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# Comparative Analysis of Rain–Induced Attenuation Models Over Some Selected Nigerian Cities

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**Abstract:** The fair investigation carried out on rain-induced attenuation at 12.245-GHz over three selected Nigerian cities was carried out in this study. For this work, a time series of rain-induced attenuation at the 12.45 GHz based on 1-minute-rain rate measurements was obtained for -LAUTECH-Ogbomosho, ESUT-Enugu, and FUGUS-Zamfara, respectively in the South West, South East and North Eastern Nigeria over a three-year period (2017–2020). The Received Signal Level (RSL) and rain intensity measurements were sampled at intervals of 10 seconds and integrated over a period of 1 minute. A performance analysis established on the collective allocation of rain rate along with the collective allocation of rain-induced attenuation gotten was reported and compared with some existing rain attenuation models (Garcia Lopez, SAM, Moupfouma and ITU-R models). Attenuation caused by rain as predicted based on the ITU-R and SAM resulted in a clear variation from the measured values by 14%, while the Moupfouma model provides a better fit to the actual attenuation data and then followed by the Garcia Lopez model. The results of this study may be used for planning similar links at the choice frequency band over the locations of interest.

**Keywords:** Attenuation, Rain-rate, Communication, Received Signal Loss, Prediction Model

## I. Introduction

Signal degradation is most influenced by rain attenuation, particularly at higher frequencies (12.245 GHz). At these high frequencies, large attenuation occurs due to absorption and scattering of the signals along the satellite-earth links. [1], [2], [3]. Therefore, thorough information on the propagation phenomena affecting signal availability in these bands is necessary. Even though, many researchers have documented the theoretical and empirical studies of rain attenuation; however, there is insufficient rain data with respect to the direct measured attenuation to deduce the link within the respective spot beam. [4]. Hence, the scarcity of rain attenuation data at some selected cities are supposed to be improved with the data generated through prediction methods at locations of interest [4], [5]. It is unfortunate that most studies were carried out in temperate regions where beacon measurements were provided by satellites [6]. Thus, in comparison, tropical regions lag behind when it comes to studies on the attenuation prediction model.

Additionally, earlier methods were mostly based on semi-empirical processes in which the rate of rainfall at some point on the earth facet is either statistically linked to the attenuation along the satellite path or the real distance of the rain channel is modified such that the effective distance established over the rain can be uniform [6], [7], [8]. Rain attenuation model in the tropics is important because rain in the tropics is usually from convective rain cells with associated small

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diameters, which is different from temperate regions usually of stratiform type i.e very light with associated large rain cell diameters [9]-[11] and usually end with very heavy downpours for a shorter period of time. Globally, precipitation is characterized by a combination of the two main types (stratiform and convective), although, the rain structure of a region could be affected by the frequency [12], [13]. [14] carried out research and presented results on 1-minute rain rate statistics required for satellite and terrestrial link designs, the drawback being that the data used was only based on a location in the South West, Nigeria and rain attenuation was not considered. The dynamical model for deriving 1-minute rain rate based on different integration time in Akure, Nigeria was also carried out; and although 3-year data was used, only one location was considered and rain attenuation was not considered.

In [15], an experimental analysis and comparison of clear-air scintillation prediction using EUTELSAT-36B Ku-band Satellite measurements in the tropical climate of Nigeria was carried out. But in this case, only one location was considered and clear air scintillation alone was investigated.

However, in this study, we set out to analyze the performance of the outcomes of rain rate and rain-induced attenuation on the 12.245-GHz satellite link over some selected sites in Nigeria which is in a tropical region and compare with some of the available models for the region, and therefrom propose a model that is most suitable for use in these selected cities in Nigeria.

The remainder of this paper is organized as follows: Section Two gives the methodology adopted, while Section Three gives the results and discussion. The concluding notes are finally presented in Section Four.

## II. Materials and Methods

The experimental sites cover three different locations in Nigeria namely: Department of Physics, Ladoke Akintola University (LAUTECH), Ogbomosho, Department of Physics, Enugu State University of Science and Technology (ESUT) Enugu and, Department of Physics, Federal University Gosau (FUGUS), Zamfara State. LAUTECH, Ogbomosho (7°17'N, 5°18'E) is located in the rain forest region, South west of Nigeria, ESUT, Enugu (07.27° N 06.25° E) is located in the Guinea Savannah of Nigeria, while FUGUS, Zamfara (12.10° N, 06.15° E) is sited in the Sudan Savannah part of Nigeria. Table.1 presents the characteristics of the experimental sites as well as the parameters for the satellite set-up and each of the location of the earth stations.

The beacon receiver antennas are directed towards EutelSat; W4/W7 located at 70.1◦ E for LAUTECH, at 72.5◦ for ESUT, and at 69.9◦ for FUGUS. The EutelSat; W4/W7 36.0E is a highly reliable satellite with a transponder RF output power of -81 dBμV at Ku-Band frequencies needed for the direct-to home services. Enugu is located in a tropical rain forest zone with a derived savannah. The city has a tropical savanna climate (Köppen: Aw). Enugu's climate is humid and this humidity is at its highest between March and November. For the whole of Enugu State, the mean daily temperature is 26.7 °C (80.1 °F).

Gusau located in the North western Nigeria, is the capital of Zamfara State, the wet season is oppressive and mostly cloudy, the dry season is partly cloudy, and it is hot year round. Over the course of the year, the temperature typically varies from 58°F to 100°F and is rarely below 54°F or above 105°F.Latitude: 12.1667, Longitude: 6.66667 12° 10' 0'' North, 6° 40' 0'' East Tropical savanna climate (Köppen climate classification: Aw).

In order to receive an intermediate frequency (IF: 950 kHz to 2150 kHz) signals from a low noise block (LNB), a SATLINK meter was used to connect to a dish placed at an elevation of 42°E. The dish receives signals from the EUTELSAT W4/W7 satellite at an orbital location of 36.0E longitude at a frequency of 12.245 GHz. The IF is supplied into a spectrum analyzer, decoder and a computer. The spectrum analyzer was used to record samples of viewed spectrum over finite periods of time. The data of the received signal are sampled at every 1- minute. The dynamic range of attenuation of the measurement is approximately 20 dB below the clear sky level.

The transmitted signal from an operational transponder was taken by a beacon measurement. The received antenna orientation was horizontal polarization. The signal output of the dish LNB was connected to a data logger via a computer system at ESUT and FUGUS, while in LAUTECH, it was linked to a spectrum analyzer, which was interfaced to a computer through a software-LabVIEW interfacing card. In all the locations, the software was used to programme and record the peaks of sixty consecutive samples each at 1-minute duration and also to combine the mean of these sixty peak values. These samples were iterated each 10 s producing six averaged peak values in a minute. In order to explain the difference in the satellite signal strength due to orbital differences, the average clear day signal strengths on the day before and after the rainy day(s) were used in the computation of the rain attenuation.

Rainfall parameters were recorded using the Integrated Sensor Suite (ISS) automatic weather station in all the sites with associated traditional rain gauge (tipping bucket) display of 20 cm width with mark on scale of 0.2 mm of rainfall per tip. The tipping bucket is a rapid response type, and the spool works as the capacitance of an oscillator whose frequency varies as a function of the water level in the spool. This can measure rainfall rates between 0.8 mm/h and 500 mm/h, with an exact value of 0.2 mm/h. Technically, the console receiver with a data logger is connected to a PC to harvest the data daily to;

Table 1. Sites Measurement Characteristics

| Site Measurement | LAUTECH/Ogbomosho | ESUT/Enugu | FUGUS/Zamfara |
|---|---|---|---|
| Earth station location | 7°17'N, 5°18'E | 07.27 ° N 06.25 ° E | 12.10° N, 06.15° E |
| Altitude to sea level (m) | 358 | 223 | 481 |
| Climatic region | Rain forest | Guinea Savannah | Sudan Savannah |
| Satellite Name | EutelSat; W4/W7 | EutelSat; W4/W7 | EutelSat; W4/W7 |
| Beacon frequency (GHz) | 12.245 GHz (H) | 12.245 GHz (H) | 12.245 GHz (H) |
| Signal rate | 27,509 bps | 27,509 bps | 27,509 bps |
| Satellite elevation (Orbital) | 036 E | 036 E | 036 E |
| Elevation angle (Degree) | 70.1 | 72.5 | 69.9 |
| Sampling time | 10 secs | 10 secs | 10 secs |
| Transponder power | -81 dBμV | -81 dBμV | -81 dBμV |
| Antenna diameter | 90 cm | 90 cm | 90 cm |
| Rain Equipment | Automatic Weather Station | Automatic Weather Station | Automatic Weather Station |
| Integration time of Gauge | 1-minute | 1-minute | 1-minute |

prevent data loss, data loss due to technicalities of data harvesting is less than 1% with the availability of about ninety – nine percent of the overall inspection time. Moreso, the remaining 1% of absence (around 7.2916667 days in 2 years) is created by 75 squelching cases, which occurs in less than an hour, and the equipment's was out of function all through, probably because of the power outage and equipment standardization.

The rain apparatus and beacon receiver were used for the heavy rain event. The squelching is the total signal outage and it measures the average outages of the three locations. Daily rain rate data measured in millimetres per hour and recorded at every 1 minute (integration time) from the three sites are processed separately. Firstly, for each location, daily data observed for the rainy days were sorted out alongside rain-induced attenuation. Non-rainy days were filtered out of the data. The collected data were pre-processed in which the beacon data and the meteorological data were synchronized and given common time stamps. Data reduction has been done by removing partially missing and erroneous data. The instrumental drifts were removed and the attenuation reference level was evaluated using complementary measurement using the spectrum analyzer. The fair atmosphere condition of the beacon data was described from the data before and after rainy days using the averaging method.

The dynamic range of attenuation, A(t) is calculated from measured data using:

$$A(t)(dB) = RSL_{\text{clear sky}} - RSL_{\text{rainy}} \qquad (1)$$

where A (t) is the Attenuation in dB and RSL is Received Signal Loss.

The resultant attenuation is defined by the variation in the RSL when the sky is clear and the RSL when it is raining. Secondly, each of the data sets (attenuation and rain rate), are classified in a class bin (for example, rain rate 0-2 mm/hr or attenuation 0-2 dB) to obtain the number of occurrences throughout the study period. Thirdly, the cumulative distribution of each of the rain rates and rain attenuation is obtained for further analysis.

Analysis of rain and rain fade characteristics based on the 3-year measurements at the three sites were based on First-order statistics while dynamical characterization of rain attenuation in terms of fade duration, fade slope and inter-fade duration based on Second-order statistics. Further characterization based on seasonal and daylight differences of rain rate and rain attenuation on the measured values were carried. In contrast, the measured and predicted values of rain attenuation was finally carried out. The attenuation models considered are ITU-R 618-15, Moupfouma attenuation model, Simple Attenuation Model and Garcia-Lopez model. Details of attenuation models used are not repeated because of space; however, it can be seen in the literatures cited.

## III. Results and Discussion

In this section, the annual distribution of rainfall over the study locations, characterization of measured rain intensities (time series analyses, annual distribution, and comparison of measured rain rate with ITU model) characterization of measured rain-induced attenuation (time series analyses, analyses of power spectra, seasonal and annual variation of rain attenuation distribution), comparison of rain attenuation with existing rain attenuation models, ITU and analyses of fade durations are discussed.

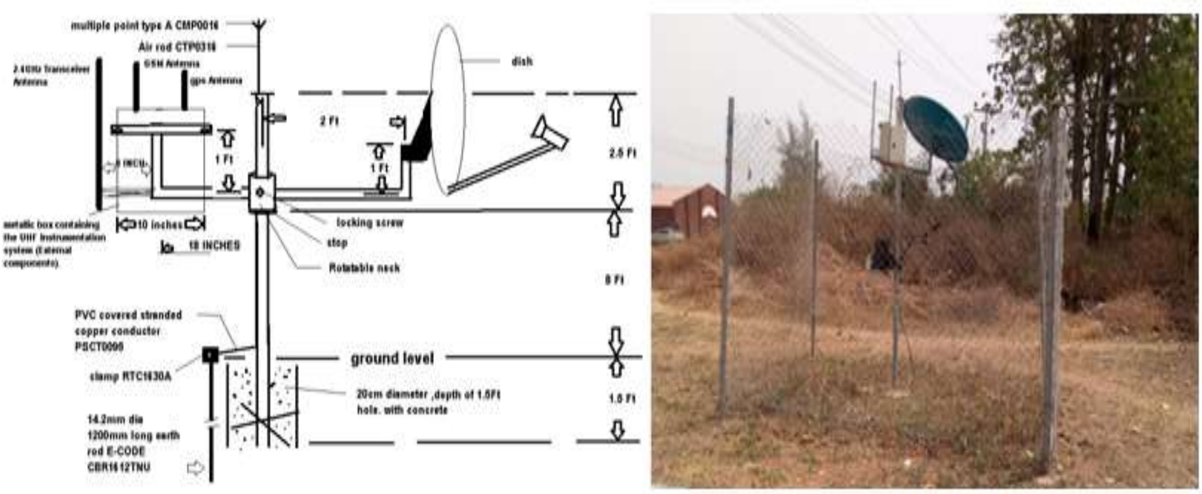


Figure 1. The schematic configuration of the experimental set up at the LAUTECH site

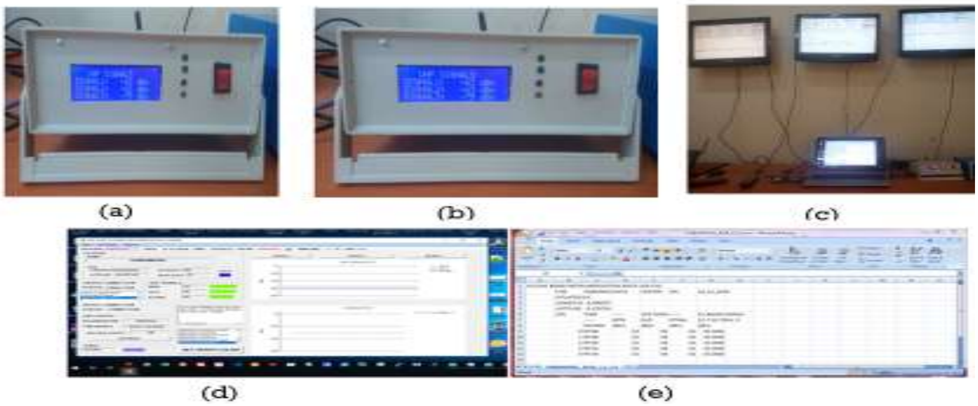


Figure 2. Typical experimental setup for beacon attenuation measurements at LAUTECH (a) Ku Fabricated Unit (b) UHF Fabricated Unit (c) Screen view of system activities (d) Locations activities viewing page and (e) Ku and UHF data logging Script.

### A. Rainfall Accumulation and Rain Rate

The average monthly rainfall accumulation for the time of measurement in the study locations is illustrated in Figure 3. It is observed in Figure 3 that ESUT, Enugu recorded more rainfall accumulation when compared with the other locations; however, LAUTECH, Ogbomoso followed as typical of a tropical rain forest climate. Figure 3 further shows that July had the highest accumulation of about 434 mm at ESUT, followed by June and September with rainfall accumulation of about 408 mm and 404 mm respectively at the same location. Rainfall tends to be frequent at ESUT even during the dry season, although with minimal occurrence, while FUGUS, Zamfara recorded little or no rain throughout the dry season. However, rainfall started improving from May with the peak occurrence in August as typical of the Sudan Savannah climate. Thus, the rainy months (for ESUT and LAUTECH) including June through September need to be subjected to further analysis in order to select the worst months in Enugu.

The increasing allocations of rain rate at measured locations are shown in Figure 4. The rain rate values are almost the same from 10% to 1% percentage of time at the three measurement locations. The rain rate varies from 0.1% to 0.001% percentage of time in ESUT when compared with the other two locations (LAUTECH and FUGUS). This is because of the intensity of rain at ESUT followed immediately by LAUTECH. At the other locations of this study excluding FUGUS, rain rate measurements are usually convective in nature. Thus, indicating slight disparity in the rain rate values for a greater percentage of time (10 and 1%) for the three sites. Generally, the overrun trends as illustrated in Figure 4 indicates the upsurge in rain rate, the trend of the slope curve slowly reduces from a large negative value. When rain structure is stratiform especially at higher time percentages, rainfall type is prevalent with slight rain rates. The convective nature at lower time percentages is typical of tropics' nature of rain, where the water droplets in the cloud are vertically conveyed to enhance the mixture of water particles and thereby transforming into convective heavy rainfall. Hence, there is always transformation from the stratiform rain at slight rain rate to the convective at relatively intense rain rates.

### A. Comparison of Prediction Models

The measured rain attenuation for the cumulative distribution was likened to the three tropical regions for the prediction models as stated in Section 2 and Figures 5 (a) to 5(c) show the differences. The ITU-R model reduces the measured rain attenuation values at ESUT site at percentage of time between 0.1 and 0.01% where rain attenuation is exceeded, but overestimated LAUTECH and FUGUS location during the percentage of time when rain attenuation is exceeded. The Moupfouma model follows closely the measured rain attenuation values for all the measurement locations during the whole percentage of time when the rain attenuation is exceeded.

The model was created based on data from the tropical region and so accommodates a margin error in the estimate of the rain cell diameters in the tropics. The Garcia Lopez follows after the Moupfouma model, although the model was created based on slight rain rate intensity of about 60 mm/hr, the model is found applicable especially at FUGUS site with averagely low rain rates.

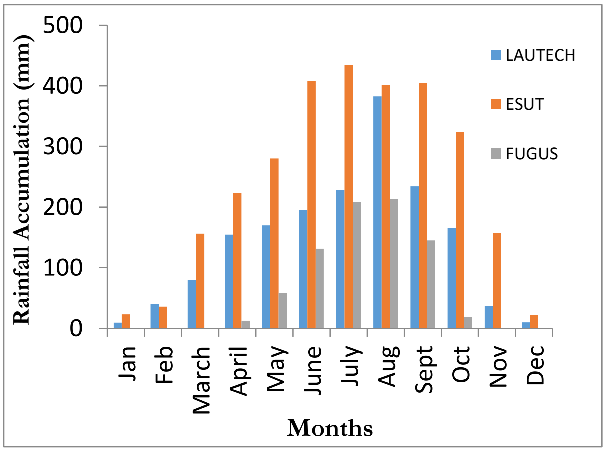


Figure 3: Average monthly rainfall accumulation during the observation time

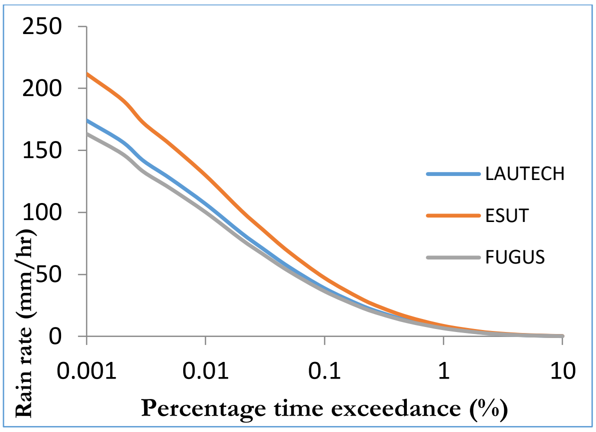


Figure 4: Cumulative distribution of rain rate at the measured location

This is a reason the model underrates the measured rain attenuation at a percentage less than 0.01% at ESUT site with relatively high rain rates. Generally, the ITU-R and SAM rain-induced attenuation prediction models showed clear change to the measured values higher than 14%, while Moupfouma model was a better fit to the actual rain-induced attenuation data follow by the Garcia Lopez model. Table 2 presents the summary of how the models performed based on the measured rain attenuation. The prediction has been based on Average relative Error (AE), Root Mean Square Error (RMSE), and CHI at 0.01% of time where rain attenuation is exceeded. The average error test is the test prescribed by ITU-R for testing prediction errors and is expressed as the percentage variation between the measured value and the predicted value (ITU-R P 311-17, 2019). Mathematically, it is expressed as:

$$\text{Average error } (AE) = \frac{(Measured - Predicted\,)}{Measured} \times 100\% \quad (2)$$

The RMSE represents the correction value that must be added to (or subtracted from) the predicted, it is given as:

$$RMSE = \sqrt{\frac{1}{N}\sum\{Measured\ - Predicted\,\}^2} \quad (3)$$

The CHI is a stability that evaluates how suitable the model is for predicting the data. It can be expressed as:

$$CHI = \frac{1}{N}\sum\left\{\frac{(Measured - Predicted\,)}{Measured\ Value}\right\}^2 \quad (4)$$

The ITU-R and SAM rain attenuation models show higher values. Conversely, the Moupfouma model shows fairly lower RMSE values which are supported by lower values of CHI and AE. Garcia Lopez follows suit to the Moupfouma model.

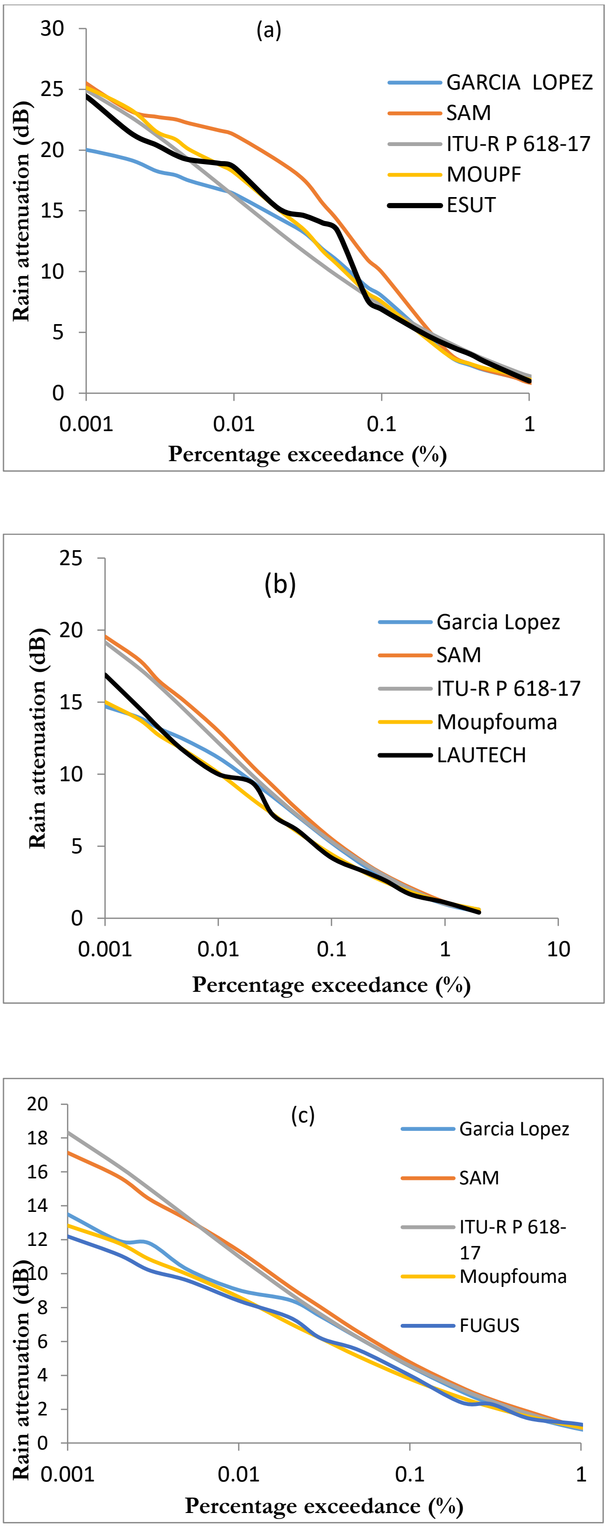


Figure 5: Comparison of measured and predicted attenuation distributions at the three locations

Table 2: Summary of the Performance of the Models Based on the Measured Rain Attenuation

| Rain Attenuation Models | ESUT | | | LAUTECH | | | FUGUS | | |
|---|---|---|---|---|---|---|---|---|---|
| | RMSE | CHI | AE | RMSE | CHI | AE | RMSE | CHI | AE |
| ITU-R | 2.85 | 2.69 | 0.38 | 6.2 | 9.28 | 0.62 | 8.15 | 10.12 | 0.62 |
| SAM | 8.78 | 9.65 | 0.68 | 7.55 | 10.24 | 0.72 | 8.45 | 11.24 | 0.76 |
| MOUPFOUMA | 1.12 | 1.27 | 0.25 | 1.07 | 0.98 | 0.19 | 0.98 | 1.45 | 0.24 |
| GARCIA LOPEZ | 3.02 | 3.29 | 0.011 | 1.6 | 1.31 | 0.22 | 1.12 | 1.89 | 0.3 |

## IV. Conclusion

One minute rainfall rates and rain-induced attenuation were measured concurrently at three locations in Nigeria with the objective of recommending a suitable model for predicting rain attenuation and link performance along Earth-space paths propagation path across the three selected climatic regions in Nigeria. Generally, the study was set up to authenticate the validity of theoretical predictions with experimentally derived results in Nigeria, so that system designers can provide adequate outage margins for telecommunication systems operating in the region. The improvement in the quality of the database is not only in the collection of rainfall data of one minute integration time but also in the concurrent measurements of beacon signal performance of the Earth-satellite link.

Understanding the dynamic properties of rain attenuation is important for designing effective mitigation methods. This report also presented estimates of the fade duration and fade slope derived from satellite beacon data at frequencies of 12.245 GHz in the selected regions.

The overall results from this study will serve as useful input for satellite system managers and planners for site diversity and other fade mitigation techniques. The major findings are as follows:

i. ESUT maintains the maximum mean annual rainfall followed by LAUTECH with an annual mean rainfall of about 385 mm in August. FUGUS continue to receive minimum rainfall all through the period of study with no rainfall throughout the dry season. Generally, the period of intense rainy months including June through September; these months are needed to be subjected to further analysis in order to select the worst months in the studied locations.

ii. Based on the time series analysis of rain rate over the study locations, ESUT experiences more rain intensities than LAUTECH; however, the possibility of frequent signal outages is possible in LAUTECH than ESUT.

iii. The cumulative distribution of rain rate over the studied locations show that for every 52 minutes of the year (0.01%), rainfall intensities were above 129 mm/h, 107 mm/hr, and 100 mm/h, for ESUT, LAUTECH and FUGUS respectively – signifying the fact that the three locations and by extension the entire country experience intense rainfall which have a huge adverse impact on the propagation of radio waves above 10 GHz.

iv. Comparisons of measured rain rate with ITU rain rate model over the study locations show that an underestimated rainfall intensity of 95 mm/h was predicted for LAUTECH at 0.01%

exceedance as against the measured rain rate of about 106 mm/h, while ESUT presented results that agree with ITU-R rain model at higher time percentages up to 0.1% but overestimated at lower time percentages with an average prediction error increasingly below 12%. The result from FUGUS follows the same pattern as that of LAUTECH with the percentage deviation up to about 10%.

v. On the time series analysis of measured rain rate and rain attenuation, it is generally observed that the variation of the rainfall intensity during the rain event follows the negative exponential characteristics, while the variation of attenuation indicates squelching of signals for rain rates sometimes at low intensities of 10 mm/h. Hence, implementing a fixed fade margin may not offer the desired QoS and availability to users. It is therefore needful to design and implement efficient modulation schemes such as the adaptive coding and modulation (ACM) for fade mitigation, for each of the locations. Such an ACM scheme would a clear sky.

vi. Analysis of time-series power spectral density shows the effect of both rain attenuation and scintillation, however with many effects of attenuation. Specific results show that rain attenuation has a -20 dB/decade slope up to 0.01-0.03 Hz, followed by typical tropospheric scintillation first at O dB/decade then a -60/3 dB/decade slope at FUGUS, while it is slightly different for LAUTECH when the power spectral density of the received signal for a rainfall events of almost five-and-half hours duration only illustrates the effect of rain up to 0.1 Hz and beyond this is the scintillation effect at O dB/decade. However, at ESUT with rainfall event of almost twelve hours duration, the result shows the huge rain attenuation effect extends the power spectral density up to Nyquist frequency.

vii. CDF of measured rain attenuation shows that rain attenuation of 10.5 dB, 11.6 dB, and 8.3 dB are exceeded for LAUTECH, ESUT, and FUGUS respectively. The implication is that for every 52 minutes of the year, rain attenuation was above 10.5 dB, 11.6 dB, and 8.3 dB, for the respective locations – signifying the fact that the three locations and by extension the entire country experience intense rainfall which have a huge adverse impact on the propagation of radio waves above 10 GHz.

viii. Overall, the results for testing the performance of rain attenuation models with measured attenuation data show that the Moupfouma model gave the least RMSE error for predicting attenuation in Nigeria followed by the ITU-R attenuation model. However, because of the wide discrepancies between the ITU-R models and measured values, the ITU-R model is not suitable for the design of GEOs, MEOs and LEOs in the study locations. The failure of the models could be attributed to the fact that the data source were majorly from temperate regions. Therefore, the Moupfouma model is recommended for predicting rain attenuation in Nigeria.

ix. On the development of models for rain-specific attenuation parameters for Nigeria, this research proposed the use of location-based k and α value for optimum prediction rain attenuation instead of the fixed value at the frequency of interest.

x. The results on fade durations show that attenuation above 15 dB accounted for between 0.01% and 0.1% of the total rainy time in the studied locations; this suggests rain attenuation has a greater impact, in terms of both the attenuation level and duration, in tropical regions.

xi. Fade slope provides a good measure of rain attenuation in the studied regions and can be expressed in terms of its standard deviation and skewness. The standard deviation of the fade slope represents the speed of change of attenuation. From the estimated standard deviation and skewness, rain in the Sudan Savannah (FUGUS) region is widespread and characterized by a slow rate of change, while in the Rain Forest (LAUTECH) and Guinea Savannah (ESUT) it is convective and has a high rate of change. Thus, it is found an apparent difference in the dynamic property of rain attenuation between Sudan Savannah and tropical regions.

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