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INVESTIGATION OF RAIN-INDUCED SIGNAL ATTENUATION FOR SATELLITE COMMUNICATION IN ABUJA AND KADUNA, NIGERIA

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ABSTRACT
This paper examines rain-induced attenuation on Ku-band (12 GHz and 14 GHz) satellite communication links over Abuja and Kaduna, Nigeria, using three years (2022–2024) of rainfall data from the Nigerian Meteorological Agency (NiMet). The Lavergnat–Gole (LG) model was employed to derive 1-minute rain rates and corresponding attenuation for both horizontal and vertical polarisations. Results revealed rainfall rates of 95.90 mm/h in Abuja and 107.01 mm/h in Kaduna exceeded for 0.01% of the time, showing stronger rainfall intensity in Kaduna. Attenuation increased with frequencies, path length and horizontal polarisation, with Kaduna experiencing higher signal losses ranging from 15.36 dB to 152.86 dB compared to Abuja with values 13.56 dB to 134.82 dB and vertical polarization 11.95 dB to 118.89 dB in Kaduna compared to 10.63 db to 105.73 dB in Abuja at 14 GHz while horizontal polarisation for Kaduna values ranges from 11.99 dB to 119.36 dB compared to 10.54 dB to 104.79 dB in Abuja and vertical polarization for Kaduna values ranges from 8.21 dB to 92.43 dB compared to Abuja with values ranging from 8.21 dB to 81.69 dB at 12 GHz operational frequencies for path-length of 2 km, 5 km, 10 km, 15 km and 20 km link. The study concludes that rain attenuation critically limits Ku-band reliability in tropical regions, and recommends sufficient fade margin and adaptive power control to enhance system performance.

Keywords: Rain attenuation, Horizontal, Ku-band, Lavergnat–Gole model, Satellite communication

INTRODUCTION
Satellite communication is a cornerstone of modern aviation systems, which enables real-time weather monitoring, air traffic control and in-flight connectivity. However, in tropical and equatorial regions like Africa, heavy rainfall poses a significant challenge to signal integrity, particularly at high frequencies (Ku/Ka-band) used in satellite links. However, atmospheric conditions, especially heavy rainfall, can cause severe signal attenuation, leading to communication disruptions and operational inefficiencies, risking flight safety and operational efficiency (Chebil *et al*., 2020).

The existing rain attenuation models of International Telecommunication union Recommendations (ITU-R P.618) are often calibrated for temperate climates and may underestimate losses in tropical Africa, where convective rainfall is intense and localized. Examples, studies in Pakistan and Malaysia reveal significant discrepancies between ITU-R predictions and actual attenuation in similar climates, highlighting the need for region-specific adaptations (Budalal *et al*., 2025; Onaya, 2023).

Therefore, predicting rain attenuation in tropical cities like Abuja and Kaduna is essential to analyse signal strength variations at frequencies above 10 GHz and studying atmospheric parameter fluctuations is critical for optimising rain-affected signal propagation and enabling reliable communication system design.

The increasing congestion of lower frequency bands has driven the need to utilize higher frequencies (> 20 GHz) to meet growing bandwidth demands. However, these centimeter and millimeter wave bands face are significant signal degradation from rain attenuation, particularly in tropical regions (Igwe *et al.*, 2021). This phenomenon not only impacts communication quality, but also increases operational costs, as these systems require greater transmission power to compensate for signal loss (Eze *et al*., 2014). Accurate rain attenuation modeling becomes crucial when designing terrestrial radio links operating above 10 GHz, as it directly affects both systems performance and economic viability in the study area.

This study addresses the critical gap in reliable satellite communication for aviation by investigating the specific and total rain attenuation. The research will enhance aviation safety and optimize communication infrastructure costs.

The aim of this research is to investigate rain-induced signal attenuation model for satellite communication systems in the study area, addressing the limitations of global models in tropical climate. The study seeks to enhance signal reliability for aviation safety and operational through; analysing rainfall intensity and satellite communication signals at 1-minute integration time data for Abuja and Kaduna, Nigeria from 2023 – 2025. Also calculating the specific attenuation of signal on satellite communication in Abuja and Kaduna and finally investigating the total rain attenuation of signal on satellite communications in Abuja and Kaduna.

MATERIALS AND METHODS
The Study Area
Abuja
Abuja is located in the center of Nigeria within the Federal Capital Territory (FCT), Abuja lies roughly between latitudes 8°25′ and 9°20′ north and longitudes 6°45′ and 7°39′ east. Abuja is the planned capital city and the center of the FCT, strategically placed to be a neutral point. Abuja borders Niger State to the west, Nasarawa State to the east and south, Kaduna State to the northeast, and Kogi State to the southwest. The Federal Capital Territory has a landmass of approximately 7,315 km^2, and it is situated within the savannah region with moderate climatic conditions.

Kaduna State
Kaduna State is situated in the North-West region of the country. Kaduna, located at 10°20′N 7°45′E. Kaduna borders Zamfara, Katsina, and Kano to the North, Bauchi and Plateau to the East, Nasarawa to the South, and Niger to the West. The rainy season in Kaduna is hot, humid, and cloudy, while the dry season is hot and partly cloudy. Throughout the year, the temperature rarely falls below 50 °F or rises above 102 °F, usually ranging between 55 °F and 95 °F.

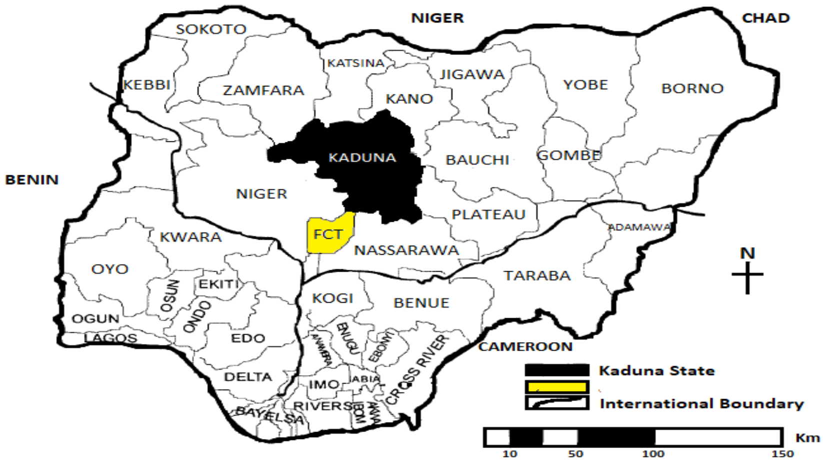

Figure 1: Map of Nigeria showing FCT and Kaduna (GIS Maps)

Data Source
The sources of data for the chosen stations will be collected with the Meteorological Agency (NiMet), Abuja. The rainfall data spanned 2022-2024. The automated weather stations provide an integrated system of components used to measure, monitor and study the weather and climate. These stations are typically used in weather, meteorology and mesonet applications.

Data Analysis
According to the International Telecommunication Union (ITU), 1-min rain rate was determined to be the best integration time for the prediction of the rain induced attenuation (Mandeep and Alnutt, 2007). Unfortunately, 1-min rain rate is not often available whereas rain rate in higher integration time is available in long term statistics. Therefore, conversion method is needed to convert the rain rate into 1-min integration time. The Lavergnat-Gole model was used in this investigation of rain attenuation of signal on satellite communication in Abuja and Kaduna respectively. The steps of Lavergnat-Gole model, which is valid at least for frequency up to 40 GHz and lengths pup to 60 km, are given below.

Conversion of Rain Rate
Step 1: According to Lavergnat-Gole, conversion of rainfall rate from a given integration time to another can be achieved using (1).

$$P_1(R_1) = h^z \times P_T(R_T) \quad (1)$$

$$R_1 = \frac{R_T}{h^z} \quad (2)$$

$$h = \frac{t_1}{t_T} \quad (3)$$

where:
z= 0.143 for tropical region (Emiliani and Luini, 2009), R_1= rain rate at one minute integration time, R_T= rain rate at T minute integration time, P_1= percentage probability of time exceedance at 1 minute, P_T= percentage probability of time exceedance at T minute, h= conversion factor, t_1= integration time at which the rain rate is required, t_T= integration time at which the rain rate is available.

Calculation of Attenuation
Step 2: The attenuation per kilometer, called specific attenuation, γ, is calculated using (ITU-R 837-5, 2007):

$$\gamma_{(0.01)} = kR^{\alpha}_{(0.01)} \text{ (dB/km)} \quad (4)$$

$$r_{0.01} = \frac{1}{1+\frac{L}{L_o}} \quad (5)$$

$$L_o = 35e^{-0.015}R_{(0.01)} \quad (6)$$

where:
$r_{0.01}$= correction factor, k and α= regression coefficients (ITU-R 837-5, 2007), L_o= rain rate dependent factor, L= path length of the terrestrial microwave link, $R_{0.01}$= rain rate at 0.01 percentage of time exceedance.

Calculation of Effective Path Length
Step 3: The effective path length, L_{eff}, expressed as:

$$L_{eff} = L \times \frac{1}{1+\frac{L}{L_o}} \quad (7)$$

Calculation of Total Attenuation
Step 4: An estimate of the total path attenuation exceeded for 0.01% of the time is given by:

$$A_{0.01} = \gamma \times L_{eff} \quad (8)$$

Table 3.1 summarizes the regression coefficients for both horizontal and vertical polarisations used for the conversion process, as available from the literature (ITU-R 837-5, 2007). The rain attenuation values are measured and recorded in dB/km and the rainfall rate is measured in mm/h.

Table 1: Values of Constants "k" and "α"

Freq. (GHz)	$k_{Horizontal}$	$\alpha_{Horizontal}$	$k_{Vertical}$	$\alpha_{Vertical}$
12	0.0239	1.1825	0.0246	1.1216
14	0.0374	1.1396	0.0413	1.0646

RESULTS AND DISCUSSION

The computed point rainfall rate, $R_{0.01}$ is given in Table 2.

Table 2: Point Rainfall Rate for the Study Area

Locations	Abuja	Kaduna
$R_{0.01}$(mm/h)	95.90	107.01

The results in Table 2 show that higher rainfall rates at 0.01% exceedance was recorded in Kaduna than Abuja, implying that rain attenuation is likely to be more significant in Kaduna than in Abuja.

The results for the step by step computation of rain attenuation for the locations using the Lavergnat-Gole model are presented in Figures 3 - 4, that is, from the derivation of the specific attenuation to that of the effective path length.

Figure 3 illustrate the annually accumulated rainfall over the 3-year observation period. The study area experiences two distinct climatic seasons each year: the dry season, which extends from November till April, and the rainy season, occurring from May to October.

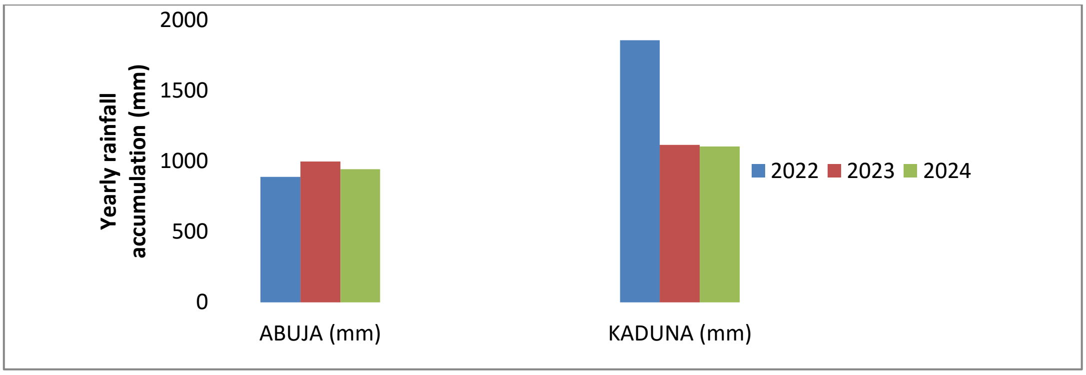

Figure 2: Annual rainfall accumulation (mm)

Figure 2 compares the yearly rainfall accumulation (in millimeters) for Abuja and Kaduna from 2022 to 2024. In Abuja, rainfall was relatively stable across the three years, with a slight increase from 2022 to 2023 and a small drop in 2024. In contrast, Kaduna experienced a much higher rainfall amount overall, with a peak in 2022 with a value of about 1900 mm followed by a significant decline in 2023 and 2024 with values of about 1120 mm and 1100 mm respectively, where rainfall levels were similar. This indicates greater year-to-year variability in Kaduna's rainfall compared to Abuja.

The analysis considered operating frequencies of 12 GHz and 14 GHz, which are commonly allocated for satellite communication systems, under both horizontal and vertical polarizations. Since the LG model is applicable to communication links with path lengths exceeding 1 km, this study examined path lengths ranging from 2 km to 20 km.

Figures 3 and 4 show rain-induced signal degradation experienced in Abuja and Kaduna respectively. From Figure 4, the attenuation values for Abuja at 12 GHz for horizontal polarisation are 10.54 dB, 26.32 dB, 52.55 dB, 78.71 dB and 104.79 dB for 2 km, 5 km, 10 km, 15 km and 20 km path-length respectively, while the values for vertical polarisation are 8.21 dB, 20.15 dB, 40.97 dB, 61.36 dB and 81.69 dB respectively for the same path-length. Similarly, the attenuation values for Kaduna at 12 GHz for horizontal polarisation are 11.99 dB, 29.96 dB, 59.84 dB, 89.64 dB and 119.36 dB for 2 km, 5 km, 10 km, 15 km and 20 km path-length respectively, while the values for vertical polarisation are 9.29 dB, 23.20 dB, 46.34 dB, 69.42 dB and 92.43 dB respectively for the same path-length.

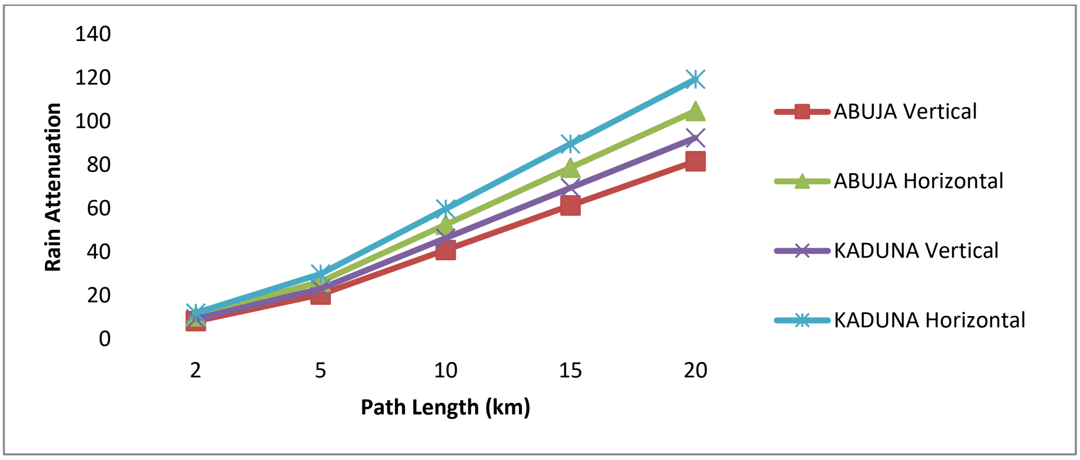

Figure 3: Rain attenuation at 12 GHz for the study area

At 14 GHz, the attenuation values for horizontal polarisations are 13.56 dB, 33.86 dB, 67.61 dB, 101.27 dB and 134.82 dB for 2 km, 5 km, 10 km, 15 km and 20 km respectively, while the vertical polarisation predicted attenuation values of 10.63 dB, 26.56 dB, 53.02 dB, 79.42 dB and 105.73 dB for the same path-length for Abuja, while the attenuation values for horizontal polarisation are 15.36 dB, 38.36 dB, 76.64 dB, 114.80 dB and 152.86 dB for 2 km, 5 km, 10 km, 15 km and 20 km respectively, while the vertical polarisation predicted attenuation values of 11.95 dB, 29.84 dB, 59.61 dB, 89.29 dB and 118.89 dB for the same path-length for Kaduna respectively as shown in Figure 5.

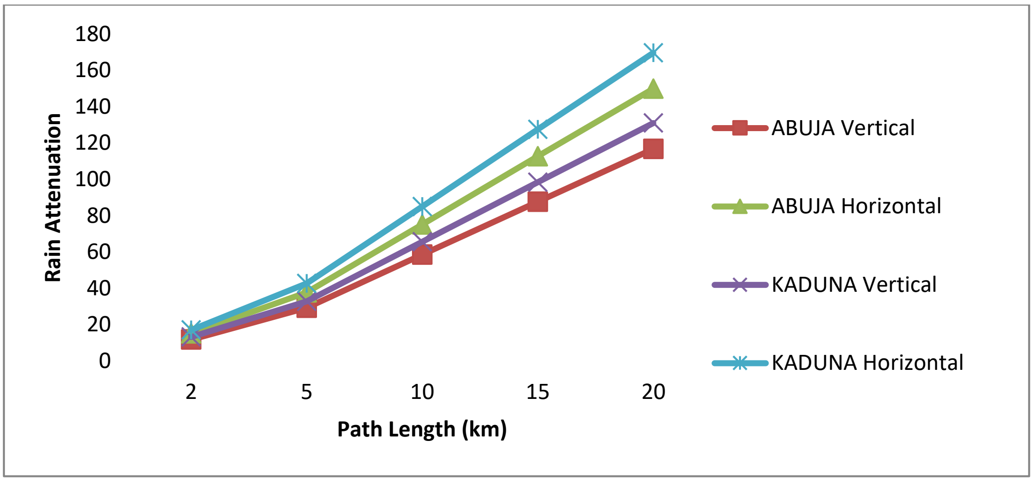

Figure 4: Rain attenuation at 14 GHz for the study area

The analysis show that the attenuation is influenced by the frequency, polarisation type and path length. The attenuation increases with increase in frequency and path-lengths. Above 2 km, there will be a significant decrease in the signal strength due to the high values of attenuation. Therefore, the output power of the transmitter has to be amplified to a value higher than the computed attenuations. The obtained results are very useful for both aviation and telecommunications systems.

CONCLUSION

Three years of rainfall data measured from 2022 to 2024 was used in this work and were from NiMET, the 1-minutes rain rate cumulative distribution function was used to predict rain induced attenuation for commercial satellite communication links for the study area. The measured rain rate at 0.01% of time exceedance is 95.90 mm/hr for Abuja and 107.01 mm/hr for Kaduna respectively. The investigation of rain attenuation at 0.01% of time exceedance was derived using LG model for horizontal and vertical polarisations at 12 GHz and 14 GHz (Ku-band) for 2km, 5 km, 10 km, 15 km and 20 km path-length for both studied area. The results show that the attenuation is influenced by the rain rate, frequency, polarisation type and path length. The results in this research will be useful for efficient and effective design of Direct-to-Home TV, VSAT networks and broadcast uplinks in the study area.

RECOMMENDATIONS

In both study areas, where intense seasonal rainfall (95.90 - 107.01 mm/h) causes significant rain-induced signal attenuation, reliable communication links should use higher fade margins, select more resilient frequency bands such as C- or Ku-band and apply adaptive techniques like power control and adaptive modulation to maintain link quality.

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