FUOYE Journal of Engineering and Technology (FUOYEJET), Volume 6, Issue 1, March 2021 ISSN: 2579-0625 (Online), 2579-0617 (Paper)

Rain Attenuation Prediction Models in Microwave and Millimeter Bands for Satellite Communication System: A Review

*Hammed O. Busari and Olaosebikan A. Fakolujo
Department of Electrical and Electronic Engineering, University of Ibadan, Ibadan, Nigeria
hammed_busari@yahoo.com | daofakolujo@yahoo.co.uk

Received: 12-SEP-2020; Reviewed: 11-OCT-2020; Accepted: 20-NOV-2020
http://dx.doi.org/10.46792/fuoyejet.v6i1.576

Abstract- The progressively demand on satellite communication systems has consequently resulted in lower frequency bands getting more congested. The usage of frequency band beyond 10 GHz is in focus nowadays as a result of the rapid expansion of radio communication systems. However, Rain is the leading attenuation factor of different communication signal of frequencies beyond 10 GHz. Attenuation due to rain has a significant propagation effect that needs to be carefully considered in satellite communication system network. Rain attenuation predictions and rain rate are essential when planning microwave satellite communication links. A review of the rain rate integration time and rain attenuation models for microwave and millimetre bands satellite system is presented.

Keywords- Frequency Band, Rain Attenuation, Rain Attenuation Model, Rain Rate, Satellite System

1 Introduction

There is a rapid need for broadband satellite services with the growth of the information technology, which will give authentic information transmission. Satellite communication is a significant part for global telecommunications. Satellite communication is a significant part for world telecommunications (Yakubu et al., 2018).

.

Microwave signals can be transmitted by satellite telecommunication systems at various frequency bands; these include C band (4-8 GHz), Ku band (12-18 GHz), Ka band (26.5-40 GHz) and V band (40-75 GHz). Improvement in telecommunication and broadcasting globally, occasioned congestion in frequency bands below 10 GHz; compelling microwave designers to higher frequencies migration. Nevertheless, deployments of millimetre wave band for communication links gives absolute benefits such as larger available bandwidths, high-speed service delivery, higher transfer speeds at lower costs. Rain events give rise to serious attenuation to propagating signals at frequencies beyond 10 GHz; hence the need for fade margin estimation of signals during rain events is required.

Rainfalls are broadly grouped into two types; stratiform and convective. The grouping is based on mechanisms which prompt cooling, condensation and associated rain. Stratiform rainfall is described by circulated, low or medium rain rates with higher durations. In stratiform rains, the upward air current that maintain clouds are so feeble that rain particles which form at the cloud top slowly gather and descend while larger in size. The concept of stratiform precipitation is often used to describe rains in temperate regions. Stratiform rain sources from growing of small ice particles combining to form bigger ones, and later morphing into raindrops. Convective rain is normally restricted to a smaller area, and the rain cells may take any shape. Convective rains occur when strong upward air current of hot and damp air possess sufficient power.

*Corresponding Author

Convective rainfall is connected to clouds produced below the 0ºC isotherm and are inspired by the strong campaign of air masses instigated by metamorphoses in tropospheric pressure (Yussuff et al., 2018).

The asperity of rain deterioration increases with frequency, and changes with climates. When planning microwave satellite and terrestrial line of- sight links, it is very significant to make an exact prediction of rain attenuation effect. Initially, attenuation prediction trials implied extrapolation of rain attenuation measurements from particular locations to other locations using frequencies or elevation angles; however, this approach is inaccurate due to complicated nature and regional variability of rainfall distributions (Afahakan et al., 2016).

Rain attenuation is the product of specific attenuation and the effective propagation path length. The ratio of rain attenuation to the specific attenuation is called the point rain rate while the product of the physical path length of a microwave link and the path reduction factor is termed the effective path length. The concept of effective path length path length is a practical method to average out the spatial inhomogeneity that is adhering in rain rate, and consequently, the specific attenuation. Owing to spatial inhomogeneity in rain rate which mostly unstable with rainfall intensity, changes in path length reduction factor can be represented as a function of rain rate or its conformable time exceedances. Attenuation can therefore be derived from direct measurements or predicted from the understanding of long-term rain rate. The rain attenuation, $A_{\%p}$ exceeded at $\%p$ of time is computed as follows:

$$A_{\%p}[\gamma(R_{\%p}), d_{eff}(R_{\%p,d})] = \gamma_{\%p} d_{eff} \quad (1)$$

$$\gamma_{\%p} = kR^{\alpha}{}_{\%p} \quad (2)$$

$$d_{eff} = dr_{\%p} \quad (3)$$

where $R_{\%p}$ (mm/hr) is the rain rate exceeded at $\%p$ of the time, $r_{\%p}$ is the path reduction factor at the same time percentage, d (km) is the link path length. Parameters k and α depend on frequency, elevation angle, rain drop shape, rain temperature and signal polarization. The values of the parameters are given in recommendation tables of ITU-R P.838 and also can be gotten by interpolation (Shrestha & Choi, 2017).

2 Review of Rain Rate Integration Time

This section reviews contributions of researchers in the area of integration time and rain rate modelling. However hourly and 5 to 30 minutes data are on record by many weather services, one-minute rain data are seldom available. 1-minute integration times checks that the peaks of rain event are adequately experimented and the use of longer integration times would result in an averaging effect making high intensity rain rate value to appear low.

The established conversion methods are grouped into different classes based on their functional principles as defined by (Ng et al., 2017):

- **Physical method**: This method involves climatic information such as annual rain rate, monthly rain rate, and yearly accumulation. The most acknowledged models are the Rice-Holmberg model, Dutton-Dougherty model, Crane model, ITU-R P.837, EXCELL method and the physical-stochastic method.
- **Analytical method**: This is a process of shifting the cumulative distribution function (CDF) of rain rate at integration time to its one-minute equivalent. Established works using this method include those of Moupfouma method , Karasawa method and Ito-Hosaya method.
- **Empirical method**: This method involves conversion from one integration time to another at same probability state. The most prominent authors are Segal method, Burgueno method, Watson method , and Chebil-Rahman method.

2.1 The Physical Method

The physical rain rate modelling uses the process of rain distribution with its mathematical representation. The physical input parameters of rain are needed in identifying its distribution patterns as a function of time measurement. Since many researchers have used climatic information in modelling the time series rain measurement, it is perfect to define such conversion methods by using the physical method. The physical modelling of the rainfall process is usually mathematically complex and principally particular to the meteorology's field, for weather forecasting activities.

2.1.1 Lavergnat and Gole model (1998)

LG model was derived from 2-year data collection in Paris by using a disdrometre that explained fine rain temporal structure rather that its intensity characteristic (Lavergnant & Gole, 1998). A conversion factor to scale both the rain and the probability were represented as shown in equation (4) and (5) respectively:

$$R_1 = R_T/h^{\alpha} \quad \text{mm/h} \tag{4}$$

$$P(R_1)_1 = h^{\propto} P(R_T)_T \tag{5}$$

Where h is conversion factor, h = 1/T, $\propto$ is the coefficient which is determined empirically, R_T is the rainfall rate in T -min integration time, R_1 represents the rainfall rate in a 1-min integration time and P possibility of occurrence.

Only one parameter is needed for conversion between integration times.

2.2 The Analytical Method

The analytical method for rain rate modelling, as defined by Ng (2017), is considered when the shape of cumulative distribution of rain rate is maintained while parameters that determine the shape depend on the rain rate integration time. Uniformly acknowledged research includes Moupfouma and Martin method, Karasawa and Matsudo method and Ito and Hosaya method. The method assumes that the rain rate cumulative distribution functions can be denoted by a given function of which the general shape remains constant.

2.2.1 Moupfouma-Martin Model

The Moupfouma-Martin rain rate model is a popular method because it includes local climatic parameters. Since climatic parameters are the key inputs that uniquely describe the distribution patterns of rain rate in any location, the incorporation of such parameters is needed to define the rain rate model expression. The Moupfouma-Martin expressions describe cumulative distribution of rain rate as:

$$P(R \geq r) = 100\left(\frac{R_{0.01}+1}{r+1}\right)^{b} e^{u(R_{0.01}-r)-\log_e(10^4)} \tag{6}$$

where:

$$b = \left(\frac{r}{R_{0.01}} - 1\right)\log_e\left(1 + \frac{r}{R_{0.01}}\right) \tag{7}$$

The climatic parameter u depends on the integration time and climatic location.

The expressions for temperate, tropic and sub-tropic locations are given by:

(a) For temperate localities

$$u(r) = \frac{\log_e(10^4)}{R_{0.01}} \frac{1}{1+\eta\left(\frac{r}{R_{0.01}}\right)^{\beta}} \tag{8}$$

where η = 4.56 and β =1.03

(b) For tropical and sub-tropical localities

$$u(r) = \frac{\log_e(10^4)}{R_{0.01}} \exp\left(-\lambda\left(\frac{r}{R_{S0.01}}\right)^{\gamma}\right) \tag{9}$$

where λ =1.066 and γ =0.214

Rain rate integration time that is less than one-hour can be converted to one-minute equivalent by the expression:

$$R(1\text{ min})_{0.01} = (R(\tau\text{ min})_{0.01})^{\alpha} \tag{10}$$

$$\propto = 0.987\left(\tau(\text{min})\right)^{0.061} \tag{11}$$

Provided 1min$\leq \tau \leq$ 1hour τ is the integration time

2.3 The Empirical Method

The empirical method is widely used in converting higher integration time to the needed one-minute rain rate. It gives simple methodical laws to express the relationship between equiprobable rain rate values. Studies which have applied this method in different regions include (Segal,1986), (Burgueno et al., 1988) for Spain, (Watson et al., 1982) for Europe, (Chebil & Rahman, 1999) for Malaysia, (Ajayi & Ofoche, 1984) for Nigeria (Flavin,1982), for Australia (Ong & Zhu, 1997), for Singapore and China (Xiao et al.,1987) .

http://dx.doi.org/10.46792/fuoyejet.v6i1.576 engineering.fuoye.edu.ng/journal

Elementarily, the two basic laws mostly used in empirical methods are the power law and the power-exponential law. In Ng et al. (2017), the laws are expressed as follows:

$$R_1(P) = aR_T(P)^b \quad (12)$$

where $R_1(P)$ and $R_T(P)$ are, respectively, the rain rate for a one-minute integration time and any integration time (T), at equal percentage of exceedance (P). Constant parameters a and b have their respective rain rate integration times, T.

2.3.1 Segal Method (1986)

A rain rate conversion factor was proposed by Segal based on the data analysis from 45 stations in Canada up to 10-year rainfall data. A specialized database of high-resolution rainfall records prepared at the Communications Research Centre was used to develop this model (Segal, 1986). The proposed method by Segal (1986) expressed as equations (13) and (14):

$$R_1(P) = \rho_\tau(P)R_\tau(P)\text{mm/h} \quad (13)$$

With conversion factor, $\rho_\tau(P)$ stated as per power law

$$\rho_\tau(P) = aP^b \quad (14)$$

$R_1(P)$ and $R_\tau(P)$ are the rain rate with a sampling interval of 1 and τ min, correspondingly, which contain a percentage of time, P. The conversion variables were be symbolized as a and b.

2.3.2 Chebil and Rahman Method (1999)

This conversion method estimating the rain rate conversion factor from 60 minute to 1- minute integration time for 82 locations in Malaysia (Chebil & Rahman, 1999). Conversion factor from 60- minute to 1-minute rainfall rate were expressed as (15) and (16):

$$\rho_{60}(P) = R_1(P)/R_{60}(P) \quad (15)$$

$$\rho_{60}(P) = aP^b + ce^{dP} \quad (16)$$

where the percentage of time is expressed as P. The rain 1-minute rain rate and 60-minute rain rate integration time to the percentage of time is designated as $R_1(P)$ and $R_{60}(P)$, respectively. The regression variables are represented as a, b, c, and d.

3 Rain Height

In order to perfectly determine rain attenuation over the slant-path of a satellite link, a proper knowledge of rain height is necessary. The method used by ITU-R presumes the rain structure to be uniform from the ground level to the Zero Degree Isotherm (ZDI) height called the effective rain height, h_R. Often the empirical formula is used to estimate the value of h_R due to scarcity of measured data. Most of the cited rain height experiments were done in Europe and Asia, and very little data is available in Africa except in West Africa (Akinyemi et al., 2018). The mean rain height above mean sea level is given as:

$$h_R = h_0 + 0.36 \text{ km} \quad (17)$$

where h_0 is the average annual 0℃ isotherm height and 0.36km is a constant. If the h_0 is not available from local data, a global contour map is used.

4 Rain Attenuation Models

There are different rain attenuation models employed for the prediction of rain-induced attenuation for satellite-to-earth communication. About sixteen attenuation due to rain models published in COST 255 reports (Harris, 2002) that claims global applicability. The commonly known rain attenuation models are further discussed in the following sub-sections (4.1-4.6).

4.1 Simple Attenuation Model

Stutzman and Dishman (1984) developed the Simple Attenuation Model (SAM) based on an effective rain rate profile. It incorporates the individual characteristics of the stratiform and convective types of rain. The SAM model is given as

$$A = \Upsilon \frac{1-\exp\left[-\Upsilon b \ln\left(\frac{R_{\%p}}{10}\right)\right] L_S \cos\theta}{\Upsilon b\left(\frac{R_{\%p}}{10}\right)\cos\theta}; \; R_{\%p} > 10mm/hr \quad (18)$$

Where L_S(km) is the slant path length given as

$$L_S(km) = \frac{H_r - H_s}{\sin\theta} \quad \theta \geq 5° \quad (19)$$

where H_r is the rain height and H_s is the station height. $\theta°$ is the elevation angle between the horizontal projection and slant path, Υ is the specific attenuation as given in ITU-R (2005) and the empirical constant, b = 1/14.

The rain height, H_r can be derived as:

$$H_r = \begin{cases} H_0; & R \leq 10mm/hr \\ H_0 + \log(\frac{R}{10}); & R > 10\ mm/hr \end{cases} \quad (20)$$

H_0 (km) is the 0° isotherm height. The seasonal mean of H_0 is obtained by (Crane,1980):

$$H_0 = 4.8 \qquad |\lambda| \leq 30° \quad (21)$$

$$H_0 = 7.8 - 0.1|\lambda| \qquad |\lambda| \geq 30° \quad (22)$$

where λ is the latitude of the station.

4.2 Svjatogor Attenuation Model

Svjatogor (1985) derived an attenuation model whose effective rain height, Hr depends on the rain intensity. The rain height is given as

$$H_r(km) = \frac{2.7}{\log_{10}(0.3R_p + 1.5)} + 0.0015R_p \quad (23)$$

The path length reduction factor is expressed as:

$$k_{rs} = e^y; \quad Y = -0.0045{R_p}^{0.68}\left[\frac{H_r}{\tan\theta}\right]^{0.6} \quad (24)$$

The rain attenuation is then given as

$$A(dB) = k{R_P}^{\alpha S} L_S k_{rs} \quad (25)$$

where :

$$L_S(km) = \frac{H_r - H_S}{\sin\theta} \quad \theta \geq 5° \quad (26)$$

$$L_S(km) = \frac{2(H_r - H_S)}{\left[\sin^2\theta + \frac{2(H_r - H_S)}{R_e}\right]^{1/2} - \sin\theta} \quad \theta < 5° (27)$$

R_e is the effective radius of the earth. It is taken as 8500 km.

4.3 The Garcia-Lopez Attenuation Model

(Garcia-Lopez et al., 1988) developed a simple method for the prediction of rain attenuation on satellite radio links which is an extension of that proposed for terrestrial links. Values of coefficients considered during calculation of the attenuation are separate for tropical regions. This method is given by

$$A = \frac{kR^{\alpha}L_S}{\left[a+\left\{\frac{L_S(bR+cL_S+d)}{e}\right\}\right]} \tag{28}$$

Where R is the point rainfall rate in mm/h, coefficients k and α are constants determined based on frequency, polarization and elevation angle as given by ITU-R (2005). a, b, c and d are constants depending on the geographical area and can be easily determined by regression techniques based on simultaneous rain intensity and rain attenuation plots. Coefficient (e) is a scaling factor and by taking e = 104, worldwide coefficients are: a =0.7, b = 18.35, c = -16.51 and d = 500 [30]. For tropical climates, a =0.72, b = 7.6, c = -4.75 and d = 2408 (Omotosho et al., 2017). Ls (km) is the slant path up to the rain height and it is as given in equation (22).

The rain height H_r is given as:

$$H_r(km) = \begin{cases} 4 & 0 < \psi < 36° \\ 4 - 0.075(|\psi| - 36°) & \psi \geq 36° \end{cases} \tag{29}$$

where ψ is the latitude of the earth station in degrees.

4.4 Bryant Attenuation Model

The Bryant attenuation model (Bryant et al., 1999) was derived based on the use of the concept of effective rain cell and variable rain height to calculate the distribution of rain attenuation. The following steps are employed in the calculation:

Step 1: calculate the PR parameter:

$$PR = 1 + \frac{2L}{\pi D} \tag{30}$$

where D is the rain cell diameter given by

$$D = 540\left({R_p}^{-12}\right) \tag{31}$$

where R_p is the point rainfall rate exceeded at p percentage of time and L is the horizontal projection given by

$$L = \frac{H_r}{\tan\theta} \tag{32}$$

Step 2: calculate the rain height, H_r :

$$H_r(km) = 4.5 + 0.0005{R_p}^{1.65} \tag{33}$$

Step 3: calculate the attenuation along the slant path:

$$A = 1.57D_m k_n Y_P \frac{L_S}{\xi L+D} \tag{34}$$

where: L_S is the slant-path length

Y_P (dB/km) is the specific attenuation

$$D_m = \left(\frac{2}{\pi}\right)D \tag{35}$$

k_n is the number of cells and it is given as

$$k_n = exp(0.007R_P) \tag{36}$$

$$\xi = \begin{cases} \frac{1}{\sqrt{2}}\, exp(\sin\theta), & \theta \leq 55° \\ 1.1\tan\theta, & x > 55° \end{cases} \tag{37}$$

4.5 The ITU-R P. 618-9 Model

This model uses rain rate at 0.01% probability level for the estimation of attenuation and then applies an adjustment factor for the predicted rain attenuation depth for other probabilities (Igwe et al., 2019; ITU-R, 2007).

The steps required for the analysis are given below:

Step 1: Determine the rain height, H_R as:

$$H_R = h_0 + 0.36km \tag{38}$$

where h_0 is the 0°C isotherm height above mean sea level of the location.

Step 2: Determine the slant path length Ls, below the rain height from:

$$L_S = \frac{H_R - H_S}{sin\,\theta} \tag{39}$$

where θ is the elevation angle and H_S is the height of the location above sea level.

Step 3: Obtain the horizontal projection, L_G, of the slant path length from:

$$L_G = L_S\cos\theta \tag{40}$$

Step 4: Obtain the point rainfall rate, $R_{0.01}$ (mm/h) exceeded for 0.01% of an average year from one-minute integration rain rate data for the location

Step 5: Obtain the Specific attenuation, $Y_{R_{0.01}}$ (dB/km) for 0.01% of time as given by:

$$Y_{R_{0.01}} = k{R_{0.01}}^{\alpha} \tag{41}$$

where parameters k and α are determined as functions of frequency in GHz as given in ITU-R P.838.

Step 6: Calculate the horizontal reduction factor, $r_{h_{0.01}}$ for 0.01% of time using

$$r_{h_{0.01}} = \frac{1}{1+0.78\sqrt{\left(\frac{L_G * Y_{R_{0.01}}}{f}\right)} - 0.38[1-\exp(-2L_G)]} \tag{42}$$

where f is the frequency in GHz is the frequency in GHz

Step 7: Calculate the vertical adjustment factor, $v_{0.01}$(km):

$$L_R = \frac{L_G r_{0.01}}{\cos\theta} \text{ for } \varrho > \theta \tag{43}$$

Otherwise,

$$L_R = \frac{H_R - H_S}{sin\,\theta} \text{ for } \varrho \leq \theta \tag{44}$$

$$\text{where } \varrho = \tan^{-1}\left(\frac{H_R - H_S}{L_G r_{h0.01}}\right) \tag{45}$$

therefore ,

$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left[31\left(1-exp\left(-\frac{\theta}{[1+\alpha]}\right)\right)\frac{\sqrt{L_G Y_{R0.01}}}{f^2} - 0.45\right]} \tag{46}$$

where

$\sigma = 36 - |\varphi|$, for $|\varphi| < 36°$ or $\sigma = 0$, for $|\varphi| \geq 36°$ φ is the latitude of the station

Step 8: The effective path length $L_{eff}(km)$ through rain is calculated as:

$$L_E = L_R v_{0.01} \tag{47}$$

http://dx.doi.org/10.46792/fuoyejet.v6i1.576 engineering.fuoye.edu.ng/journal

Step 9: The predicted rain attenuation exceeded for 0.01% of an average year is obtained from:

$$A_{0.01} = \gamma_{R0.01} L_E \quad (48)$$

Step 10: The attenuation for other percentage exceedances are obtained using the expression below:

$$A_p(dB) = A_{0.01}\left(\frac{p}{0.01}\right)^{-[0.655+0.033ln(p)-0.045ln(A_{0.01})-Z\sin\theta(1-p)]} \quad (49)$$

where p is the percentage probability of interest, and z is given by

if p ≥1%, z=0 (50)

if p< 1%, z=0 if $|\varphi| \geq 36°$ (51)

$$z = 0.005(|\varphi| - 36) \text{ for } \theta \geq 25° \text{ and } |\varphi| < 36° \quad (52)$$

$$0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta, \text{ for } \theta < 25° \text{ and } |\varphi| < 36° \quad (53)$$

4.6 Synthetic Storm Technique (SST) Prediction Model

The Synthetic Storm Technique (SST) was originally introduced by (Drufuca, 1973), specifically for terrestrial radio link, and was premised on the concept of the Hamilton-Marshall "synthetic storm". The SST input data was the rainfall rate time series over a physical distance by adopting a storm translation velocity in transforming time to distance. The synthesized storms express rainfall rate (R) as a function of distance (x) by aggregating the statistical physiognomies of an enormous quantities of synthetic storms. The transformation of rain rate to specific attenuation (γ)and by extension, the attenuation, across a distance (L) was achieved by Equation (57).

$$A(x_0, L) = \int_{x_0}^{x_0+L} \gamma(x)dx(dB) \quad (54)$$

Other essential inputs in the formulation of SST are advection velocity of rain cells and the slant path length of the location of interest. The SST slant path vertical structure is modelled into tropospheric two layers, A and B. Layer A represents the rain layer where precipitation occurs while layer B is the melting layer, where ice transforms into water as it begins to melt. Layer A comprised homogenous rain precipitation (R_A) and layer B symbolize ice with apparent rain rate(R_B). The combination of both is expressed as:

$$(R_B) = 3.134(R_A) \text{ (mm/hr)} \quad (55)$$

The resultant slant path rain attenuation is:

$$A = \int_0^{L_A} K_A R^{\alpha_A}(x_0 + \Delta x_{0,}\zeta)\delta\zeta + K_B(3.134)^{\alpha_B}\int_{L_A}^{L_B} R^{\alpha_B}(x_0, \zeta)\,\delta\zeta(dB) \quad (56)$$

ζ is the distance measured along the satellite slant path, Δx_0 is a shifting parameter that accounts for the radio path, while K and α are statistical coefficients which correspond to the satellite signal elevation angle, polarization, rain drop size distribution and frequency of operation. All these parameters are available in the [8] for water at 20℃ and Parson's law drop size distribution for 20℃ .

Again, the radio path lengths L_A and L_B can be described by Equations 60 and 61:

$$L_A = \frac{H_A - H_S}{\sin\vartheta} \quad (57)$$

$$L_B = \frac{H_B - H_S}{\sin\vartheta} \quad (58)$$

Yussuff et al. (2018) revealed that the probability distribution function that was generated by SST can consistently be represented by $A = [C_0 K_A R^{\alpha_A} + (1 - C_0)K_B(3.13R)^{\alpha_B}]L^m(dB)$ (59)

Where L(km) is the long term slant path in the rainfall (and m is a random variable) and is given as:

$$L_A = L_A + L_B \quad (60)$$

The value of the random variable m is derived from

$$m = \frac{\Delta A/A}{\Delta L/L} \quad (61)$$

The integration constant, C_0 is given as

$$C_0 = L_A/L = \frac{0.4}{H_B - H_S} \quad (62)$$

H_B is the vertical dimension of the melting layer's tip and 0.4 km is supposed thickness of the melting layer.

5 Conclusion

In this paper, review of the study on the effects of rain attenuation for microwave and millimetre bands satellite system has been presented. The review focused mainly on rain rate integration time, rain height and rain attenuation models.

References

Afahakan, I. E., Udofia, K. M., & Umoren, M. A. (2016, January 1). Analysis of Rain Rate and Rain Attenuation for Earth-Space Communication Links over Uyo - Akwa Ibom State. *Nigerian Journal of Technology (NIJOTECH), 35*, 137 – 143.

Ajayi, G. O., & Ofoche, E. (1984, April). Some Tropical Rainfall Rate Characteristics at Ile-Ife for Microwave and Millimetre wave Applications. *Journal of Climate and Applied Meteorology, 23, No. 4*, 562-567.

Akinyemi, G. A., Falade, J. A., & Kolawole, L. B. (2018, August). Estimation of rain attenuation at microwave bands in Nigeria. *Zhurnal Radioelektroniki - Journal of Radio Electronics*(8). doi:10.30898/1684-1719.2018.8.18

Bryant, G. H., Adimula, I., Riva, C., & Brussard, G. (1999). Rain attenuation statistics from rain column, diameters and heights. *Int. J. of Sat. Commun., 19*, 263-283.

Chebil, J., & Rahman, T. A. (1999). Rain rate statistical conversion for the prediction of rain attenuation in Malaysia. *Electronics Letter, 35*, 1019-21.

Crane, R. K. (1980, Sept.). Prediction of attenuation by rain. *IEEE Trans. Comm. COM, 28*(9), 1717 – 1733.

Drufuca, G. (1973). *Rain Attenuation Studies.* United States Air Force: Canada ,1-105.

Flavin, R. K. (1982). Rain Attenuation Considerations for Satellite paths in Australia. *Australian Telecommunications Research, Vol. 16*, 11-24.

Garcia-Lopez, J. A., Hernando, J. M., & Selga, J. (1988). Simple rain attenuation method for satellite radio links. Year-to-year variability of rainfall for microwave applications in the USA. *IEEE Trans. on Ant. and Propag., 36(3)*, 444-448.

Igwe, K. C., Oyedum, O. D., Ajewole, M. O., & Aibinu, A. M. (2019, March 11). Evaluation of some rain attenuation prediction models for satellite communication at Ku and Ka bands. *Journal of Atmospheric and Solar-Terrestrial Physics, 188*, 52-61.

Harris, R. A. (2002). *COST Action 255, Radiowaves propagation modeling for SATCOM services at Ku-Band and above.* Noordwijk, Netherlands: European Space Agency publication Division.

ITU-R. (2007). Propagation data and prediction methods required for the design of earth–space telecommunication systems. *Rec. P.618-9, ITU-R P Sers., Int.*

Lavergnat, J., & Gole, P. (1998). A stochastic raindrop time distribution model. *AMS Journal of Applied Meteorology, 37*, 805-818.

Omotosho, T. A., Ometan, O. O., Adewusi, M. O., Mandeep, J. S., & Abdullah, M. (2017). Earth-Space Rain Attenuation Prediction: Its Impact at Ku, Ka and V-band Over Some Equatorial Stations. *Journal of Informatics and Mathematical Sciences, Vol. 9, No. 2*, pp. 359–374.

Ng, Y.-Y., Singh, M. S., & Thiruchelvam, V. (2017 , October 9). Performance Analysis of 60-Min to 1-Min Integration Time Rain Rate Conversion Models in Malaysia. *Journal of Atmospheric and Solar-Terrestrial Physics, 167*, 13-22.

Ong, J., & Zhu, C. (1997, January). Rain Rate Measurements by a Rain Gauge Network in Singapore. *Electronics Letters, Vol. 33*, 240-242.

Segal, B. (1986). The influence of raingage integration time on measured rainfall-intensity distribution functions. *J. Atmos. Oceanic Technol., 3*, 662–671.

Shrestha, S., & Choi, D. Y. (2017). Rain attenuation over terrestrial microwave links in South Korea. *IET Microw. Antennas Propag., 11*(7), 1031-1039.

Stutzman, W. L., & Dishman, W. K. (1984). A simple model for the estimation of rain-induced attenuation along Earth space paths at millimetre wavelengths. *Radio Sci., 19*, 946.

Svjatogor, L. (1985). Prostranstvennaia korelacia vypadenjija dozdjej vdol zemnoj poverchnostji (in Russian). *Symposium expertov stran uchastnic programmy INTERKOSMOS (Interkosmos symposium, theme 5 of the established telecommunication working group, Dresden, GDR)*.

Watson, P. A., Gunes, M., Potter, B. A., Sathiaseelan, V., & Leitao, J. (1982). *Development of a Climatic Map of Rainfall Attenuation for Europe.* Final Report of ESA/ESTEC Contract No.4162/79/NL/DG/ (SC).

Yakubu, A., Adamu, A. A., & Adaeze, E. (2018). Estimation of rainfall rate and rain attenuation for satellite communication in Imo, Osun and Niger State of Nigeria. *International Journal of Applied Research, 4(10)*, 157-166.

Yussuff, A. I., Koleoso, I. E., & Nor, H. H. (2018, March 1). Investigating Rain Attenuation Models for Satellite Links in Tropical Nigeria. *Indonesian Journal of Electrical Engineering and Informatics (IJEEI), 6*, 61-69.

Xiao, J. M., Cheng, D. H., & Wang, L. J. (1987). Rain Rate Statistics and Analysis in Xian District In Chinese. *China Journal of Radio Science, 2(1)*, 39-48.

http://dx.doi.org/10.46792/fuoyejet.v6i1.576 engineering.fuoye.edu.ng/journal