Analysis of Rain Attenuation for Earth-Space Communication Links at Ku and Ka-Bands

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Abstract

Rain rate and rain attenuation predictions are very vital considerations when designing microwave satellite communication systems. In this research work, rainfall data bank of 33 years (1983-2015) was obtained from the Nigerian Meteorological Agency (NIMET) for Gombe and Akwa-Ibom States which was used for the prediction of rain rate and rain attenuation. Chebil rain rate model was used to predict the point rainfall rate, while ITU-R P. 618-9 model was used for the prediction of the rain attenuation for the two locations. The rain attenuation values computed were at horizontal polarization and for links to Nigerian Communication Satellite-1 Replacement (NIGCOMSAT-1R). The results obtained from this work will be good as preliminary design tools for earth-space communication links and will also provide a broad idea of rain attenuation for microwave engineers.

Keywords: Earth-space link, Ka-band, Ku-band, Rain attenuation, Rainfall rate.

1. Introduction

Signal energy degradation that occurs as a result of absorption, scattering and refraction of microwave energy by rain drops is a major challenge to satellite transmission operating at a frequency of 10 GHz and above. Attenuation caused by rain may be measured directly from beacon experimental setups and it can as well be predicted from rain-rate or raindrop size distributions. To predict rain attenuation of satellite signals from rain rate along the satellite link path, the statistics of point rainfall rate characteristics peculiar to the location of interest must be available (Mandeep *et al.*, 2008).

Empirical and physical methods are the two types of prediction methods for rain attenuation on earth space paths. Empirical method is the method for measurement of data bases from stations in different climatic zones within a given territory. Physical method is used to recreate the physical behaviour involved in the attenuation process. Not all the input parameters needed for analysis when using the physical method is available, therefore empirical method is mostly used for methodologies (Crane, 1980).

The rainfall rate of 1-minute integration time necessary for the study of rain induced impairment to telecommunication signal especially in the tropical region is scarce or totally unavailable. This is because global national weather institutions were established to satisfy more traditional requirements such as those for agriculture, hydrology and forest management. A method for converting the specific rain rate data to the equivalent 1-minute rain rate cumulative distribution is therefore needed (Ajayi and Ofoche, 1983).

Satellite communication systems are already migrating to higher frequency bands due to increase in demand for wide bandwidth as a result of developments in the complex multimedia applications. However, these higher frequency bands are affected adversely by rain-induced degradation. This has thus demanded for the pragmatic necessity for careful and detailed analysis of the effects of rain-induced degradation on system performance in these frequency bands (Panagopoulos *et al*, 2009, Igwe *et al.*, 2019).

2. Relevant Theory

2.1 Rain Rate Model

2.1.1 Chebil Rain Rate Model

Chebil-Rahman (Chebil and Rahman, 1999) came up with an experimental technique for estimating rainfall rate conversion element by using the conversion process from 60-minute and 1-minute integration time of rainfall intensity data in Malaysia. The 1-minute rainfall data were obtained from 3 different tipping bucket stations over 3 years period and the 60-minute rainfall data were acquired from Malaysia Meteorological Department (MMD) formerly known as Malaysia Meteorological Service (MMS) for 35 stations and for a period of 12 years. The proposed conversion formula is expressed as follows:

$$\mathrm{\rho 60(P)} = R_1(P)/R_{60}(P) \tag{1}$$

where R_{60}(P) is the precipitation rate in 60 minute integration time and $\mathrm{\rho60(P)}$ is the rainfall rate at 1-minute integration time. $\mathrm{\rho60(P)}$is expressed as a mixed power-exponential law:

$$\rho 60(\mathrm{P}) = aP^{b} + ce^{(dp)} \quad (2)$$

where a, b, c and d are the regression variables analysed from statistical analysis of rainfall data. The accuracy of this method has been further tested for other lower integration time intervals to estimate $R_{0.01}$.

The use of Chebil's model is suitable since it allows the usage of long-time mean annual accumulation, M at the location of interest.

The power law relationship of the model is given by:

$$R_{0.01} = aM^{\beta} \quad (3)$$

where α and β are the regression coefficients. Chebil has made a comparison between some models based on measured values of $R_{0.01}$, and M in Malaysia, Indonesia, Brazil, Singapore and Vietnam. The regression coefficients α and β are defined as:

$\alpha = 12.2903$ and $\beta = 0.2973$

2.2 Rain Attenuation Model

2.2.1 The ITU-R P. 618 model

The ITU-R P. 618-9 model (ITU-R, 2007) provides the estimation of the long-term statistics of the slant path rain attenuation at a given location for frequencies up to 55 GHz. The model was developed based on the data obtained from ITU-R data storage using a satellite beacon with elevation angles from 6° to 82.5°. The model uses mainly rainfall information at one probability level ($R_{0.01}$) to calculate the attenuation. The ITU-R model provides global rain statistics by dividing the earth into rain regions and assigning a rain rate to each region along with the probability of that rain being exceeded (Seybold, 2005). This model uses the rain rate at 0.01% probability level for the estimation of attenuation and an adjustment factor is applied to the predicted rain fade depth for other probabilities. It can be used for the frequencies from 4 - 55 GHz and 0.001 – 5% percentage probability range. It is based on log-normal distribution and both rain intensity and path attenuation distribution conform to the same log-normal distribution.

The method consists of the following procedure, which is proposed to calculate the long-term statistics of the slant path rain attenuation at a frequency up to 30GHz. The method consists of several steps shown below.

The following parameters are required:

$R_{0.01}$: point rainfall rate for the location for 0.01% of an average year (mm/h)

h_s: height above mean sea level of the earth station (km)

θ: elevation angle (degrees)

φ□: latitude of the earth station (degrees)

f : frequency (GHz)

R_e : effective radius of the Earth (8500 km).

If local data for the earth station height above mean sea level is not available, an estimate can be obtained from the maps of topographical altitude given in Recommendation ITU-R P.1511.

The geometry is illustrated in Fig. 1

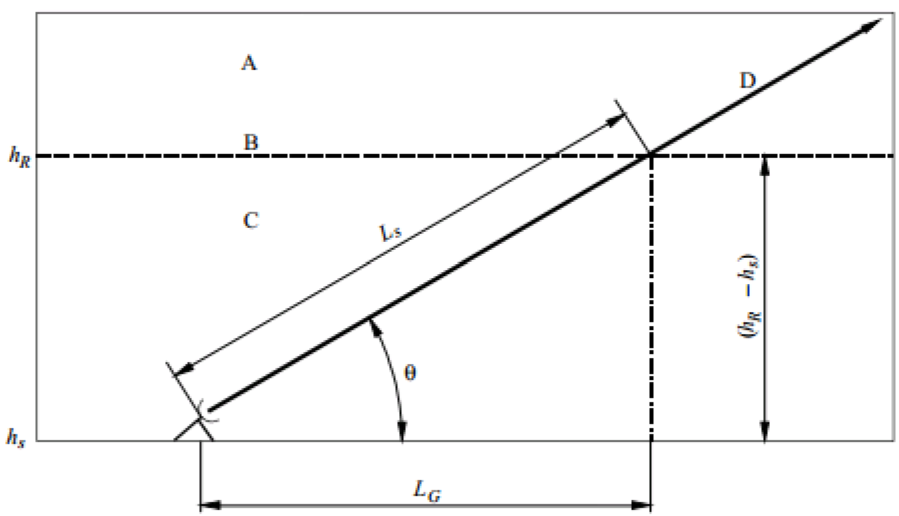


Fig. 1: Schematic presentation of an Earth-space path.

A: frozen precipitation

B: rain height

C: liquid precipitation

D: Earth-space path

Step 1: Determine the rain height, h_R, as given in Recommendation ITU-R P.839.

Step 2: For $\theta \geq 5°$ compute the slant-path length, L_s, below the rain height from:

$$L_S = \frac{(h_R - h_s)}{\sin\theta} \text{ km} \quad (4)$$

For $\theta < 5°$, the following formula is used:

$$L_S = \frac{2(h_R - h_s)}{\left(\sin^2\theta + \frac{2(h_R - h_s)}{R_e}\right)^{1/2} + \sin\theta} \text{ km} \quad (5)$$

If h_R-h_s is less than or equal to zero, the predicted rain attenuation for any time percentage is zero and the following steps are not required.

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

$$L_G = L_S \cos\theta \text{ km} \quad (6)$$

Step 4: Obtain the rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year (with an integration time of 1 min). If this long-term statistics cannot be obtained from local data sources, an estimate can be obtained from the maps of rainfall rate given in Recommendation ITU-R P.837.

If $R_{0.01}$ is equal to zero, the predicted rain attenuation is zero for any time percentage and the following steps are not required.

Step 5: Obtain the specific attenuation, γ_R using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$ determined from Step 4 by using:

$$\gamma_R = k\,(R_{0.01})^{\alpha} \text{ dB/km} \quad (7)$$

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

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)} \quad (8)$$

Step 7: Calculate the vertical adjustment factor, $v_{0.01}$, for 0.01% of the time:

$$\zeta = \tan^{-1}\left(\frac{(h_R - h_s)}{L_G r_{0.01}}\right) \quad \text{degrees} \tag{9}$$

For $\zeta > \theta$

$$L_R = \frac{L_G r_{0.01}}{\cos\theta} \quad \text{km} \tag{10}$$

Else,

$$L_R = \frac{(h_R - h_s)}{\sin\theta} \quad \text{km} \tag{11}$$

If $|\varphi| < 36°$,

$$\chi = 36 - |\varphi| \quad \text{degrees} \tag{12}$$

Else,

$$\chi = 0 \quad \text{degrees} \tag{13}$$

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\frac{\sqrt{L_R \gamma_R}}{f^2} - 0.45\right)} \tag{14}$$

Step 8: The effective path length is:

$$L_E = L_R \, v_{0.01} \quad \text{km} \tag{15}$$

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

$$A_{0.01} = \gamma_R L_E \quad \text{dB} \tag{16}$$

Step 10: The estimated attenuation to be exceeded for other percentages of an average year in the range 0.001% to 5% is determined from the attenuation to be exceeded for 0.01% for an average year:

If $p \geq 1\%$ or $|\varphi| \geq 36°$: $\quad \beta = 0$

(17)

If $p < 1\%$ and $|\varphi| < 36°$ and $\theta \geq 25°$: $\quad \beta = -0.005(|\varphi| - 36)$

(18)

Otherwise: $\quad \beta = -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta$ (19)

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - \beta(1-p)\sin\theta)} \tag{20}$$

This method provides an estimate of the long-term statistics of attenuation due to rain. When

Comparing measured statistics with the prediction, allowance should be given for the rather large year-to-year variability in rainfall rate statistics.

3. Methodology

The rainfall data of 33 years (January, 1983 to December, 2015) collected from the Nigerian Meteorological station (NIMET) in Akwa-Ibom and Gombe was analysed using the Chebil rain rate model and the ITU-R P. 618-9 rain attenuation model stated in section 2.

4. Results and Discussion

4.1 Point Rainfall Rate for the Study Area

The point rainfall rate obtained using Chebil rain rate model is given in Table 1. Attenuation varies from location to location due to different rainfall rate experienced in the various locations. Akwa-Ibom State has a higher rainfall rate when compared to Gombe State, hence there will be more signal attenuation occurrence.

Table 1: Point rainfall for the study area.

Study Area	Gombe	Akwa-Ibom
Point Rainfall	94.75 mm/h	136.72 mm/h

The parameters used in the analysis of rain attenuation are shown in Table 2

Table 2: Rain attenuation parameters for the study area.

LOCATION	GOMBE	AKWA-IBOM
Longitude	11.02°	7.57°
Latitude	10.19°	5.00°
Elevation	42.5°	42.5°
Height above sea level	0.422 Km	0.163 Km
Polarisation	Horizontal	Horizontal
Operating frequencies	11 GHz for downlink and 14 GHz for Uplink Ku-band.	11 GHz for downlink and 14 GHz for Uplink in Ku-band.
	20 GHz for downlink and 40 GHz for Uplink Ka-band.	20 GHz for downlink transmission and 40 GHz for Uplink Ka-band.

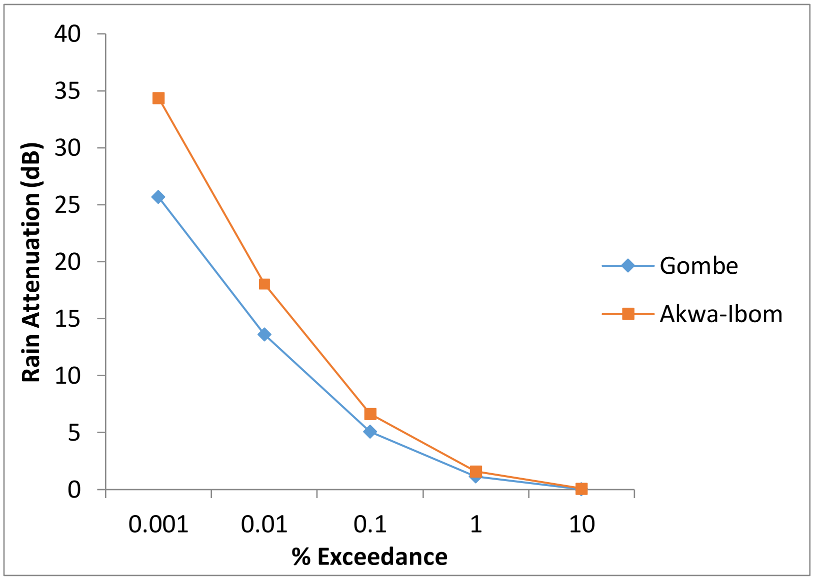
4.2 Rain Attenuation for the Study Area

The predicted rain attenuation for the study area at 11 GHz and 14 GHz downlink and uplink frequencies respectively and 20 GHz and 40 GHz downlink and uplink frequencies respectively at 0.01% exceedance are given in Table 3.

Table 3: The predicted attenuation at 0.01%

Frequency(GHz)	Gombe	Akwa-Ibom
11	13.6229	18.0471
14	27.7331	29.8146
20	44.3253	57.5429
40	117.2618	147.9524

Rain does not occur all the time in a year and its rate does not remain the same all the time when it occurs, therefore the amount of rain fade margin needed to compensate for the rain effect varies with time. Figures 2-5 show the graphical comparison of the rain attenuation for a horizontally polarised signal at different percentages of time for Ku-band downlink (11 GHz) and uplink (14 GHz) and Ka-band downlink (20 GHz) and uplink (40 GHz) frequencies.



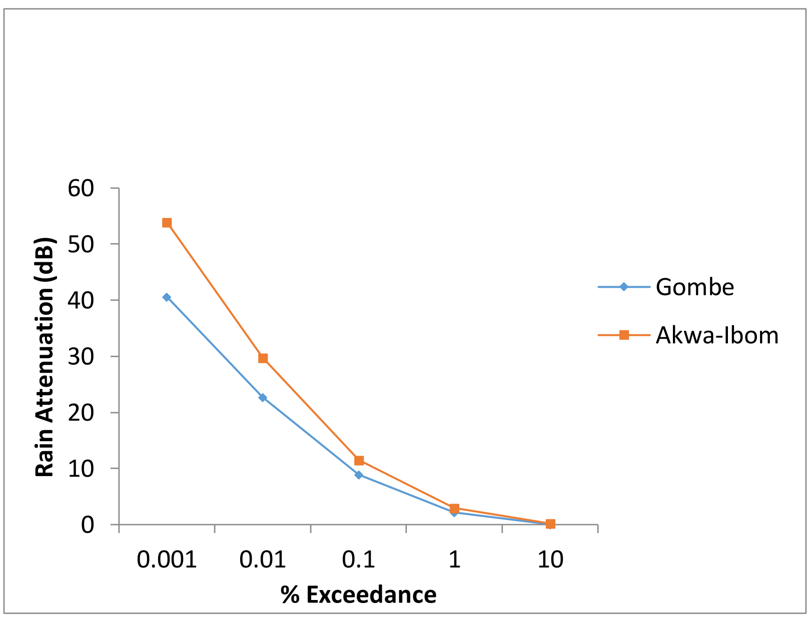


Figure 2: Rain attenuation at 11 GHz

Figure 3: Rain attenuation at 14 GHz

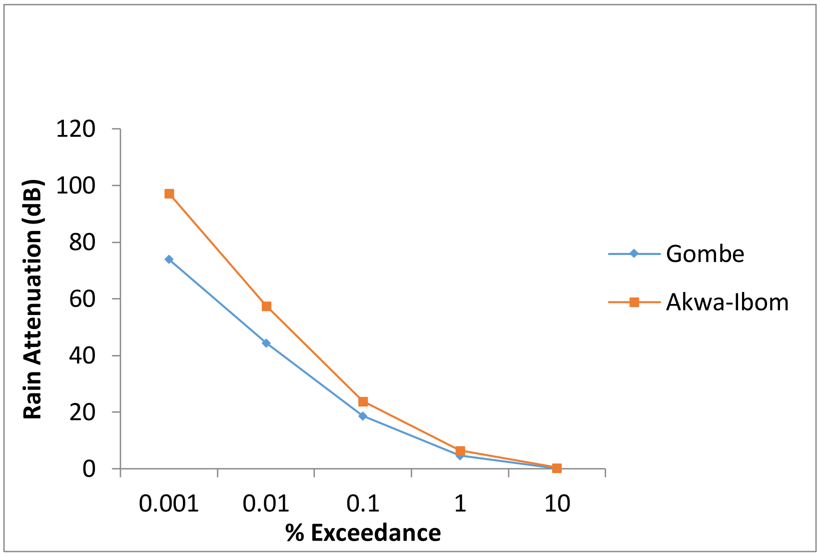


Figure 4: Rain attenuation at 20 GHz

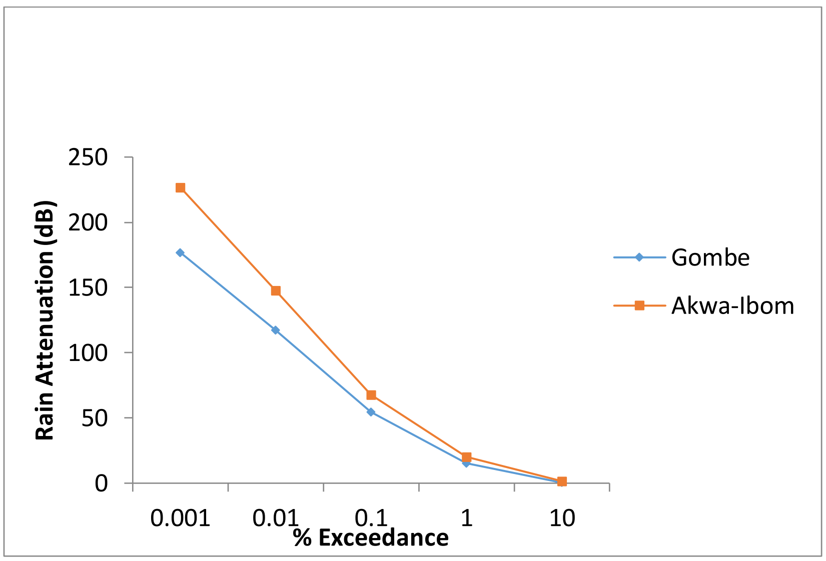


Fig. 5: Rain attenuation at 40 GHz

For 0.01% of the year (99.99% availability), the rain attenuation in Gombe at Ku-band downlink and uplink frequencies are 13.62 dB and 22.73 dB respectively. At Ka-band downlink and uplink frequencies, the attenuation is 44.33 dB and 117.26 dB respectively.

Similarly in Akwa-Ibom, the rain attenuation for Ku-band downlink and uplink frequencies are 18.05 dB and 29.81 dB respectively. At Ka-band downlink and uplink frequencies, the attenuation is 57.54 dB and 147.95 dB respectively. This shows that attenuation experienced in Gombe is lesser in comparison to that experienced in Akwa-Ibom. Attenuation is also a function of frequency which is also true from the results obtained, as increase in frequency leads to a corresponding increase in signal attenuation.

5. Conclusion

The effect of rainfall on earth-space communication link at Ku and Ka-bands have been investigated for links to Nigerian communication satellite-1 Replacement (NIGCOMSAT-1R) based on local input data. Rain attenuation for Gombe and Akwa-Ibom States were predicted for 0.001-10% time exceedance using the ITU-R P. 618-9 attenuation model. For the downlink and uplink frequencies of Ku-band, 13.62 dB and 22.73 dB respectively were predicted, while 44.33 dB and 117.26 dB were predicted for the downlink and uplink frequencies respectively of Ka-band at 0.01% for Gombe State. For Akwa Ibom State, 18.05 dB and 29.81 dB were predicted for the Ku-band downlink and uplink frequencies respectively, while 57.54 dB and 147.95 dB were predicted for the Ka-band downlink and uplink frequencies respectively. The results obtained clearly show that satellite links in Akwa Ibom State will surfer more rain attenuation than those in Gombe State. These results are the consequent effects of the point rainfall rate values deduced for the two States.

References

Ajayi, G. O. & Ofoche, E. B. C. (1983). Some tropical rainfall rate characteristics at Ile-Ife for microwave and millimetre wave application, *Journal of Climate and Applied Meteorology*, 23, 562 – 567.

Chebil, J. & Rahman, T. A. (1999). Rain rate statistical conversion for the prediction of rain attenuation in Malaysia. *Electronics Letters*, 35, 1019-1021.

Crane, R. K. (1980). Prediction of attenuation by rain. *IEEE Transactions on Communications,* 28, 9, 1717 – 1733.

Igwe, K. C., Oyedum, O. D., Ajewole, M. O. & Aibinu, A. M. (2019): 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.*

ITU-R. (2001). Rain height model for prediction methods. *Recommendation P.839-3, ITU-R P Series, International Telecommunication Union,* Geneva, 1-2.

ITU-R. (2001). Topography for Earth-to-space propagation modelling. *Recommendation P.1511, ITU-R P Series, International Telecommunication Union,* Geneva, 1-2.

ITU-R. (2005). Specific attenuation model for rain for use in prediction methods. *Recommendation P.838-3, ITU-R P Series, International Telecommunication Union,* Geneva, 1-8.

ITU-R. (2007). Propagation data and prediction methods required for the design of earth-space telecommunication systems. *Recommendation P.618-9, ITU-R P Series, International Telecommunication Union,* Geneva, 1-7.

Mandeep, J. S., Hassan, S. I., Ain, M. F. & Tanaka, K. (2008). Rainfall propagation impairments for medium elevation angle satellite-to-earth 12 GHz in the tropics. *International Journal of Satellite Communications and Networking, 26 (4), 317-327.*

Panagopoulos D. J., Chavdoula, E. D. & Margaritis, L. H. (2009). Bio-effects of mobile telephony radiation in relation to its intensity or distance from the antenna. *International Journal of Radiation Biology, 86(5), 345-357.*

Seybold, J. S. (2005). Introduction to RF propagation. Wiley-Interscience, John Wiley and Sons Inc. ISBN-13978-0-471-65596-1.