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EHF Attenuation Derived from Emission Temperatures in Light Rain

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EHF attenuation derived from emission temperatures in light rain

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Volume 1

EHF attenuation from emission measurements in rain
Scattering in rain
Emission from rain at EHF
Rain attenuation at EHF

Atmospheric emission measurements have routinely been used to determine the total attenuation on an earth-space path at the centimeter and millimeter wavelengths. In the presence of rain, scattering effects have to be taken into account at frequencies > 20 GHz when one interprets emission data to derive the total attenuation. If one uses the radiometric relation to derive the attenuation, assuming an absorptive medium, one finds that the predicted attenuation underestimates the true attenuation. The reason for
ABSTRACT (Continued)

...this is that the rain scatters more emission energy out of the direct ray path than into it. Calculations of the atmospheric emission temperature and attenuation in light-to-moderate rain at different frequencies and rain rates are performed, taking into account molecular absorption, and varying cloud cover and ground temperature. The results show that for typically encountered meteorological conditions, the radiometric formula can be used to derive the total attenuation (< 10 dB) from emission measurements with accuracies of the order less than 1 dB, provided that the empirical constant in the radiometric formula, dependent on the ambient temperature, is a function of frequency and ground temperature.
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I. INTRODUCTION

Atmospheric emission measurements have been used to determine the total attenuation in rain on an earth-to-space path at the centimeter and millimeter wavelengths (Wilson, 1969; Wulfsberg and Altshuler, 1972; Meyerhoff et al., 1974; Hogg and Chu, 1975; Meyerhoff, 1975; Brussaard, 1977; Lin et al., 1979; Ishakov et al., 1980; Babkin et al., 1982). If the propagating medium is entirely absorptive, the attenuation can be obtained by inverting the equation of radiative transfer, which, for radio wavelengths, can be expressed as

\[ T_e = \int_0^{\tau_0} T_0 e^{-\tau} \, d\tau \]  \hspace{1cm} (1)

where \( T_e \) is the measured emission temperature, \( T \) is the temperature of the medium, \( \tau \) is the opacity (\( d\tau = \alpha dx \)), \( \alpha \) is the absorption coefficient, and \( x \) is the distance along the ray path. If \( T \) is a constant, \( T_0 \) [Eq. (1)] reduces to the usual radiometric formula

\[ T_e = T_0 \left(1 - e^{-\tau_0}\right) \]  \hspace{1cm} (2)

and the total opacity is given by

\[ \tau_0 = \ln\left(\frac{T_0}{T_0 - T_e}\right) \]  \hspace{1cm} (3)

and \( A \), the attenuation in decibels, is given by \( 4.34 \tau_0 \). In the atmosphere, the temperature changes with height, but not by a large percentage (typically less than 10%) in the region where most of the attenuation takes place. Thus, in practice, an effective medium temperature \( T_m \) is used, and Eq. (3) gives a good measure of the atmospheric attenuation, with errors typically less than 1 dB, in the range of attenuations less than 12 dB. \( T_m \) is substituted for the term \( T_0 \) in the equation.

In the presence of rain, scattering effects have to be taken into account at frequencies \( > 20 \) GHz when one interprets emission data to derive the total
attenuation. The relative significance of the scattering effects can be seen in Fig. 1, which shows the absorption-to-extinction ratio as a function of frequency in light-to-moderate rain, assuming a Marshall-Palmer [1948] drop-size distribution. Zavody [1974] showed that, at millimeter wavelengths, attenuations derived from emission observations can be significantly low if the attenuation in rain is assumed to be due only to absorption. Calculations of atmospheric emission in rain were made at 37, 72, and 110 GHz at three elevation angles, taking into account multiple scattering, including ground contributions. An isothermal atmosphere (273 K) was assumed, with a 3-km-thick rain layer. The ground temperature was the same as the atmosphere. In the calculation, molecular — but not cloud — effects were included.

Chadha and Lane [1977] used a sun-tracking 37-GHz radiometer to measure the attenuation during rain, first directly, using the sun as a source, and second, using emission measurements. They found that the attenuations derived from the emission measurements, assuming a purely absorptive medium, underestimated the true attenuation by 10 to 15% for vertical polarization and by 30 to 35% for horizontal polarization at elevation angles in the range of 10 to 35 degrees. These results are in reasonable agreement with the predictions of Zavody [1974] for horizontal polarization, but the theory overestimates the attenuation for vertical polarization.

Ishimaru and Cheung [1980] calculated atmospheric emission in rain from the equation of radiative transfer using a scattering matrix approach. They calculated the emissions for vertical and horizontal polarizations at 30, 60, 90, and 120 GHz (at various elevation angles and for rainfall rates of 0.25 and 12.5 mm/hr) for 1-km and 3-km rain layers, assuming a constant rain temperature of 273 K. The ground temperature was 283 K, with an albedo of 0.5. Molecular and cloud effects were not included in the formulation. The results are in good agreement with the measurements of Chadha and Lane [1977]. In the papers by Zavody [1974] and Ishimaru and Cheung [1980], a Laws-Parsons [1943] drop-size distribution was assumed for rain.

In this report we calculate the atmospheric emission and attenuation at various frequencies in light-to-moderate rain, and investigate the errors in
Fig. 1. Curves showing the ratio of the absorption ($Q_a$) to extinction ($Q_e$) coefficients for rain, assuming a Marshall-Palmer drop-size distribution. Curves are shown for two rain rates, $R = 0.25$ and $R = 10$ mm/hr.
the attenuation derived from emission measurements when the weather conditions and measurement geometry vary. A stratified atmosphere is assumed.
II. FORMULATION

The atmospheric model used in the calculations is shown in Fig. 2. The
mission temperatures are computed at zero height from a zenith direction,
The ground has unit emissivity at a temperature $T_g$. The atmospheric tem-
perature is $T_g$ at $h = 0$ and decreases linearly at a rate that gives a tem-
perature of 273 K at $h_1$ ($h_1 = 3$ km), which height is the top of the rain layer
and bottom of the clouds. The top of the cloud layer is at $h_2$ ($h_2 - h_1 = 1$
m), and the cloud liquid-water content is LWC. At the wavelengths con-
dered, the cloud medium is absorptive, and the expression for attenuation is
given by Gunn and East [1954], as

$$\alpha_c = 8.186 \frac{\text{LWC}}{\lambda} \text{Im} \left( -\frac{m^2 - 1}{m^2 + 2} \right) \text{dB/km} \quad (4)$$

where Im means the imaginary part, LWC is the liquid content in g/m$^3$, $\lambda$ is the
wavelength in cm, and $m$ is the complex index of refraction for liquid water at
273 K. The pressure is 1013 mb at the surface and drops off exponentially
with a scale height of 8.4 km. The water vapor density was assumed to be that
for a 100 percent relative humidity at all heights. The oxygen absorption was
simply characterized with two lines of equal linewidth, one centered at zero
frequency and one centered at 60 GHz [Van Vleck, 1947] using the Van Vleck-
Weisskopf [1945] lineshape and line parameter constants of Ho et al. [1972].
The absorption coefficient for water vapor was calculated from the formula of
Waters [1976]. The oxygen line at 118 GHz and the water vapor line at 183 GHz
were not included in the formulation, since these lines had negligible effect
on the attenuations at the frequencies where the computations were made. The
molecular effects are included from the surface to a height of 5 km. The rain
layer was assumed to be of infinite horizontal extent and the index of refrac-
tion of the rain droplets was given by the formula of Ray [1972] for liquid
water at a temperature $T = \frac{1}{2}(T_g + 273)$.

The procedure for calculating the emission temperature follows that given
by Zavody [1974]. The main differences are that in this report, a linear
y Oguchi [1960, 1964], and subsequently by others. The differential attenuation of horizontally and vertically polarized waves through rain is a function of frequency, rain rate, and elevation angle. From the results of Morrison and Chu [1973] and Chu [1974] for the meteorological conditions considered in this study, the largest differential attenuation occurs for $R = 10$ mm/hr at 44 GHz, and amounts to $\sim 0.4$ dB/km. If accuracies in the determination of the attenuation of the order of 1 dB are satisfactory, it appears that from estimates of the rain rate and rain height, the differential attenuation corrections as calculated by Morrison and Chu [1983] and Chu [1974] can be applied to the unpolarized results and correct for the effect of non-spheroidal drops on polarized waves.

The results of this study can be applied to the 37-GHz attenuation measurements of Chadha and Lane [1977]. In Fig. 8 are shown the best-fit curves for the measured attenuations for horizontal and vertical attenuations. The bottom curve is the predicted attenuation, and uses the radiometric formula and a value of $T_m$ estimated from local meteorological data (based on temperature and type of rainfall). The values of $T_m$ used were in the range 273 to 280 K. From Eq. (7), the modified values of $T_m$ at 37 GHz are 261 K and 265 K for ground temperatures of 273 K and 280 K, respectively. Using the modified values of $T_m$ obtained from Eq. (7), the predicted attenuations for unpolarized signals are plotted as range bars, using the measured emission data of Chadha and Lane [1977]. It is seen that there is a reasonably good agreement between the measurements and the predicted attenuations from this study.
The column marked $\sigma$ is the standard deviation of the $T_m$'s in the attenuation range between 9 and 11 dB. At 10 and 16 GHz, the attenuations are less than 9 dB in all cases, and no entries for this parameter are given for these frequencies. The derivative $\frac{dA}{dT_m}$ gives the sensitivity of the derived attenuation to errors in $T_m$. For $T_m = 273$ K and $A = 10$ dB, $|\frac{dA}{dT_m}| = 0.14$ dB/K, indicating that for the conditions here, emission measurements can be used to determine atmospheric attenuations at EHF, i.e. the range less than 10 dB, with standard errors less than 1 dB.

If the meteorological conditions encountered in practice generate $T_m$'s with greater variabilities than those modeled in this study, the errors in the derived attenuations will be correspondingly greater. If this occurs, in order to improve the accuracy in the determination of the attenuation using emission measurements, the value of $T_m$ will have to be more accurately determined. Information about the rain rate, rain height, elevation angle, and cloud liquid-water content could be utilized. The elevation angle and surface rain rate are directly measurable, but the integrated rain rate, rain height, and cloud LWC can only be estimated indirectly. Estimates or perhaps bounds of the LWC, the rain height, and the integrated rain rate can be obtained from the surface rain rate and from statistical weather data of the particular geographic location, or from multifrequency emission measurements. Utilization of these data will decrease the errors in the attenuation by the determination of a better estimate of $T_m$ in the radiometric relation.

There is one further correction that has to be applied, and that is for polarization. The calculations here have been performed for spherical rain drops and for unpolarized signals. The fact is that rain drops falling at their terminal velocity are not spherical but are approximately oblate spheroids, [Pruppacher and Pitter, 1971] and, in atmospheric conditions, the major axes of the droplets are canted at some small angle from the horizontal. The result is that on a propagation path in the atmosphere through rain, horizontally polarized signals are attenuated more strongly than vertically polarized signals. The effect of oblate raindrops on propagation was first studied
The values of the derived $T_m$ do not have much scatter for $f < 20$ GHz, and one can conclude that radiometric measurements will be most accurate for determining attenuation at these frequencies. For $f > 30$ GHz, there is increased scatter, with a corresponding decrease in the accuracy. A measure of the accuracy of the emission method for the determination of attenuation is given by the standard deviation of $T_m$. The plots show a dependence on $T_g$ for which a correction can be applied, and the statistics given will be derived for the cases where $T_g = 290$.

For the meteorological conditions considered in this study, emission measurements can be used to determine the atmospheric attenuation in rain at EHF within 1 dB for zenith angles less than 70 degrees, and for attenuation levels less than 10 dB. In order to accomplish this, the parameter $T_m$ in Eq. (3) needs to be a function of frequency and ground temperature. A simple form is given by

$$T_m(f, T_g) = T_1(f) + 0.6(T_g - 290) \quad (7)$$

In Table 1, the values of $T_1(f)$ derived for the stated meteorological conditions are listed. The attenuations for 220 GHz were greater than 10 dB in all cases, and the parameters for this frequency were not included in the table.

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>$T_1(f)$</th>
<th>$\sigma$ (9 &lt; $A$ &lt; 11 dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>274</td>
<td>1.1</td>
</tr>
<tr>
<td>30</td>
<td>272</td>
<td>2.1</td>
</tr>
<tr>
<td>44</td>
<td>271</td>
<td>3.2</td>
</tr>
<tr>
<td>90</td>
<td>268</td>
<td>2.0</td>
</tr>
<tr>
<td>140</td>
<td>272</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Fig. 6. Derived $T_m$'s for the calculated emission temperatures and attenuations.
Fig. 5. Derived $T_m$'s for the calculated emission temperatures and attenuations.
Fig. 4. Derived $T_m$'s for the calculated emission temperatures and attenuations.
and 12 dB, respectively. Suppose, for a given application, attenuations up to, say, a maximum of 10 dB are to be determined by radiometric measurements. Then, the best fit $T_m$ for the 10-dB level should be used in the radiometric formula. This minimizes the error at the maximum attenuations, noting that errors in the attenuation at the lower levels are not as sensitive to improper values of $T_m$.

In Figs. 4-7 are plotted the values of $T_m$ (for $A < 15$ dB and $z < 70$ degrees) for the different frequencies. These $T_m$'s are derived from the calculated attenuations and emission temperatures using the radiometric formula, for the five cases listed above. The scatter in $T_m$ gives an indication of the accuracy with which atmospheric attenuations can be determined by emission measurements. In the plots the crosses are obtained from cases 1, 2, and 3, those cases with different cloud covers but with the same ground temperature $T_g = 290$ K. The triangles and boxes are obtained from cases 4 and 5, respectively.

A few observations can be made about emission temperatures in rain. The variation in emission temperature for the same attenuation increases as the scattering effects increase. In the frequency range between 20 and 140 GHz, the scattering-to-extinction ratio for rain changes significantly as the rain rate increases from 0.25 to 10 mm/hr (see Fig. 1). The relatively high values of $T_m$ in this frequency range for low attenuations occur at $R = 0.25$. At this rain rate the attenuation due to absorption dominates and the emission temperature is highest for a given attenuation. As the rain rate increases, the scattering effects increase and $T_m$ decreases. When the scattering effects are significant, say $Q_s/Q_e > 0.3$ where $Q_s$ and $Q_e$ are the rain scattering and extinction coefficients, respectively, clouds can noticeably affect the value of $T_m$ which satisfies the radiometric relation. If the cloud absorption is a sizable fraction of the total attenuation, a significant fraction of the cloud emission gets scattered out of the direct ray path without fully compensating multiple scattering contributions, and lower values of $T_m$ result. The lowest values of $T_m$ in the plots occur for low rain rates, the largest LWC, and at the largest secant angles.
energy scattered out of the direct ray path is greater than the energy scattered into it. This is the reason the use of the radiometric formula in rain conditions will underestimate the true attenuation if one assumes the medium to be absorptive. This has been noted in previous studies (e.g., Wilson, 1969; Gray, 1972; Zavody, 1974; Hogg and Chu, 1975). If, for the given meteorological conditions, one is able to determine an effective radiometric medium temperature $T_m$, somewhat smaller than that derived for an absorptive medium, then emission measurements can be used to determine the atmospheric attenuation with sufficient accuracy, for certain applications.

The calculations show that if the radiometric relation given by Eq. (3) is to be used to determine the attenuation accurately in all conditions for a large range of attenuations, the parameter $T_m$, used in place of $T_0$ in Eq. (3), cannot be a constant, but is a function of frequency, rain rate, rain height, elevation angle, cloud cover, and ambient temperature. In practice, it would be desirable to have $T_m$ dependent on as few parameters as possible, and in addition, these parameters should be measurable, or known quantities. Of the above quantities, the frequency, the elevation angle, and the ground temperature can be measured, whereas the integrated rain rate along the ray path, and the LWC in the clouds, are not directly measurable. So at most, $T_m$ should be a function of frequency, zenith angle, and ground temperature. The errors in the attenuation derived from Eq. (3) arise from errors in the measurement of $T_e$ and from using the wrong value of $T_m$ in the radiometric formula.

With the present technology, well-designed radiometers at EHF have sensitivities and uncertainties in the absolute calibrations, which are less than 1 K for a one-second integration time. Therefore, the significant errors in the attenuations derived from emission measurements will not arise from the measurements themselves, but rather from the variability in the measurement geometry and in the meteorological conditions, which factors determine the proper value of $T_m$ in the radiometric formula. For a given error in $T_m$, the error in the derived attenuation depends on the attenuation level. For example, for $T_m = 273$ K, in using Eq. (3), a 5-K error in $T_m$ gives errors of 0.05 dB, 0.65 dB, and 1.0 dB in the attenuation at levels of 2 dB, 10 dB,
Fig. 3. Calculated emission temperatures and zenith attenuations.
III. RESULTS

The emission temperatures and attenuations of the atmosphere were calculated at zenith angles from 0 to 90 degrees, in 10 degree increments, at 10, 16, 20, 30, 44, 90, 140, and 220 GHz, for rain rates 0.25, 0.5, 1, 2, 4, 6, 8, and 10 mm/hr, for the following cases: (1) $T_g = 290$, $LWC = 0.3$; (2) $T_g = 290$, $LWC = 0.6$; (3) $T_g = 290$, $LWC = 1.2$; (4) $T_g = 283$, $LWC = 0.3$; and (5) $T_g = 303$, $LWC = 0.3$. We are primarily interested in the EHF region, but calculations at 10, 16, and 20 GHz are included for comparisons.

A plot of the calculated emission temperatures and attenuations in the zenith direction, as a function of frequency, for four of the rain rates for case 2 is shown in Fig. 3. Although the calculations were made at the eight discrete frequencies, smooth curved segments were drawn in the vicinity of these frequencies to indicate the trend and to help distinguish the curves of the different rain rates. Also shown in the attenuation plots are the fractional contributions of the molecular and cloud absorptions to the total attenuation for 44, 90, 140, and 220 GHz. The oxygen absorptions at these frequencies are relatively small, and are depicted by pedestals on the vertical lines marked $A_m$, the total molecular absorption. At the lower rain rates the cloud and molecular absorption are the main causes of attenuation and must be taken into account in the design of EHF satellite communication systems with small link margins.

In rain, a fraction of the energy emitted by the absorbing particles directly at the radiometer gets scattered out of the path and does not contribute to the measured emission temperature. However, the rain also scatters energy, including that from the ground, into the direct ray path, and the application of the radiometric formula for accurate attenuation measurements depends on the relative quantities of the two scattered energies described above, for different conditions. In typical meteorological conditions with rain, the emission temperature will be less than that obtained from a completely absorbing medium with the same total attenuation. In other words, the
subdivision and self checking. Two-dimensional cubic splines are then used to approximate the function at arbitrary angles. Further simplifications are obtained by taking advantage of the assumed infinite horizontal extent of the rain, and cylindrical symmetry can be utilized. Also, the computations can be reduced by one fourth, by noting the following symmetries:

\[
S(\theta, \zeta) = S(\zeta, \theta) \\
S(\theta, \zeta) = S(\pi - \zeta, \pi - \theta)
\]  

(6)
temperature gradient from the ground to the freezing level is assumed, and cloud effects are included. The formulation of Deirmendjian [1963] was used to calculate the scattering coefficients. The calculations are done for unpolarized radiation. Briefly, the emission temperature at each zenith angle \( z \) is given by

\[
T_e(z) = \Sigma_{n=0}^{\infty} T^{(n)}_A(z) + \Sigma_{n=1}^{\infty} T^{(n)}_G(z)
\]

(5)

where the first summation includes the temperature contributions from absorbers in the atmosphere, and the second summation gives the ground contributions scattered into the antenna beam. \( T^{(0)}_A(z) \) is the temperature contribution of all absorbers in the direct ray path, extincted by absorption and scattering. The terms, \( T^{(n)}_A(z) \), for \( n > 1 \), are the temperature contributions from energy scattered \( n \) times before it enters the antenna from the zenith direction \( z \). Included are the emissions from the cloud layer and molecules above the rain, which get scattered within the rain layer. \( T^{(n)}_G(z) \) are contributions resulting from ground emission multiply scattered by the rain. In the summations, all temperature contributions greater than 0.1 K are included.

At the higher frequencies and rain rates, up to eleven orders of scattering have to be taken into account. The computations were done in the following way. Given the physical properties of the rain, the scattering coefficient at a point is a function of a single variable, the scattering angle \( \gamma \). This angle \( \gamma \), in turn, can be expressed as a function of three angles at the scatterer: \( \theta \), the angle between the zenith and the incident ray; \( \zeta \), the angle between the zenith and the scattered ray; and \( \phi \), the azimuthal angle between the incident and scattered ray. The scattering coefficient is then made independent of \( \phi \) by integrating over \( 2\pi \), and is designated by \( S(\theta, \zeta) \).

In the multiple-scattering computations, the function \( S(\theta, \zeta) \) is used over and over again, and the computational time was reduced by the following procedure. \( S(\theta, \zeta) \) is a smooth function and is evaluated every 10 deg in both the \( \theta \) and \( \zeta \) directions by using two-point Gaussian quadrature with interval
Fig. 2. Schematic of the rain model used for the emission and attenuation calculations.
Fig. 8. Comparison of the predicted attenuations from the results of this study and the measurements of Chadha and Lane [1974].
IV. CONCLUSIONS

If emission measurements are used to determine atmospheric attenuation at EHF in rain, scattering effects must be taken into account when applying the radiometric formula to derive the attenuations. In order to obtain the attenuation from the radiometric formula in all conditions for a large range of attenuations, the effective medium temperature $T_m$ cannot be a constant but is a function of frequency, rain rate, rain height, elevation angle, cloud cover, and ambient temperature. However, for applications requiring the determination of attenuations less than $10 \, \text{dB}$ with accuracies of the order of $1 \, \text{dB}$, the use of a $T_m$ in the radiometric formula which is a simple function of frequency and ground temperature will suffice, at least for the conditions considered in this study. The results are in agreement with reported measurements.
REFERENCES


LABORATORY OPERATIONS

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