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Statistical Analysis of Effective Rain Height for Fade Margin in Tropical Regions at MW Frequencies

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Abstract:

The prediction of rain fade margin over satellite link paths relies on the prediction method proposed by ITU-R which uses rain height as one of the parameters. The ITU-R rain height model, which is based on radiosonde data collected in temperate climate zones, tends to overestimate rain attenuation when applied to tropical regions, leading to unsatisfactory results. There is a need to test available ITU-R models with actual measurements for tropical rain attenuation. In the present study, the statistical behavior of effective rain height (RH_{eff}) on four tropical locations in India has been analyzed. Based on the experimental data, a statistical model called the Rain-Based Statistical Model (RBSM) has been proposed to estimate effective rain height

Keywords:

rain rate, rain attenuation, raindrop size distribution, rain height, satellite link

1 Introduction

Millimeter wavelengths (frequencies above 10 GHz) experience significant signal loss during transmission over Earth-space paths due to scattering, depolarization, and absorption by rain and atmospheric gases. Rain, with its high dielectric constant, is a major contributor to signal loss, producing large displacement currents and absorption whereas the rain height is also one of the important parameters to predict the fade margin [1-2]. This effect is particularly pronounced in tropical regions, where high rainfall intensity and large raindrops exacerbate the issue [3-4]. To meet the growing demand for higher channel capacities, utilizing frequency bands above 20 GHz has

[*] *Corresponding author: Department of Electronics and Communication Engineering, Chandigarh College of Engineering and Technology in Chandigarh, sector 26, India, IN 160 019, Phone: +91 017 22 75 09 43, Fax: +91 017 22 75 09 43, E-mail: saritasharma@ccet.ac.in. ORCID 0009-0006-0559-0064.*

become essential for terrestrial and satellite communication. Additionally, millimeter waves have numerous military applications due to their inherent advantages.

For reliable communication system design in specific locations, it is crucial to consider rain-induced attenuation and rainfall rates at the operating frequency, as rain fading can significantly impact system reliability. Data on rainfall rates and rain attenuation is highly sought after for various applications, including radar systems, remote sensing, and radio link systems [5].

This necessitates extensive research into the performance of these higher frequencies under tropical conditions, such as those found in India. The current ITU-R approach for predicting rain fade on Earth-to-space paths relies on a constant physical rain height, specifically the height of the 0 °C isotherm, during rainy seasons [6]. This method has been shown to overestimate rain attenuation when applied to tropical regions because it is based on data from temperate climates and assumes a uniform rainfall distribution from the ground up to the rain height or rain height H_r to the height of the 0 °C isotherm (physical rain height) [7-8]. Research has indicated that using the 0 °C isotherm height as a substitute for actual rain height is not suitable for tropical areas [9].

In tropical regions, rainfall is non-uniform from the ground to the rain height, and therefore to avoid an unsatisfactory response while implementing this method in tropical regions, the consideration of effective rain height RH_{eff} at that particular location has been introduced. It emphasizes the importance of incorporating effective rain height into attenuation models to improve the accuracy of predictions in tropical environments [10].

The schematic of earth space communication link path as shown in Fig. 1.

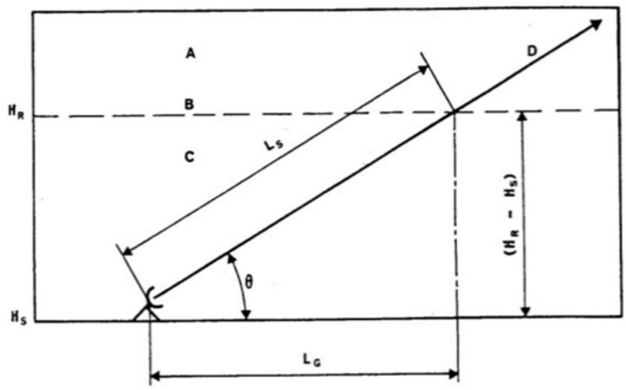

Fig. 1 Schematic of earth space slant-path

Therefore, to avoid an unsatisfactory response while implementing this method in tropical regions, the consideration of effective rain height (RH_{eff}) at a specific location has been introduced.

This research demonstrates a method to develop a statistical model for effective rain height using radiometric and rainfall data collected in tropical regions. This model can then be used to accurately predict rain fade margin for earth-space communication links in tropical environments.

2 Methodology and Measurement Technique

2.1 Methodology

The rain fade model particularly for tropical regions depends on the estimation of effective rain height. To establish the statistical dependence of effective rain height RH_{eff} for the prediction of rain fade margin, the following types of data at four tropical locations have been studied and analyzed:

- radiometric or Zenith path attenuation data,
- rainfall rate data,
- specific attenuation.

The experimental data collected during the winter and monsoon periods at four tropical locations has been analyzed. Rainfall rate and raindrop size distribution are two important parameters required for rain fade data analysis. Geographical coordinates of four test sites and ITU-R rain climate zones are given in Tab. 1. ITU-R divided the whole globe into different rain climate zones based on geographical coordinates [11-14]. The ITU-R's classification of the globe into different rain climate zones based on geographical coordinates allows for more accurate and reliable predictions of rain-induced attenuation, considering the unique rainfall characteristics of each region. This approach ultimately supports the development of more effective communication systems worldwide.

Tab. 1 Geographical coordinates of four Tropical Locations

Location	Latitude	Longitude	ITU-R Rain Climate Zone
Amritsar	31°36'' N	74°56'' E	L
New Delhi	28°37'' N	77°13'' E	M
Dehradun	30°31'' N	78°0'' E	L
Kolkata	22°32'' N	88°27'' E	N

2.2 Measurement Technique

Radiometric data helps in measuring the effective rain height RH_{eff}, which is essential for predicting rain attenuation. Analysis of sky noise temperature provides insights into the vertical structure of rainfall, which is particularly important in tropical regions where rainfall patterns can be complex. Radiometric or Zenith Path attenuation data using vertically polarized zenith-looking radiometers at 20 GHz and 11 GHz were collected at the above four locations. Zenith-looking radiometers measure the sky noise temperature under different atmospheric conditions. Sky noise temperature data were recorded on a strip line chart in terms of voltages along with rain data for analysis. Measurements of radiometric data have been performed continuously for two years. The average observation time of the radiometer was 8 594 hours in each year.

The average percentage uptime of the radiometer is 98 %. Experimentally collected data during rainy seasons has been analyzed to predict long-term statistics of zenith path attenuation and effective rain height. Seventy-five rainy days have been taken from two-year data to determine the zenith path attenuation (at different rain rates) and effective rain height. Calculated values of effective rain height at four tropical locations have been further analyzed for the probability distribution statistics of rain height. The regression technique was used to develop a statistical model (RBSM) of effective rain height suitable for tropical regions from probability distribution statistics. RBSM model was used to predict rain fade margin over propagation path. The proposed model can be used to predict the rain fade model on an earth-space path for any tropical locations where rainfall data is not available.

3 Data Analysis and Results

The point rain rate distribution is an important parameter in the prediction of long-term attenuation statistics. It refers to the statistical distribution of rainfall intensity measured at a specific geographic location or point. It describes the probability of the occurrence of different rain rates at that particular point. Due to considerable temporal and spatial variability of the cumulative distribution of rain rate, information on the statistics of rainfall intensity data obtained from local sources is very useful for rain fade prediction. The monthly, daily, and hourly rainfall accumulation data published by meteorological services cannot be directly used to obtain the cumulative distribution of rainfall intensity down to a small percentage of time. However, to obtain better attenuation statistics, continuous point rainfall and raindrop size data collected during winter and monsoon seasons at all four tropical locations have been analyzed to determine the cumulative distribution of rain statistics. Fast-response rain gauges were installed for measuring continuous rainfall during the rainy seasons for the period of two years. In tropical regions, the intensity of rainfall varies with time and place [15], so the statistics of rain intensity obtained from local measuring tools (rain gauges) are very useful for accurate attenuation prediction. Therefore, the best data set of rainfall intensity measured during rainy seasons has been taken for further analysis.

For the prediction of raindrop size distribution (RDSD) and rain rate statistics R, the data of point rainfall rate and raindrop size collected through simultaneously located rain gauges and distro meter has been analyzed. Slant path attenuation statistics and effective rain height RH_{eff} are also predicted based on the analysis of radiometric data. It is important to note that there are two distinct sets of data involved in this analysis. The first set includes rainfall rate and raindrop size data, which are essential for estimating specific attenuation. The second set consists of radiometric data, used to determine zenith path attenuation. Both of these primary data sets have been utilized to estimate the effective rain height, which is crucial for predicting slant path attenuation at the desired frequency.

3.1 Long-Term Statistics of Rain Rate

Long-term statistics of rain rate refer to the comprehensive analysis of rainfall data collected over extended periods, which helps in understanding the variability and trends in rainfall intensity. The measurement of point rainfall rate is made by use of a Tipping bucket rain gauge having an orifice of 12-inch diameter and is coupled to a mercury switch. One tip is marked for each 0.01 inch of rainfall. Upon the filling of one bucket and tips, the collection is made in the second bucket. Each rainfall event is recorded at the moment the tipping bucket mechanism activates, which is facilitated by a magnet and a mercury switch. This setup is connected to a strip chart recorder, where the recorded data is displayed in real time. Measurement of the rain rate [mm/h] at an instant is made from the distance between the two consequent tips as per the following relation:

$$R = \frac{0.254x}{d} \quad [\text{mm/h}] \tag{1}$$

where d denotes the distance between the two tips in millimeters and x denotes the speed of the chart in [mm/h].

The point rainfall data during the winter and monsoon seasons have been analyzed for the cumulative rain rate statistics for the period of two years. Figs 2-5 show the cumulative distribution of rain rate derived from measured data over four tropical locations (Amritsar, Dehradun, Kolkata, and New Delhi) and that of ITU-R.

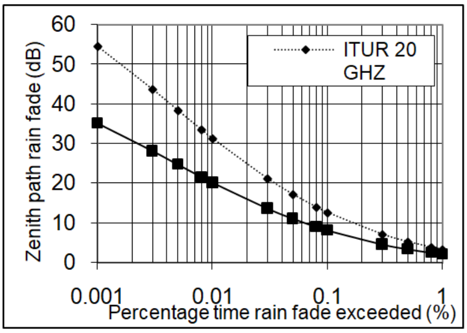

Fig. 2 Rain rate statistics for Amritsar: obtained experimentally and from ITU-R model

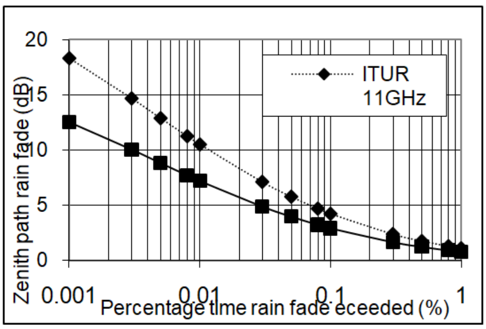

Fig. 3 Rain rate statistics for Dehradun: obtained experimentally and from the ITU-R model

The cumulative distribution of rainfall provided by ITU-R is observed to be lower than the measurements taken at all four tropical locations. Consequently, using ITU-R values for rainfall rates in these areas is likely to yield inaccurate results. Rainfall rates that exceed 0.01 % of the time are particularly important for predicting attenuation statistics, which are necessary to mitigate rain fade margins for communication links that require 99.99 % reliability.

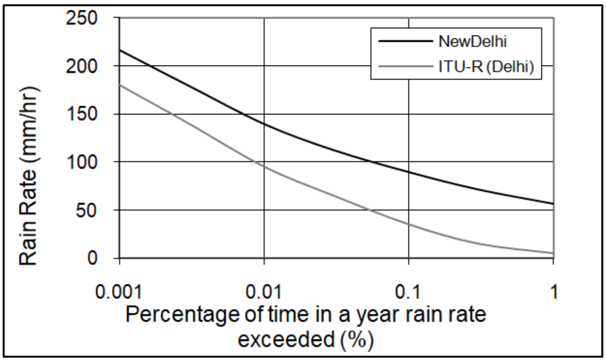

Fig. 4 Rain rate statistics for New Delhi: obtained experimentally and from ITU-R

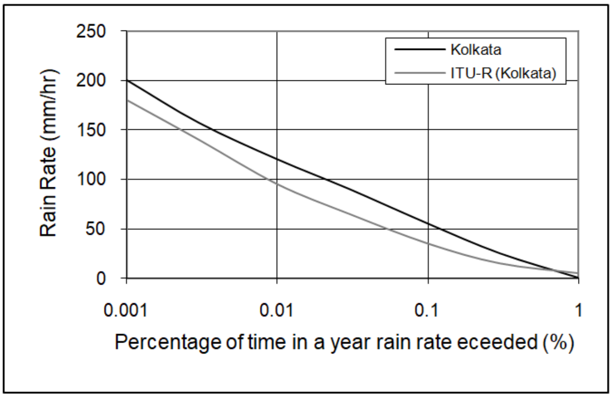

Fig. 5 Rain rate statistics for Kolkata: obtained experimentally and from the ITU-Rmodel

3.2 Rain Induced Specific Attenuation

Rain-induced specific attenuation quantifies the loss of signal strength due to rain, which is essential for evaluating the quality of communication links, particularly for microwave and millimeter-wave frequencies. Estimation of the rain attenuation for terrestrial and earth space path is based on the measurement of specific attenuation, α [dB/km] and can be calculated using raindrop size distribution (RDSD) [13, 16].

Previous observations [14, 17] established the following relationship between specific attenuation α [dB/km] and rainfall rate R [mm/h].

$$\alpha = aR^b \quad [\text{dB/km}] \tag{2}$$

The co-efficient values of a and b are dependent on raindrop size distribution, rain temperature, and the frequency of operation.

The present study makes use of the Medhurst technique for the evaluation of specific attenuation. The Medhurst technique for evaluating specific attenuation is based on the analysis of raindrop size distribution and its relationship with the total volume of water reaching the ground. This method utilizes a model of raindrop size distribution to estimate specific attenuation, which is expressed as a function of the rainfall rate [18]. The raindrop size data was collected by the Distrometer. The values of attenuation co-efficient *a&b* or the calculation of specific attenuation at a given frequency have been evaluated from raindrop size distribution at various rain rates at 20 and 11 GHz at four tropical regions under consideration.

Based on experimental models, specific attenuation values at frequencies of 20 GHz and 11 GHz have been evaluated for different rain rates across four tropical regions. These values were then compared with those derived from ITU-R standards, as illustrated in Figs 6 and 7.

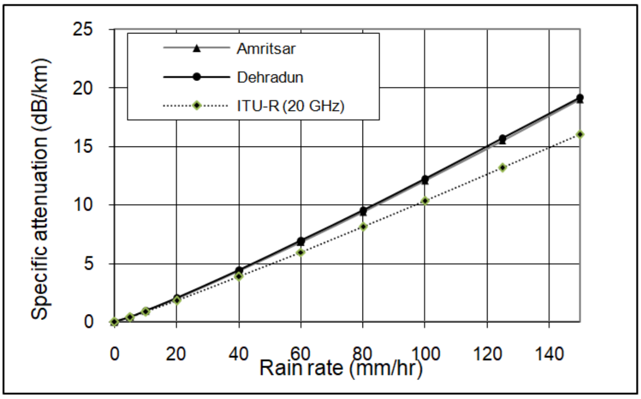

Fig. 6 Comparison of measured specific attenuation with ITU-R model at 20 GHz

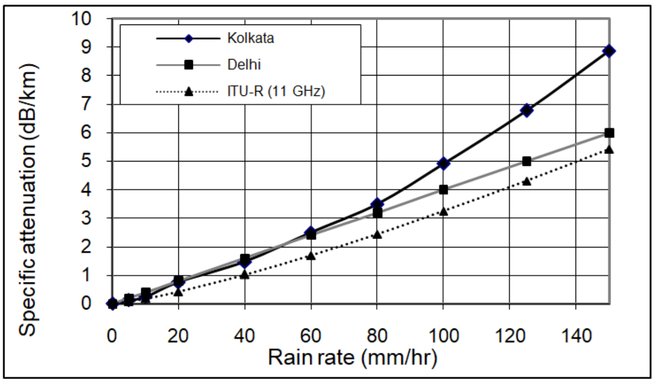

Fig. 7 Comparison of measured specific attenuation with ITU-R model at 11 GHz

The comparison of specific attenuation values at 20 GHz and 11 GHz for different rain rates across four tropical regions, as shown in Figs 6 and 7, reveals that the ITU-R model underestimates the specific attenuation measured experimentally at these locations. This observation has important implications for designing reliable earth-space communication links in these regions

3.3 Zenith Path Attenuation

Zenith path attenuation refers to the signal loss experienced by electromagnetic waves propagating vertically through the atmosphere due to the presence of rain. It is a crucial parameter for predicting rain-induced attenuation on slant paths used in satellite and terrestrial communication links. The results presented here are based on data from 20 GHz and 11 GHz radiometers. These findings were derived from sky noise measurements collected during the rainy season. The excess path attenuation A_R is obtained from antenna temperature using Eq. (3) [5].

$$A_R = 10\log\frac{T_m - T_{cs}}{T_m - T_a} \quad [\text{dB}] \tag{3}$$

where T_m, T_a and T_{cs} represent the absorbing medium temperature, radiometric antenna temperature, and the cosmic noise temperature 3 K respectively. The antenna temperature T_a is calculated from the voltages recorded on the strip line chart about the sky noise received at the radiometer and using calibration curves, Eq. (4) represents the excess path attenuation due to rain considering the values of T_a' and T_a'' under the clear sky and rainy conditions respectively.

$$A_R = 10\log\frac{T_m - T'_a}{T_m - T''_a} \quad [\text{dB}] \tag{4}$$

The accurate computation of the absorbing medium temperature T_m is essential. The ITU-R P-618 reports a constant value of 260 K for T_m, which is notably lower than the measured values, particularly when the antenna temperature T_a exceeds 295 K during high rain rates. In tropical latitudes, where both the measured rain rate and temperature tend to be higher, this results in elevated values of T_m. Therefore, the current work adopts a medium temperature of 295 K for T_m, applicable for 1 % of the time. For instances of fog and clear sky conditions, the zenith path attenuation calculations use Tm set at 285 K for percentages above 1 %. The present measurements focus solely on non-scattering losses caused by the absorption of electromagnetic energy by raindrops.

The analysis of zenith path attenuation at 20 GHz and 11 GHz has been conducted using measured radiometric data from the four specified locations, employing the mathematical model outlined in Eq. (4). A strong correlation between zenith path attenuation and rain rate has been established through regression analysis of the measured data. This regression analysis also provides the probability distribution of zenith path attenuation, with the cumulative distribution for each tropical location depicted in Figs 8 and 9.

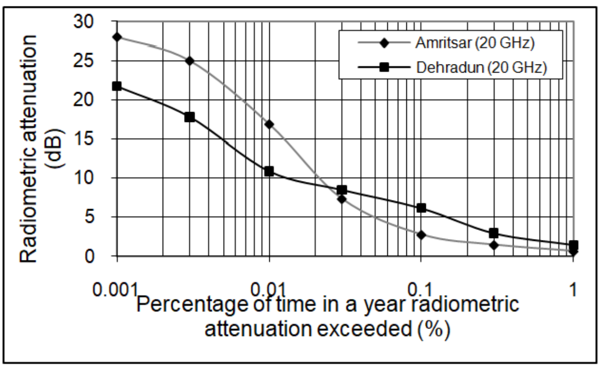

Fig. 8 Cumulative distribution of radiometric attenuation at 20 GHz

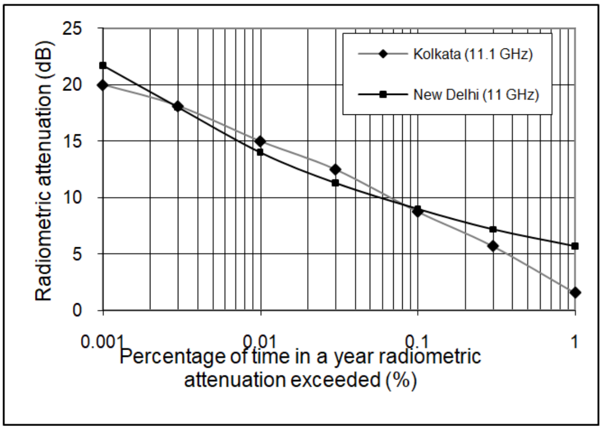

Fig. 9 Cumulative distribution of radiometric attenuation at 11 GHz

3.4 Effective Rain Height (RH_{eff})

Effective Rain Height refers to the average height at which rain contributes to signal attenuation. It is not necessarily the physical height of the rain but rather a statistical representation that considers how rain impacts signal propagation. The prediction of rain fade over satellite links path is made based on the estimation of effective rain height. A study of the statistical behavior of the effective rain height has been made in tropical regions using radiometric and point rain data [19-21]. From the experimentally measured data of Zenith path attenuation and specific attenuation at a particular rain rate, the effective rain height at various rain rates R [mm/h] has been calculated using the relation given below

$$RH_{eff} = \frac{A_R}{\alpha_R} \tag{5}$$

where A_R represents the total zenith attenuation and α_R is the specific attenuation induced by rain at a given rain rate R [mm/h].

The dependence of effective rain height RH_{eff} on rain rates at frequencies of 11 GHz and 20 GHz has been analyzed for two rainy seasons over two years. This analysis is based on the relationship between zenith path attenuation A_R and specific attenuation R at various rain rates R, as described by Eq. (5). The probability distribution of effective rain height has been determined for four locations, as shown in Fig. 10.

The results indicate that the effective rain height exhibits spatial variability and cannot be considered constant. This finding has important implications for the calculation of slant path attenuation. The results indicate that the effective rain height exhibits spatial variability and cannot be considered constant. This finding has important implications for the calculation of slant path attenuation. Instead of using a constant physical rain height, as suggested by [9, 22] and ITU-R [2], the effective rain height should be employed. The effective rain height better represents the actual altitude at which rain contributes to signal attenuation, leading to more accurate predictions of slant path attenuation.

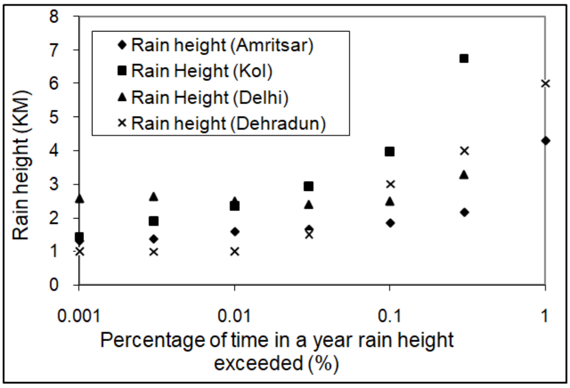

Fig. 10 Comparison of rain height measured at four tropical locations in India

The response variable for effective rain height (RH_{eff}) is directly proportional to the explanatory variable (%P), and a power regression technique has been employed to develop a power statistical model (RBSM) that is suitable for tropical regions. The probability distribution graph is presented in Fig. 11. The best-fit curve is represented by Eq. (6), which has a regression coefficient of r = 8.25, allowing for the estimation of effective rain height at various percentages of time (p) in specific tropical areas.

$$RH_{\text{eff}} = 5.2319\,P^{0.215} \tag{6}$$

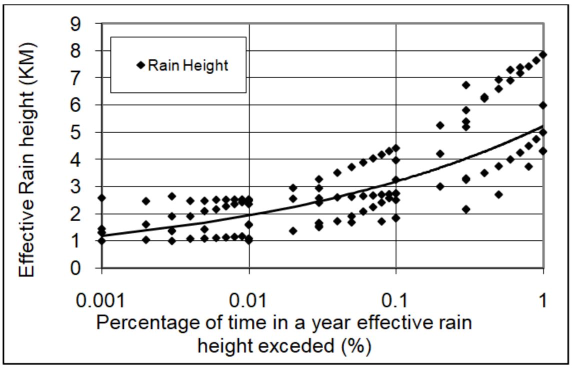

Fig. 11 Cumulative distribution of effective rain height for tropical regions

Developing a statistical model to calculate effective rain height is crucial for estimating slant path attenuation in tropical regions. While the experimental data is limited to four locations due to the constraints of the typical experimental setup, the measurements obtained from these sites have been adequately utilized to create an empirical model for effective rain height. Consequently, in the absence of experimental data from other tropical areas, this statistical model can be applied to estimate effective rain height and predict slant path attenuation in similar tropical regions.

Moreover, using an effective rain height that exceeds 0.01 % of the time for predicting path attenuation is significantly more beneficial than relying on a constant rain height. This approach is particularly important for engineering communication links that require 99.99 % reliability, as it helps address the challenges posed by rain fade margins.

4 Slant- Path Attenuation Prediction

Slant path attenuation refers to the reduction in signal strength experienced by electromagnetic waves as they travel through the atmosphere along a slanted path, particularly in the presence of precipitation. Slant path attenuation due to rainfall is given by ITU-R [1-2] as

$$A_r = \alpha L_S r_P \tag{7}$$

where A_r is the total attenuation along the slant-path, L_S is the slant-path length below the rain height H_r and r_P is the reduction factor.

Fig. 1 illustrates the Earth-Space communication link path, highlighting various parameters necessary for determining the effective path length L_S. The effective rain height RH_{eff} is represented by the broken line labelled B. The ITU-R rain height models are based on the common assumption regarding effective rain height, which is estimated at the 0 °C isotherm. This isotherm indicates the transition height between the lower atmospheres, where only freezing particles are present. In the figure, point A corresponds to frozen precipitation, point B represents the rain height, point C denotes the liquid precipitation, and point D indicates the Earth-Space path.

Concerning Fig. 1 the extent of slant–-path, L_S, below the rain height RH_{eff} is given by

$$L_S = \frac{RH_{eff} - H_S}{\sin\theta} \quad [\text{km}] \quad \theta \geq 5 \tag{8}$$

For vertical (zenith) path elevation angle θ = 90° and reduction factor r_P = 1 and the height of earth station above mean sea level H_S [m] can be neglected in comparison of rain height H_r or RH_{eff} [km], then Eq. (7) becomes

$$A_r = H_r \quad \text{where} \quad H_r = RH_{eff} \tag{9}$$

The value of effective rain height for the rain rate pertains to various percentages of time $P\%$ and can be found from the empirical model (RBSM) and specific attenuation α can be found from ITU-R [23] (p 838-1) at various rain rates or from available empirical models for a particular region to evaluate slant path attenuation or rain fade margin.

The rain fade values for the Earth-Space path at frequencies of 20 GHz and 11 GHz, calculated using the RBSM model of effective rain height, have been compared with those derived from the ITU-R rain height model. Figs 12 and 13 illustrate the slant path rain fade for both the RBSM model and the ITU-R model at 20 GHz and 11 GHz, respectively.

5 Conclusion

This research investigates the impact of using effective rain height instead of the constant rain height recommended by ITU-R in tropical regions. The analysis includes rainfall data, raindrop size data, and radiometric data, leading to the development of an empirical model for effective rain height. This model aims to improve predictions of rain attenuation and address rain fade margins in future microwave satellite communication systems.

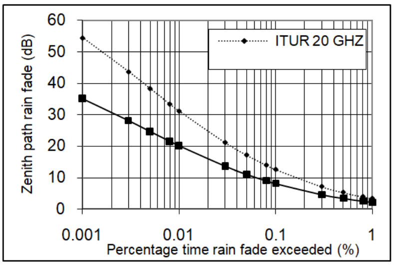

Fig. 12 Zenith path rain fade using RBSM & ITU-R model at 20 GHz

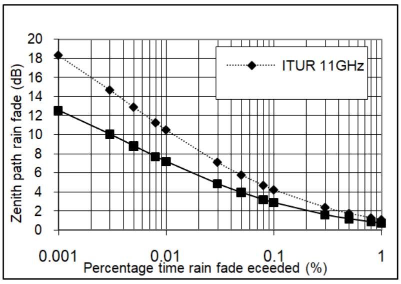

Fig.13 Zenith path rain fade using RBSM & ITU-R model at 11 GHz

Key findings include:

- Measured cumulative rainfall statistics differ significantly from ITU-R predictions.
- Zenith Path rain fade values calculated at a rain rate of 90 mm/h (0.01 %) and an effective rain height of 1.94 km are lower than those predicted by ITU-R.
- The effective rain height based on the RBSM model is approximately 2 km 0.01 % of the time, compared to the ITU-R's suggested constant height of about 3 km. This indicates that effective rain height should be used for estimating slant path attenuation instead of the constant physical rain height assumed by ITU-R, which may lead to overestimations.

The suggested statistical model for effective rain height is well-suited to Indian tropical regions due to the similarity in rainfall and raindrop size distributions even in the absence of experimental data from other tropical are as but, cannot be applied globally due to the spatial variability in rainfall intensity and effective rain height across different regions. Although the model's applicability is limited to regions with similar rainfall characteristics, it provides a useful tool for estimating effective rain height and improving slant path attenuation predictions in Indian tropical regions.

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