Nigerian Journal of Theoretical and Environmental Physics (NJTEP)
ISSN Print: 3026-9601
ISSN Online: 1597-9849
DOI: https://doi.org/10.62292/njtep.v4i1.2026.142
Volume 4(1), March 2026

Comparative Analysis of ITU-R P.618-14 and Ajayi-Olsen Models for Rain-Induced Signal Attenuation on Aviation Satellite Communication Links in Some Northern Nigeria

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Keywords:
Rain Attenuation,
ITU-R P.618-14,
Ajayi-Olsen Model,
Aviation Satellite Communication,
Northern Nigeria,
Ku-band,
Ka-band,
Tropical Propagation.

ABSTRACT

Rain-induced signal attenuation remains one of the most critical impairments affecting satellite communication links operating above 10 GHz in tropical environments. This study presents a comparative analysis of the ITU-R P.618-14 standard model and the Ajayi-Olsen tropical propagation model for predicting rain attenuation on aviation satellite communication links across four selected states in Northern Nigeria; Abuja/FCT, Kaduna, Jos/Plateau, and Sokoto. Five years of daily rainfall data (2021–2025) obtained from the Nigerian Meteorological Agency (NiMET) were fitted to a Gamma distribution to derive the 0.01% exceedance rain rate ($R_{0.01}$) for each station. Both models were applied at Ku-band (12 GHz) and Ka-band (30 GHz). Results reveal that $R_{0.01}$ values range from 1.827 mm/hr at Abuja to 4.415 mm/hr at Sokoto. The Ajayi-Olsen model consistently predicts 8–10% higher Ku-band attenuation than ITU-R P.618-14, confirming that the global model underestimates rain attenuation in Northern Nigeria. Ka-band attenuation $A_{0.01}$ ranges from 1.911 dB at Abuja to 4.330 dB at Sokoto under ITU-R predictions. A Ku-band correction factor of +10% to ITU-R predictions is recommended for aviation satellite link budget design across Northern Nigeria.

INTRODUCTION

Rain-induced signal attenuation is a dominant propagation impairment for satellite communication systems operating at frequencies above 10 GHz (Olsen et al., 1978). At Ku-band (12 GHz) and Ka-band (30 GHz), rain droplets absorb and scatter electromagnetic waves, reducing received signal power and degrading link quality (Ippolito, 2017). For aviation satellite communication systems which support critical air traffic control (ATC), Controller-Pilot Data Link Communications (CPDLC), real-time weather relay, and emergency coordination because reliable signal propagation is essential for flight safety (ICAO, 2023).

Nigeria's tropical climate is characterised by intense convective rainfall events that produce large raindrop size distributions (DSD), causing significantly higher attenuation than what temperate-climate-based ITU-R models predict (Ojo & Ajewole, 2008). The Ajayi-Olsen model was specifically calibrated for tropical West African rainfall characteristics and offers a more regionally appropriate prediction framework (Ajayi & Ofoche, 1983). Despite the strategic importance of Northern Nigeria's aviation infrastructure, no dedicated study has characterised rain attenuation on aviation SATCOM links across the four stations selected for this study spanning Guinea Savannah (Abuja), Sudan Savannah (Kaduna), Highland Plateau (Jos), and Sahel Semi-arid (Sokoto) climatic zones.

This paper addresses this gap by conducting a systematic comparative analysis of ITU-R P.618-14 and Ajayi-Olsen model predictions for Ku-band and Ka-band rain attenuation across these four stations using five years of NiMET rainfall data (2021–2025). The study: (i) derives $R_{0.01}$ using Gamma distribution fitting; (ii) computes rain attenuation at Ku-band and Ka-band using both models; and (iii) quantifies the model discrepancy and its implications for aviation satellite link budget design in Northern Nigeria.

MATERIALS AND METHODS

Study Area

The study covers four stations in Northern Nigeria selected to represent the dominant climatic zones of the region. Table 1 presents the geographic and station parameters. Abuja/FCT lies within the Guinea Savannah zone with moderate rainfall intensities. Kaduna occupies the Sudan Savannah transition zone with a shorter but more intense wet season. Jos/Plateau is located at high altitude (1,280 m a.s.l.) with orographic rainfall. Sokoto is situated in the Sahel Semi-arid zone, characterised by very low annual totals but intense short-duration convective storms that produce disproportionately high rainfall rates.

Table 1: Geographic and Satellite Link Parameters for Selected Stations

Parameter	Abuja/FCT	Kaduna	Jos/Plateau	Sokoto	Unit
Latitude	8.90°N	10.52°N	9.87°N	13.07°N	°N
Longitude	7.37°E	7.44°E	8.90°E	5.24°E	°E
Altitude	342	645	1,280	278	m a.s.l.
Elevation Angle (θ)	42.1°	41.8°	38.4°	37.2°	degrees
Climatic Zone	Guinea Savannah	Sudan Savannah	Highland Plateau	Sahel Semiarid	—

Rainfall Data

Daily rainfall data for the period 2021–2025 were obtained from the Nigerian Meteorological Agency (NiMET) for all four stations, measured using calibrated tipping-bucket rain gauges at Automatic Weather Observation Systems (AWOS). The dataset spans five complete years providing 1,826 daily observations per station. The year 2022 recorded exceptionally high rainfall across Northern Nigeria consistent with documented flooding events attributed to intense convective activity (NEMA, 2022) which is clearly reflected in the elevated $R_{0.01}$ values for that year.

Method

R0.01 Derivation Using Gamma Distribution

The 0.01% exceedance rainfall rate $R_{0.01}$ represents the rainfall rate (mm/hr) exceeded for 0.01% of the time (99.99th percentile). Daily NiMET data were fitted to a two-parameter Gamma probability distribution using maximum likelihood estimation (MLE). The Gamma probability density function is:

$$f(x;\alpha,\beta) = \beta^{\alpha}/\tau(\alpha)x^{\alpha-1}e^{-\beta x} \quad (1)$$

Where x is rainfall rate (mm/hr), α is the shape parameter, β is the scale parameter, and Γ (α) is the Gamma function. The fitted distribution was extrapolated to the 99.99th percentile to yield $R_{0.01}$ per station per year. The five-year mean $R_{0.01}$ was used as the representative rain rate in all model comparisons.

ITU-R P.618-14 Attenuation Model

The ITU-R P.618-14 recommendation (International Telecommunication Union [ITU-R], 2021) computes specific attenuation γ_R (dB/km) using the power-law relationship:

$$\gamma_R = K(R_{0.01})^{\alpha} \quad (2)$$

Where k and α are frequency-dependent coefficients from ITU-R P.838-3 (ITU-R, 2022). For Ku-band (12 GHz): k = 0.0188, α = 1.217; for Ka-band (30 GHz): k = 0.187, α = 1.021. Total path attenuation $A_{0.01}$ (dB) is:

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

Where L_E is the effective path length (km) through the rain layer, computed from the slant path geometry, rain height from ITU-R P.839-4 (ITU-R, 2013), station altitude, and elevation angle θ.

Ajayi-Olsen Tropical Propagation Model

The Ajayi-Olsen model (Ajayi & Ofoche, 1983) was developed from tropical rainfall measurements in West Africa with empirically derived coefficients calibrated for the higher proportion of large raindrops characteristic of Nigerian convective precipitation. The model follows the same power-law form as ITU-R but applies regionally calibrated coefficients k_{AO} and α_{AO} that better represent the tropical Nigerian DSD environment (Ajayi & Ofoche, 1983; Ajayi et al., 1996). All computations and graphs were produced using Python (NumPy for numerical calculations, Matplotlib for graphical output).

RESULTS AND DISCUSSION

Rainfall Characterization and R0.01 Derivation

Table 2 presents the annual and five-year mean $R_{0.01}$ values derived from the Gamma distribution fit for all four stations. Sokoto consistently records the highest $R_{0.01}$ across all five years with a five-year mean of 4.415 mm/hr, despite having the lowest annual rainfall total. This reflects the Sahelian regime of intense short-duration convective storms (Panagopoulos et al., 2004). The year 2022 produced the highest $R_{0.01}$ across all stations, consistent with the severe flooding events documented by NEMA across Northern Nigeria (NEMA, 2022). Abuja records the lowest five-year mean $R_{0.01}$ at 1.827 mm/hr.

Table 2: Annual and Five-Year Mean R0.01 Values (mm/hr) All Stations (2021–2025)

Station	2021	2022	2023	2024	2025	5-yr Mean
Abuja/FCT	1.642	1.872	2.616	1.803	1.203	1.827
Jos/Plateau	2.114	2.850	3.200	2.500	2.217	2.576
Kaduna	2.890	4.187	2.760	3.001	2.443	3.056
Sokoto	3.710	5.165	4.370	4.990	3.840	4.415

ITU-R P.618-14 Ka-band Attenuation Results

Figure 1 presents the annual Ka-band rain attenuation $A_{0.01}$ predicted by ITU-R P.618-14. Sokoto records the highest Ka-band attenuation with a five-year mean of 4.330 dB and a peak of 5.10 dB in 2022. Abuja records the lowest at 1.911 dB. All four stations remain below the standard Ka-band lower fade margin of 8 dB, confirming Ka-band technical feasibility across Northern Nigeria under typical rainfall conditions. The 2022 anomaly is clearly visible across all stations, validating the extreme rainfall event identified in Table 2.

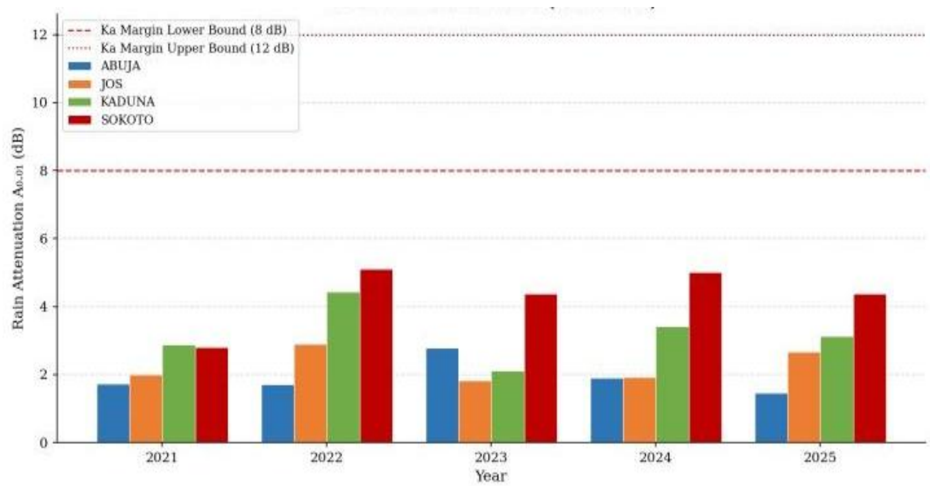

Figure 1: Annual Ka-band rain attenuation A0.01 (dB) predicted by ITU-R P.618-14 for all four stations (2021–2025). Dashed line = Ka lower fade margin (8 dB); dotted line = upper margin (12 dB)

ITU-R P.618-14 Ku-band Attenuation Results

Table 3 summarises the five-year mean Ku-band attenuation predicted by ITU-R P.618-14. Ku-band $A_{0.01}$ values range from 0.255 dB at Abuja to 0.670 dB at Sokoto approximately one order of magnitude lower than the corresponding Ka-band values, well below the Ku-band lower fade margin of 3 dB. A strong positive linear correlation between $R_{0.01}$ and $A_{0.01}$ (Pearson $r > 0.95$) confirms the validity of the power-law relationship at both frequency bands.

Ajayi-Olsen vs ITU-R Model Comparison

Figure 2 presents the annual comparison of ITU-R P.618-14 and Ajayi-Olsen predictions for both Ku-band and Ka-band at all four stations across 2021–2025. Figure 3 shows the five-year mean side-by-side comparison across all stations. Table 3 presents the complete quantitative comparison. The Ajayi-Olsen model consistently predicts higher attenuation than ITU-R P.618-14 at all stations and in all years.

For Ku-band, the model discrepancy ranges from 8% to 10%, with the highest discrepancy at Sokoto (five-year mean difference: 0.065 dB; percentage difference: 9.7%). For Ka-band, the discrepancy is smaller at 1–5%, because the Ka-band ITU-R regression coefficients are already more sensitive to large raindrop sizes. This systematic Ku-band underestimation by ITU-R is physically explained by the higher proportion of large drops in Nigerian tropical convective rain, a characteristic captured by the Ajayi-Olsen tropical coefficients but not fully accounted for in the ITU-R global model (Ajayi & Ofoche, 1983; Mandeep et al., 2018). This finding is consistent with previous studies in southern Nigeria (Nwafor et al., 2018; Adediji et al., 2017) and extends the evidence base to Northern Nigeria for the first time.

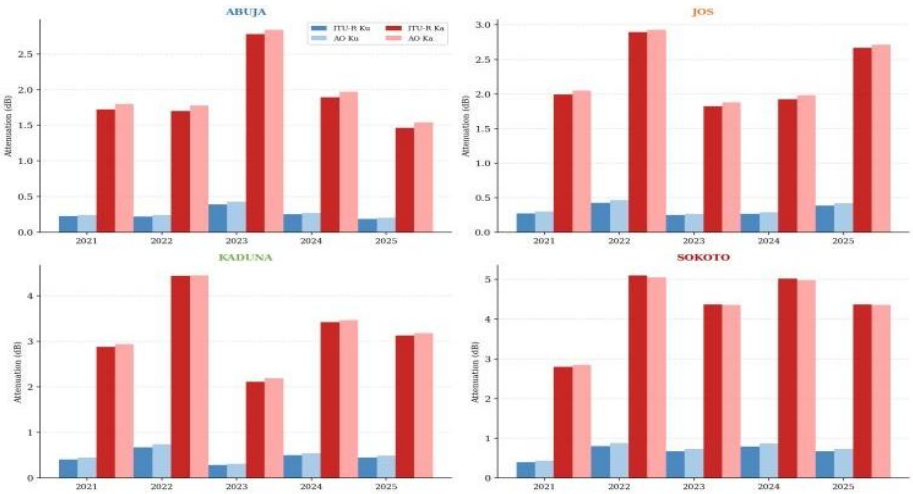

Figure 2: Annual ITU-R P.618-14 vs Ajayi-Olsen model comparison between Ku-band and Ka-band attenuation (dB) at all four stations (2021–2025). Dark bars = ITU-R; light bars = Ajayi-Olsen

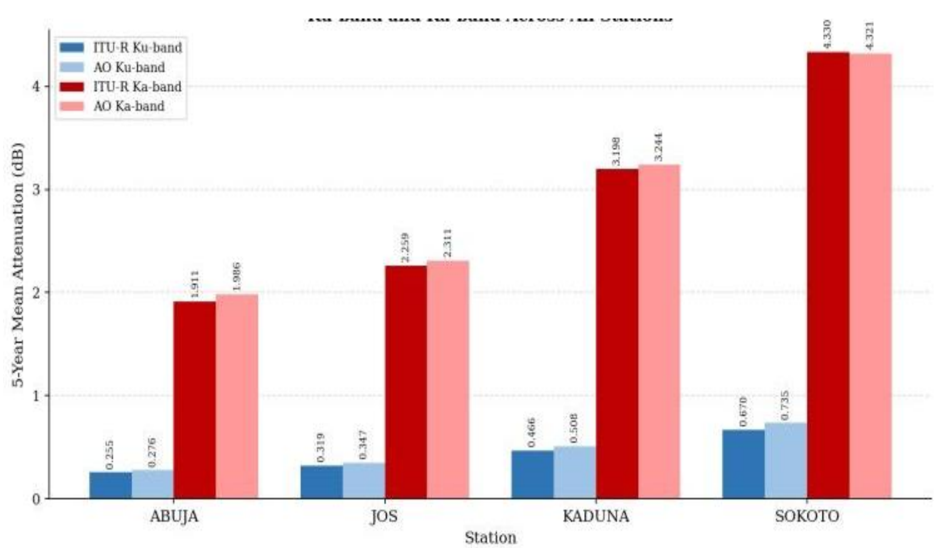

Figure 3: Five-year mean ITU-R P.618-14 vs Ajayi-Olsen rain attenuation comparison Ku-band and Ka-band across all four stations. Values in dB

Table 3: Five-Year Mean ITU-R P.618-14 and Ajayi-Olsen Rain Attenuation (dB) All Stations and Frequency Bands

Model / Band	Abuja (dB)	Jos (dB)	Kaduna (dB)	Sokoto (dB)	Mean Diff. (dB)	% Difference
ITU-R Ku-band	0.255	0.319	0.466	0.670	—	—
AO Ku-band	0.276	0.347	0.508	0.735	0.043	8.7 – 9.7%
ITU-R Ka-band	1.911	2.259	3.198	4.330	—	—
AO Ka-band	1.986	2.311	3.244	4.321	0.029	1.4 – 3.9%

Discussion

Three important implications arise from these results. First, the ITU-R P.618-14 model underestimates Ku-band rain attenuation in Northern Nigeria by 8–10%. Link budget engineers should apply a +10% correction factor to ITU-R Ku-band attenuation predictions for aviation SATCOM link design at all four study stations. Second, Sokoto presents the most challenging propagation environment despite being in the driest climatic zone annual rainfall total is a poor predictor of link impairment. What determines satellite link degradation is $R_{0.01}$, and Sokoto's intense convective storm characteristics produce higher extreme rain rates than its wetter neighbouring stations. Third, the smaller

Ka-band discrepancy (1–5%) compared to Ku-band (8–10%) reflects the greater sensitivity of Ka-band ITU-R coefficients to large drop sizes, partially closing the gap with the Ajayi-Olsen model. Nonetheless, the Ajayi-Olsen model remains the recommended choice at both frequency bands for precision link budget design in Northern Nigeria.

It is important to note that the $R_{0.01}$ values derived in this study are based on daily NiMET rainfall accumulation data converted using Gamma distribution fitting, rather than the 1-minute integrated rainfall rates specified by ITU-R P.837. This approach was necessitated by the unavailability of 1-minute resolution rainfall data for the study stations. As a consequence, the derived $R_{0.01}$ values (1.827–4.415 mm/hr) are expected to be conservative underestimates of the true 1-minute $R_{0.01}$, which existing literature suggests may range from 40–80 mm/hr for comparable Nigerian locations. The attenuation values predicted in this study should therefore be interpreted as lower-bound estimates, and future work using 1-minute resolution data is recommended to provide more precise link budget inputs for Northern Nigerian aviation SATCOM design.

CONCLUSION

This study has presented the first comparative analysis of ITU-R P.618-14 and Ajayi-Olsen rain attenuation model predictions for aviation satellite communication links across four climatically distinct stations in Northern Nigeria. The following conclusions are drawn:

R0.01 values range from 1.827 mm/hr (Abuja) to 4.415 mm/hr (Sokoto); despite recording the lowest annual rainfall, Sokoto produces the highest R0.01, reflecting the intense convective storm characteristics of the Sahelian climate. ITU-R P.618-14 Ka-band attenuation ranges from 1.911 dB (Abuja) to 4.330 dB (Sokoto), all below the 8 dB lower aviation fade margin, confirming Ka-band technical feasibility with adequate link budget planning. The Ajayi-Olsen model consistently predicts 8–10% higher Ku-band attenuation than ITU-R P.618-14 at all stations and in all years, confirming systematic ITU-R underestimation under Northern Nigerian tropical conditions, while the Ka-band discrepancy is smaller at 1–5%. A Ku-band correction factor of +10% to ITU-R P.618-14 predictions is recommended for aviation satellite link budget design at all four study stations in Northern Nigeria, and the Ajayi-Olsen model is the recommended propagation prediction tool for precision aviation SATCOM link design in Northern Nigeria at both Ku-band and Ka-band frequencies. These findings provide the first localised propagation database for aviation SATCOM system design in Northern Nigeria and contribute an important correction to the application of global ITU-R models in West African tropical and Sahelian environments.

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