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CHARACTERIZATION OF TROPICAL RAINFALL STRUCTURE FOR SOME SELECTED LOCATIONS IN NIGERIA

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Abstract

Rainfall rate for any location is required for rain attenuation modeling for the region of interest. The characteristics of tropical rainfall structure in Nigeria have been investigated. The data was collected from the Tropical Data Acquisition network (TRODAN) set up by the Center for Atmospheric Research (CAR) in Nigeria. The rainfall rates were measured at 5-minutes integration time. The results were then compared with those predicted by the ITU-R model, and those from other tropical locations. The results revealed that the ITU-R model performs best only in the Southern Guinea Savannah (SGS) region of the country. In other geographical locations, the ITU-R model either under-estimates or over-estimates rainfall rates. The Cumulative Distribution Functions (CDFs) at the 0.01% time of exceedence showed that the percentage difference in the measured rain rate and the ITU-R estimates varied from a minimum of 4.89% in SGS to a maximum of 22.93% in the Derived Savannah (DS). At the 0.001% of time, these differences varied from a minimum of 11.90% to a maximum of 38.80% in these respective regions. These results and others from the tropics suggest the need for the modification of the ITU-R model for predicting rain attenuation in the tropical region to take into account the peculiar characteristics of rainfall in the region.

Keywords: Rainfall structure, Rainfall rate, Cumulative Distribution Function, ITU-R estimates

1.0 Introduction

Rainfall is the major factor (among other hydrometeors) that impairs the propagation of electromagnetic waves at centimeter and millimeter wavebands from the transmitter to the receiver. When the signal comes in contact with the rain-filled medium, the signal can be absorbed, scattered, depolarized and diffracted by the raindrops [1,2]. The influence of rain is more critical in the tropical areas, like Nigeria, characterized by high rainfall rate, heavy thunderstorms, intense and large raindrop sizes which changes according to geographical location [3, 2]. As a result, the electromagnetic waves propagating through the rain-filled medium can be greatly attenuated especially as the propagating frequency approach the threshold of 10 GHz and above [4, 5, 6, 7, 2]. The influence of rain on radio links operating at frequencies as low as 7 GHz has been reported by [8] and [9].

In the design of terrestrial and earth-space microwave systems, accurate and high resolution rainfall-rate statistics are important. The extensive precipitation data accumulated by most national weather services which are mostly hourly, daily, monthly or annual rainfall accumulations, is of potential value to radio system planners but the temporal resolution is relatively coarse and the values far beyond the integration time for direct use in rain attenuation determination. The precipitation data requirements of radio communications community are generally more demanding than those accumulated for these services. The rapidly time varying nature of rainfall at any given location informs the inadequacy of cumulative distributions of hourly or even 5-minutes duration rainfall statistics. According to the International Telecommunication Union (ITU), 1-minute rain gauge integration time is the most desirable compromise for attenuation prediction; hence fairly precise rainfall rate statistics are essential.

The International Telecommunication Union – Radio communication Sector (ITU-R) has provided a methodological approach for predicting rain attenuation on any terrestrial radio link. The model, however, does not perform well in tropical

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climates because it is based on data collected from temperate regions [10, 11, 12]. The severity of rainfall impairments is more in the tropical and equatorial climates, where intense rainfall events are common and raindrops are larger [13, 14, 15]. The failure of the ITU-R method in tropical regions has been demonstrated by many works [10, 16, 11]. In order to predict reliable rain attenuation for a given location, one have to determine the characteristics of rainfall rate at the location of interest [17].

The cumulative rainfall distribution, Cumulative Distribution Functions (CDF) of rainfall rates based on different integration times, annual cumulative distribution of rainfall rates of six locations spread across Nigeria has been investigated in this paper. The locations are the South East, South-South and the North Central region. The cumulative rainfall rates measured at the given locations were compared with the ITU-R estimate. This enabled the characterization of rainfall structure for rain attenuation prediction for terrestrial and earth-space services for Nigeria.

2.0 METHODOLOGY

The six years 5-min rainfall data was collected from Tropospheric Data Acquisition Network (TRODAN) setup. TRODAN is a project under the Nigeria Center for Atmospheric Research (NCAR) which has been taking measurements of meteorological parameters since 2007 [18]. Initially the project had eighteen stations spread across the climatological and vegetation belts of Nigeria but regrettably, however, some of the station equipment broke down shortly after the start of the project due to technical problems and inadequate trained man power to manage the facility. These challenges were overcome at different times and from station to station. This accounted for the different dates and length of data used in this study. We chose stations that have data for not less than 4 years spread across all the climatic and vegetation belts of Nigeria. The rainfall structure at these locations depends on the position of the Inter Tropical Discontinuity (ITD) which is sometimes referred to as the Inter Tropical Convergence Zone (ITCZ). The movement of the ITD dictates the seasonal weather pattern in the tropics. The specification of the tipping bucket rain gauge used at each TRODAN station is TE525WS, the orifice is 20.3 cm and the resolution (rainfall per tip) is 0.254 mm. It has an accuracy of up to 1 in./hr:±1%, and an operating temperature from 0^o to +50^{o}C [19]. The rain gauge measure rainfall at 5 minutes interval and the values were transmitted as electronic pulses to a CR1000 data logger for storage. The data was retrieved using computer system equipped with appropriate software (Loggernet). The characteristics of the stations used in this study, which cuts across all the geographical zones in Nigeria, is presented in Table 1.

The accumulated rainfall was converted to rain rate (R_D) using the method of [20] and [21] given as

$$R_D = L * \frac{60}{T} \tag{1}$$

where R_D is the rain rate in mm/hr and L is the maximum rainfall in mm for the time interval T in minutes.

Table 1: The climatological characteristics of the stations

Stations	Coordinates	Altitude (m)	Average annual rainfall (mm/yr)	Geographical region
Nsukka	6.86^{o}N, 7.40^{o}E	259	1442.68	Derived Savanna
Eburumiri	6.61^{o}N, 7.35^{o}E	359	1295.63	Derived Savanna
PortHarcourt	4.75^{o}N, 7.00^{o}E	468	1684.13	Humid Forest
Minna	9.61^{o}N, 6.56^{o}E	223	1238.15	Southern Guinea Savanna
Anyigba	7.63^{o}N, 7.29^{o}E	420	476.85	Derived Savanna
Makurdi	7.73^{o}N, 8.54^{o}E	140	734.38	Derived Savanna

2.1: Rain rate conversion methods:

In a bid to accurately predict point rain rate cumulative distribution, several models have been developed. According to [22], the established models were grouped into three broad classes namely physical, analytical and empirical models. Models that belong to the physical class include: [23, 24, 25, 26]; [27. 16, 28, 29] constitutes the analytical models while [30, 31, 32, 33] are the empirical models. The empirical methods have been extensively used to convert rainfall data from higher integration time to lower equivalence because of its experimental dependence and simplicity. According to [29], all other models are derived experimentally, hence the need to exercise caution towards applying them to other locations and integration times that were not used to derive them. Among the analytical models, the Lavergnat and Gole (LG) [27] model has the advantage over others because it allows a conversion between any integration times. The conversion of rain rate of higher integration time to 1-minute integration time as recommended by ITU-R was achieved using the LG model which was found suitable for this region among other models. The LG model (Eqn. 2), which was obtained after series of transformations and using Laplace transform properties, allows a rain-rate distribution observed using an integration time kt to be changed into one that would have prevailed for an integration time t.

$$Q_c(r,t) = K^{\zeta-1} Q_c\left(rK^{\zeta-1}, kt\right) \quad (2)$$

where $Q_c(r,t)$ is the cumulative probability of rain rate r (= h/t) that would be obtained with rain gauge at an integration time t. Equation (2) was used to convert the TRODAN data of 5-min to 1-min integration time after which further analysis was carried out. The ITU-R [34] model was used to generate the rainfall rate predicted values from 0.0001% to 10% exceedence.

3.0: RESULTS AND DISCUSSION

3.1: *Characteristics of rainfall at the study sites.*

The estimated rain rate values at various percentages of exceedence are presented in Table 2. The comparison between ITU-R rain rates predicted values and measured values, at different percentages of exceedence is given in Table 3. At 0.01% of exceedence, the minimum rainfall rate of 80.92 mm/hr occurred at Eburumiri while the maximum of 109.10 mm/hr occur at PortHarcaourt according to the ITU-R (Table 2). On the other hand, the measured rainfall rates showed that the minimum of 31.30 mm/hr occurred at Anyigba while the maximum (105.00 mm/hr) occurred at Eburumiri (Table 3). At 0.001% of exceedence the minimum rainfall rate of 149.30 mm/hr occurred at Nsukka while the maximum is 173.4 mm/hr at PortHarcourt. According to the measured values, the minimum rainfall rate of 121.50 mm/hr occurred at Makurdi while the maximum of 240.70 mm/hr occurred at Anyigba. Clearly, there is a disparity between the ITU-R and the measured rainfall rate in Nigeria. This is another short coming of the ITU-R model in the tropical region as evidenced by earlier researchers [16] etc. These measured rain rate values can be continuously exceeded at least once a year for about 4 minutes, 3 min and 40 seconds [35]. These high rainfall rates occurring for long periods could lead to unacceptable outages on radio link operating in the microwave and millimeter wave regions. Such high rainfall rate with long durations can constitute serious outage problems on communication systems operating above 10 GHz [35].

Table 2: ITU-R estimated rain rate values at different percentages of exceedence

Percentage of time	Locations					
	Nsukka	Eburumiri	Port Harcourt	Minna	Anyigba	Makurdi
10	0.023	0.023	0.685	0.060	0.1246	0.0221
1	3.442	2.442	8.150	4.350	5.067	3.232
0.3	10.270	11.070	25.565	13.281	14.991	8.040
0.1	28.172	27.672	47.500	32.600	35.163	33.700
0.03	56.414	52.414	83.949	62.133	64.926	50.234
0.01	81.923	80.923	109.100	91.557	94.379	91.900
0.003	119.090	118.090	145.540	124.710	127.530	122.61
0.001	149.300	149.830	173.400	155.330	158.140	155.400
0.0001	159.230	159.980	180.210	160.230	162.340	161.230

Table 3: Rainfall rate (mm/hr) at 0.01% of exceedence and 1-min integration time

0.01%				0.001%		
Station	Measured	ITU-R	Difference (%)	Measured	ITU-R	Difference (%)
Eburumiri	105.00	80.92	22.93	149.83	149.83	0
PortHarcourt	95.50	109.10	14.24	135.00	173.40	28.44
Nsukka	96.27	81.92	14.91	*	149.30	*
Minna	96.27	91.56	4.89	192.53	155.33	19.32
Anyigba	31.30	94.38	-201.53	240.70	158.14	34.30
Makurdi	70.00	91.90	-31.29	121.50	155.40	-27.90

3.2: *Accumulated Rainfall Distribution*

The monthly cumulative rainfall distribution and annual accumulated rainfall is given in Figs.1 & 2 respectively. The months that gave the highest rainfall amount and the corresponding year are shown in Table 4. Fig.1 show that the peak of the rainy season varied from one climatic region to another and from one station to the other. The highest cumulative monthly rainfall distribution (Table 4) also varies from a minimum of 110.70 mm at Anyigba in 2011 to a maximum of 522.30 mm at Minna in 2008. On the other hand, the minimum annual accumulated rainfall of 548.60 mm occurred at Anyigba in the year 2011 while the maximum of 2356.10 mm occur in PortHarcourt in the year 2009. These months with the highest monthly cumulative rainfall distribution are considered the worst calendar months for radio link and the corresponding years with the highest annual accumulated rainfall are the worst calendar years for radio links for the respective stations. Generally, the peak of rainfall occurs in August in the northern part of Nigeria which comprises of the Guinea Savannah, Sudan and Sahel climatic regions while in the south, which comprises of rainforest and Mangrove regions, rainfall peaks occur in September due to the two to three weeks August break experienced in late July to early August in the south. From Fig.2, it will be observed that the wettest year for the period under investigation is 2009 as demonstrated in Table 5.

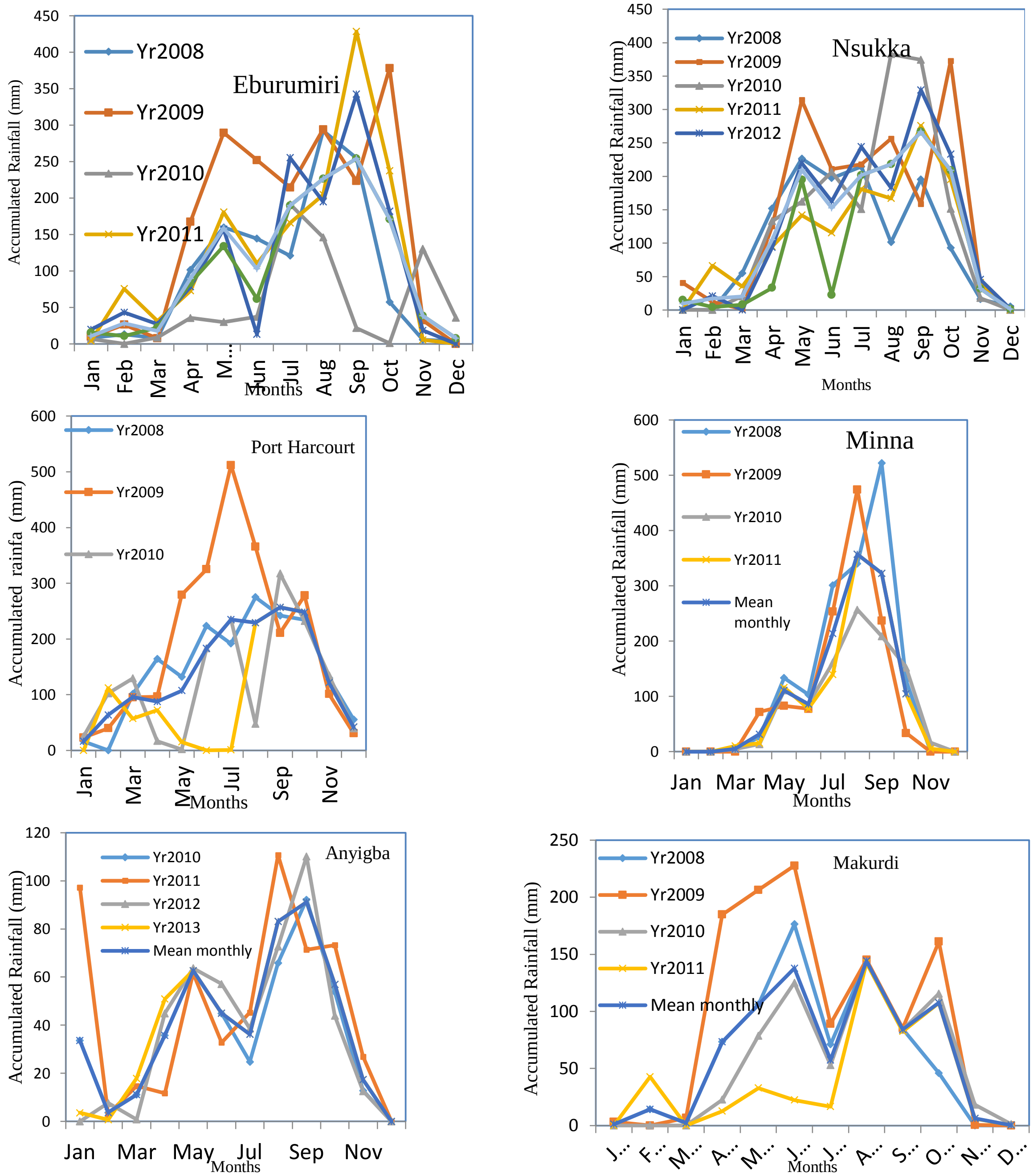


Figure 1: Cumulative monthly Rainfall Distribution (mm)

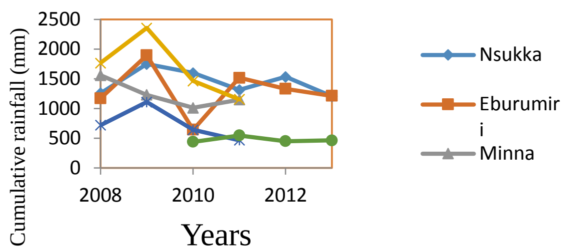


Fig.2: Annual Accumulated Rainfall (mm)

Table 4: Highest cumulative monthly rainfall amounts and year of occurrence

Station	Rainfall Amount(mm)	Month	Year
Minna	522.30	September	2008
Makurdi	227.60	June	2009
Anyigba	110.70	August	2011
Eburumiri	428.60	September	2011
Nsukka	382.60	August	2010
Port Harcourt	511.90	July	2009

Table 5: Highest annual accumulated rainfall and year of occurrence

Station	Rainfall Amount(mm)	Year
Minna	1560.6	2008
Makurdi	1110.1	2009
Anyigba	548.6	2011
Eburumiri	1895.7	2009
Nsukka	1748.4	2009
Port Harcourt	2356.1	2009

Rainfall occurrences are dynamic and distributed in time and space. This result in month to month, year to year and season to season variability in the rainfall rate distribution. Accounting for the rapid changes of rain intensity and the consequent temporal fluctuations of the associated attenuation, the ITU-R recommends the use of rain rate complementary cumulative distribution functions (CCDFs) with 1-minute integration time[36, 7]. The integration time is the time between readings of rainfall. One minute rain rate (mm/h) is the rainfall for one minute (mm/minute) multiplied by 60 [38, 21]. The knowledge of one-minute rainfall rate data is necessary for the prediction of rain attenuation at any location. The knowledge of the local rain rate occurrence is a mandatory requirement for any model aimed at estimating rain attenuation on earth-space links [39]. However, due to the scarcity of 1-minute rainfall data in many countries of the world especially in the tropical regions like Nigeria, several methods of converting the rainfall rate distribution over a long integration time into one-minute rate have been developed. The LG model [27] gave the best result for Nigeria and hence adopted for this work to convert the 5-minutes rainfall rate to 1-minute integration time.

3.3: *Cumulative Distribution Function (CDF) of Rain Rates based on Different Integration times*

Rainfall rate distribution is a function of the sampling interval of rain gauge. Higher rain gauge sampling interval causes under estimation of measured rain rate. One minute accumulation removes the fluctuations caused by the rain gauge measurement process and maintains the important geophysical variations [25]. The rainfall rate distribution at 1- and 5-minutes (Fig 3) show that the 5-minutes rainfall rate under estimate the rainfall rate at 0.1%, 0.01% and 0.001% percentage of exceedance in all the stations (Table 6).

Table 6: Rainfall rate at different percentages of exceedance for 1- and 5-minutes.

	Rainfall rate (mm/hr) at percentages of exceedance					
	0.001%		0.01%		0.10%	
Station	**1-min**	**5-min**	**1-min**	**5-min**	**1-min**	**5-min**
Nsukka	120.33	100.00	96.27	80.00	36.10	30.00
Eburumiri	144.40	120.00	96.27	80.00	26.00	36.10
PortHarcourt	104.50	132.00	90.50	71.00	45.00	30.00
Minna	192.50	149.50	110.00	80.00	36.10	26.00
Anyigba	120.00	80.00	36.10	30.00	20.00	10.00
Makurdi	130.00	100.00	60.00	58.00	12.00	8.00

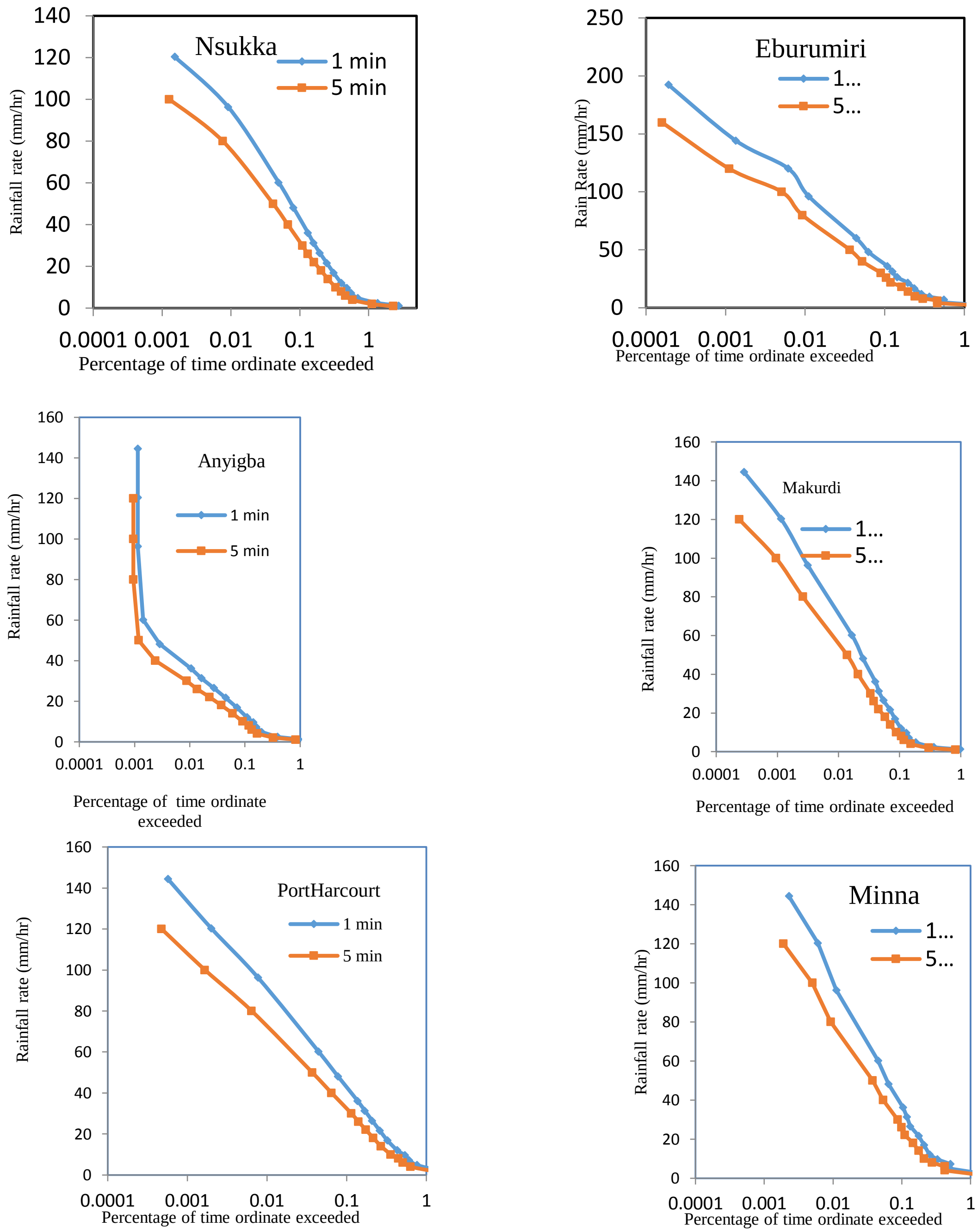


Fig. 3: Rainfall rate distributions at 5-min and 1-min integration time

It will be observed from Fig.3 and Table 6 that in all the stations, the 5-minutes rainfall integration times underestimates the rainfall rate at all percentages of exceedence; making it not suitable for estimating rain attenuation studies. Hence, the 5-minute rainfall was converted to 1-minute rainfall integration time using the LG model.

3.4: ***Annual Cumulative Distribution of Rainfall Rates***

The cumulative distributions of rainfall rates were obtained based on annual rainfall rates and percentage of time. According to ITU-R [34] recommendation on characteristics of precipitation for propagation modelling, consideration of the rainfall rate exceeded for 0.01% of an average year is the expected standard as this amount to 99.99% radio signal availability. The variation of the annual cumulative distribution of the average 1-minute integration time rainfall and their mean is presented in Fig.4. The cumulative distribution of rainfall rate at 0.01% percentage of exceedance is given in Table 7.

Table 7: Rain rate (mm/hr) distribution at 0.01% of exceedance

Station	Rainfall accumulated (mm/hr)	Mean	Annual rainfall (mm)
Nsukka	20.0 - 65.5	51.67	1442.68
Eburumiri	23.0 - 75.0	45.50	1295.63
PortHarcourt	20.0 – 68.0	49.75	1684.13
Minna	30.0 - 75.0	51.75	1238.15
Anyigba	6.5 - 25.0	18.13	476.85
Makurdi	2.0 -54.0	17.75	734.38

The values in column two of Table 7 show the range of values of the rain rate at 0.01% of exceedence for the different years shown in Fig. 4.

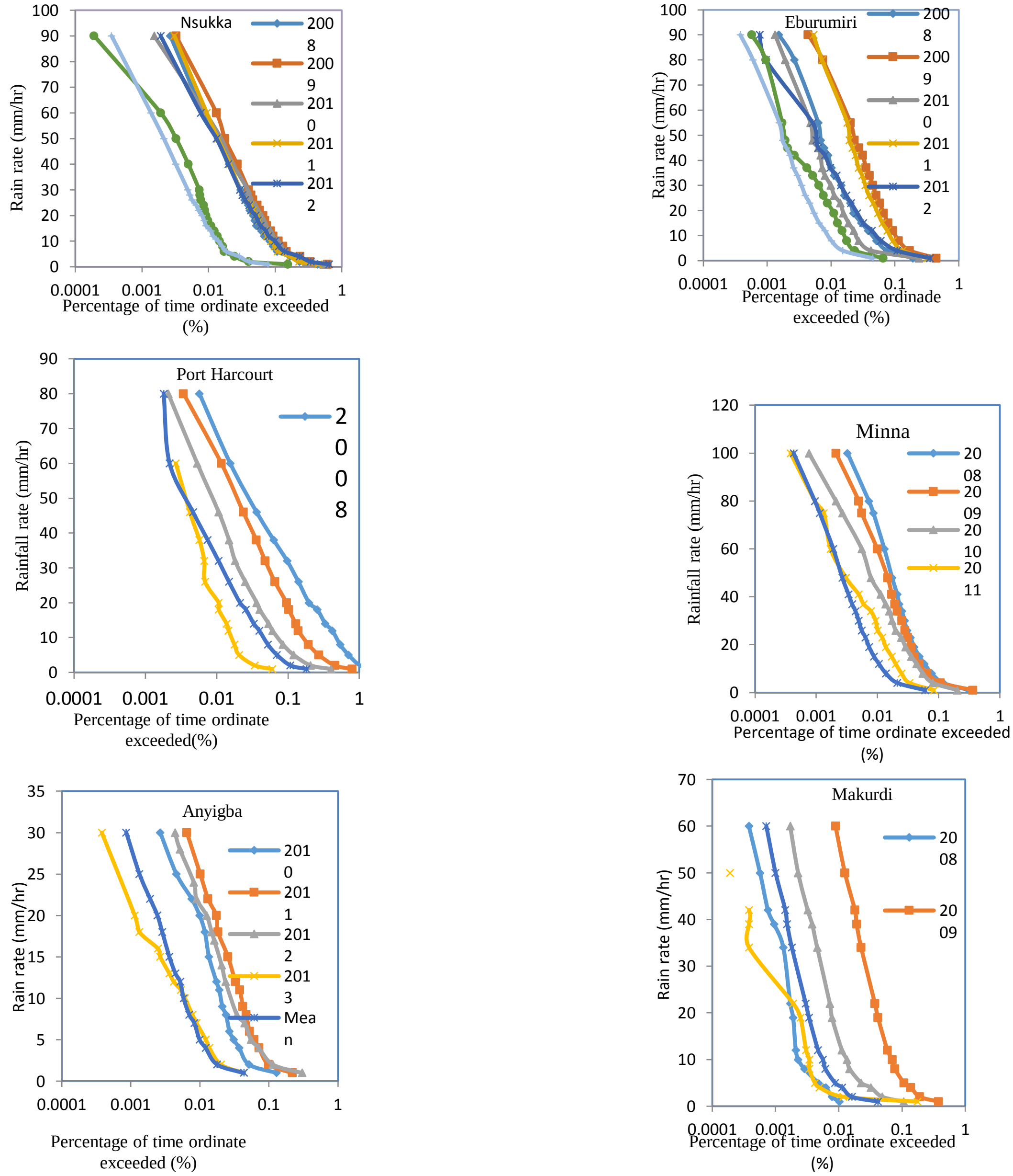
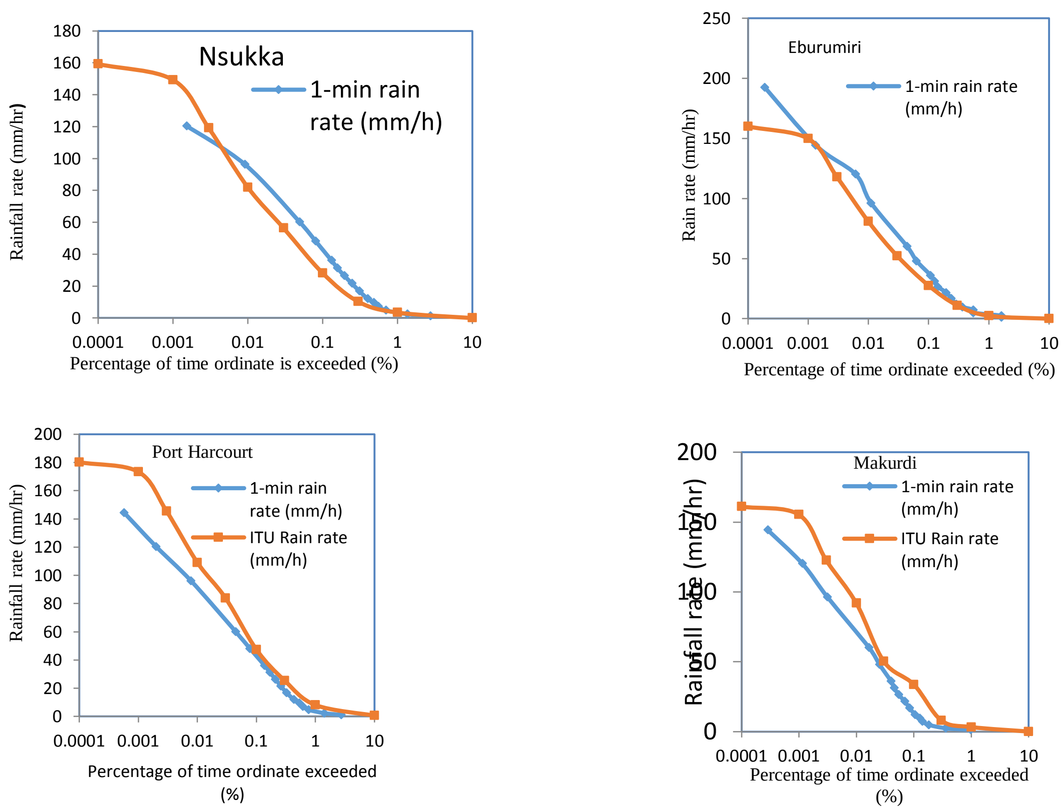


Figure 4: Annual Cumulative probability function of rainfall rates at 1-minute integration time

3.5: *Cumulative rainfall Rates and ITU-R Estimate*

The International Telecommunication Union, Radio Communication Sector (ITU-R) has provided a step by step approach for the prediction of rain attenuation on any terrestrial radio link [12, 11]. This model (ITU-R model), however, does not perform well in tropical regions and at high rainfall rate [39, 40] because the average radius of raindrop in tropical regions are greater than those in non-tropical climates. Furthermore, the ITU-R model is based on data collected from temperate regions of the world with different rain characteristics. In order to predict reliable rain attenuation for a given location, it is essential to determine the characteristics of rainfall rate at the location of interest which is geographically dependent [17]. The comparison of the measured Cumulative probability Distribution Functions (CDF) of rainfall rate at 1-minute integration time and ITU-R recommendation is given in Figure 5. Observe that only in the Southern Guinea Savanna (SGS) region (Minna station) that the ITU-R model performed very well. In the other geographical regions- Derived Savanna (DS) and Humid Forest (HF) represented by Makurdi, Nsukka, Eburumiri, Anyigba, and PortHarcourt respectively, the ITU-R model either underestimated or overestimated the rainfall rate. This is further evidenced in Fig. 6 where the ITU-R estimated 1-min rain rate grossly under estimated the measured 1-min rain rate at all percentages of exceedence. This lend further evidence to the inappropriateness of the ITU-R model [16, 11] in estimating rainfall rate and hence prediction of rain attenuation in the tropics. The importance of local climatic data input was emphasized by [41] (noting the effect of local climatology on wireless systems operating at frequencies above 10 GHz) for accurate prediction of the performance of radio communication applications operating at frequencies higher than 10 GHz. The comparison of the CDFs at different percentages of exceedence of the measured and "ITU-R rainfall rate" cumulative distribution for each station and their difference is given in Tables 10-13. Observe from these tables that the percentage difference between the measured and ITU-R values of the rain rates vary from a minimum of 4.89% at Minna in SGS to a maximum of 22.93% at Eburumiri in DS. It will be observed that at the 0.01% percentage of time, the performance of the ITU-R model varied from one geographical region to the other. It over estimated the rain rate at PortHarcourt (Humid Forest) and Anyigba and Makurdi both in DS and underestimated rain rate at Nsukka and Eburumiri also in the DS region.



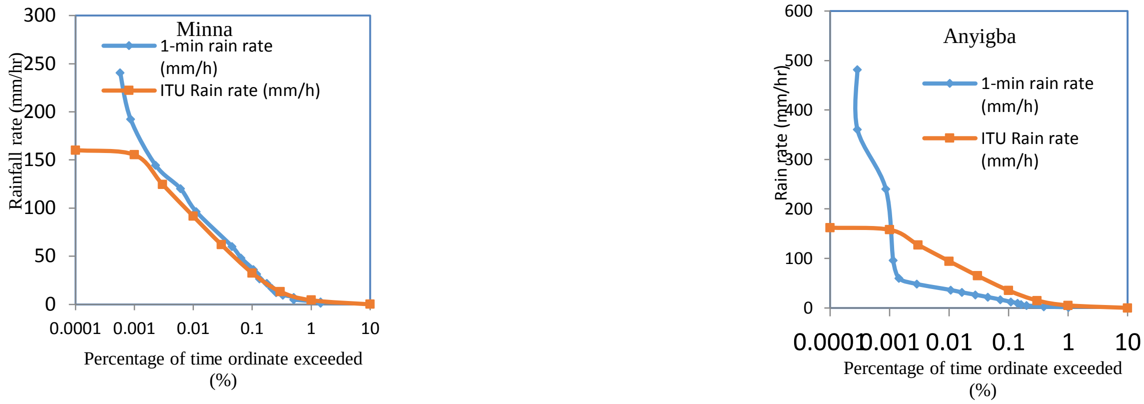


Figure 5: Cumulative Distribution functions of rainfall rate of 1-minute integration time compared with the ITU-R values

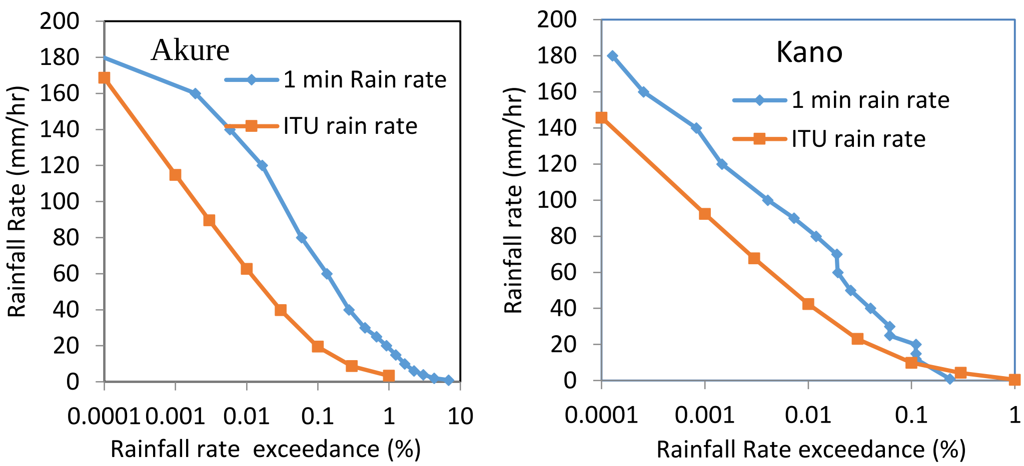


Fig. 6: Measured and ITU-R estimate of 1-minute Rain Rate distribution over Akure and Kano

Table 8: ITU-R Percentage of exceedence at different rain rates CDF for Nsukka.

ITU-R Rain Rate Exceedence for Nsukka (%)	ITU-R Rain Rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative Distribution (mm/hr)	Difference (%)
10	0.02	-	-
1	3.44	4.50	23.56
0.3	10.27	16.85	39.05
0.1	28.17	44.00	35.98
0.03	56.41	76.00	25.78
0.01	81.92	96.27	14.91
0.003	119.09	112.00	-5.95
0.001	149.30	-	-
0.0001	159.23	-	-

Table 9: ITU-R Percentage of exceedance at different rain rates CDF for Eburumiri.

ITU-R Rain rate Exceedencies for Eburumiri (%)	ITU-R Rain rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative Distribution (mm/hr)	Difference (%)
10	0.02	-	-
1	2.44	2.44	0
0.3	11.07	11.07	0
0.1	27.67	36.10	23.35
0.03	52.41	75.00	30.12
0.01	80.92	105.00	22.93
0.003	118.09	130.00	9.16
0.001	149.83	149.83	0
0.0001	159.98	-	-

Table 10: ITU-R Percentage of exceedencies at different rain rates CDF for Port Harcourt

ITU-R Rain rate Exceedencies for PH (%)	ITU-R Rain rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative Distribution (mm/hr)	Difference (%)
10	0.68	-	-
1	8.15	-	-
0.3	25.57	16.85	51.75
0.1	47.50	45.00	5.56
0.03	83.95	66.00	27.20
0.01	109.10	95.50	14.24
0.003	145.54	118.00	23.33
0.001	173.40	135.00	28.44
0.0001	180.21	-	-

Table 11: ITU-R Percentage of exceedance at different rain rates CDF for Minna.

ITU-R Rain rate Exceedencies (%)	ITU-R Rain rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative Distribution (mm/hr)	Difference (%)
	0.06	-	-
1	4.35	4.35	0.00
0.3	13.28	13.28	0.00
0.1	32.60	32.60	0.00
0.03	62.13	65.00	4.42
0.01	91.56	96.27	4.89
0.003	124.71	130.00	4.07
0.001	155.33	192.53	19.32
0.0001	160.23	-	-

Table 12: ITU-R Percentage of exceedence at different rain rates CDF for Anyigba.

ITU-R Rain ate Exceedencies (%)	ITU-R Rain rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative Distribution (mm/hr)	Difference (%)
10	0.12	-	-
1	5.07	5.10	0.59
0.3	14.99	15.00	0.07
0.1	35.16	35.20	0.11
0.03	64.93	25.00	-159.72
0.01	94.38	31.30	-201.53
0.003	127.53	50.00	-155.06
0.001	158.14	240.70	34.30
0.0001	162.34	-	-

Table 13: ITU-R Percentage of exceedence at different rain rates CDF for Makurdi.

ITU-R Rain rate Exceedencies (%)	ITU-R Rain rate Cumulative Distribution (mm/hr)	Measured Rain Rate Cumulative. Distribution (mm/hr)	Difference (%)
10	0.02	-	-
1	3.23	3.20	-0.94
0.3	8.04	8.00	-0.50
0.1	33.70	9.60	-251.04
0.03	50.23	50.50	0.53
0.01	91.90	70.00	-31.29
0.003	122.61	88.00	-39.33
0.001	155.40	121.50	-27.90
0.0001	161.23	-	-

The comparison of the estimated rainfall rate by the ITU-R model with the measured values at some tropical and sub-tropical countries [42, 17] is shown in Fig 7. Clearly the ITU-R model does not estimate rainfall rate accurately in these regions of the world. There is therefore the need to modify the ITU-R model for the topics and sub-tropical regions.

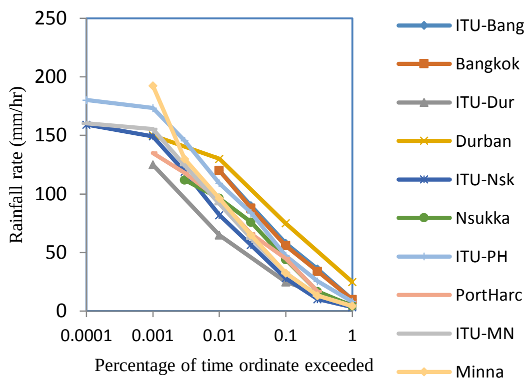


Figure 7: ITU-R rainfall rate estimate in some tropical and sub-tropical locations (Durban, (South Africa), Bangkok (Malaysia) and Nigeria).

4.0: *CONCLUSION*

In order to predict attenuation due to rain accurately, rainfall rate with 1-min integration time is required. Comparison of the measured 1-min rain rate with the ITU-R estimated values showed that the ITU-R under estimate rain rate at all percentages of time in this region. These findings are consistent with earlier works [16, 42, 6, 3, 11] which show that the ITU-R model does not performed very well in the tropics. The implication is that communication equipment designed with the ITU-R recommended rainfall rate estimates at these locations will perform below expectation. The worst month and worst calendar years vary from location to location. This could be as a result of the change in the peaks of rainfall from north to south thereby altering the worst months and years for radio wave propagation.

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