CHAPTER-6

NOISE TEMPERATURE DUE TO CLOUD

6.1 Introduction

The total attenuation is the sum of the individual contributions of the major constituents of the atmosphere such as oxygen, water vapour, rain and the clouds. For microwave radiation at frequencies below 100GHz and cloud particles smaller than 100 \( \mu \text{m} \), the effect of scattering is small and absorption is the only contribution to attenuation. The absorption medium itself radiates power into a radio receiver and contributes to the total system noise temperature. Other contributions to the system noise temperature are cosmic background, the ground and the receiver. Noise temperature effect of water vapour content of the atmosphere was studied by Westwater, 1978, Gairud et al, 1979, Sen et al, 1993 at 22.235 GHz for its estimation. Smith et al, 1981 presented the effect of the gaseous atmosphere. Studies on precipitable water by Gunn & East, 1954 reported the effect of clouds. Considering the presence of all the constituents of the atmosphere together it has been useful to analyse the effect of clouds. Rain is an important hydrometeor when considered along with the effects of water vapour. As a matter of fact the rain spells are rather occasional as compared to the clouds. Further, the rain is also very much dependent on the location and seasons.
Clouds are persistent for longer periods and more common than the rain. But the presence of some of the major components of the atmospheric constituent such as oxygen and water vapour are invariably taken into account when the total attenuation is calculated in a cloudy situation. Calibration aspects at millimetrewave propagation must incorporate the results of attenuation for the accuracy in observations.

The study reveals that the noise temperature is more informative and useful as compared to attenuation. The attenuation for clear air situation from 10GHz to 100GHz varies from 0.0973 dB to 5.1720 dB, on the other hand the attenuation due cloudy conditions have been found to be from 0.3258 dB to 28.0139 dB. The noise temperature due to cloud has been estimated to be ~ 135 K at 45GHz. The effects of water content in cloud and height (thickness) of the cloud on cloud noise temperature have also been discussed in this paper. The estimated change in signal to noise ratio due to cloud indicates that the change in signal to noise ratio increases from 70GHz considerably.

6.2 Theoretical consideration/ Statement of the problem

The total attenuation of a radiowave propagating in the medium is due to water vapour, oxygen, cloud, etc., The specific attenuation due to water vapour is given by (CCIR, 1986) as follows:
\[
\gamma_w = \left[ 0.067 + \frac{2.4}{(f - 22.235)^2 + 6.6} + \frac{7.33}{(f - 183.5)^2 + 5} + \frac{4.4}{(f - 323.8)^2 + 10} \right] \times f^2 \rho \times 10^{-4}
\]

...(6.1)

where \( \gamma_w \) is the specific attenuation coefficient due to water vapour in dB/Km, \( f \) is the frequency in GHz and \( \rho \) is the water vapour density in gm/m\(^3\).

For calculation of the total attenuation along the slant path the necessary scale height \( H \) can be obtained using the following relation.

\[
H = \frac{4}{\sqrt{\sin^2 \theta + \frac{4}{R} \sin \theta}}
\]

...(6.1a)

where \( R \) is the earth radius (6370 Km.) and \( \theta \) is the angle of elevation of the satellite.

Water vapour is not at all a well-mixed constituent of the atmosphere and hence it shows variation due to change of site, season and local meteorological conditions (Sarkar, et al 1987). Also the vertical and horizontal distribution of water vapour varies with space and time.
(Slobin, 1982), (Staelin, 1966) presented the values of cloud absorption as a function of temperature and wavelength. An expression for the absorption coefficient $\alpha$ based on (Staelin, 1966) is given by

$$\alpha_{\text{cloud}} = \frac{4.343 \times M \times 10^{0.012N(291-T)} \times 1.16}{\lambda^2}$$ \hspace{1cm} (6.2)

where

- $M$ cloud water particle density, g/m$^3$;
- $T$ cloud particle temperature, Kelvins;
- $\lambda$ wavelength, cms.

The absorption coefficient as used in radiation transfer calculations is

$$\alpha \ (\text{Np/Km}) = \alpha \ (\text{dB/Km})/4.343 \hspace{1cm} (6.3)$$

The noise temperature at a given frequency received by an ideal antenna with infinitely narrow beam width looking upward at source outside the atmosphere and ignoring scattering is given by the equation of radiative transfer

$$T_a = T_a'e^{-t} + \int_0^a T(s)\alpha(s) \left[ \exp(-\int_0^t \alpha(s')ds') \right] ds \hspace{1cm} (6.4)$$
$T_a$ is effective antenna noise temperature in Kelvins

$T_a'$ is noise temperature of source outside the atmosphere (e.g., Black body disc temperature of Sun, moon or cosmic backgrounds) in Kelvins

$T(s)$ is physical Temperature of a point $s$ in the atmosphere in Kelvins

$\tau$ is total atmospheric attenuation (Optical depth) in Np(Nepers).

$\alpha(s)$ is total atmospheric attenuation at point $s$ in the atmosphere.

$s$ is distance from the antenna to a point in the atmosphere in Km

The total absorption coefficient $\alpha(s)$ is the sum of the individual coefficients of all the atmospheric constituents. The loss through the entire atmosphere is

$$L(ratio) = e^\tau = \exp \int_0^s \alpha(s') ds'$$

...(6.5)

$L$ is the loss through the entire atmosphere, $\tau$ is the optical depth in Nepers.

$\alpha_{total}$ - is total attenuation due to a single constituent.

$$\alpha_{total}(db) = \int_0^h \alpha(z) dz = \alpha_0 z_0$$

...(6.6)
where $\alpha_0$ is the surface attenuation coefficient in decibels per Km and $Z_0$ is the scale height for absorption, in Kms.

Knowing the surface attenuation of water vapour, oxygen and cloud then using their respective scale heights, the total attenuation is deduced. Thus, the total attenuation is alternatively given by

$$A_r = \sum \alpha_\phi Z_0 \quad \ldots \quad (6.7)$$

In this paper scale height of 5.4 Km for oxygen and 3 Km for cloud have been used. But total attenuation due to water vapour has been obtained by the model represented by equation (6.1) and along the zenith the necessary scale height with correction factor applied using equation (6.1.a).

For a homogenous, isothermal atmosphere, $\alpha(s) = \alpha$, the mean absorption coefficient and $T(s) = T_p$, physical temperature at a point in the atmosphere.

For a narrow antenna beam which keeps the source away from the receiver. The equation of radiative transfer then becomes (assuming $T a' = 0$)

$$T_a = T_p \alpha \int_0^l e^{-\alpha s} ds$$
Variation of attenuation due to main constituents (oxygen and water vapour) has been shown in the work of Jacobs and Stacey, 1974 to be approximately proportional to density. Dependence of attenuation in turn, with height, is given by

\[ \alpha(z) = \alpha_0 e^{-z/Z_0} \]  

...(6.10)

Where \( \alpha_0 \) is the surface attenuation coefficient, in dB/Km and \( Z_0 \) is the scale height for attenuation in Kms as usual.

The total attenuation thus is the sum of significant or measurable contributions from the atmospheric constituents obtained using equation (6.7). The models used for each of the contributors like water vapour and cloud, are fairly established, have been used directly. Equations (6.1) and (6.2) give the
specific attenuation, also, the scale heights for each of these in the mid-latitudes are 2Km and 3 Km (for the worst condition i.e. M=1gm/m³) respectively. For the oxygen component the well-accepted values of (CCIR Reports Recommendations, 1982) have been used for the estimation of the total attenuation using scale height of 5.4 Km.

Evidently, the total attenuation was calculated and the order of the noise temperature so obtained was also compared with the observed values of the brightness temperature recorded by the remote sensing organisations. It has been observed to be very close after deducting the ground effect which itself is satisfactory. Further, the comparison of the radiative transfer results and with approximation calculations have also been dealt in Slobin(1982). They differ marginally. Even in the real atmospheric situation the noise temperature shows similar dependence on the mean physical temperature of the constituents near the scale height and the total loss factor (L). The analytical results are presented in comparison with the simple approximation in the following section.

Again applying the same condition of a narrow antenna beam that keeps the source away from the receiver. Equation of radiative transfer becomes (assuming Ta = 0)

\[ T_e = \int_0^\infty T(s)\alpha(s)\left[\exp-\int_0^s\alpha(s')ds'\right]ds \]  

...(6.11)
The calculation of \( T \) from the above expression still is cumbersome even with use of computers. This is mainly due to the double integral form of the equation. We make the calculation little easy without loss of generality and realistic condition.

We take

\[
T(s) = T_0 e^{\chi z} \quad \ldots (6.12)
\]

where \( \chi = \left( \frac{R \beta}{H_\circ} \right) = 0.0278 \) (at Kolkata), using \( \beta \) as the lapse rate \( R \) as the gas constant \( H_\circ \) as the scale height for hydrostatic pressure and \( g \) the acceleration due to gravity.

Equation (6.11) then reduces to a much simpler form using the above relations (6.10) and (6.12)

\[
T_0 = T_0 \int_0^\infty \alpha e^{-T_0 z} e^{-e^{-\chi z}} dz
\]

\[
= T_0 \alpha e^{-T_0} \int_0^\infty e^{-z} e^{-\chi e^{z}} du
\]

Substituting \( -z/z_0 = u \)

\[
= \alpha T_0 z_0 \int_0^\infty e^{-z} e^{-\chi e^{z}} du
\]

Now substituting \( t = e^{-u} \)
\[ T = \alpha_0 T_0 Z_0 \int_0^x e^{-\alpha_0 x} \, dx \]

\[ = \frac{T_0}{(\alpha_0 z_0)^x} \int_v^0 e^{-v} \, dv \]

Thus, the integration with \( v \) would give the following result

\[ = T_0 \left( I + \frac{1}{A_r} + \frac{1}{A_r^2} + \ldots + \frac{1}{A_r^{n-1}} \right) - \frac{\Gamma(n+1)}{A_r^n} \left[ \frac{1}{L} - \frac{1}{L} \right] \ldots \text{(6.13)} \]

Now, it is easy to see that gamma function part is negligible due to obvious reasons of \( n \)-value and the denominator. Also, it is observed that \( 1/v \ll 1 \), for the frequency more than 15 GHz, (as has been observed from the calculated values of \( A_r = \alpha_0 z_0 \)-total attenuation due to the atmosphere) and \( T_p = T_0 e^{-\alpha_0 z_0} \)

applying the above constants of the equation takes the form

\[ T_a = T_0 \left[ \frac{1}{1 - 1/A_r} \right] \left[ \frac{1}{L} \right] \ldots \text{(6.13 a)} \]

Which approximates to

\[ T_a = T_p \left[ \frac{1}{L} \right] \ldots \text{(6.14)} \]
It is worthwhile to see that it assumes the same form as (6.9), thus, this aspect substantiates the well-drawn conclusion.

The loss factor for each constituent then may be found from

\[
L(\text{ratio}) = 10 \frac{[\text{dB}]}{10} \quad \ldots(6.15)
\]

Cloud temperatures have been estimated by using the surface temperature and the lapse rate (6.5K/Km).

6.3 Cloud types and properties

Cloud consists of liquid water particles having diameters from about 1 micron(\(\mu\)m) to as much as 400 microns(\(\mu\)m) (Tsang et al., 1977). For comparison, raindrops have size distributions from 100 \(\mu\)m (0.1mm) to 5 mm. Clouds are not water vapour (which is clear, colourless gas), although relative humidity is nearly 100\% within cloud. Clouds can exist at high temperatures + 20\(^\circ\)C as well temperature below freezing point at - 10\(^\circ\)C. High level clouds such as cirrus, are composed of ice crystals and are not generally found at temperatures above -12\(^\circ\)C (Valley, 1965). Ice clouds do not contribute substantially to microwave attenuation (though they may to depolarization), A particular cloud type will have a range of water particle sizes. Fair-cumulus clouds have particles with diameters from 4 to 15\(\mu\)m; cumulonimbus clouds have particle diameters from 2
up to 100 μm, where the distinction between cloud particles and suspended rain is not clear. Typical model cloud drop size spectra (number of particles versus diameter) for numerous cloud types are shown in the work of (Carrier et al. 1967). For a justifiable analysis of the clouds, we use the results of most recent amongst them is the Liebe’s Model used in collecting the NOAA data and according to the Liebe’s model, Table 6.1 presents the cloud properties over Kolkata. This also has been found to be true in mid latitudes (Falcone and Abreu, 1979). The variations as depicted in the tabulated results using this model has been incorporated to see the resultant effect due to the range of variation. Further, the observed changes in the noise temperature analysis with the parametric changes give some conclusive results about the characteristics of the cloud under study.

The emphasis has been laid on some directly deducible properties of the clouds while using for microwave communication purpose. In order to elucidate this aspect the effect of the cloud mass density and cloud height, The observed range of variation has been used to estimate the change in noise temperature at a desired frequency of operation.

The attenuation and noise temperature effects of cloud at microwave frequency band lead to degradation in the performance of radio systems. If the noise temperature is assumed to be $T_{new}$ for the cloudy condition and $T_{base}$ is the noise temperature for clear air condition and $\Delta A$ is the difference of attenuation
due to cloud and clear air then the change in signal to noise ratio (ΔSNR) is given by

\[ ΔSNR = 10 \log_{10} \left( \frac{T_{\text{new}}}{T_{\text{base}}} \right) + δA \]  

...(6.16)

### TABLE 6.1

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>M (g/m³)</th>
<th>Cloud Bottom</th>
<th>Height (m) Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulus</td>
<td>1.00</td>
<td>660</td>
<td>2700</td>
</tr>
<tr>
<td>Altostratus</td>
<td>0.41</td>
<td>2400</td>
<td>2900</td>
</tr>
<tr>
<td>Stratocumulus</td>
<td>0.55</td>
<td>660</td>
<td>1320</td>
</tr>
<tr>
<td>Nimbo-stratus</td>
<td>0.61</td>
<td>160</td>
<td>1000</td>
</tr>
<tr>
<td>Stratus</td>
<td>0.42</td>
<td>160</td>
<td>660</td>
</tr>
<tr>
<td>Stratus</td>
<td>0.29</td>
<td>330</td>
<td>1000</td>
</tr>
<tr>
<td>Stratus-cumulus</td>
<td>0.15</td>
<td>660</td>
<td>2000</td>
</tr>
<tr>
<td>Stratocumulus</td>
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<td>660</td>
<td>2000</td>
</tr>
<tr>
<td>Nimbo-stratus</td>
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<td>160</td>
<td>660</td>
</tr>
<tr>
<td>Cumulus-cumulus</td>
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<td>660</td>
<td>2700</td>
</tr>
<tr>
<td>Congestus</td>
<td></td>
<td>660</td>
<td>3400</td>
</tr>
</tbody>
</table>

(After Falcone and Abreu, 1979)

### 6.4 Results and discussions

The attenuation due to the clear air atmosphere and also cloudy conditions for the operational frequencies in the range from 10GHz to 100 GHz have been
deduced and presented in Figs. 6.1(a) and 6.2(a). Attempt is made to relate the results so obtained to use the proper frequency of the microwave for the study of cloud characteristics. The total microwave attenuation is the sum of the attenuation due to water vapour and oxygen for clear air condition. For cloudy conditions there is an additional attenuation term due to cloud. However, it has been observed that the noise temperature is more informative and useful for study of characteristics of the constituents of the atmosphere than the attenuation. It is seen in Fig. 6.1 that the maximum attenuation is observed at 60 GHz is due to oxygen component. For operating frequencies between 50 GHz and 70 GHz there is marked increase in the attenuation with a maximum at 60 GHz for the characteristic line of oxygen. But in the estimation and analysis, noise temperature have been found much more advantageous than the attenuation. The atmospheric noise temperature deduced for clear air situation and cloudy condition are presented in Figs.6.1(b) and 6.2 (b). It is seen in these figures that the noise temperature under clear air condition between 10 GHz and 100 GHz varies abruptly at different frequencies while under cloudy condition the variation of noise temperature is systematic from 10 GHz to 80GHz.
Fig. 6.1a Variation of Specific attenuation of clear air situation
Fig. 6.1b Variation of Noise temperature in clear air situation
Fig. 6.2a  Variation of Specific attenuation in Cloudy conditions
Fig. 6.2b Variation of Noise temperature in cloudy conditions
The noise temperature is around 285 K from 80 GHz to 100 GHz. Since, the characteristic of variation of noise temperature clearly indicates that certain frequencies in the range of operation are really energy consuming and results in radiation losses due to absorption of the major constituents of the earth's atmosphere. Particularly, the losses due to water vapour and oxygen give rise to increase in noise temperature and peaks at frequencies of 22.235 GHz and 60 GHz respectively (Fig. 6.1b)

The noise temperature due to cloud, which is the difference of noise temperature under cloudy condition and clear air situation in the present study, has also been determined and presented in Fig. 6.3. It has been estimated that the noise temperatures due to cloud at 45 GHz and 80 GHz are 135 K and 125 K respectively which are maximum values in the frequency range from 10 GHz to 100 GHz. The noise temperatures due to cloud at 55 GHz and 60 GHz are 0.05 K and 0 K. It is also seen in Fig. 6.3 that the noise temperature due to cloud increases from 10 GHz to 45 GHz and two minima are found at 55 GHz and 60 GHz. The noise temperature due to cloud at 70 GHz is around 112 K and having a second maxima at 80 GHz with 125 K. The noise temperature due to cloud starts decreasing from 80 GHz as seen in Fig. 6.3. The frequency 45 GHz is most ideal for cloud related studies since the maximum noise temperature due to cloud is observed at this frequency.
Fig. 6.3 Change in noise temperature variation with frequency due to clouds relative to clear air situation
Fig. 6.4 a Variation of Noise temperature for cloudy condition at operational frequency of 45 GHz with mass density of cloud
Fig. 6. 4 b  Variation of Noise temperature Difference due to clouds at operational frequency of 45 GHz with mass density of cloud
It has been seen that the liquid water content in the cloud varies from 0.1 gm/m³ to 1 gm/m³. The noise temperature due to cloud having cloud height 3 km has been determined at 45 GHz for various water contents in the cloud and the results have been presented in Fig. 6.4. It is seen that the noise temperature due to cloud increases exponentially. The cloud noise temperature at 1 gm/m³ is nearly about 135 K while at 0.5 gm/m³, it is around 85 K at 45 GHz.

It has been seen that the noise temperature due to cloud depends strongly on the thickness of the cloud. Also, the cloud noise temperature increases exponentially with cloud thickness. The cloud noise temperature for 5 km cloud thickness is found to be 165 K while at 1 km the cloud noise temperature is 5 K.

The attenuation and noise temperature due to clouds lead to serious degradation in the performance, especially for satellite borne low noise microwave radio systems. It is therefore essential to derive the results on change of signal to noise ratio at different frequencies. The change in signal to noise ratio is estimated by equation (6.16). The change in signal to noise ratio is appreciable upto 55 GHz and such is due to major contribution from cloud noise temperature while the large changes in signal to noise temperature from 60 GHz is mainly due to the contribution of attenuation due to clouds.
Fig. 9.5a Variation of Noise temperature due to clouds at operational frequency of 45 GHz with cloud height.

Fig. 9.6 Signal-to-Noise Ratio variation with frequency for the cloudy condition in relation to clear air situation.