^{-5}	341.7×10^{-5}	357.6×10^{-5}	9.0×10^{-6}	4.429×10^{-8}	21.60

TABLE XVI—MIE EXTINCTION PARAMETERS AT 21.0 CM WAVELENGTH (1.43 GHz), H_2O INDEX OF REFRACTION 9.00—0.275i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$	Medium Index of Refraction $\bar{m}$		Phase Change $\left(\frac{deg}{km}\right)$
				$Re(\bar{m} - 1)$	$Im(1 - \bar{m})$	
0.25	0.0005909×10^{-5}	0.4531×10^{-5}	0.4537×10^{-5}	0.0×10^{-6}	0.009192×10^{-8}	0.0
1.25	0.005543×10^{-5}	1.746×10^{-5}	1.752×10^{-5}	0.1×10^{-6}	0.03347×10^{-8}	0.17
2.5	0.01406×10^{-5}	3.137×10^{-5}	3.151×10^{-5}	0.2×10^{-6}	0.05885×10^{-8}	0.34
5.0	0.03743×10^{-5}	5.774×10^{-5}	5.811×10^{-5}	0.4×10^{-6}	0.1065×10^{-8}	0.68
12.5	0.1288×10^{-5}	13.17×10^{-5}	13.30×10^{-5}	1.0×10^{-6}	0.2390×10^{-8}	1.71
25.0	0.3449×10^{-5}	24.66×10^{-5}	25.01×10^{-5}	1.8×10^{-6}	0.4431×10^{-8}	3.09
50.0	0.9399×10^{-5}	46.29×10^{-5}	47.23×10^{-5}	3.2×10^{-6}	0.8237×10^{-8}	5.50
100.0	2.491×10^{-5}	90.75×10^{-5}	93.24×10^{-5}	6.1×10^{-6}	1.619×10^{-8}	10.5
150.0	4.138×10^{-5}	134.8×10^{-5}	139.0×10^{-5}	8.9×10^{-6}	2.408×10^{-8}	15.3

TABLE XVII—MIE EXTINCTION PARAMETERS AT 0.6328 μ WAVELENGTH, H_2O INDEX OF REFRACTION 1.33—0.0i, FOR LAWS AND PARSONS RAIN

Rain Rate (mm/hr)	Scattering Coef. $(km)^{-1}$	Absorption Coef. $(km)^{-1}$	Extinction Coef. $(km)^{-1}$
0.25	0.08093	0.00	0.08093
1.25	0.2482	0.00	0.2482
2.5	0.3977	0.00	0.3977
5.0	0.6519	0.00	0.6519
12.5	1.273	0.00	1.273
25.0	2.069	0.00	2.069
50.0	3.221	0.00	3.221
100.0	5.689	0.00	5.689
150.0	8.046	0.00	8.046

decreased from 21 to 0.1 cm. This phenomenon is also illustrated in Fig. 26 of a paper previously presented in this journal by Chu and Hogg (1968).[9] It serves to warn the reader that he should be very careful when applying the common rules of thumb relating wavelength and attenuation.

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