CHAPTER - 4

Rain structure estimation from X-band radar reflectivity measurements for radio system applications in microwave and millimeter wave frequency bands

4.1 Introduction

In this chapter, the horizontal and vertical extension of rain deduced from radar Plan Position Indicator (PPI) and Range Height Indicator Range (RHI) measurements are shown in [Fig 4.1(a,b), Fig. 4.2(a,b), Fig. 4.3(a,b)] Such results of rain extension have also been deduced as a function of radar reflectivity factor (dBz). The radar reflectivity factor Z, is the measure of the strength of the scattering cross section of the rain cells. The scattering cross section is responsible for causing interference to the radio signals. Probability distribution of radar reflectivity (dBz) deduced from both horizontal (PPI) and vertical extension (RHI) of rain cells has also been estimated.

The estimation of interference of radio signals to and from different transmitting sources of various agencies likely to be brought about by the scattering of the transmitted energy by rain and other hydrometeors is important. Such results of interference are essential for designing and planning of radio systems including terrestrial and earth-space communication links and remote sensing devices in microwave and millimeter wave frequency bands (Hall and Goddard, 1978, Olsen and Lammers, 1978)
Fig. 4.1 (a,b) Horizontal rain structures observed on radar PPI during 1 August 2000 and 15 April 2000
Fig. 4.2 (a,b) Vertical rain structures observed on radar RHI during 2 May 2000 at 16.51 hrs IST and 17.51 hrs IST
Fig. 4.3 (a,b) Typical vertical rain structures observed on radar RHI during 27 May 2000 and 1 August 2000
In recent years some studies on radar bright band are of major interest to the radar community by using wind profiler (Fabry and Zawadzky, 1995) and MST radar (Rao, 1999). But the present study is on rain structure in relation to radio wave propagation application. A computer controlled and sophisticated X-band radar belonging to the India Meteorological Department operating at 9.375 GHz has provided us good opportunity to study micro structure of rain in relation to its horizontal and vertical extensions. The back-scattered echoes from rain cells are reproduced over the PPI and RHI of the radarscope. The radar reflectivity (dBz) is a measure of the fraction of back scattered energy received from the precipitation cells (Clift 1985). The strength of the received back scattered energy of different strength has been expressed in different colours on the radar scope. In this radar system the different designated colours are green, dark green, yellow, orange, red and dark red which correspond to the radar reflectivity~ 23 dBz to 28 dBz, 28 dBz to 33 dBz, 33 dBz to 38 dBz, 38 dBz to 43 dBz, 43 dBz to 53 dBz and ≥ 53 dBz respectively. The in built Z-R relation in the radar system has been used to deduce rain intensity from radar reflectivity measurements. The higher radar reflectivity is associated with high rain intensities. The radar reflectivity ~ 23 dBz, 28 dBz, 33 dBz, 38 dBz, 43 dBz, and 53 dBz are associated with rain rate ~ 1 mm/hr, 2.4 mm/hr, 2.6 mm/hr, 9 mm/hr, 18 mm/hr and 75 mm/respectively.
4.2 Source of data and radar characteristics

The India Meteorological Department, Calcutta, has taken several PPI and RHI displays during rainy events in July-August, 2000 on round the clock basis by using the X-band radar. The calibration of the radar system is made on the basis of simultaneous radar reflectivity measurements and rain rate observations taken by rain gauge having low response rain gauge. Each PPI and RHI display has been analyzed and studied carefully. The characteristics of the X-band radar 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~23dBz (1 mm/hr)

The horizontal extension of rain is very important to deduce results on attenuation of radio wave due to rain for terrestrial (horizontal) communication links (Sarkar, 1998). Some results on horizontal extension of rain were derived in the past (Sarkar et al, 1989) 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 events observed on radar PPI are presented in Fig.4.1 (a,b). It is seen in Fig.4.1a (1 August 2000) that the rain of low intensity~ 1 mm/hr is scattered all over the region. Marshall Palmer distribution is utilized to deduce rain rate. The high intensity of rain has been found to occur over very small region. Figure 4.1a depicts that the high intensity rain is localized phenomena. Figure 4.1b shows that rain of high intensity has occurred over large area and rain with low intensity has been found to occur over places scattered all over the region. A typical rainstorm observed at 13.52 hrs, IST on 15 April, 2000 occurring at a distance of 30 km-40 km from the point of measurements has been found to be extended over large distance. This rainstorm consists of rain cells having low, moderate and high rain intensity. In order to estimate the attenuation of radio wave due to rain over earth space paths, the rain height is one of the most important parameters other than the rain intensity. Some results on provisional rain height in relation to 0°C isotherm height over different geographical regions have been determined (Sarkar et al, 1996 and Mondal et al, 2001). But, such results do not provide the rain rate which is usually associated with rain height.

The typical vertical extension of rain observed on 2 May 2000 at 16.51 hrs, IST and 17.51 hrs, IST are shown in Fig.4.2 (a, b). The rain has taken place from the well-developed cloud and rain extends upto the height of 15 km. It is also
shown that the rain intensified with time and moved towards the radar center with the speed of nearly 40 km/hr. The red and orange colors at the core of the rainstorm signify strong water content with rain intensity as high as ~ 75 mm/hr. Such rain occurring from 10 km or 11 km is found to be associated with thunderstorm. Such thunderstorm is quite common over this region during the months of April and May. Another typical RHI profile observed on 27 May 2000 is shown in Fig.4.3a. It is seen that the rain event is associated with different rain intensity. Such rain having different intensity is associated with different height. The vertical spreading of the rain is also seen to be quite large. The vertical extension of rain observed on 1 August 2000 has been presented in Fig.4.5b. It is seen that the rain having rain intensity ~ 2.6 mm/hr is occurring from an altitude of around 6 km and the rain intensity ~ 75 mm/hr is found to occur from an altitude of 4 km upto the surface. The horizontal spread of the rain is around 5 km. Such exact height is important for estimation of attenuation of radio wave due to rain for satellite communication.

Figure 4.4 shows the variation of horizontal extension of rain (average results) of horizontal extension with the radar reflectivity. Such results have been derived by taking all PPI measurements. It is seen that the horizontal extension varies from ~14 km to 4 km while the radar reflectivity varies from 28 dBz to 53 dBz. The large value of dBz that an indication of high rain rate in the present study is associated with low horizontal extension of rain.
Fig. 4.4 Horizontal extension of rain from X-band radar measurement over Calcutta
The radar reflectivity ~43 dBz which is a measure of rain rate ~ 18 mm/hr is associated with horizontal extension ~ 8 km while the radar reflectivity ~ 33 dBz which is a measure of rain rate ~ 2.6 mm/hr is associated with horizontal extension ~ 10 km. The low radar reflectivity is associated with large horizontal extension.

Figure 4.5 presents the results on the variation of vertical extension of rain with radar reflectivity. These results suggest that the height from which the rain of different intensities is occurring. It is seen in Fig. 4.5 that the vertical extension of rain varies from 9 km to 5.75 km. These measurements were taken in monsoon months. It is seen that the low vertical extension of rain ~5.75 km is associated with radar reflectivity ~ 53 dBz when rain intensity ~ 74 mm/hr. The vertical extension of rain from 8 km to 9 km is found to be associated with 28 dBz to 43 dBz and the rain rate varies from ~ 2.4 mm/hr to 18 mm/hr.

The probability distributions derived from the observed radar reflectivity of the PPI observations and RHI during July-August 2000 have been presented in Figs. 4.6 and 4.7. It is seen in Figs. 4.6 and 4.7 that the probability distributions follow almost same variation in both PPI and RHI observations. The radar reflectivity 40 dBz exceeds for around 28% of the time in PPI case while it exceeds for around 34% of the time for RHI case. Similarly, it has been found that the radar reflectivity ~53 dBz which corresponds to ~ 75 mm/hr exceeds for 4% of
time in PPI case while it exceeds also for around 4% of time. It is also seen in Figs.4.9 and 4.10 that up to 30 dBz and again above 50 dBz both the curves for PPI and RHI follow similar variation up to 30 dBz and above 50 dBz. There is difference in variation of the two curves shown in Figs.4.6 and 4.7 and (between 30 dBz and 50 dBz. Such difference of variation is marginal. For instance at 50% probability level, the radar reflectivity is found to be 34.5 dB in case of PPI and for RHI it is 36.5 dB. The different radar reflectivity is associated with different rain rate. Figs.4.6 and 4.7 depict that rain intensity of different magnitude exits for equal percentages of time both in horizontal and vertical extension of rain. In order to deduce the attenuation of rain, we need the probability distribution of rain rate. The probability distribution of rain rate derived from horizontal extension and vertical extension of radar reflectivity measurements by using the Z-R relation ($Z=200R^{1.6}$) which is also shown in Figs.4.6 and 4.7 can be utilized for rain attenuation estimation for both horizontal and earth-space paths. However, still such derived rain rate distribution from radar reflectivity observations is to be validated with the rain rate distribution derived from the ground based rapid response rain gauge measurements.
Fig. 4.5 Vertical extension of rain deduced from X-band radar measurement over Calcutta
Fig. 4.6 Probability distribution of radar reflectivity from radar PPI measurement
Fig. 4.7 Probability distribution of reflectivity from radar RHI measurement

- Z=23 dBz, R=1 mm/hr
- Z=28 dBz, R=2.4 mm/hr
- Z=33 dBz, R=2.6 mm/hr
- Z=38 dBz, R=9 mm/hr
- Z=43 dBz, R=18 mm/hr
- Z=53 dBz, R=75 mm/hr
The vertical and horizontal extensions of rain cells from the observed radar reflectivity from the PPI and RHI are all based on empirical relationship $Z=200R^{1.6}$ does not give the rain rate with the kind of accuracy needed for determining the attenuation due to rain. Firstly, the relations in between $Z$ and $R$ are quite different for different ranges of rain rates (Bhattacharya et al, 1998) due to rain. The constant of empirical relation as well as the exponential value differs for the varied range. The attenuation deduced from the rain rates using the empirical relation thus shows variance, as the later is also an exponential relation.

The empirical relation gives the following rain rates in the Table 4.1 given below.

<table>
<thead>
<tr>
<th>Radar Reflectivity (dBz)</th>
<th>Rain Rate (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>28</td>
<td>2.44</td>
</tr>
<tr>
<td>33</td>
<td>2.58</td>
</tr>
<tr>
<td>38</td>
<td>8.55</td>
</tr>
<tr>
<td>43</td>
<td>17.96</td>
</tr>
<tr>
<td>53</td>
<td>75</td>
</tr>
</tbody>
</table>

Other aspect that seriously affects the rain cells estimation is heavy rain episodes, where many rain cells may be present simultaneously on the same path. The existence of number of rain cells in the path affects the exact estimation of rain rates. There is a need for programming the numerical relationships in such occasions. The path length and the
existence of heavy rain cells along the path should have the auto-corrective measures for estimating rain rates.

However, the RHI is quite a good indicator of the extent of rain rates and rain cells. The micro-structure of rain cells could be best analysed when both the PPI and RHI are simultaneously used spatio-temporally for visualization. A better relation could be arrived at after having an in-depth study of numerous such cases. Spatio-temporal distributions for estimation of location specific rain falls are definitely detected and are of immense use for validating high-resolution numerical models for evolving atmosphere.

The radar is still the best ground based equipment to locate the rain cells. The squall line development and weather phenomena are very well recorded. Who knows that some day high-resolution models are developed centring the location of the equipment. The idea is obviously for the accuracy of the method for better estimation.

The complexity of the problem due to the path and existence of the multi-cells could be sorted out with differential method using variable frequencies and mobile equipment. Thus, the use of tunable frequency is likely to remove the errors substantially. The perturbation due to the change in frequency could broaden the scope of detailed micro-structure of rain cells. The PPI and RHI images then could be used for
rain rates measures with high resolution. Here, for still better understanding of radar reflectivities, it would require the satellite images and raingauge data for real-time data.

The micro-structure of rain cells could be related to the Radar reflectivity very appropriately if exact measure of humidity and buoyancy could be known. The high Z value regions are the characteristic zones with higher scattering cross sections due to the presence of water vapour. Additionally, the bright band in radar output indicates the change of cloud state to water and ice particles, which falls under gravity in the form of precipitation. Rain rates and radar reflectivity has been analytically later in Chapter 10. Attempt has been made to relate them with the scattering cross sections of the constituents.

From the drop size estimates per m³ mm⁻¹ from radar measurement reveal higher number of smaller droplets at lower rain rates. It is also seen that the different Z-R relations at rain rates ≤ 25 mm/hr, 25 mm/hr to 50 mm/hr and rain rate ≥ 100 mm/hr should have been used.

The horizontal extensions are mainly dependent on the extent of pumped moisture. The horizontal extension of the rain cells during monsoon vary from 10-150 Km near the coastal areas, but have different rain rate due to different vertical extensions. In cases of vertical extensions of 7-10 Km with radar reflectivity 40-55 dBz give heavy rainfalls, where as 23-30 dBz gives trace to drizzle rains.
4.3 Results & Conclusion

This study reveals that X-band conventional radar has the capability to provide results on horizontal and vertical extension of rain, but it is to be used cautiously. Firstly, we have seen in our study that only one Z-R relation has been used in this radar system. In fact, the investigation suggests that different Z-R relation for different rain type would have given more accurate results particularly at low and very high rain intensities. One, Z-R relation should have been for rain rate up to 25 mm/hr and the other one from 25 mm/hr to 100 mm/hr and the third one above 100 mm/hr. The operating frequency of the present radar is 9.375 GHz. In this frequency the factor of worry about which is attenuation. It may have corrected at the design and installation stage, but still it is difficult to do with high degree of accuracy.

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