Recent studies on cloud and precipitation phenomena for propagation characteristics over India

S K Sarkar & Anil Kumar
Radio and Atmospheric Sciences Division, National Physical Laboratory, New Delhi 110 012, India
e-mail:sk_sarkar@mail.nplindia.ernet.in

Received 3 August 2007; accepted 21 August 2007

Radio propagation above a frequency of 10 GHz is affected by precipitation in terms of attenuation due to its high dielectric constant. As far as Indian subcontinent is concerned, rain and cloud are the most important ones. Thus, there is still tremendous need to develop a strong database on these parameters. The work carried out on cloud and rain characteristics in relation to radio wave propagation over India in recent years only, from 2000 till today is reviewed in this paper. These results are useful to design as well as for estimation performance of microwave communication and for radar propagation over different locations situated in different geographical regions of India.

Keywords: Precipitation, Rain, Cloud, Thunderstorm, Microwave communication, Millimeter wave communication, Attenuation, Noise temperature, Conventional radar, Doppler radar

PACS No.: 92.60. Nv; 84.40.-x

1 Introduction

In recent years, there is a shift from C-band to higher frequency bands in India from the user point of view for radio communication and remote sensing applications. Such higher frequency is needed due to the requirement of larger bandwidth of radio systems. The radio propagation above 10 GHz is affected by precipitation. The measurements of various precipitation parameters should be carried out over as many locations as possible. Infact, some measurements have been carried out over different geographical regions of India in recent years by various scientific institutions. Parameters, which affect microwave communication and radar propagation, are mainly rain rate, horizontal extension of rain, rain height, rain drop size distribution, cloud characteristics and cumulus cloud cells responsible for formation of thunderstorm. All these parameters are taken as input parameters for estimation performance of microwave communication systems. Several techniques such as rapid response rain gauge, conventional rain gauge, radar, radiosonde, etc., are used to deduce these results. In addition to precipitation measurements, communication links operating over both paths like horizontal and earth space path above 10 GHz should be monitored to deduce results on attenuation of radio wave due to rain and cloud. Some links operating in Ku and Ka bands are also monitored to investigate the effects of rain on the performance of communication systems. Preferably such links should be monitored where heavy rainfall occurs.

2 Low cloud occurrences morphology over various selected locations

Due to shift of interest to higher frequencies, many assumptions made for lower frequency bands are no longer valid for higher frequency bands. Attenuation due to clouds in millimeter wave and microwave frequency bands also leads to serious degradation in the performance of radio communication, especially for low noise systems. The cloud morphology, particularly in relation to radio wave propagation over different geographical regions of India is very essential and important. In view of this, systematic studies on cloud occurrence morphology over different geographical locations in India have been undertaken recently. It is important to mention here that cloud related work in relation to radio wave propagation over India has not been carried out and therefore statistical effects are relatively unknown. It is well known that there are several types of clouds, such as altostratus, cumulonimbus, cumulus, fair-weather cumulus, nimbostratus, stratus, stratocumulus, etc. Among all these types of clouds, the cumulus type is very
important over tropical India. Each cloud type is peculiar in nature in terms of dimensions, shape, moisture content, liquid water content, etc.

The cloud occurrences morphology over several Indian stations, for Kolkata by Kumar and Sarkar\textsuperscript{11}, over northern India by Sarkar and Kumar\textsuperscript{12}, over Hyderabad by Sarkar et al\textsuperscript{13}, over other Indian stations by Sarkar et al\textsuperscript{14} and other Eastern Indian stations by Kumar and Sarkar\textsuperscript{15} has been deduced from the low-level cloud data. The cloud data were obtained from the India Meteorological Department and pertain to the period 1990-95. The advantage of using the cloud data from the India Meteorological Department is that these are available for a large number of stations in India pertaining to large periods. The cloud observations here in India are taken four times during the day and four times during the night times. The observations are taken during 0830, 1130, 1430 and 1730 hrs IST in the day and also at 2030, 2330, 0230 and 0530 hrs IST in the night. The low clouds are found to occur between 2 km and 6 km heights.

It has been seen that the times of observations of clouds in Indian stations were chosen in such a way that four daytime and four nighttime observations are truly good enough to be the representative conditions of day and night in Indian subcontinent\textsuperscript{14}. The averaged monthly results observed during daytime and nighttime on temperature, humidity and pressure is also the representative of the daily results of these meteorological parameters\textsuperscript{16}. The number of days (average of 0830, 1130, 1430 and 1730 hrs IST) and nights (average of 2030, 2330, 0230 and 0530 hrs IST) in each month during which the sky is covered totally and partially with clouds over various stations\textsuperscript{11-15} are presented in Table 1.

The low level cloud coverage over the Indian subcontinent is also being monitored\textsuperscript{13} by the Meteosat-5. A typical cloud coverage diagram over the Indian subcontinent observed on 11 Feb. 2004 at 0000 hrs UT by Meteosat-5 is presented in Fig. 1. It is seen from Fig. 1 that the subcontinent is substantially covered with low clouds. Some scattered mid-level and high-level cloud coverage were also observed. Such satellite observations on cloud coverage are also useful for on-line atmospheric conditions for satellite communication and remote sensing application work in microwave and millimeter wave frequency bands.

Reddy\textsuperscript{17} has studied the temporal variations of vertical structure of precipitating clouds in tropical India with the 1.357 GHz lower atmospheric wind profiler (LAWP) at Gadanki. On the basis of these observations, he has classified the precipitating cloud systems into (1) convective, (2) transition and (3) stratiform. Diurnal and seasonal variations of the occurrence of precipitating cloud systems show that the precipitation primarily occurs in the afternoon and also the convective and transition clouds are most

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\hline
Mumbai & & 1 & 3 & 5 & 10 & 26 & 28 & 31 & 30 & 29 & 18 & 8 & 2 \\
& & (1) & (2) & (4) & (9) & (26) & (28) & (30) & (30) & (28) & (12) & (3) & (1) \\
Nagpur & & 6 & 8 & 11 & 16 & 14 & 25 & 30 & 30 & 23 & 17 & 9 & 5 \\
& & (3) & (4) & (6) & (10) & (13) & (23) & (27) & (27) & (17) & (10) & (3) & (2) \\
Ahmedabad & & 1 & 4 & 2 & 4 & 9 & 22 & 31 & 31 & 25 & 9 & 3 & 1 \\
& & (1) & (2) & (1) & (2) & (5) & (18) & (29) & (28) & (18) & (3) & (2) & (1) \\
Hyderabad & & 10 & 12 & 16 & 22 & 26 & 29 & 30 & 30 & 28 & 24 & 17 & 11 \\
& & (5) & (7) & (11) & (21) & (26) & (28) & (28) & (31) & (28) & (25) & (14) & (6) \\
& & (2) & (3) & (4) & (4) & (8) & (18) & (25) & (27) & (19) & (6) & (2) & (1) \\
Ranchi & & 5 & 11 & 9 & 14 & 19 & 22 & 25 & 26 & 22 & 18 & 11 & 5 \\
& & (3) & (6) & (6) & (8) & (14) & (23) & (27) & (25) & (18) & (11) & (5) & (2) \\
& & (4) & (9) & (16) & (23) & (23) & (25) & (30) & (30) & (27) & (21) & (12) & (2) \\
New Delhi & & 6 & 9 & 8 & 8 & 8 & 14 & 21 & 20 & 17 & 3 & 4 \\
& & (4) & (6) & (5) & (5) & (6) & (12) & (23) & (19) & (14) & (2) & (2) & (1) \\
Kolkata & & 7 & 8 & 13 & 18 & 24 & 28 & 30 & 30 & 28 & 23 & 11 & 8 \\
& & (3) & (5) & (9) & (15) & (20) & (24) & (26) & (26) & (22) & (13) & (7) & (4) \\
\hline
\end{tabular}
\caption{Summaries of occurrences of low clouds during daytime and nighttime over various stations\textsuperscript{11-15}}
\end{table}

Results in brackets pertain to nighttime
3 Rain bearing cloud/rain height distribution over the Indian subcontinent

Rain bearing cloud height/ rain height is an important input parameter, which is needed for estimation performance of satellite communication and remote sensing applications. The rain height can be estimated from the results of 0°C isotherm-height. One of the best ways to estimate 0°C isotherm height is from radiosonde observations. Mondal et al. and Mondal and Sarkar deduced some results on rain height over different stations on rain height in relation to 0°C isotherm height recently from the upper air meteorological observations obtained from the India Meteorological Department pertaining to the period 1990-97. Mondal and Sarkar deduced the range of variation of rain height/rain bearing cloud height in relation to 0°C isotherm height, \( H_i \) over different stations in India during different seasons. It has been observed by them that \( H_i \) decreases in the months of winter as latitude increases.

It is well known that before the rainy situation, there are cloudy conditions in Indian tropical stations. Some times it is observed that the sky is fully covered with heavy dark cloud just before rain over Indian stations. It is now a well-established fact that the clouds present before rainy situation are rain bearing clouds have maximum cloud water particle density. It is therefore necessary and useful to estimate attenuation of the radio wave due to cloud over the region, when the cloud water particle density is maximum, as such attenuation results are important to the radio engineers for satellite communication systems. Cloud height is also required to estimate temperature of the cloud. Some results on rain/ rain bearing cloud height in relation to 0°C isotherm height over various stations are presented in Table 2.

In the months of monsoon season, the variation of \( H_i \) is not substantial, particularly over inland. This is due to the fact that the rainfall in monsoon is almost evenly distributed throughout India. The study has revealed that \( H_i \) is not dependent on topographical features, but it depends more on seasons. It is useful to highlight the results of \( H_i \) over the two south-east coastal stations, Chennai and Visakhapatnam, which are near Gadanki, where MST radar facility is located. During summer, \( H_i \) varies between 3.7 and 6 km for Chennai, and between 3.7 and 5.95 km over Visakhapatnam. During monsoon, \( H_i \) varies between 4.05 and 6.2 km over Chennai, while over Visakhapatnam it varies from 4.2 to 5.9 km. The variations of \( H_i \) over both these stations in different seasons are insignificant, particularly at low and intermediate probability levels. This is due to the fact that these, being coastal stations on the same side of Bay of Bengal, are having similar climatic conditions and rainfall pattern. The average temperature in January and February over Chennai are 23 and 25°C, respectively. The annual mean temperature over Chennai and Visakhapatnam are 27 and 28.1°C, respectively. The annual rainfall over Chennai has been recorded to be 1215 mm and that over Visakhapatnam to be 973 mm. The peak monsoon months over Chennai are October and November with total rainfall of 267 and 309 mm, respectively. In case of Visakhapatnam also the monsoon months are October and November and rainfall during these months are 167 and 259 mm, respectively.

<table>
<thead>
<tr>
<th>Table 2—Rain/ rain bearing cloud height over various locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
</tr>
<tr>
<td>Mumbai</td>
</tr>
<tr>
<td>Nagpur</td>
</tr>
<tr>
<td>Ahmedabad</td>
</tr>
<tr>
<td>Hyderabad</td>
</tr>
<tr>
<td>Kolkata</td>
</tr>
<tr>
<td>Chennai</td>
</tr>
<tr>
<td>Visakhapatnam</td>
</tr>
</tbody>
</table>
The 0°C isotherm height is associated with melting layer and a bright band\textsuperscript{50}. The bright band height as well as the characteristics of bright band has been investigated recently by Kiran Kumar\textsuperscript{20} at Gadanki by using the MST radar observations. The height of the bright band is dependent on the height of 0°C isotherm level in the atmosphere and is different for different seasons. The bright band height varies in the range from 3.9 to 4.65 km. It is shown that the bright band is centered around 4.2 km. It was also shown that the average bright band thickness deduced from the Indian MST radar observations is found to be in the range between 600 and 1200 m. The maximum probability of occurrences of bright band thickness has been found to be around 750 m.

Recently, bright band height (melting layer height) has been deduced from tropical rain measuring mission (TRMM) observations. The TRMM data pertain to the period 1998-2000. It has been seen that the bright band height deduced from TRMM results underestimate the rain height in relation to 0°C isotherm height, when it is compared with the results deduced from radiosonde observations over the Indian stations (Fig. 2). The year-to-year variation of bright band height over different Indian latitudes and stations were also deduced and it has been found that the year-to-year variation of bright band height is quite significant in the latitude range from 20° to 35°, while there is no variation of bright band from year-to-year for latitude from 5° to 20°.

Staelin\textsuperscript{21}, Gunn and East\textsuperscript{22}, Mali and Sarkar\textsuperscript{23} have shown that the attenuation of radio wave due to cloud is dependent on cloud temperature. To determine temperature of the cloud, cloud height is needed. One of the ways to deduce rain bearing cloud height is from the observations of 0°C isotherm height. The other better way to determine the cloud height is from radar measurements. The cloud height for different periods can be obtained (deduced) from radar observations when radar is operated in Range Height Indicator (RHI) mode. Sarkar et al.\textsuperscript{24} determined height of the cloud from radar measurements on RHI over Kolkata. The sophisticated and computer controlled radar belonging to the India Meteorological Department has been utilized to estimate the cloud height during July and August, which constitute the monsoon months in Kolkata. The characteristics of the conventional X-band radar belonging to the India Meteorological Department are the following:

- Frequency = 9.375 GHz; Transmitted power = 200 kW; Beam width = 1°; Pulse width = 0.8 μs and 2 μs; Pulse repetition frequency = 1250 pps and 750 pps; Range for maximum time = 240 km; Maximum range = 400 km; Accuracy = 2 dB at 240 km for Rainfall (1 mm/h) ∼ 23 dBz.

The RHI scans during the cloud and rain events in July-August are recorded with radar. The backscattered echoes from rain cells are reproduced over the RHI of the radarscope. The vertical extension of rain observed on X-band radarscope shows that rain having intensity of 2.6 mm/h is occurring from an altitude of around 6 km and the rain intensity of ∼ 75 mm/h is from an altitude of 4 km up to the surface. The horizontal spread of the rain is around 5 km.

Once cloud height is obtained, cloud temperature is estimated by using the temperature lapse rate ∼ 6.5 °C/km. It is seen that the temperature of particles differs from the temperature of the surrounding air, usually by only a few tenths of a degree\textsuperscript{1}. Cloud height over Kolkata for worst months (July-August) has been estimated from conventional radar observations. It is seen that cloud height over Kolkata during these months varies from 5 to 12 km. It is seen\textsuperscript{24} that clouds occur at an altitude of 6 km maximum percentage of time (43 %), while it is significant at 5 km (28 %) and 7 km (24 %). For 3 % of the time cloud is found to occur at 8 km and 9 km, while it is quite less at altitude above 10 km. It is seen that the cloud occurrences at 11 km is 0.2 % while at 12 km it is 0.4 %. Since it is seen that most of the cloud occurrences over Kolkata during worst months are around 5-7 km, for long term morphological study the cloud height\textsuperscript{24} can be taken as 6 km.

![Fig. 2—Rain height deduced from Radiosonde and TRMM observations](image-url)
4 Specific attenuation and total attenuation due to cloud

On the basis of rain bearing cloud height, cloud water particle density and wavelength of the radiowave, the attenuation of radio wave due to cloud at different wave length has also been deduced and the expression used for the attenuation of radio wave, \( \alpha \) due to cloud\(^{10,21-23} \) is given by

\[
\alpha = 4.343 \times M \times \left( 10^{0.0123(291-T)/1} \right) \times 1.16 / \lambda^2 \text{ dB/km}
\]  \( \text{... (1)} \)

where, \( \alpha \) is specific attenuation due to cloud (in dB/km), \( M \) the cloud water particle density (in g/m\(^3\)), \( T \) the cloud temperature in K and \( \lambda \) the wavelength of radio waves (in cm).

The total atmospheric temperature at 32 GHz over Mumbai, Nagpur and Ahmedabad has been found to be around 265-279, 278-268 and 263-283 K, respectively. It is seen that range of specific attenuation over Mumbai for water content \( \sim 1 \) g/m\(^3\) at 10, 18, 32, 44 and 70 GHz is 0.0784-0.1146, 0.2541-0.3712, 0.8030-1.2045, 1.518-2.2183 and 3.8424-5.6144 dB/km, respectively. The variation in specific attenuation is due to the variation of cloud particle temperature. It is important to mention here that over Kolkata\(^{11} \); a tropical station located in Indian eastern sector, for water content \( \sim 1 \) g/m\(^3\), specific attenuation at 10 GHz is 0.077 dB/km, while that at 100 GHz, it is 7.690 dB/km. Over Delhi, located in northern India, for water contents \( \sim 1 \) g/m\(^3\) in summer and monsoon months, specific attenuation range at 10 and 100 GHz are 0.0608-0.1190 and 6.8460-11.9810 dB/km, respectively\(^{12} \). Over Hyderabad situated over Indian southern plains, at 10, 40 and 75 GHz, specific attenuation varies in the range 0.0788-0.0987 (Ref. 13), 1.2622-1.5803 and 4.4375-5.557 dB/km, respectively.

The method provided by ITU-R\(^{25} \) has also been used to estimate attenuation due to clouds. The ranges of specific attenuation has been estimated by ITU-R method on the basis of liquid water content 1 g/m\(^3\) and for temperature of the cloud over Mumbai, Nagpur and Ahmedabad, and at 32 GHz were found to be \( \sim \) 0.80-1.20, 0.78-0.98 and 0.70-1.41 dB/km, respectively\(^{14} \). The attenuation due to clouds for the worst probability level (1 %) has also been estimated by using the total columnar content of liquid water \( L \) (kg/m\(^2\)) and by using the ITU-R relation\(^{25} \). An elevation angle of 56\(^\circ\) has been used since all the Indian stations are visible by geosynchronous satellite at this elevation angle\(^{25} \). The results on attenuation deduced by ITU-R method were higher at 10 and 18 GHz, and the values are relatively lower at 44 and 70 GHz, as compared to the other method, while results at 32 GHz are comparable as obtained by both the methods\(^{25} \).

5 Total atmospheric noise temperature

The noise temperature of cloud degrades the performance of satellite communication for frequencies above 10 GHz. The total atmospheric noise temperature due to water vapour and oxygen including the noise temperature due to clouds with thicknesses \( \sim 1, 1.5 \) and 1.5 km, have been deduced over several locations in India by Sarkar and his colleagues\(^{11-15} \) and the estimation of total atmospheric noise temperature, \( T_a \) is made on the basis of the following relations\(^{10,21-23} \)

\[
T_a = T_p (1 - 1/L_n)
\]  \( \text{... (2)} \)

and

\[
L_n = 10^{(\alpha_{\text{total}} \text{ (dB)})/10}
\]  \( \text{... (3)} \)

where \( T_p \) is physical temperature and \( \alpha \) the attenuation in dB.

The extra noise in terms of noise temperature generated by clouds degrades the signal-to-noise ratio of the satellite receivers. For example, when cloud moves in the antenna beam, the total system temperature increases from the clear air system noise temperature. The effect of increase of noise temperature is more severe for lower noise receiving satellite systems. Such estimation of cloud attenuation and atmospheric noise due to cloud over some locations in India have been reported by the present authors in several publications\(^{11-15,24} \).

The total atmospheric temperature at 32 GHz over Mumbai, Nagpur and Ahmedabad varies in the ranges 95.87-160.27, 89.90-154.30 and 94.76-159.16 K, respectively, during the month of July. The results on total atmospheric noise temperature over Mumbai are shown in Fig. 3 as a representative diagram.
distribution, irrespective of rainfall intensity. Rao et al.\textsuperscript{28} low rainfall intensities, but became closer to the data approximated an exponential distribution for type distrometer. It was shown that in June and July, the size was measured by using a Joss-Waldvogel distribution measured at Thiruvananthapuram, Kerala. Kumar\textsuperscript{530, 300, 150 and 10, respectively at the variability of the shape-slope relation with the climatic regime and also as a function of height. Aloft with VHF and UHF radar measurements at Gadanki during south-west monsoon. They studied the size with a peak power of 500 kW.

6 Rain drop size distribution

It has been shown recently by Mali et al.\textsuperscript{26} that from radar reflectivity measurements raindrop size distribution (RDSD) at different rain intensities can be deduced. The values of $D$, the most probable raindrop diameter vary from $\sim 0.1$ to $1.4$ mm, while the radar reflectivity varies from $23$ to $58$ dBz. The values of $D$ have also been found to vary exponentially with rain rate. At higher rain rate of $\sim 100$ mm/h, $D$ is around $\sim 1.25$ mm. It was seen that the maximum number of drops is around $\sim 1800$ per m$^3$mm$^3$ and associated with most probable raindrop diameter around $\sim 0.75$ mm at $49$ mm/h. Significant number of rain drops is associated with diameters more than $\sim 1.5$ mm. Large numbers of small rain drops also have been observed at $\sim 49$ mm/h. For rain rate $\sim 75$ mm/h, the maximum number density, $N(D)$ per m$^3$mm$^1$ was observed around $\sim 640$, while the maximum rain drop diameter was around $\sim 3.9$ mm. Considerably large number of rain drops with large diameter have also been observed at $\sim 75$ mm/h. The number of drops [$N(D)$] per m$^3$mm$^1$ associated with rain drop diameter $\sim 1, 1.5, 2, 2.5$ and $3$ mm, have been found to be $\sim 630, 530, 300, 150$ and $10$, respectively at $\sim 75$ mm/h.

Kumar et al.\textsuperscript{27} recently reported results on drop size distribution measured at Thiruvananthapuram, Kerala. The size was measured by using a Joss-Waldvogel type distrometer. It was shown that in June and July, the data approximated an exponential distribution for low rainfall intensities, but became closer to $\Gamma$-distribution, irrespective of rainfall intensity. Rao et al.\textsuperscript{28} derived gamma parameters on the ground and aloft with VHF and UHF radar measurements at Gadanki during south-west monsoon. They studied the variability of the shape-slope relation with the climatic regime and also as a function of height. Backscattering efficiency and radar reflectivity for a wide range of rain rates by using Mie scattering formulation from the classical electromagnetic theory were derived by Rao et al.\textsuperscript{29} The coefficients of $Z-R$ ($Z =$ radar reflectivity factor, $R =$ rain rate, mm/h) relationship have been theoretically computed for 2.84 GHz (used in coastal Doppler radars), 13.8 GHz (used in the space borne precipitation radar on-board TRMM satellite) and also 35.5 GHz (to be used in Global Precipitation Mission Radar). The Raleigh approximations appear to be valid for the computation of backscattering coefficient over the range of realistic values of size parameter for the radar frequency of 2.84 GHz, but this is not so for 13.8 GHz or higher frequencies. The study highlights the fact that the use of Raleigh approximation for the higher frequencies results in inaccuracies in rain attenuation, especially in intense rain conditions.

7 Cloud characteristics by using Doppler radar over Kolkata

Sarkar et al.\textsuperscript{24} reported that the cloud attenuation and cloud noise temperature can be deduced effectively if more measured parameters in relation to cloud morphology are available. Such cloud related parameters are cloud coverage, cloud height, cloud thickness, cloud liquid water content, etc. It is seen that various such cloud parameters can be deduced from the C-band Doppler radar belonging to the India Meteorological Department. The meteorologists of India have studied cloud morphology as well as cloud dynamics for the weather forecasting purposes. The authors have deduced results on various cloud parameters for radio wave propagation work by utilizing the observations taken by the sophisticated computer controlled Doppler radar belonging to IMD over Kolkata. It is also important to mention here that the worst atmospheric condition is important and needed to the radio engineers, radio researchers and users for estimation performance of microwave communication and radar propagation. In view of this argument results on several parameters on cloud/rain bearing cloud/rain characteristics taken during worst months have been provided. The Doppler radar operates in C-band at frequency $\sim 2700$-$2900$ MHz with a peak power of 500 kW.

Several cloud parameters, viz. radar reflectivity, cloud thickness, cloud height, cloud vertical integrated liquid water content, etc., have been deduced in probability distribution scale. The
horizontal extension of rain is very important to deduce rain for terrestrial communication links. Some results on horizontal extension of rain were derived in the past by using the measured results on total attenuation (dB) of radio wave due to rain and the results on specific attenuation (dB/km) obtained theoretically. The typical representative rain bearing cloud/rain events observed on Doppler radar PPI (plan position indicator) mode is presented in Fig. 4. It is seen that low intensity rain/cloud is scattered all over the places and high intensity rain/rain bearing cloud is very much a localized phenomena. Similarly the vertical extension of rain/rain bearing cloud is estimated from the Doppler radar reflectivity observations when radar is operated in RHI mode. One of the important parameters for estimation of attenuation of radio wave due to cloud/rain bearing cloud is cloud thickness. The Doppler radar provides results on cloud/rain bearing cloud base height and cloud/rain bearing cloud top height over the radar scanned region. The difference between rain-bearing cloud top height and rain bearing cloud base height provides the results on cloud thickness.

One of the important parameters for route diversity work for communication links is the results on rain characteristics over different locations. Doppler radar has provided the opportunity to deduce results on rain rate intensity (mm/h) and rain accumulation (mm) occurring simultaneously over different places. Results of rain intensity and rain accumulation have also been deduced from Doppler radar measurements within a range of 120 km. For rain bearing cloud attenuation, another important parameter is the Vertical Integrated Liquid (VIL). Such results are derived from Doppler radar measurements and these results spread over different locations have been deduced. Another important parameter for cloud attenuation work is the result on the velocity of water droplets present in the cloud and rain events as well as velocity of cloud. The radial velocity of the cloud/rain bearing cloud is measured by Doppler radar. The results on attenuation of radio wave due to rain, rain bearing cloud and cloud are always presented in distribution scale. Therefore it is always useful to provide results of several parameters on rain and cloud in distribution scale for worst condition attenuation of radio wave due to rain and cloud related work, in monsoon season, i.e. monsoon months. The probability distribution of various parameters of rain bearing cloud/rain parameters has been deduced by the present authors. The high intensity rain over horizontal and vertical path occurs

---

**Fig. 4**—Radar reflectivity in PPI mode observed by Doppler radar
for less percentage of time, while the low intensity rain occurs for more percentage of time in both modes. It is seen from the Doppler radar measurements over Kolkata that the cloud height ~ 6.6 km occurs for the maximum percentage of time (Fig. 5).

Another important parameter for estimation of attenuation of radio wave due to rain is rain intensity. The Doppler radar measurements of rain provide results on rain intensity over several radar scanned locations simultaneously. Several rain events in terms of rain intensity which occurred over Kolkata during monsoon months were measured by Doppler radar. The probability distribution of rain intensity was derived from all such measurements. It is seen that higher rain intensity occurs for less percentage of time. However, the rain intensity results deduced from Doppler radar are of lower order as compared to those deduced from rapid response rain gauge having low integration time. Therefore for radio wave propagation work, some correction factor is to be incorporated in the results obtained by Doppler radar. The results on measured velocity of rainfall for rain drop size distribution work are very essential. Most of the work on rain drop size distribution is carried out on the basis of rainfall velocity results obtained theoretically. From the Doppler radar measurements of rainfall velocity over Sriharikota, the distribution of rainfall velocity have been deduced, which is shown in Fig. 6. The radar was put in operation in vertical mode. It is seen in Fig. 6 that the rainfall velocity varies from 0.4 to 15.4 m/s. It is important to mention here that most of the rainfall velocity was around 0.4 m/s. More such observations of rainfall velocity by using Doppler radar available at different places are needed.

8 Results on rain attenuation measurements at frequency above 10 GHz

In the present day scenario of radio communication, it has become necessary to provide more channels as per the demand of users. Using higher radio frequencies, particularly above 10 GHz can meet such a demand. In a tropical country, there are regions where heavy rainfall occurs with high rain intensity. The use of higher frequency in radio wave gives rise to problems like attenuation of radio waves due to rain as well as performance deterioration of the links. Though efforts are on to generate more database of rain attenuation in microwave frequencies to develop model for estimation of attenuation due to rain over this part of the world, there is a dearth of such measurements in the tropical regions of India.

Recently, some systematic simultaneous monitoring of communication links operating at frequencies above 10 GHz belonging to different operational agencies and measurements of rain rate were undertaken in Indian eastern sector by using terrestrial communication links and some very useful results on attenuation were derived by Sarkar et al.30-34 The attenuation results over several different paths at 13 GHz at different probability levels were deduced. It was seen that the signal level is characterized with steady signal with a fade depth ~ 1-2 dB under non-precipitation condition. The communication link exhibited heavy loss of signal around 20-25 dB during heavy rains (Fig. 7). Attenuation values as high as 31 dB has been observed during torrential rain at 13 GHz. Attenuation values of ~ 5.5, 10 and 31 dB are found to be associated with rain rates of ~ 20, 36 and 160 mm/h, respectively. The estimated results on specific attenuation at different rain rate derived by

---

Fig. 5—Occurrence of cases in percentage of the cloud height determined from Doppler radar

Fig. 6—Probability distribution of rain/cloud water droplet fall velocity deduced from Doppler radar measurements
using the ITU-R relation\textsuperscript{35} (earlier known as CCIR). $A = 0.02515 \, R^{1.164}$ have been compared with the measured values. The specific attenuation deduced by using ITU-R and from the measured total attenuation over the path of length of 8 km shows good agreement\textsuperscript{33} up to a rain rate of 60 mm/h.

The probability distribution of attenuation at 18 GHz over the communication link situated over Kolkata having path length ~ 8 km has been deduced by Sarkar et al.\textsuperscript{31} It was observed that under normal condition when there is no precipitation the measured signal level is −48 dBm. It is seen that the observed attenuation is around 7 dB at 20 mm/h and it is 18.6 dB at 60 mm/h. There is not much increase in attenuation from 120 to 160 mm/h.

Performance deterioration of two microwave communication links situated in Indian east coast and operating at ~ 13 GHz and 12.8 GHz during the months of monsoon has also been tested by Sarkar et al.\textsuperscript{32} This study provided the percentage of time for which the communication link does not serve the purpose under rainy conditions during the monsoon months over Kolkata region.

9 Rain attenuation over earth space path for direct-to-home (DTH) service over Delhi

Though rain is the most important parameter that affects the radio wave operating above 10 GHz, the radio wave is affected even by clear air. The three different meteorological conditions are clear air, cloud and rain. Among the propagation mechanisms there are scattering, reflection, absorption and multipath. In satellite communication also sometimes multipath phenomena becomes quite important.

The authors have also investigated the variation of carrier intensity over earth space path of satellite communication at Ku band, affected by three atmospheric conditions, viz. clear air, cloud and rain. The signal amplitude variations were measured during the monsoon months of 2005. Though the signal is found to lie in Ku band, the exact frequency of operation is around 12 GHz. The free space basic path loss at 12 GHz over the satellite path is around 205 dB. Under clear sky condition the signal level was found to vary from −66 to −69 dBm. The maximum fade of 3 dB was observed. However, for 52 % of the time, signal was of −67.5 to −69 dBm and for 48 % of time the signal level was found to vary between −66 and 67.5 dBm under clear sky condition. Such low variation of signals of the order of 1-3 dB is associated with scattering phenomena.

It has been observed that the satellite signal over the earth space path is attenuated due to clouds. Also such attenuation is due to the absorption of the signal by the liquid water content of the cloud. It has been seen that the attenuation of radio waves due to cloud is between 1 and 7 dB. The signal level from −67.5 dBm exceeds for 50% of the time, while that from −66.5 dBm exceeds for 7.8 % of the time under cloudy condition. The analysis suggests that even under cloudy condition signal level becomes of low order for considerable time. The probability distribution of the satellite signal level under rainy condition is illustrated in Fig. 8. It is seen that signal level varied from −66 to −78 dBm under rainy situation. A maximum attenuation of the order of 12 dB was observed. The signal level was found to vary from −67.5 to −78 dBm for 56 % of the time, while it varied from −66 to −67.5 dBm for 44% of the time. It has been reported that DTH services affected severely during rain over Delhi. The services may be improved by increasing the gain of the

![Fig. 7—Typical record of carrier intensity at 13 GHz during rain intensity ~ 35-42 mm/h](image)

![Fig. 8—Probability distribution of carrier intensity measured over satellite path under rainy situation](image)
receiving system. The extra gain is to be provided either in the form of antenna gain or by introducing extra LNA in the system.

Rain attenuation studies were also made by Rao et al.\textsuperscript{36} at 11.7 GHz by utilizing INSAT-2C satellite signals over southern India during rain events. The observed cumulative distribution functions were compared with prominent predicted models and it was found that the ITU-R method deviates considerably from the observed rain attenuation.

Propagation measurements at Ku-band over an earth space path have been carried out at Kolkata by Maitra and Chakravarty\textsuperscript{37} by receiving a signal at 11.172 GHz from the satellite NSS-6 (geostationary at 95°E). The amplitudes of the co-polar signal and the cross-polar component have been monitored, accompanied by simultaneous measurements of rain rate and drop size distribution by an optical rain gauge and a disdrometer, respectively. Three phenomena studied with these experimental data are rain attenuation, depolarization and scintillation\textsuperscript{38}. Results on effective rain height have been deduced by Sharma et al.\textsuperscript{38} from zenith attenuation statistics at 29.9 GHz. The average effective rain height at Amritsar has been estimated to be 3 km. Kumar and Sharma\textsuperscript{39} developed an empirical model for rain attenuation on the basis of rain attenuation data collected over line of sight (LOS) link propagation experiment at 19.4 and 28.75 GHz over Amritsar and rainfall rate measured, using tipping bucket rain gauges. The total attenuation over the link path measured experimentally has been compared with ITU-R model. Kumar and Sharma\textsuperscript{40} also reported measurements of zenith path attenuation due to rain in winter and monsoon seasons at Amritsar using zenith looking radiometer operating at 19.9 GHz. Specific attenuation for various rain rates has been evaluated from measured rain drop size data using lognormal drop size distribution. Rainfall study has been carried out over Salem in southern India by Rajasri et al.\textsuperscript{41} Rainfall values were recorded using a rapid response rain gauge installed at Salem. The derived rainfall rates were utilized to estimate attenuation in the 10-100 GHz frequency range. Using estimated co-polar attenuation cross-polar discriminations (XPD) were computed using ITU-R\textsuperscript{42} model.

\textbf{10 Thunderstorm characteristics}

The other important parameter in relation to precipitation characteristics is thunderstorm, which is quite common in some parts of India. Thunderstorm is a strong frontal system, which produces violent damaging effects to the community, such as hail, lightning, high winds, flash and floods. The primary effects include hail and wind damage. Secondary effects include communication failure and the communication outages are of considerable dimension in Ku and Ka band. The thunderstorm is associated with cumulus cells and lot of rain and cloud. Clouds, particularly the rain bearing clouds, become a point of concern at higher frequencies. Therefore the characteristics of thunderstorm need to be understood and studied. To begin with, the authors have investigated different aspects of atmospheric cells (cumulus) responsible towards the formation of thunderstorm. The various aspects of the cells in relation to their stages, tendencies, intensities, weather condition, their distribution in different time and direction have been examined. All these results are deduced from conventional weather radar measurements. The characteristics of such cells (varying, decreasing, increasing (structure), weak, moderate, strong in intensity) in different months and local time over Kolkata have been estimated on the basis of X-band radar echoes taken during the course of many thunderstorms.

Analysis of 900 cumulus cells has been made. It is seen that among 900 cases, around 740 cases are associated with cloudy situation, when around 160 cases are associated with rain. The nature of cumulus cells also has been investigated. It is seen that most of the cells are varying in nature. It is difficult to predict whether the cells have increasing or decreasing tendency. The intensity of the cells in terms of weak, moderate and strong has also been tested. It is seen that most of the cells around 575 cases are weak in nature, while around 310 cases are of moderate intensity and very negligible few are of strong intensity. It has been seen that the cumulus cells with moderate intensity are good enough to contribute towards the formation of thunder activity. The cumulus cells distribution observed in different direction centered around Kolkata has been studied.

It is seen that large number of cells are found to occur in 0°-120° quadrant. A considerable number of cells are also found in 150°-240° quadrant. The cumulus cells which are responsible towards the formation of thunder activity have different type of characteristics. Such cells are having natures like broken type, isolated kind, scattered, varying in...
nature, forming type, increasing and decreasing kind, dissipating and maturing kind, etc. Cells observations taken by X-band radar showed such types of characteristics of cumulus cells. For considerable percentage of time cells are isolated and scattered (Fig. 9). These types of observational evidences are essential for developing a model for thunder activity prediction. The present study also reveals when cell formation takes place, it is not necessary that all the cells will form to lead a thunder system. It is seen that around 40% of the cells get matured and around 10% get dissipated. Results in relation to the number of cases (echoes) observed during different times indicate that majority of the cases around 300 are observed around afternoon at 3 pm, while significant number of cases around 175 and 150 are found to occur at 12 noon and 6 pm. It is therefore inferred that majority of the thunder activity occurs in the late afternoon and centered between 3 and 4 pm. Such different aspects of cells are to be taken into account for modeling purpose, in order to forecast thunderstorm, which also affects our communication systems.

Recently, by using Doppler radar observations over Kolkata, Singh and Pradhan reported that a very severe thunderstorm in the month of March, 2003, traversed across Gangetic West Bengal, India and adjoining areas of Bangladesh. It was seen that one particular cell of the system lasted for over 12 h. Based on the internal structure, reflectivity, duration and weather pattern on the ground, it was concluded that the cell was a supercell.

11 Conclusions
Results on cloud and rain in relation to radio wave propagation, deduced in recent years over selected locations in India are presented in this paper. These results will be useful to design as well as to estimate performance of microwave communication and radar propagation over different locations situated in different geographical regions in India.

Acknowledgements
The authors wish to express their heart felt gratitude to all whose contributions from their publications have made it possible to prepare this review article. Thanks are also due to various user agencies for providing all help and support with their data, systems, infrastructures, and facilities, etc., to carry out the work. Many work reported here were carried out with the support of financial agencies. The author wishes to thank all financial agencies for their help. The TRMM and rainfall velocity (Doppler radar) observations were provided by Prof D Narayana Rao and Dr Sanjay Sharma, respectively. The authors wish to thank them for providing the data.

References
3 Hall M P M, Effect of the troposphere on radio communication, Institution of Electrical Engineers, IEE Electromagn Wave Ser 8 (UK & USA), 1979.
8 Tat-Soon Yeo, Pang-Shyan Kooi, Mook-Seng Leong & Le-Wei Li, Tropical rain drop size distribution for the prediction of rain attenuation of microwave in the 10-40 GHz band, IEEE Trans Antennas Propag (USA), 49 (2001) 80.
Soblin S D, Microwave noise temperature and attenuation of clouds: Statistics of these effects at various sites in the United States, Alaska and Hawaii, Radio Sci (USA), 6 (1982) 1443.


11 Sarkar S K & Rajesh Kumar, Cloud characteristics and cloud attenuation in microwave and millimeter wave frequency bands for satellite and remote sensing applications over a northern Indian tropical station, Int J Infrared Millim Waves (USA), 23 (2002) 937.


14 Anil Kumar & Sarkar S K, Cloud attenuation and cloud noise temperature over some Indian eastern stations for satellite communication, Indian J Radio Space Phys, 36 (2007) 375.

15 Climatological Tables of Observatories in India, India Meteorological Department, (1988).


20 Staelin D H, Measurements and interpretation of the microwave spectrum of the terrestrial atmosphere near 1-centimeter wavelength, J Geophys Res (USA), 71 (1966) 2875.


41 ITU-R 618-7(2002).