Microwave Noise Temperature and Attenuation of Clouds at Frequencies Below 50 GHz

Stephen D. Slobin

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National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
ABSTRACT

The microwave attenuation and noise temperature effects of clouds can result in serious degradation of telecommunications link performance, especially for low-noise systems presently used in deep-space communications. Although cloud effects are generally less than rain effects, the frequent presence of clouds will cause some amount of link degradation a large portion of the time.

This report presents a general review of cloud types, water particle densities, radiative transfer, attenuation and noise temperature calculations, and examples of basic link signal-to-noise ratio calculations. The results of calculations for twelve different cloud models are presented for frequencies of from 1 to 50 GHz and elevation angles of 30-degrees and 90-degrees. These case results may be used as a handbook to predict noise temperature and attenuation values for known or forecast cloud conditions.
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INTRODUCTION

Microwave propagation through the earth's atmosphere is affected adversely by the presence of rain and clouds. As communications systems operate at higher and higher frequencies (greater than 30 GHz), attenuation and noise temperature effects become increasingly severe. Although rain effects are generally greater than those of clouds, rain occurs less than about five-percent of the time. Clouds, on the other hand, may be present fifty-percent of the time as a yearly-average or continuously for periods of weeks on end. Thus, the integrated cloud effects (dB-hours or Kelvin-hours) may be much larger than those for rain.

Compared to rain studies, little has been done to characterize the statistics of cloud effects. Clearly, the best method of determining noise temperature statistics is to go out and measure noise temperature! Lacking the resources and equipment to do this, an alternative method is to draw upon the vast amount of historical weather data (surface observations, radiosonde profiles, pilot reports, etc.) and turn this real weather data into estimates of noise temperature and attenuation. To this end, a cloud model and computational scheme have been developed to calculate attenuation and noise temperature using real weather observations as program inputs. Forecasts of real weather parameters can also be used to give forecasted cloud effects, using this model.

This report presents a general discussion of cloud characteristics and the computational model. Sample case calculations for twelve specific cloud cases are given for a frequency range of 1 to 50 GHz. Future work will involve calculation of cloud effect statistics based on real weather observations at numerous locations throughout the United States.
I. CLOUD DESCRIPTIONS

A cloud may be described as a random distribution of liquid water particles above the ground having diameters of from 0 to 100 microns (\(\mu m\)). For comparison, raindrops have a size distribution of approximately 100 microns (0.1 mm) to 3 mm (Refs. 1 and 2). Rare cases will be found where particle sizes will be outside the ranges stated. Clouds are not water vapor, which is a clear, colorless gas, like oxygen and nitrogen, although the relative humidity is usually 100% within the cloud. Clouds can exist at high temperatures (+20°C) as well as at temperatures below freezing (-10°C) where they remain liquid (supercooled) and pose a great icing threat to aircraft penetrating them. High-level clouds, such as cirrus, are composed of ice crystals and will not generally be found at temperatures above -12°C. (Ref. 2)

Figure 1 (Ref. 3) and Table 1 (Ref. 3) show typical model cloud drop spectra for different cloud types. These spectra may be integrated over the range of cloud drop radii (\(~0\) to 30 microns) to determine the average cloud density and average drop diameter for the various cloud types. Table 2 gives the results of these calculations for the cloud types of Ref. 3. The spectra in Figure 1 are for illustrative purposes only.
FIGURE 1. MODEL CLOUD DROP SPECTRA
(after Carrier, et al., Ref. 3)
### Table 1. Model Cloud Drop Size and Concentration

(after Carrier, et al, Ref. 3)

<table>
<thead>
<tr>
<th>CLOUD TYPE</th>
<th>N</th>
<th>r\text{mode}</th>
<th>r\text{min}</th>
<th>r\text{max}</th>
<th>\Delta r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratus I</td>
<td>464</td>
<td>3.5</td>
<td>0</td>
<td>16.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Altostratus</td>
<td>450</td>
<td>4.5</td>
<td>0</td>
<td>13.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Stratocumulus</td>
<td>350</td>
<td>3.5</td>
<td>0</td>
<td>11.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Nimbostratus</td>
<td>330</td>
<td>3.5</td>
<td>0</td>
<td>19.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Fair-weather cumulus</td>
<td>300</td>
<td>3.5</td>
<td>0.5</td>
<td>10.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Stratus II</td>
<td>260</td>
<td>4.5</td>
<td>0</td>
<td>20.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Cumulus congestus</td>
<td>207</td>
<td>3.5</td>
<td>0</td>
<td>16.2</td>
<td>6.7</td>
</tr>
<tr>
<td>Cumulonimbus</td>
<td>72</td>
<td>5.0</td>
<td>0</td>
<td>30.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

N = total concentration, no./cm³

r\text{mode} = radius corresponding to the maximum number of droplets, microns

r\text{min} = minimum radius, microns

r\text{max} = maximum radius, microns

\Delta r = bandwidth of the drop-size distribution at half-value points, microns
### TABLE 2

**SUMMARY OF CLOUD MODEL DENSITIES AND AVERAGE RADII**

<table>
<thead>
<tr>
<th>#</th>
<th>CLOUD TYPE</th>
<th>CONCENTRATION (no/cm³)</th>
<th>DENSITY (g/m³)</th>
<th>AVERAGE RADIUS (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>STRATUS I</td>
<td>464</td>
<td>0.27</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>STRATOCUMULUS</td>
<td>350</td>
<td>0.16</td>
<td>4.8</td>
</tr>
<tr>
<td>3</td>
<td>FAIR-WEATHER CUMULUS</td>
<td>300</td>
<td>0.15</td>
<td>4.9</td>
</tr>
<tr>
<td>4</td>
<td>STRATUS II</td>
<td>260</td>
<td>0.49</td>
<td>7.6</td>
</tr>
<tr>
<td>5</td>
<td>CUMULONIMBUS</td>
<td>72</td>
<td>0.98</td>
<td>14.8</td>
</tr>
<tr>
<td>6</td>
<td>CUMULUS CONGESTUS</td>
<td>207</td>
<td>0.67</td>
<td>9.2</td>
</tr>
<tr>
<td>7</td>
<td>NIMBOSTRATUS</td>
<td>330</td>
<td>0.99</td>
<td>9.0</td>
</tr>
<tr>
<td>8</td>
<td>ALTOSTRATUS</td>
<td>450</td>
<td>0.46</td>
<td>6.2</td>
</tr>
</tbody>
</table>
The stratus I cloud is based on observations taken off the coast of California. Stratus II is found over land. The altostratus and stratocumulus clouds observed had bases approximately 2000 meters above ground and tops up to 4000 meters above ground, with a typical thickness of 1800 meters. For reference, the standard temperature at 4000 meters above sea level is about -5°C. It is suggested in Ref. 2 that the drop size spectra for nimbostratus and fair-weather cumulus be used for altocumulus clouds. A standard pictorial listing of cloud types is given in the U.S. National Weather Service Cloud Code Chart (Ref. 4). The clouds portrayed on the chart conform to the standard types approved by the World Meteorological Organization and serve as a common point of reference for use in cloud observations and predictions.

Although Table 2 shows cloud densities of less than 1 g/m³, several investigators (Ref. 2) have observed cloud densities of up to 10 g/m³. Convective type clouds (cumulus, cumulonimbus) in the summer have maximum water contents of 3 (cumulus humilis) to 10 (cumulonimbus) g/m³, although for clouds with large vertical development (cumulonimbus exceeding 10 km in height), there is some question as to the relative proportions of actual cloud particles and suspended precipitation particles.

Four cloud models used by other investigators (Ref. 5) are summarized in Table 3. These models are consistent with descriptions above, except in the case of altostratus clouds.
### TABLE 3

**CLOUD MODELS USED IN REFERENCE 5**

<table>
<thead>
<tr>
<th>TYPE</th>
<th>MODEL 1</th>
<th>MODEL 2</th>
<th>MODEL 3</th>
<th>MODEL 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASES*</td>
<td>COASTAL STRATUS</td>
<td>STRATO-CUMULUS</td>
<td>STRATO-CUMULUS</td>
<td>ALTO-STRATUS</td>
</tr>
<tr>
<td>TOPS*</td>
<td>0.500 km</td>
<td>1.000 km</td>
<td>1.000 km</td>
<td>2.500 km</td>
</tr>
<tr>
<td>WATER DENSITY</td>
<td>0.33 g/m³</td>
<td>0.33 g/m³</td>
<td>0.20 g/m³</td>
<td>0.15 g/m³</td>
</tr>
</tbody>
</table>

*above ground level*
Table 4 (Ref. 6) gives typical fog and cloud models which are representative of midlatitude conditions. This table is of particular interest because of its listing of cloud bottom and top heights.

The term "precipitable water" is used to describe the total amount of water through which one looks along a path through the entire atmosphere. Precipitable water has the units g/cm$^2$, or simply cm (i.e., 1 cm$^3$ of water weighs 1 g.). For a cloud with a density of 1 g/m$^3$, 1 km thick, the precipitable water (vertically) is 0.1 g/cm$^2$ or 0.1 cm. By comparison, a typical value of precipitable water vapor is 1.5 g/cm$^2$ along a vertical path through the entire atmosphere.
### TABLE 4. TYPICAL FOG AND CLOUD MODELS

(Ref. 6)

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>Density ((g/m^3))</th>
<th>Heights above ground ((m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Fog 1</td>
<td>0.37</td>
<td>0</td>
</tr>
<tr>
<td>Heavy Fog 2</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>Moderate Fog 1</td>
<td>0.06</td>
<td>0</td>
</tr>
<tr>
<td>Moderate Fog 2</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>Cumulus</td>
<td>1.00</td>
<td>660</td>
</tr>
<tr>
<td>Altostratus</td>
<td>0.41</td>
<td>2400</td>
</tr>
<tr>
<td>Stratocumulus</td>
<td>0.55</td>
<td>660</td>
</tr>
<tr>
<td>Nimbostratus</td>
<td>0.61</td>
<td>160</td>
</tr>
<tr>
<td>Stratus</td>
<td>0.42</td>
<td>160</td>
</tr>
<tr>
<td>Stratus</td>
<td>0.29</td>
<td>330</td>
</tr>
<tr>
<td>Stratus-Stratocumulus</td>
<td>0.15</td>
<td>660</td>
</tr>
<tr>
<td>Stratocumulus</td>
<td>0.30</td>
<td>160</td>
</tr>
<tr>
<td>Nimbostratus</td>
<td>0.65</td>
<td>660</td>
</tr>
<tr>
<td>Cumulus-Cumulus Congestus</td>
<td>0.57</td>
<td>660</td>
</tr>
</tbody>
</table>
II. ABSORPTION AND SCATTERING EFFECTS

The total attenuation (or extinction) of a radio wave by a cloud is the sum of the absorption and scattering by particles in the cloud. Absorption of microwave energy by a cloud particle heats it up slightly, and it then re-radiates isotropically (equally in all directions) with an emissivity less than 1.0 at its particular physical temperature. Scattering results in a re-direction of the incident energy so that it does not arrive at its "straight line" destination. Scattering in certain directions is enhanced depending on the wavelength of incident energy, particle size distribution, and dielectric constant of the scattering particles. Scattering may be advantageous for some applications, such as in troposcatter communication systems.

The absorbed energy is lost and does not contribute to the noise temperature (power) received by a radiometer. The absorbing medium itself does radiate power into the receiver and contributes to the total system noise temperature. This is discussed further in Sections III and IV.

A good general description of scattering by water and ice particles is found in Battan (Ref. 7), who draws on the original work of Mie (Ref. 8). A detailed discussion of scattering theory is beyond the scope of this survey article, but for the case of microwave radiation (1 to 50 GHz for communications bands) and cloud particles (diameters 1 to 100 microns) certain computational simplifications become possible.
A common parameter used in scattering calculations is

\[ \alpha = \frac{2\pi a}{\lambda} \]

where \( a \) = drop radius \\
\( \lambda \) = wavelength of incident radiation

For the case \( \alpha \ll 1 \), the scattered component of the incident radiation is small compared to the absorptive component; and the total attenuation (extinction) is due to absorption. For the shortest wavelength (0.6 cm for 50 GHz) and the largest cloud drop diameter (100 microns), \( \alpha = 0.052 \), which satisfies the relationship \( \alpha \ll 1 \). Using the cloud drop spectrum suggested by Diermendjian (Ref. 9), Dutton and Dougherty (Ref. 10) make the argument that even for frequencies as high as 350 GHz (\( \lambda = 0.086 \text{ cm} \)) "Rayleigh" approximations are valid (see Battan, Ref. 7) and extinction of microwave energy is almost entirely due to absorption.

The attenuation of cloud drops is given by (Ref. 7, Eqn. 6.14):

\[ k_C = \left[ 0.4343 \frac{6\pi}{\lambda} \text{Im}\left\{\frac{-1}{m^2+1}\right\} \right] M \]

\[ = k_1 M \]

where \( m \) = complex index of refraction of water, function of temperature and wavelength \\
\( M \) = density of cloud water particles, g/m^3 \\
(range ~ 0 to 10 g/m^3)
Values of $K_1$, taken from Gunn and East (Ref. 11) are given in Table 5. Bean and Dutton (Ref. 12) also use these values in their discussion of cloud attenuation.

**TABLE 5**

One-Way Attenuation Coefficient, $K_1$, in Clouds, dB/km/g/m$^3$
(from Gunn and East, Ref. 11)

<table>
<thead>
<tr>
<th>TEMPERATURE ($^\circ$C.)</th>
<th>WAVELENGTH (Cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9(33.31GHz)</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>20....</td>
<td>0.647</td>
</tr>
<tr>
<td>10....</td>
<td>0.681</td>
</tr>
<tr>
<td>0....</td>
<td>0.99</td>
</tr>
<tr>
<td>- 8....</td>
<td>1.25</td>
</tr>
<tr>
<td>Ice</td>
<td></td>
</tr>
<tr>
<td>0....</td>
<td>8.74X10^-3</td>
</tr>
<tr>
<td>-10....</td>
<td>2.93X10^-3</td>
</tr>
<tr>
<td>-20....</td>
<td>2.0 X10^-3</td>
</tr>
</tbody>
</table>

Note that ice clouds have attenuation coefficients about two orders of magnitude less than water clouds. Their attenuation (absorption) effects may be neglected as long as the ice particles continue to satisfy the relationship $\alpha \ll 1$. In the absence of liquid water clouds, scattering by ice clouds will be the only contribution to signal attenuation.
Rather than using the tabulated cloud attenuation values (Table 5), a convenient expression to use for cloud absorption (in the region 1 to 50 GHz) is (following Staelin, Ref. 13):

\[
A_{\text{cloud}} = \frac{4.343 \times M \times 10^{0.0122(291-T)-1}}{\lambda^2} \times 1.16 \text{ dB/Km}
\]

where

- \( M \) = cloud water particle density, g/m\(^3\)
- \( T \) = cloud particle temperature, Kelvins
- \( \lambda \) = wavelength, cm.

4.343 = changes nepers* to dB
1.16 = factor to match the Staelin expression to the Gunn and East values, within 10%

For use in radiative transfer calculations, an absorption coefficient \( \alpha \) (nepers/km) must be used where

\[
\alpha \text{ (nepers/km)} = A \text{ (dB/km)}/4.343
\]

*The neper is used here in the "power" sense (1 neper = 4.343 dB) rather than the traditional "voltage" sense (1 neper = 8.686 dB).

\[
P_2 = P_1 e^{-\alpha x}
\]

\[
P_2/P_1 \text{ (dB)} = 10 \log_{10}e^{-\alpha x}
\]

\[
= -10 \alpha \log_{10}e \quad (x = 1 \text{ km})
\]

\[
= -4.343 \alpha
\]
III. EQUATION OF RADIATIVE TRANSFER

The description and use of the equation of radiative transfer is given by numerous authors (Refs. 14-20, et al). The noise temperature at a given frequency received by an ideal antenna with infinitely narrow beamwidth looking upward at a source outside the atmosphere and ignoring scattering is given by (See Figure 2):

\[ T_a = T_a' e^{-\tau} + \int_0^\infty T(s) \alpha(s)e^{-\int_0^s \alpha(s')ds'} ds \]

where \( T_a \) = effective antenna temperature, Kelvins.

\( T_a' \) = noise temperature of source outside the atmosphere (e.g., black body disc temperature of the moon), Kelvins

\( T(s) \) = physical temperature of a point \( s \) in the atmosphere, Kelvins.

\( \tau \) = total atmosphere attenuation (optical depth), nepers

\( \alpha(s) \) = total absorption coefficient at a point \( s \) in the atmosphere, nepers/km (neglecting scattering)*

\( s \) = distance from antenna to a point in the atmosphere, km

* In the case of scattering (attenuation = scattering + absorption), simple first-order considerations will show that \( \alpha(s) \) will be the absorption coefficient and \( \alpha(s') \) will be the total attenuation coefficient. This condition is not considered for this cloud survey, but scattering must be considered for propagation through rain, particularly at frequencies greater than 10 GHz.
$s = \infty (\text{TOP OF ATMOSPHERE})$

"MOON" $T_a$

$\int a(s, s', T(s)) ds$

LOSS FACTOR $L = \int_s a(s') ds'$

FIGURE 2. ELEMENTS OF RADIATIVE TRANSFER EQUATION
The total absorption coefficient \( \alpha(s) \) nepers/km is the sum of the individual absorption coefficients of all atmospheric constituents (water vapor, oxygen, clouds, rain). If any component is absent, its individual absorption coefficient equals zero. The loss ("loss factor") through the entire atmosphere is:

\[
L(\text{ratio}) = e^{-\tau} = e^{-\int_{0}^{\infty} \alpha(s') ds'} \geq 1.0
\]

where \( \int_{0}^{\infty} \) represents the total path through the atmosphere, approximately 30 km at zenith, and \( \tau \) is the optical depth (nepers).

The "transmissivity" of the atmosphere is defined as:

\[
T = 1/L = e^{-\tau} , \quad 0 < T < 1
\]

The "absorptivity" or "opacity" is defined as:

\[
A = 1-T = 1 - e^{-\tau} = 1-1/L , \quad 0 < A < 1
\]

The first term of the radiative transfer equation gives the net brightness temperature of a source located outside the atmosphere after transmissivity reduction \( 1/L \). The second term represents the sum of infinitesimal brightness temperature contributions \( T(s) \alpha(s) ds \), each attenuated by the atmosphere between it and the receiving antenna (path length \( s \)). For atmospheric studies using passive radiometry only, and no source in or outside of the atmosphere, the term \( \int_{0}^{\infty} (T' e^{-\tau}) \) is equal to zero.
Sun- and moon-tracker studies (sources outside the atmosphere) enable one to determine space diversity improvement and various atmospheric parameters (Refs. 21-25).

The total atmospheric absorption, $A(\text{dB})$, through the atmosphere, can be derived from the loss factor $L$ by:

$$A(\text{dB}) = 10 \log_{10}(L)$$

$$= 10 \tau \log_{10}e = 4.343 \tau$$

where $\tau = \int_0^\infty a(s)ds$ along a path through the entire atmosphere (nepers)

An effective mean physical temperature, $T_p$, of the atmosphere may be derived from the relationship*

$$T_a = T_p \times (\text{Absorptivity})$$

$$= T_p (1 - e^{-\tau})$$

$$= T_p (1 - 1/L)$$

where $T_a =$ antenna temperature due to emission from the absorptive ("lossy") atmosphere, kelvins

$$T_p =$ mean physical temperature, Kelvins

$L =$ loss factor, $> 1.0$

* This equation is strictly true only for an isothermal atmosphere, but is a good practical approximation for the earth's atmosphere, where the bulk of attenuation occurs in regions whose temperatures are within 10% of 273 K.
A more rigorous derivation of this expression begins with the equation of radiative transfer:

\[ T_a = \int_0^{\infty} T(s) \alpha(s) e^{-\int_0^s \alpha(s') ds'} ds \]

For an isothermal, homogeneous atmosphere

\[ \alpha(s) = \alpha, \text{ the mean absorption coefficient} \]
\[ T(s) = T_p, \text{ the mean physical temperature} \]

Then,

\[ T_a = \alpha T_p \int_0^\ell e^{-\alpha s} ds, \text{ where } \ell = \text{ top of atmosphere} \]
\[ = T_p (1-e^{-\alpha \ell}) \]
\[ = T_p (1-1/L) \]

This relationship is discussed in more detail by Waters (Ref. 14).
As a specific example (based on an actual calculation using the equation of radiative transfer) consider an atmosphere (heavy clouds, at 32 GHz) whose antenna temperature and attenuation at zenith are:

\[ T_a = 99.04636 \text{ Kelvins} \]
\[ A = 1.93854 \text{ dB} \quad (L = 1.56262) \]

\( T_p \) is found to be

\[ T_p = T_a \left[ \frac{L}{(L-1)} \right] = 275.091 \text{ Kelvins} \]

This physical temperature corresponds to a region in the atmosphere where the "bulk" of the attenuating material lies (in this case, clouds at an altitude of approximately 3 km). The surface temperature for this case was 293.16 Kelvins and the lapse rate was 6.3 K/km down to a minimum temperature of 220 K.

It should be noted that \( T_p \) is an artifact and not a "constant" of the atmosphere. It is found after performing the radiative transfer calculation. For the case of temperature and/or attenuation gradients in the atmosphere, the \( T_p \) found will depend on whether the atmosphere is "viewed" (integrated) from below or above.

A further discussion of atmospheric modelling and noise temperature errors is given by Stelzried and Slobin (Ref. 26).
Using these simplified formulae, it is instructive to attempt to predict the antenna temperature for this cloud model at an elevation angle of 30°. To a good approximation, the attenuation at 30°-elevation is twice the zenith attenuation. Thus,

$$A(\text{dB}) = 3.87708 \text{ dB } (L = 2.44179)$$

Using $T_P = 275.091 \text{ K}$, the antenna temperature is calculated to be:

$$T_a = 162.431 \text{ K}$$

Actual radiative transfer integration at 30°-elevation yields:

$$T_a = 161.660 \text{ K}$$

a difference of 0.771 K.

Using

$$T_a = 161.660 \text{ K}$$

and

$$A = 3.87708 \text{ dB } (L = 2.44179)$$

the 30°-elevation mean physical temperature is calculated as

$$T_P = 273.785 \text{ K}$$

which is different by 1.306 K from the zenith mean physical temperature.

These one-Kelvin differences reflect an equivalent resolution well within present ability to measure or forecast cloud parameters. Thus, elevation angle modelling of attenuation and noise temperature is adequate for stratified atmospheres. For the case of scattered clouds, non-simple geometries, or low elevation angles, complete radiative transfer calculations should be carried out.
IV. SAMPLE CASE CALCULATIONS OF CLOUD ATTENUATION AND NOISE TEMPERATURE

A computer program has been written to calculate the atmospheric noise temperature and absorption of water vapor, oxygen, clouds, and rain, (using the equation of radiative transfer) along various paths in the atmosphere. For computational purposes, the atmosphere is divided into 300 layers, each 100 meters thick, up to a height of 30 km above the ground. For specific cloud/rain models and/or frequencies at which the attenuation coefficient is very large ($\alpha \approx 1$ neper/km (4.34 dB/km)), the 100 meter step size must be reduced (~10m) and the number of steps increased (~3000) in order to avoid large computational errors. The effect of these errors is to calculate a value of noise temperature that is too low (for the case of very dense clouds, at least). The present version of the program is not "smart" (or self-adjusting); but the calculations appear to be adequate for all cloud cases, excluding rain, except very near the peak of the oxygen absorption band (60 GHz), or for very heavy clouds at high frequencies (>60 GHz). The presentation here is restricted to frequencies less than 50 GHz.

Since clouds do not exist independent of water vapor and oxygen, the effects of these two species must be included in any calculation of cloud noise temperature and attenuation.
The particular constituent models are described as follows:

**WATER VAPOR**

1. CCIR Profile (Ref. 27)
2. 7.5 g/m$^3$ at surface
3. 2 km scale height
4. 20°C at surface
5. 6.3 K/km temperature lapse rate
6. 220 K minimum temperature
7. Bean and Dutton absorption coefficient (Ref. 12), modified slightly to yield agreement with values calculated by the JPL Radiative Transfer Program (Ref. 28)

**OXYGEN**

1. CCIR Profile (Ref. 27)
2. 1013.6 mb at surface
3. Pressure profile curve-fit $P = P_0 e^{-0.116h}$, h in km (pressure scale height = 8.62 km)
4. 20°C at surface
5. 6.3 K/km temperature lapse rate
6. 220 K minimum temperature
7. Bean and Dutton absorption coefficient (Ref. 12) modified slightly to yield agreement with values calculated by the JPL Radiative Transfer Program (Ref. 28)

**CLOUD**

1. Absorption model from Staelin (Ref. 13)
2. Modified to fit Gunn and East values (Ref. 11)
3. Water particle densities derived from drop size distribution in Carrier, Cato, and von Essen (Ref. 3)
Figure 3 shows a schematic view of the cloud and clear air models used in the calculations. In these models, \( h \) is the height (km) above the ground; \( h_0 \) is the height of the ground above sea level.

The cloud model has up to two layers, base and top heights specified, and water particle density determined by specification of cloud type as defined by the World Meteorological Organization Cloud Code Chart (Ref. 4). The relative humidity is not adjusted to be 100% within the cloud layer; the absolute humidity is defined by an exponential decrease with a 2 km scale height.

A number of specific weather cases were considered for calculation using the equation of radiative transfer to determine noise temperature and attenuation. Table 6 lists the 12 cases (1 clear, 11 cloudy); they represent increasingly dense and thick cloud layers.

This table will be discussed further with respect to S, X, and K\( A \)-Band noise temperature and attenuation effects of clouds.
$h = 30 \text{ km TOP OF ATMOSPHERE}$

$\text{TEMPERATURE PROFILE}$

$-6.3 \text{ K/km}$

$220 \text{ K MINIMUM}$

$\text{ABSOLUTE HUMIDITY PROFILE } e^{-h/2.0}$

$\text{UPPER CLOUD}$

$\text{LOWER CLOUD}$

$\text{PRESSURE PROFILE } e^{-0.116(h/h_{o})}$

$\text{SEA LEVEL}$

$\text{FIGURE 3. CLOUD AND CLEAR AIR MODELS}$
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<tr>
<th>CASE</th>
<th>LOWER CLOUD</th>
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<th>S-BAND (2.3 GHZ) ZENITH</th>
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Notes:
1) Clear and cloud models as described in text
2) Cases 2-12 are clear air and clouds combined
3) Antenna located at sea level
4) Heights are above ground
5) No cosmic background or ground contribution considered
6) T(K) is atmospheric noise temperature at zenith
7) A(dB) is atmospheric attenuation along vertical path from ground to 30 km above ground
Table 7 shows a printout of the temperature, pressure, and absolute humidity profiles used in the calculations up to a height of 10 km above the ground. The values are given at the center of the 0.1 km-thick layers. The receiving antenna is considered to be located at sea level and the clouds are horizontally stratified. The specific case shown in Table 7 is for clouds plus rain (10 mm/hr at the ground). The columns labeled ALPHT1 and ALPHT2 are the extinction (total attenuation) and absorption coefficients (nepers/km) at 32 GHz, respectively, for the case where scattering from rain is considered. The clouds are not considered to scatter at frequencies below 100 GHz for the purpose of these calculations. DENC is the cloud water particle density, 1.00 g/m³ for the lower cloud and 1.00 g/m³ for the upper cloud. The rainrate (mm/hr) is given in the last column, based on a specific model. The rain is considered to start at 3.5 km above the ground and the rate increases in a downward direction.

Returning to Table 6, the last columns show the S-, X-, and KA-Band zenith noise temperature and attenuation effects for the cloud models shown. The notes at the bottom of the table describe the models used and will clarify the tabulated values.

Table 6 shows the increasingly severe effects of clouds as the frequency changes from S-thru KA-Band. S-Band is affected only slightly by even the heaviest clouds, whereas KA-Band shows very large effects, which are quite severe for the case of low-noise receiving systems.
## TABLE 7
### PROFILES USED IN CLOUD CALCULATIONS

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<th>HEIGHT</th>
<th>TEMP</th>
<th>PRESS.</th>
<th>ABS HUM.</th>
<th>ALPHT1</th>
<th>ALPHT2</th>
<th>DENC</th>
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## CLOUD

- TEMP: Temperature
- PRESS: Pressure
- ABS HUM: Absolute Humidity
- ALPHT1: Alphanet 1
- ALPHT2: Alphanet 2
- DENC: Density
- RNRT: Reflectivity
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The change in signal-to-noise ratio ($\Delta$SNR, dB) is given by:

$$\Delta\text{SNR} = \Delta dB + 10 \log_{10} \left( \frac{T_{\text{op}}}{T_{\text{base}}} \right)$$

where $\Delta dB$ = change in attenuation, relative to clear air baseline

$T_{\text{op}}$ = system noise temperature with clouds, Kelvins

$T_{\text{base}}$ = baseline system noise temperature, including ground, waveguide horn, clear air, and cosmic background contributions, Kelvins

As an example, consider a low-noise receiving system at Kα-Band with a baseline zenith system noise temperature of 35 Kelvins. Using Case 10 (Table 6), it is seen that the zenith attenuation increases from 0.228 dB to 1.939 dB. The atmospheric noise temperature increases from 14.29 Kelvins to 99.05 Kelvins. The 2.7 Kelvin cosmic background effect decreases from 2.56 Kelvin (2.7 attenuated by .228 dB) to 1.73 Kelvin (2.7 K attenuated by 1.939 dB). The new $T_{\text{op}}$ is $35 + (99.05-14.29) + (1.73-2.56) = 118.93$ Kelvins. Thus,

$$\Delta\text{SNR} = (1.939-0.228) + 10 \log_{10} \left( \frac{118.93}{35} \right) = 7.021 \text{ dB, at zenith}$$

Most of the signal-to-noise degradation in low noise receiving systems comes from the noise temperature increase. For high noise receiving systems (> 500 Kelvins), the atmospheric attenuation will cause the greatest SNR degradation.

The Appendix of this report contains numerous curves of total atmospheric attenuation coefficients, atmospheric noise temperature, and atmospheric attenuation for the cloud models in Table 6. The curves are in sets of five, one set for each of the twelve cases listed. The five curves of each set are:
1) Total atmospheric attenuation coefficient at 32 GHz, vs. height, all constituents, no scattering because clouds only (labelled -1)

2) Atmospheric noise temperature at zenith vs. frequency (labelled -2)

3) Atmospheric attenuation at zenith vs. frequency (labelled -3)

4) Atmospheric noise temperature at 30°-elevation vs. frequency (labelled -4)

5) Atmospheric attenuation at 30°-elevation vs. frequency (labelled -5)

The eight parameters of each plot are printed at the bottom.

They are:

1) ELEV = elevation angle from horizontal, degrees
2) LAST LOOP = counting loop, internal use only
3) DENCLOW = density of lower cloud, g/m³
4) LOWCLDTHK = thickness of lower cloud, km
5) DENCLMID = density of upper cloud, g/m³
6) MIDCLDTHK = thickness of upper cloud, km
7) RAINRATE = rainrate at the ground, mm/hr
8) RAINTHICK = thickness of the rain, km
Table 8 shows results of tests of integration step size on the determination of atmospheric noise temperature and attenuation for the "worst-case" cloud, Case 12, at five different frequencies. NL is the number of layers in the atmosphere up to 30 km above the ground. For NL=300, layer thickness = 100 meters; NL=1000, 30 meters; NL=3000, 10 meters. Assuming the NL=3000 case to give the "correct" answer, noise temperatures at the same frequency but different step sizes are compared to that value. At all frequencies shown, the errors at zenith are less than two percent. However, at higher frequencies or for cases including rain (where the attenuation coefficient exceeds approximately 1 neper/km), care must be exercised in choosing an optimum number of tropospheric layers. Carrying out all calculations at NL=3000 makes computation of even a few cloud cases prohibitively expensive. Future work will involve the development of computational methods which strike an acceptable balance between accuracy and cost.
TABLE 8
"WORST CLOUD"* TEST CASE OF INTEGRATION STEP SIZE

<table>
<thead>
<tr>
<th><strong>NL</strong></th>
<th>FREQ GHZ</th>
<th>90°-ELEV</th>
<th>30°-ELEV</th>
<th>***</th>
<th>30°-ELEV</th>
<th>***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T(K)</td>
<td>A(dB)</td>
<td>% ERROR</td>
<td>T(K)</td>
<td>A(dB)</td>
</tr>
<tr>
<td>300</td>
<td>10</td>
<td>26.84</td>
<td>0.457</td>
<td>-0.11</td>
<td>51.01</td>
<td>0.915</td>
</tr>
<tr>
<td>(100 m)</td>
<td>20</td>
<td>94.35</td>
<td>1.864</td>
<td>-0.33</td>
<td>155.97</td>
<td>3.729</td>
</tr>
<tr>
<td>RC=1</td>
<td>30</td>
<td>159.18</td>
<td>3.891</td>
<td>-0.83</td>
<td>224.41</td>
<td>7.782</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>214.08</td>
<td>6.912</td>
<td>-1.44</td>
<td>258.09</td>
<td>13.823</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>251.92</td>
<td>11.682</td>
<td>-1.92</td>
<td>269.91</td>
<td>23.364</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>26.96</td>
<td>0.460</td>
<td>+0.33</td>
<td>51.26</td>
<td>0.919</td>
</tr>
<tr>
<td>(30 m)</td>
<td>20</td>
<td>94.88</td>
<td>1.875</td>
<td>+0.23</td>
<td>157.11</td>
<td>3.749</td>
</tr>
<tr>
<td>RC=3.4</td>
<td>30</td>
<td>160.64</td>
<td>3.910</td>
<td>+0.07</td>
<td>227.50</td>
<td>7.819</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>216.89</td>
<td>6.943</td>
<td>-0.15</td>
<td>263.50</td>
<td>13.887</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>255.98</td>
<td>11.737</td>
<td>-0.34</td>
<td>276.86</td>
<td>23.473</td>
</tr>
<tr>
<td>3000</td>
<td>10</td>
<td>26.87</td>
<td>0.458</td>
<td>0.00</td>
<td>51.11</td>
<td>0.916</td>
</tr>
<tr>
<td>(10 m)</td>
<td>20</td>
<td>94.66</td>
<td>1.869</td>
<td>0.00</td>
<td>156.94</td>
<td>3.738</td>
</tr>
<tr>
<td>RC=38.3</td>
<td>30</td>
<td>160.52</td>
<td>3.895</td>
<td>0.00</td>
<td>227.93</td>
<td>7.790</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>217.21</td>
<td>6.917</td>
<td>0.00</td>
<td>264.80</td>
<td>13.835</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>256.85</td>
<td>11.697</td>
<td>0.00</td>
<td>278.75</td>
<td>23.395</td>
</tr>
</tbody>
</table>

* CASE NO. 12, TABLE 6

** NUMBER OF LAYERS IN 30-KM-THICK ATMOSPHERE, THICKNESS OF LAYER AND RELATIVE COST

NOTE THE ANOMALOUS BEHAVIOR OF ATTENUATION AT NL=1000 AND 3000, FREQUENCY=50 GHZ, WHERE NOISE TEMPERATURE INCREASES AND ATTENUATION DECREASES; ALSO OSCILLATORY BEHAVIOR OF ERROR

*** TEMPERATURE ERROR COMPARED TO VALUE AT SAME FREQUENCY WITH NL=3000; VALUE AT NL=3000 ASSUMED TO BE CORRECT
REFERENCES


CASE 1-1

ATMOS ATTN COEF NEPERS/KM

ABSORPTION ONLY AT 32 GHz

HEIGHT

Z
KM

ELEV

LAST LOOP

DEW
LOW
HIGH

RBLK

RAIN

0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000

0.0000
2.0000
0.0000
0.0000
0.0000
0.0000
0.0000

0.0000
2.0000
0.0000
0.0000
0.0000
0.0000
0.0000

0.0000
2.0000
0.0000
0.0000
0.0000
0.0000
0.0000

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CASE 1-2

ATMOS NOISE TEMP VS FREQ

FREQUENCY GHz

ATMOS NOISE TEMP KELVIN

ELEV LAST LOOP DEMO HIGH LOW LOW MID HIGH MID LOW MID LOW MID RAIN RATE RAIN THICK

0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
CASE 1-5

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ELEV LAST LOOP DENCHLAN LOWCLOTHA DENCLHII MIDLCLTHA RAINRATE RAINTHICK

00000 000000 000000 000000 000000 000000 000000 000000
CASE 2-1

ATMOS ATTN COEF NEPERS/KM

ABSORPTION ONLY AT 32 GHz

HEIGHT Z KM

ALPHTI NEPERS/KM

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CASE 2-2

ATMOS NOISE TEMP VS FREQ

FREQUENCY GHz

ATMOS NOISE TEMP KELVINS

ELEV LAST LOOP DRY LOW MILD WET LOW MILD WET RAIN RATE RAIN THICK
CASE 2-3

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

0 5 10 15 20 25 30 35 40 45 50

TOTAL ATM ATTENUATION DD

0 2 4 6 8 10 12 14 16

CASE 2-3
TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY (GHz)

ATMOSPHERIC ATTENUATION (db)

0.000000001 1.000000002 2.000000001 2.000000001 0.0000000 0.0000000 0.0000000 0.0000000
CASE 3-2

ATMOS NOISE TEMP VS FREQ

FREQUENCY GHz

ELEV
LAST LOOP
DEMOLWM
LOWCLOTH
DEMOLHID
MIDCLOTH
RAINMATE
RAINTHICK

9.000000-01 1.500000-02 0.000000 0.000000 2.000000-01 1.999999-01 0.000000 0.000000

ATMOS NOISE TEMP KELVINS

0 10 20 30 40 50 60 70 80 90

0 5 10 15 20 25 30 35 40 45 50
CASE 3-5

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0

ATMOS ATTENUATION DB

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
ATMOS ATTN COEF NEPERS/KM  ABSORPTION ONLY AT 32 GHz

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ATMOS NOISE TEMP VS FREQ.
TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ATMOSPHERIC ATTENUATION dB
CASE 6.5

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ATMOSPHERE ATTENUATION DB

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ATMOSPHERE ATTENUATION DB
CASE 8-2

ATMOS NOISE TEMP VS FREQ

FREQUENCY GHz

ELEV  LAST LOOP  DECHLOW  LOWCLOTH  DECHMID  MHCLOTH  RAINRATE  RAINTHICK
9.99999999E-01  4.99999999E-02  9.99999999E-01  1.00000000E+00  9.99999999E-01  1.00000000E+00  0.00000000  0.00000000

ATMOS NOISE TEMP KELVINS

0  20  40  60  80  100  120  140  160

0  5  10  15  20  25  30  35  40  45  50  55  60  65  70  75  80  85  90  95  100

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TOTAL ATM ATTENUATION VS FREQ

ATMOS ATTENUATION DB

FREQUENCY GHz

ELEV  LAST LOOP  DEW POINT  LOW CLOUD  LOW CLW  MID CLOUD  RAIN RATE  RAIN THICK
6.000000E-01 4.500000E-02 5.000000E-01 1.000000E-00 5.000000E-01 1.000000E-00 0.000000E+00 0.000000E+00
ATMOS NOISE TEMP VS FREQ

FREQUENCY GHz

CLEV LAST LOOP LONLCLOTH NLCLOTH MIDCLOTH RAINRATE RAINTHICK

9.0000000-01 5.1005000-02 7.0000000-01 1.0000000-00 7.0000000-01 1.0000000+00 0.0000000 0.0000000
CASE 9-3

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

ATMOS

ATTENUATION DB

FREQUENCY GHz

0.0000000-01 5.1000000-02 7.0000000-01 1.0000000-00 7.0000000-01 1.0700000-00 0.0000000 0.0000000

89
CASE 9-5

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

ATMOS ATTENUATION DB

FREQUENCY GHz

ELEV 5 4000000.02 7 0000000.01 1 0000000.00 7 0000000.01 1 0000000.00 0 0000000.00 0 0000000
CASE 10-3

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ATMOSPHERIC ATTENUATION DB

FREQUENCY GHz

ELEV | LAST LOOP | DENSITY | LOWCLOTH | MEDIUMCLOTH | HIGHCLOTH | RAINRATE | RAINTHICK
---|---|---|---|---|---|---|---
9.000000E-01 | 9.700000E-02 | 1.000000E+00 | 1.000000E+00 | 1.000000E+00 | 1.000000E+00 | 0.000000 | 0.000000
TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

CASE 10-5
CASE 11-1

ATMOS ATTN COEF NEPERS/KM

ABSORPTION ONLY AT 32 GHz

HEIGHT Z KM

ALPHA NEPERS/KM

ELEV LAST LOOP DENWIL MIDWIL DENWIL MIDWIL DENWIL MIDWIL RAINRATE RAINTHICK

9.000000E-01 6.230000E-02 1.000000E+00 1.500000E+00 1.000000E+00 1.500000E+00 0.000000 0.000000

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CASE 11-4

ATMOS NOISE TEMP VS FREQ

FREQUENCY, GHz

ATMOS NOISE TEMP KELVINS

0.0 5. 10. 15. 20. 25. 30. 35. 40. 45. 50.

0. 50. 100. 150. 200. 250. 300.

ELEV LAST LOOP DEN CLOTH LOW CLOTH DEN CLOTH MID CLOTH RAIN RATE RAIN THICK
3.0000000-01 6.0000000-02 1.0000000-00 1.5000000-00 1.0000000-00 1.5000000-00 0.0000000-05 0.0000000-00

102
TOTAL ATM ATTENUATION VS FREQ
ABSORPTION ONLY

FREQUENCY GHz
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
0 2 4 6 8 10 12 14 16 18
ATMOS ATTENUATION DB

ELEV
3.000000E-01
LAST LOOP
6.660000E-02
DEGLOM
1.000000E+00
LONGLOTHK
1.500000E+00
DEGLOMID
1.000000E+00
HIDLOTHK
1.500000E+00
RAINFREATE
0.000000E+00
RAINTHICK
0.000000E+00

103
CASE 12-1

ATMOS ATTN COEF NEPERS/KM

ABSORPTION ONLY AT 32 GHz

<table>
<thead>
<tr>
<th>HEIGHT Z KM</th>
<th>ALPHTI NEPERS/KM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.00</td>
<td>0.00</td>
</tr>
<tr>
<td>15.00</td>
<td>0.00</td>
</tr>
<tr>
<td>20.00</td>
<td>0.00</td>
</tr>
<tr>
<td>25.00</td>
<td>0.00</td>
</tr>
<tr>
<td>30.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

ELEV 9 0000000-01  RAINTHICK 0.0000000-00
LAST LOOP 6.8300000-02  RAINRATE 0.0000000-00
DEWLOTH 1.0000000-00  MIDCLOTH 2.0000000-00
POLLOTH 4.0000000-00  LOWCLOTH 1.0000000-00

CASE 12-3

TOTAL ATM ATTENUATION VS FREQ

ABSORPTION ONLY

FREQUENCY GHz

ATMOS ATTENUATION DB

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

0 2 4 6 8 10 12

ELEV 0.0000000001 0.0000000002 0.0000000008 0.0000000002 0.0000000001 0.0000000000 0.0000000000 0.0000000000

LOW CLOTH

MOD CLOTH

HIGH CLOTH

RAIN RATE

RAIN THICK