



## Micro rain cell measurements in tropical India for site diversity fade mitigation estimation

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[1] Intersite separation (ISS) between two terminals is one of the important parameters required for implementation of site diversity (SD), as a fade mitigation technique (FMT), in moderate to heavy rain conditions usually encountered in tropical climates. This paper presents the findings of an experiment during the monsoon periods of years 2007 and 2008. It establishes the existence of micro rain cell (MRC) at a tropical site, Ahmedabad (23.06°, 72.62°), India, using measurements from tipping bucket rain gauge network. Spatial extent of MRCs and derived attenuation cells is examined on the basis of their maximum occurrence for initial to mid and last spells of years 2007 and 2008. The analysis also presents ISS statistics of monsoon periods for both the years. Microscale SD as FMT has been discussed on the basis of the calculated diversity gain at  $K_a$  band frequency in view of the proposed GSAT-4 satellite. These are the very first findings of their kind over the region of study.

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### 1. Introduction

[2] There is a worldwide interest to use higher-frequency band spectrums such as  $K_u$  and  $K_a$  bands for future satellite communication systems. The most prominent problem faced during the employment of these millimeter wavelength signals is the attenuation by the tropospheric elements such as rain, cloud and gas [Crane, 2003]. The rain induced fades are more threatening to system performance operating at higher-frequency bands. In the tropical region, rain fall rate is generally higher than that of temperate region and storms with very high rainfall rates are commonly experienced with convective type rain [Green, 2004; Li and Zhang, 1983; Simpson, 1988; Pan and Bryant, 1992]. Indian Space Research Organization (ISRO) will be launching GSAT-4 satellite carrying  $K_a$  band beacon (20 and 30 GHz) for carrying out  $K_a$  Band Propagation Experiment over Indian tropical region [Dasgupta et al., 2009].

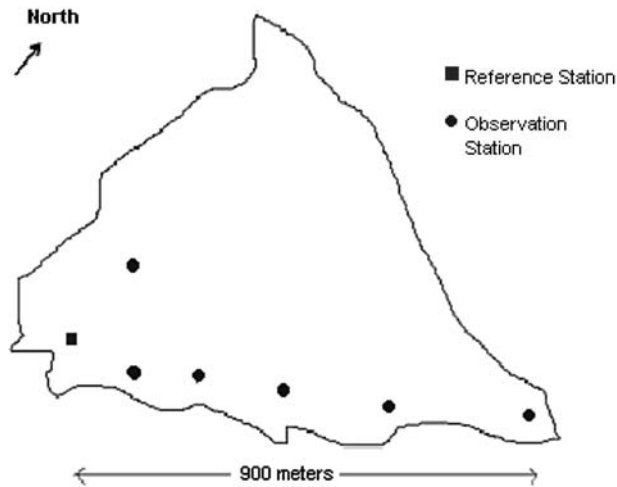
[3] Power margins help the space communication system using lower-frequency band to operate at an acceptable performance level, in spite of weather-dependent path attenuation [Ippolito, 1986; Castanet et al., 1998]. Larger power margins are required for the systems using higher frequencies, but are not feasible either technically or economically [Panagopoulos et al., 2004]. In such situations some alternative methods must be considered to overcome the severe attenuation conditions, which may be helpful in restoring availability of the links and maintaining the quality of service specifications [Enjamio et al., 2002].

[4] Site diversity (SD) is a promising restoration technique available to the system designers for overcoming severe attenuation conditions in Earth-space links. This technique improves the overall satellite link performance by taking advantage of the limited size and extent of intense rain cells [Wilson, 1970; Ippolito, 1986; Enjamio et al., 2002; Panagopoulos et al., 2004].

[5] Rain cells are defined as identified continuous contours inside which the rain rate always exceeds a given rain rate threshold [Crane, 1996; Enjamio et al., 2003; Matricciani, 2003; Feral et al., 2003]. Mathematically, it can be expressed as the space over which

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**Figure 1.** Locations of rain gauges inside SAC campus.

where  $R$  and  $T$  are rain rate and predefined rain rate threshold, respectively.

[6] The knowledge of the statistical characteristics of the rain structure is important for successful implementation of SD concept. Experimental work has been carried out since 1970s to study the rain cell horizontal distribution [Capsoni *et al.*, 1987; Goldhirsh, 2000; Enjamio *et al.*, 2005; Feral *et al.*, 2005] as well as SD applications [Panagopoulos *et al.*, 2004; Hall and Allnut, 1975; Vogel *et al.*, 1976; Hodge, 1974]. Most of the initial studies were carried out over temperate region. In the past few years, propagation studies for  $K_u$  and  $K_a$  band signals have started over tropical region as well. Dynamical properties of rain fall at  $K_u$  and  $K_a$  band were carried out over Guwahati, India in 1998 [Timothy *et al.*, 1998]. In 2001, rain cell study and analysis of the SD technique was reported in Singapore [Timothy *et al.*, 2001]. Weather radar observations have also shown widespread events with embedded convection and explored the rain cell structures [Konrad, 1978; Hildebrand *et al.*, 1979; Testud *et al.*, 1996; Tournadre, 1998; Feral *et al.*, 2001].

[7] In all the earlier cases, study of SD over larger site separation (more than few kilometers) was done. It has been found that SD is effective, even when the two Earth stations are only few hundred meters apart [Matriccioni, 2003]. Such microscale SD is possible due to formation of micro rain cells (MRCs) with intense rain fall. In some of the earlier works characteristics of microscale rain cells have been studied and their spatial extent was established [Enjamio *et al.*, 2003; Khamis *et al.*, 2004]. Sauvageot [1992], has also observed that in nature, radar-detectable individual rain cells with a size smaller than some hundred meters exist, which are commonly associated with the well known convective generating cells of stratiform clouds [Sauvageot *et al.*, 1999; Sauvageot, 1992] and

are generally confined to a narrow, but tall column of rain [Timothy *et al.*, 2003].

[8] These studies on MRC are among very few published literature available till date. As per authors' knowledge, this paper explores the characteristics of MRCs in Indian tropical region for the very first time. This study establishes the existence of MRCs in Indian tropical region using rainfall data collected with an array of tipping bucket rain gauges inside Space Applications Centre (SAC), Ahmedabad ( $23.06^\circ$ ,  $72.62^\circ$ ), India, for the years 2007 and 2008. Selection of site is a natural choice since Ahmedabad experiences tropical climatic conditions such as convective rainfalls.

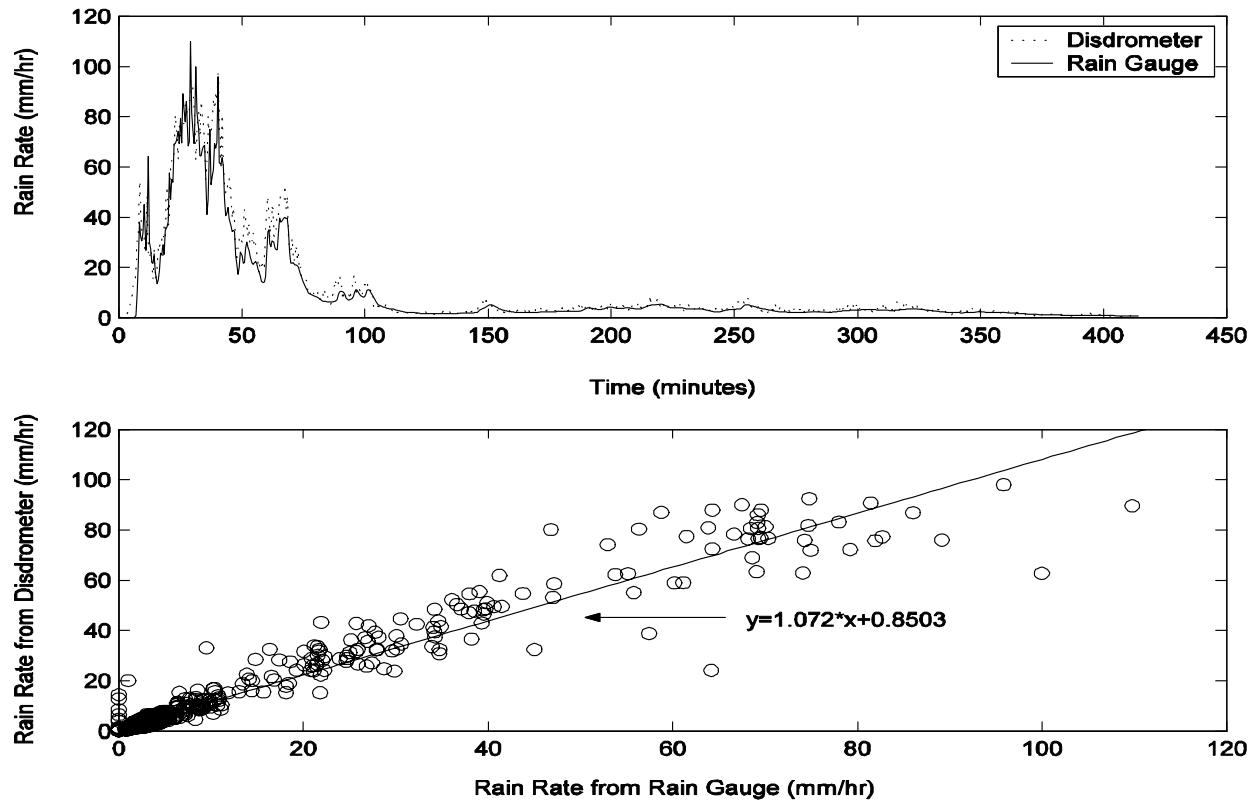
[9] As per the organization of the paper, section 2 provides the experimental details. Section 3 makes a comparison between tipping bucket rain gauge data and disdrometer data. Section 4 describes the characteristics of tropical rain fall. Section 5 deals with the existence of MRCs in tropical region. Data analysis is covered in section 6 while results and discussion are presented in section 7. Conclusions are given in section 8 of the paper.

## 2. Experimental Details and Method of Approach

[10] Seven tipping bucket rain gauges were deployed at various locations inside SAC campus. The arrangement of rain gauges is shown in Figure 1. The square represents the rain gauge location taken as reference station while the circles represent the other observation stations. Rain gauges were kept at the roofs of the respective establishments (around 5 m high). This was done to minimize the effect of wind turbulence from nearby obstructions such as buildings and tall trees inside the campus. The distance between the two nearest rain gauges was around 180 m while the farthest ones were nearly 900 m apart. Rain gauges were operational for the months of June, July, August, and September covering the monsoon periods of 2007 and 2008. Calibration of rain gauges was done by pumping accurately known volume of water into tipping bucket rain gauges in different intervals simulating different rain fall rates.

[11] The tipping bucket rain gauge used in this experiment, collects 0.25 mm of rainwater at every tip. The rain gauge unit records the time instant of the tip. These time stamps are recorded on a data file by the data logger and rain amount time series is generated thereafter. To obtain the rain rate time series the amount of rain collected at every tip (0.25 mm) is divided by the time interval, measured in seconds, between two consecutive tips. The rain rate in mm/h is given as:

$$R = \frac{0.25}{\Delta t} 3600(\text{mm/h}) \quad (1)$$



**Figure 2.** Comparison of rain rates recorded from disdrometer and rain gauge with their scatterplot.

where,

$$\Delta t = t_2 - t_1 \text{ (in seconds)}$$

Here  $t_1$  and  $t_2$  are two consecutive tipping instants. Using the above expression, rain rate time series is generated against rain amount time series. The rain rate time series obtained from the rain gauge is converted to a continuous rain rate time series by interpolating rain rate values for every second using cubic spline interpolation.

### 3. Comparison Between Rain Rate Data From Rain Gauge and Disdrometer

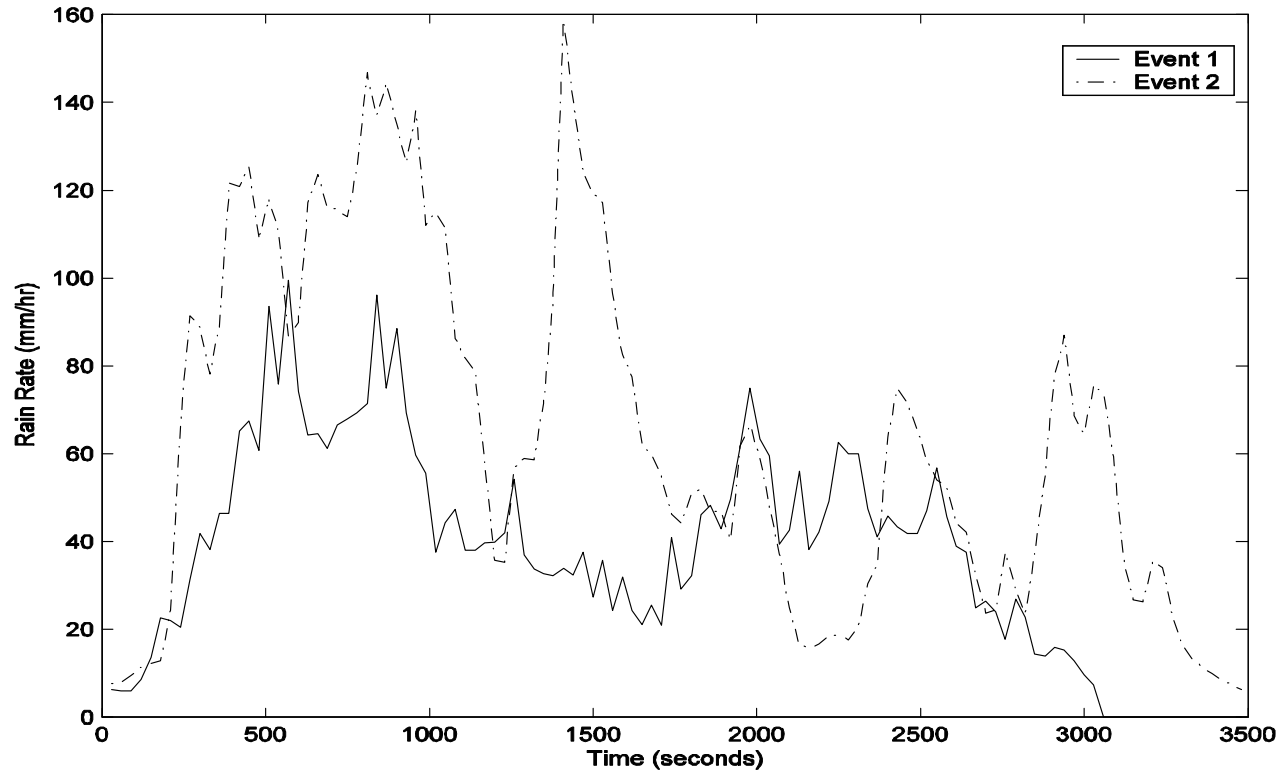
[12] A comparison of rain data obtained from the tipping bucket rain gauge with collocated impact-type disdrometer (Disdromet RD-80) is done. Disdrometer has an integration time of 30 s. For the comparison purpose, Figure 2 shows the plots of rain rates and their correlation of a simultaneous rain event recorded by disdrometer and rain gauge on 9 July 2009 at Ahmedabad.

[13] It is seen that there is a very good correlation (with correlation coefficient as 0.96) between the two data sets.

There is still some bias seen in disdrometer data at lower rain rates, and a small bias in rain gauge data at very high rain rates. This is due to the fact that disdrometer can sense the smaller size raindrops more accurately than the rain gauge. Moreover, disdrometer accommodates all the larger drops ( $>5.3$  mm) in 5.3 mm size bin only. This results in underestimation of rain rate by disdrometer at higher rain rates consisting of bigger raindrops in comparison to rain gauge measurements [Sasi Kumar *et al.*, 2007].

### 4. Rain Features in Tropical Region

[14] In tropical region, there is a large temporal and spatial variation of rainfall [Sarkar *et al.*, 2004]. Figure 3 shows two separate rain events over the observation site with threshold rain rate as 10 mm/h. As evident from Figure 3, for event 1 rain intensity is varying slowly with time. The maximum value attained is around 100 mm/h. While during the second event, the variation of rain intensity is significantly faster as compared to the rain event 1. The maximum rain intensity is approximately 160 mm/h for rain event 2. Events shown by Figure 3 typically reflect the characteristic of the temporal variation



**Figure 3.** Comparison of rain rate of two events with slow and rapid variations.

of tropical rain. Rainfall in tropical region have a varied spatial characteristic as well, which is the main study of this paper and would be discussed in detail in the coming sections.

[15] Table 1 shows comparison between the actual and ITU-R P.837–5 [International Telecommunication Union, 2007b] generated rain rate exceedances for various time percentages (0.1, 0.01, and 0.001% of the year) over Ahmedabad for the years 2007 and 2008. It can be clearly observed from Table 1 that the ITU-R P.837–5, in general, underestimates the exceedance values than that of actual values over the tropical region.

## 5. Existence of Rain Cells in Tropical Region: Concept of Micro Rain Cell

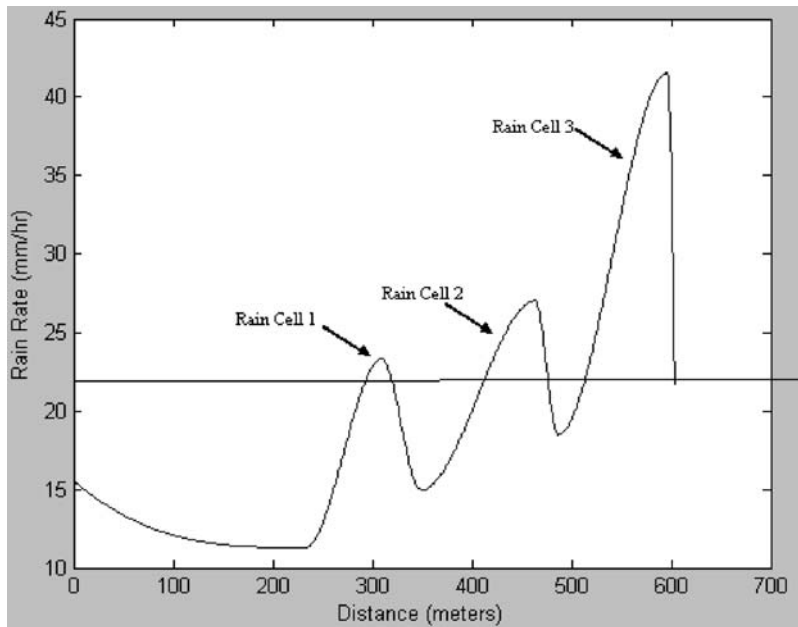
[16] Convective rain is common over the tropical regions as evident from the discussions in section 4. Intense rain with limited spatial confinement is generally observed in such regions. These intense rain are characterized by convective rain cells, termed as MRCs, which are of even smaller dimension (of few hundred meters) than the generally observed rain cells (of few kilometers order) over nontropical regions. The MRC is defined as

the continuous contour of smaller dimension (less than a few hundred meters) inside which the rain rate always exceeds a given rain rate threshold [Enjamio *et al.*, 2003; Matricciani, 2003].

[17] Figure 4 illustrates the concept of MRC. It is generated from the actual data recorded on 28 July 2007 from the mentioned rain gauge network. In Figure 4, the horizontal line at rain rate value of 22 mm/h represents the predefined threshold. The continuous curve showing the shape and dimension of the rain cells is generated by using cubic spline interpolation using the rain rate recorded at different locations. There are three MRCs,

**Table 1.** Rain Rate Exceedances for Different Percentage of Year

|                  | Rain Rate Exceeded in a Year (mm/h) |       |        |
|------------------|-------------------------------------|-------|--------|
|                  | 0.1%                                | 0.01% | 0.001% |
| 2007             | 14.0                                | 68.0  | 104.0  |
| 2008             | 17.0                                | 72.0  | 110.0  |
| ITU-R rain model | 12.5                                | 51.8  | 102.8  |



**Figure 4.** Illustration of concept of micro rain cell.

clearly observed in Figure 4. Depending upon the threshold, rain cells of different diameter can be observed.

## 6. Data Analysis

[18] Data are collected and analyzed for different periods of monsoon. The complete monsoon period is divided into two major parts for analysis. These are initial to mid and last spell of monsoon, respectively. The reason for this division is to capture the characteristics of MRCs during the arrival to establishment of monsoon, and departure of it.

### 6.1. Event Selection

[19] The rain gauge located at the extreme end of the SAC campus, was taken as the reference station. Rain rates from other rain gauges were recorded along with their distance from the reference station. The part of the rain rate time series, during which rain rate at the reference station remains greater than a given threshold value for a period of 2 min is defined as a rain event. In the similar manner, attenuation event was defined for a given attenuation value.

### 6.2. Estimation of Spatial Extent of Micro Rain Cell

[20] Rain events with different rain rate thresholds were selected. A 30 s averaging is done for all the rain events. Filtering rain rates over 30 s provides averaged rain rate

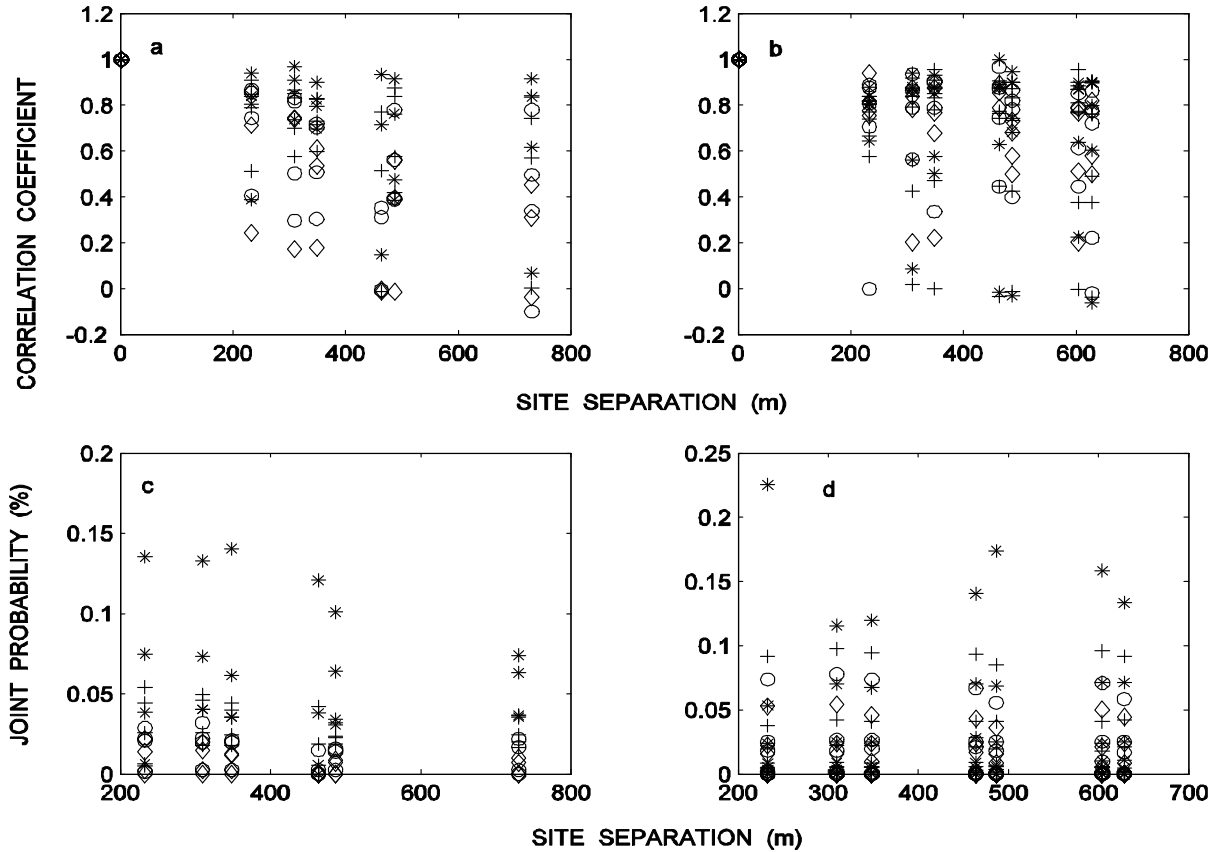
values and still contains the spatial variability in it. As in the present study the dynamics of rain cell is not taken into account, existence of any advection velocity would not affect the measurements and the results. Using this data, spatial distribution of rain rate is obtained over all the observation sites. After getting the spatial distribution, regions are identified over which rain rate exceeds the set threshold. The horizontal extent of such regions gives the diameter of the MRCs for the predefined rain rate threshold. For a fixed value of threshold all available events are studied and the extent of various possible rain cells are categorized in different cell size bins.

### 6.3. Attenuation Data Generation

[21] Rain induced attenuation for 30 GHz  $K_a$  band signal transmitted from a proposed geostationary satellite GSAT-4 (at  $83^\circ\text{E}$  longitude), is calculated for Ahmedabad site with an elevation angle of around  $61^\circ$ . Specific attenuation is calculated assuming that the raindrop scatterers are spherical in nature and elevation angle is used to calculate the slant path length only. The specific rain attenuation ( $\gamma$ ) is calculated using ITU-R P.838-3 [International Telecommunication Union, 2005] as

$$\gamma(\text{dB/km}) = aR^b, \quad (2)$$

where the values of the constants 'a' and 'b' (for horizontal polarization) are taken as 0.2403 and 0.9485,



**Figure 5.** Dependence on distance of (a) correlation coefficients during initial to mid spell of monsoon 2007, (b) correlation coefficients during last spell of monsoon 2007, (c) joint probability during initial to mid spell of monsoon 2007, and (d) joint probability during last spell of monsoon 2007, for rain thresholds of 10 mm/h (asterisk), 20 mm/h (plus), 30 mm/h (circle), and 40 mm/h (diamond).

respectively. The rain height is taken as 5 km as per the ITU-R P.839–3 [International Telecommunication Union, 2001]. The rain attenuation is calculated using ITU-R P.618–9 [International Telecommunication Union, 2007a]. Since the rain cell model in ITU-R is a statistical model, calculation of attenuation is done for the probability exceedances of 0.01% and 0.001% to 5% separately using equations (7) and (8) of ITU-R P.618–9.

[22] Rain attenuation for 0.01% exceedance ( $A_{0.01}$ ) is calculated as:

$$A_{0.01} = \gamma L_E \quad (3)$$

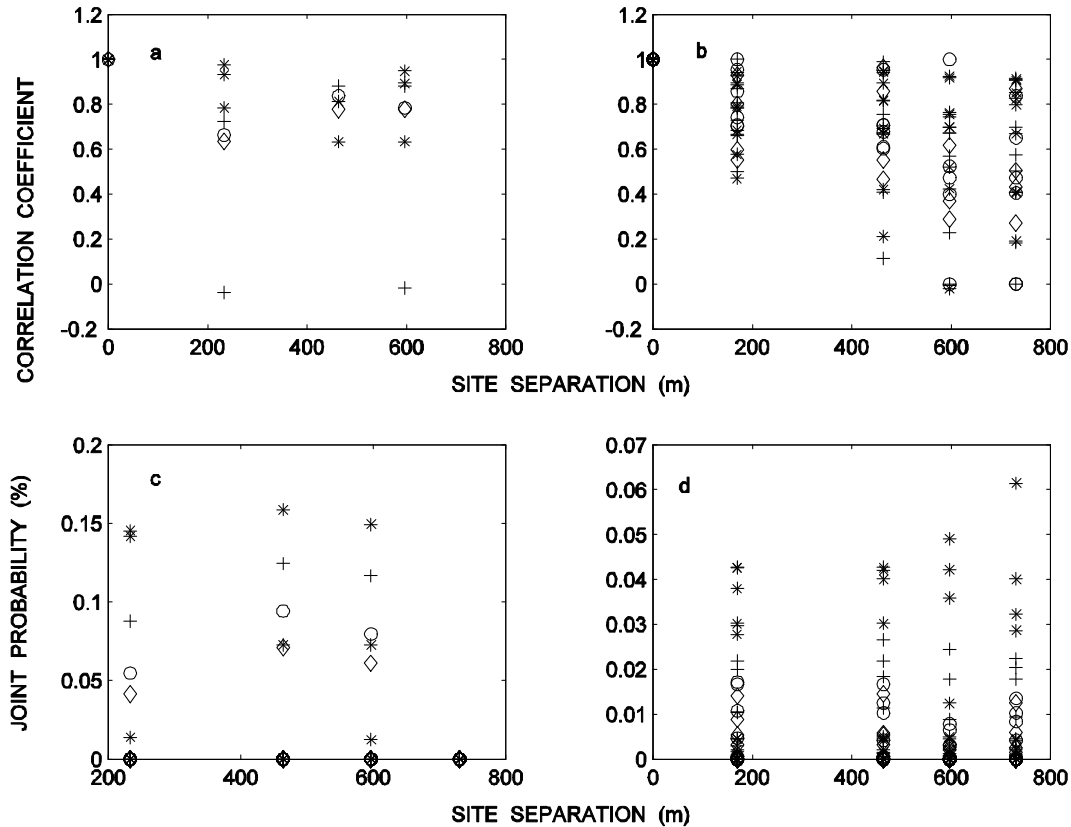
Here,  $L_E$  is the effective path length under the rain height and is calculated as per ITU-R P.618–9 model [International Telecommunication Union, 2007a]. For the present data set,  $L_E$  is found to be 6.65 km.

[23] Rain attenuation ( $A_p$ ) for any other percentage ‘p’ (0.001% to 5%) exceedances is calculated as:

$$A_p = A_{0.01} \left( \frac{p}{0.01} \right)^{-(0.655 + 0.033 \ln(p) - 0.045 \ln(A_{0.01}) - \beta(1-p) \sin \theta)} \quad (4)$$

where  $\beta$  is calculated as per ITU-R P.618–9, and  $\theta$  is the elevation angle of the slant path in degrees.

[24] The regions are identified over which attenuation exceeds the threshold. The length/horizontal extent of such regions gives the diameter of the (micro) attenuation cells, with the chosen attenuation threshold. The effect of wind direction may be assumed to be negligible as all



**Figure 6.** Dependence on distance of (a) correlation coefficients during initial to mid spell of monsoon 2008, (b) correlation coefficients during last spell of monsoon 2008, (c) joint probability during initial to mid spell of monsoon 2008, and (d) joint probability during last spell of monsoon 2008, for rain thresholds of 10 mm/h (asterisk), 20 mm/h (plus), 30 mm/h (circle), and 40 mm/h (diamond).

possible wind directions were present over long duration of data collection.

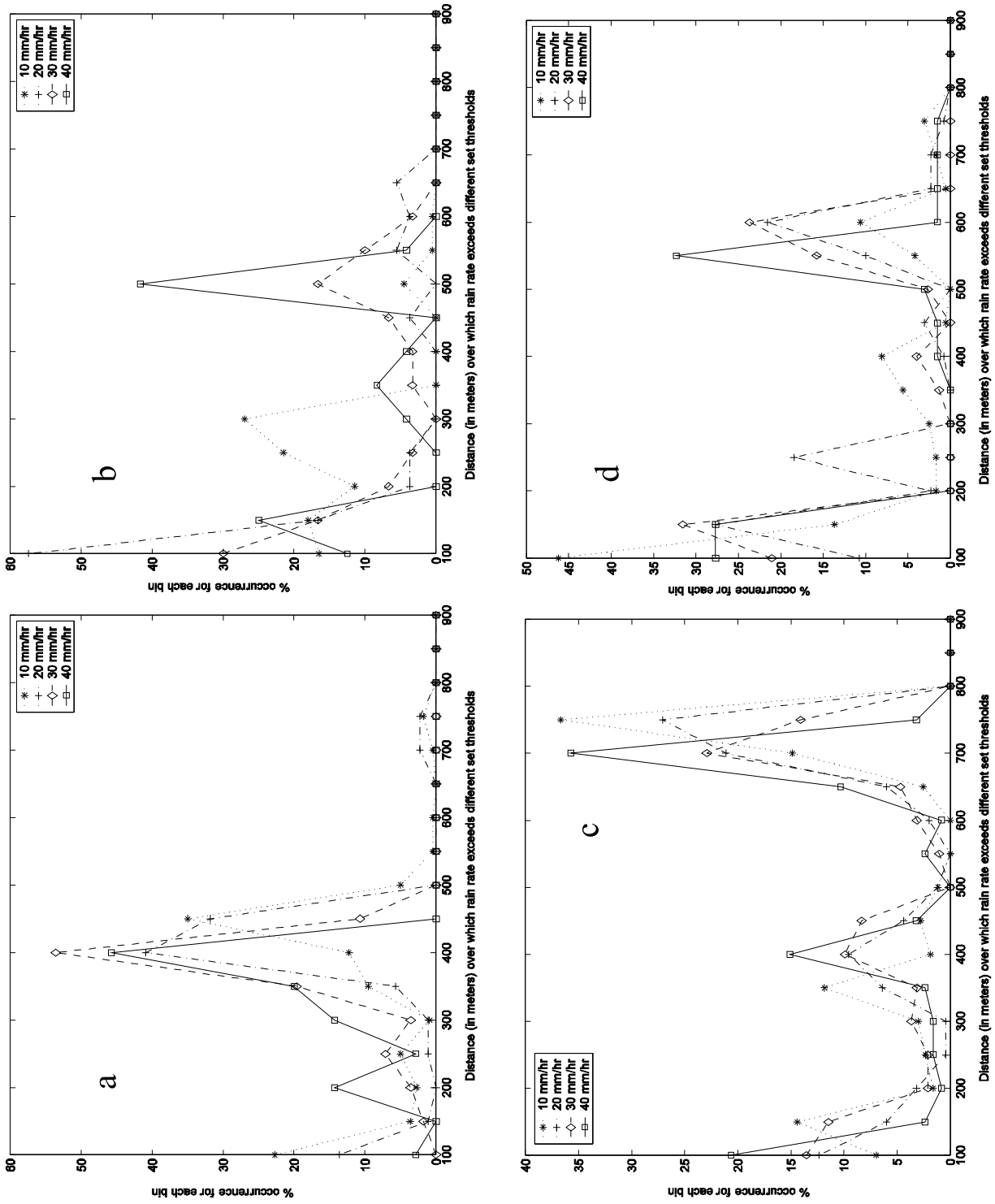
## 7. Results and Discussion

### 7.1. Statistics of Spatial Extent of Micro Rain Cells

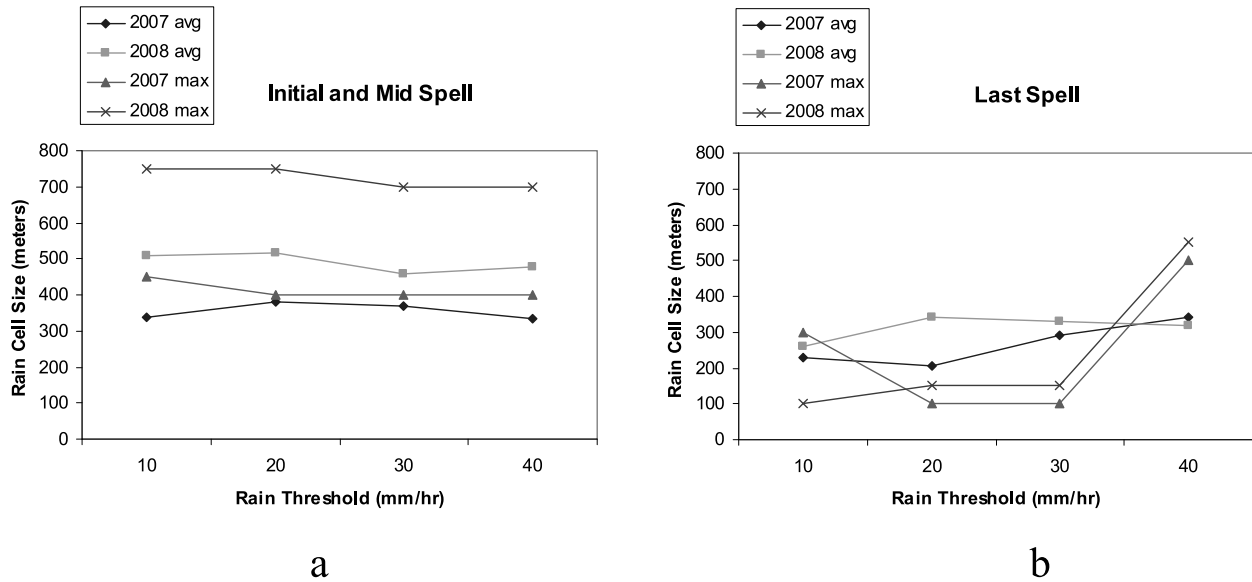
[25] The analysis is done for initial to mid monsoon period and last spell of monsoon of years 2007 and 2008. Rain rate thresholds for the analysis are set from 10 to 40 mm/h in steps of 10 mm/h. These thresholds cover moderate to heavy rainfall conditions. Higher rain rate thresholds (>40 mm/h) are not considered as any FMT may not be much effective for such rain rates. To show the variation of rain rate with distance, correlation coefficients and joint probabilities, are calculated and plotted (Figure 5) for different ISS for initial to mid, and last spells of monsoon 2007, respectively, following Garcia *et al.* [2002].

[26] It is observed from Figures 5a and 5b that correlation coefficients decrease with distance and intensity thresholds. A steeper slope is observed beyond the distance of around 300 m. This fact is important and can be used for the implementation of MSD, since it indicates that the correlation starts decreasing at these small distances in tropical region. From Figures 5c and 5d, it is observed that joint probabilities also decrease with increasing ISS and rain rate. Similar observations are made from the analysis for the year 2008, shown by correlation and joint probability plots given by Figures 6a–6d, respectively.

[27] The comparison of the observations of average and maximum occurrence (percentage) of rain cells shown by Figures 7a–7d are summarized in Figure 8a (initial to mid spell) and Figure 8b (last spell) for the years 2007 and 2008, respectively. It is observed from Figures 8a and 8b that during the initial to mid monsoon period of both the years, maximum occurrence of the rain cells was extended



**Figure 7.** Percentage occurrence of MRCs of different cell size ranges at given rain rate thresholds during: (a) initial to mid spell of monsoon 2007, (b) last spell of monsoon 2007, (c) initial to mid spell of monsoon 2008, and (d) last spell of monsoon 2008.

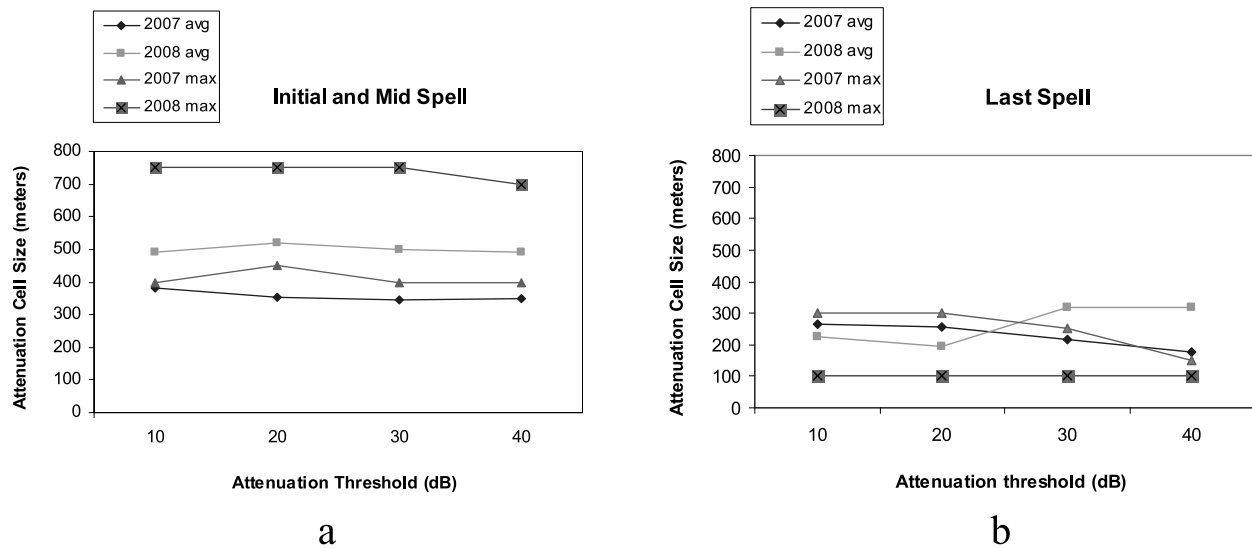


**Figure 8.** Average and maximum occurrence of rain cells of various sizes for different rain rate thresholds for years 2007 and 2008 during: (a) initial and mid spell of monsoon and (b) last spell of monsoon.

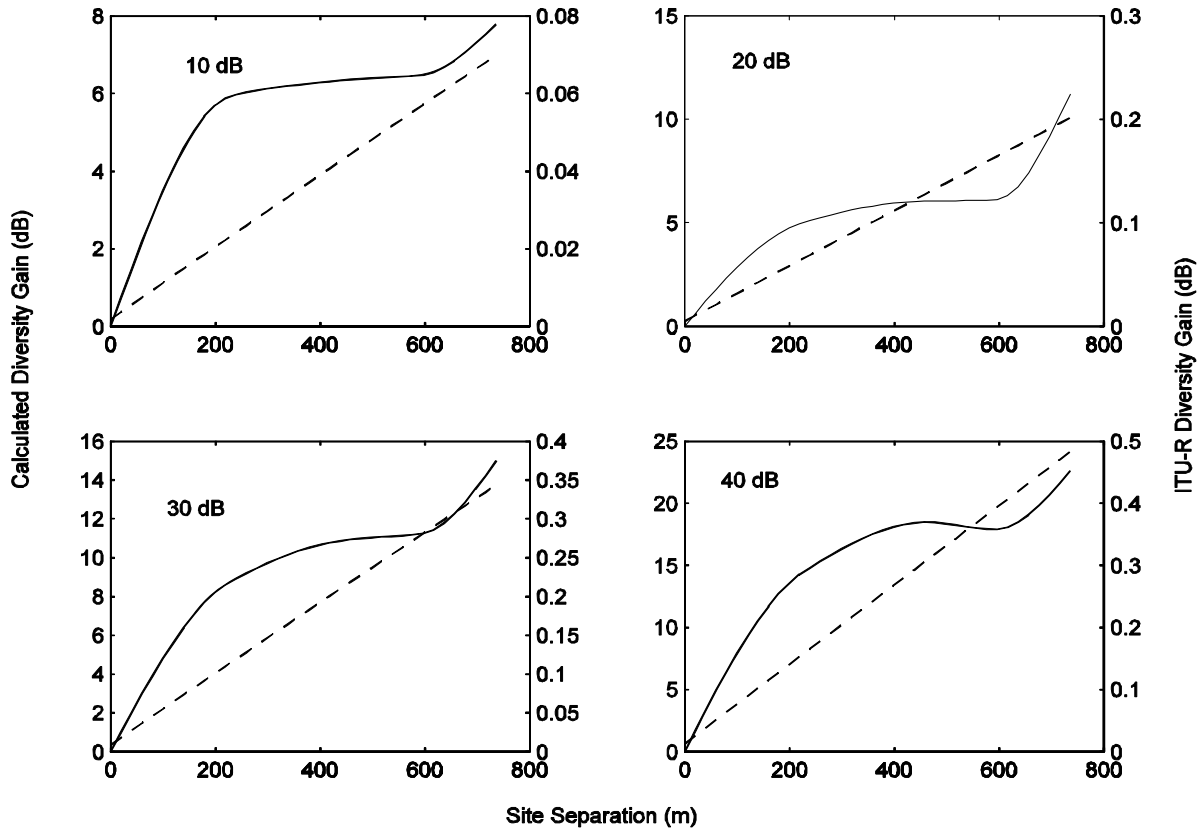
over a large region (around 400 m in 2007 and 725 m in 2008) (Figure 8a), while during the last spell of monsoon, it was limited to a much shorter extent (around 125 m in 2007 and 150 m in 2008) (Figure 8b). As observed from Figures 7b and 7d, for 40 mm/h rain rate MRCs with maximum occurrence have extent of around 500 and 550 m, respectively. Possible reason for the occurrence of this

larger diameter at higher rain rate (40 mm/h) may be due to the union of two or more rain cells. These observations need further investigation by using more years' data.

[28] Average diameter of MRCs is also shown in Figures 8a and 8b which may be a parameter of interest when more years' data would be available from the experiment. It is observed from Figures 8a and 8b that



**Figure 9.** Average and maximum occurrence of attenuation cells of various sizes for different attenuation thresholds for years 2007 and 2008 during: (a) initial to mid spell of monsoon and (b) last spell of monsoon.



**Figure 10.** Comparison of variation of diversity gain with intersite separation for different single site attenuations for the year 2007.

the average diameter for the initial to mid spell of year 2007 and 2008 is around 400 and 500 m, respectively, while for the last spell of monsoon, it is around 250 and 300 m. These observations establish and highlight the characteristics of MRCs over the region of study.

## 7.2. Attenuation Cells

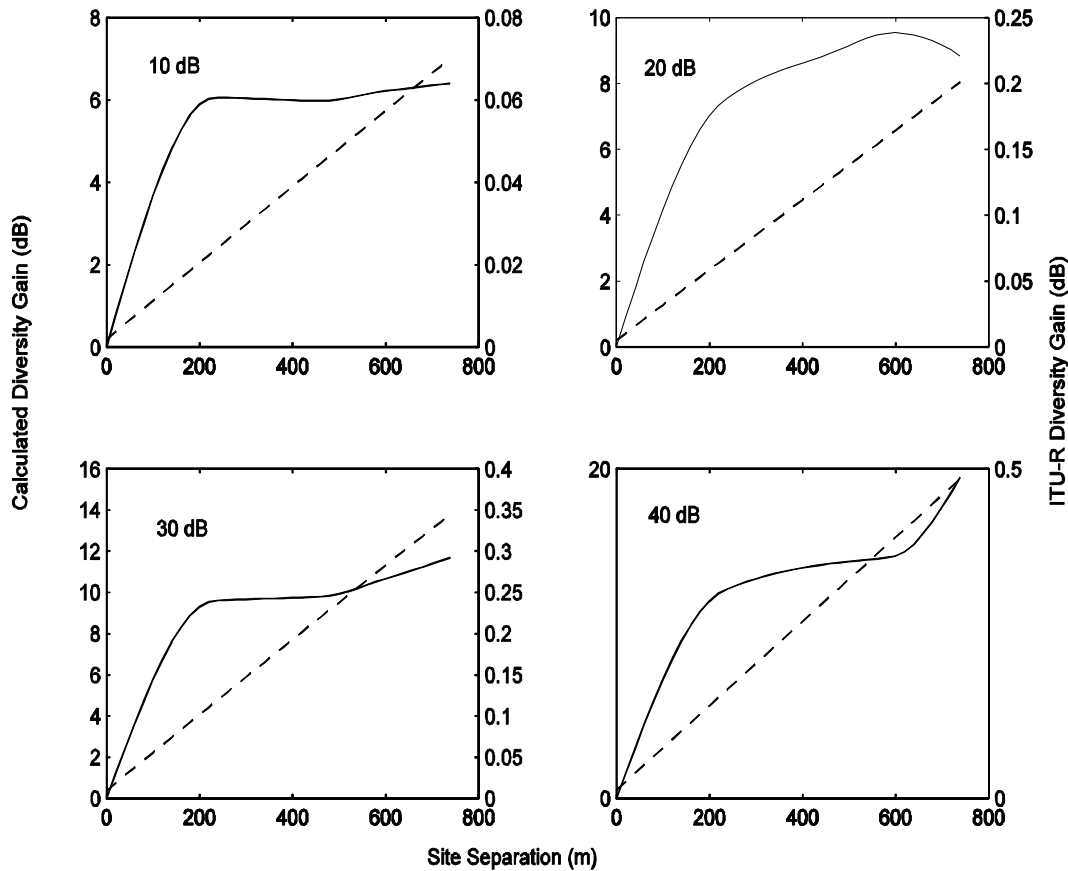
[29] The spatial extent of attenuation cells has also been obtained as per the description of section 6.3. All available events are analyzed for predefined values of attenuation threshold and extent of the various possible attenuation cells are categorized in different cell size ranges. Analysis similar to that of MRC was done to observe the average and maximum occurrence (percentage) of attenuation cell for both initial to mid spell and the last spell of monsoon. A summary of the results is provided in Figures 9a and 9b with almost similar observations as that of MRC.

## 7.3. Diversity Gain

[30] The concept of diversity gain (DG) was first introduced and characterized by Hodge [1976], in order to measure the advantage introduced by employing space diversity configuration. The DG is the difference between

the path attenuations associated with the single terminal and a diversity of modes of operation for a given percentage of time.

[31] In this paper, DG is estimated and compared with ITU-R P.618–9 [International Telecommunication Union, 2007a] recommended empirical prediction model through Figures 10 and 11 for the years 2007 and 2008, respectively. Four different single site attenuation thresholds from 10 to 40 dB, in steps of 10 dB, with different ISS are shown in Figures 10 and 11. Estimated diversity gain (in dB) is shown by solid line and its value is given on left vertical axis. The DG as per the ITU-R P.618–9 model is shown with dashed line and its magnitude is given on right vertical axis. From Figures 10 and 11, it is observed that estimated DG shows significant variation with ISS. For the year 2007, it may be seen that DG increases with ISS up to around at 463 m and then decreases with increasing the separation for all the thresholds. This may be the probable radius of MRC for the year 2007. Similarly, from Figure 11, it is observed that in general DG is maximum at around 233 m which again indicates the radius of the MRC for the year 2008. This observation is also supported by the average MRC diameters for the years 2007 and 2008,



**Figure 11.** Comparison of variation of diversity gain with intersite separation for different single site attenuations for the year 2008.

respectively (Figures 7 and 8). From both Figures 10 and 11, it is observed that ITU-R P.618–9 model shows a linear variation of DG for these distances and does not seem to capture the small-scale variations of DG due to MRCs. Also DG predicted by ITU-R P.618–9 model is very less in magnitude in comparison to the calculated DG and hence suitable model which is more representative for Indian tropical region is required to be developed.

## 8. Conclusions

[32] Existence of MRC is established for Ahmedabad, a tropical location in India using a network of tipping bucket rain gauges in an experiment during monsoon of years 2007 and 2008. Statistics of spatial extent of MRCs is derived on the basis of their maximum and average occurrences for different rain rate thresholds. Variation in the spatial extent of MRC is observed for initial to mid and the last spells of monsoon of the years 2007 and 2008. From the observations, it is found that in general, the MRCs are extended over a larger area (400 to 700 m) in

initial to mid spell of monsoon while they are confined to a smaller area (100 to 300 m) in the last monsoon spell. This may be due to the occurrence of more intense rainfall confined over much smaller area during last spell of monsoon in comparison to initial to mid spell.

[33] The paper also presents ISS statistics for the years 2007 and 2008. Microscale SD as FMT has also been discussed on the basis of calculated DG. Estimated DG is also compared with the ITU-R P.618–9 recommended (Modified Hodge) model of DG. Comparison shows that Hodge Model does not seem to capture the microscale SD features for the region of study. This study may be advantageous especially in the applications using  $K_a$  band signal where very high bit rate data transfer inside a small campus with better link availability is required.

[34] **Acknowledgments.** The authors express their sincere thanks to Deval Mehta, senior colleague, for the internal review of the manuscript. The authors are also thankful to the anonymous reviewers for their constructive suggestions toward the improvement of this paper.

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