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Analysis of dynamical rain duration and return periods for terrestrial and satellite communication applications in a tropical climate.

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Abstract— Understanding the intensity, duration and return periods of tropical rain events are critical to radio and satellite system engineers. As current and future satellite systems use and will use higher frequency bands, rain attenuation continues to pose more threat to link availability for microwave propagation operating in the frequencies above 10 GHz. Despite the enormous research on rain mitigations, few studies have addressed the dynamic of rain duration and return periods of tropical rain events. In this paper, an attempt has been made to analyze the dynamical rain duration and return periods for terrestrial and satellite communication applications in a tropical climate. 3-year rain rate data collected at Akure (7.17 ^{o}N, 5.18 ^{o}E) between July 2012 and June, 2015 is used. The dependence of integration time on the cumulative distribution of rain rate has been compared with results earlier obtained in Nigeria and other parts of the world. The Result shows that the power law relationship exists between the equiprobable rain rates of two different integration times. The value of conversion factors $C_E(R)$ and C_R ($R_{0.01\%}$) obtained for Akure are 0.15(*30*) and 0.33(*110*) respectively. The overall results show that different conversion factors are required for different locations, even within the same climatic region.

Index Terms— Conversion factor , Rain duration, Return periods, Propagation Impairment, Microwave applications

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1 INTRODUCTION

THE demand for the rainfall characterization studies has been increased in recent years due to the need for high capacities links especially for digital satellite and terrestrial networks at high microwaves and millimeter frequencies band. Among the rainfall characterization studies with few study area is the dynamical intensity, duration and return periods of rain rates especially at the tropical climates- high intensity rainfall which is normally accompanied with thunderstorm. The duration of time and the return periods of specific rain rates is defined by Harden *et al*., [1] as thus, let the rainfall rate rise above some fixed value R at time t_o, exceed this value continuously until time t_1, at which time it falls to a value less than R. At a later time t_2, the rain again rises above R. Then the duration is t_1-t_o and the return period is t_2-t_1. The knowledge of the duo is essential in the design of microwave and millimeter wave radio links, operating at frequency above 10 GHz in order to avoid long outages on the radio links especially in the tropical region. Raindrops absorb and scatter radio waves, leading to signal attenuation and reduction of the system availability and dependability. The severity of rain impairment increases with frequency and varies with regional locations [2]. The severities are even more pronounced at the tropical region, where rainfall is often of convective, characterized by large raindrop sizes, of high intensity and often times accompanied by severe lightning and thunderstorm [3] as compared to the temperate region as reported in the work of Ajayi, [2].

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It is no longer a gainsaying that for satellite system design operating at frequencies above 10 GHz, rain is the predominant among the hydrometeor that heavily caused tropospheric-propagation impairments [3-4]. Hence, it is essential to study rainfall characteristics (rain duration and return period) for efficient and reliable design of radio networks at frequency above 10 GHz. The excess attenuation caused by precipitation will in most cases have to be based upon information on the precipitation in the actual geographical area, as direct measurement of attenuation are compared with the number of links to be designed [5].

In the time past, few efforts have been made to examine the subject matter in Nigeria, among is the work of Ajayi and Ofoche [5] and Ajayi [6] where rainfall intensity were statistically characterized over a location (Ile-Ife) in Southern part of Nigeria based on few months data (28 months). Semire and Raji [7], also characterized rainfall intensity in Ogbomosho within the Southern Nigeria based on data measured for a period of 10 months (although, the issue of return period was not addressed). Others include the recent work by Obiyemi et al [8] where the equivalent 1-minute rain rate statistics and seasonal fade estimates in the microwave band based on 12 months data was examined (also, the issue of return period was not addressed). Since rainfall is dynamic in nature, the result obtained in such studies may not be applicable to this study area due to the climatic differences.

In this paper, analysis of the dynamical influence of rain duration and return periods needed for terrestrial and satellite communication applications are presented based on 3-year rain rate data measured at Akure using a tipping bucket raingauge with an integration time of 1-minute. The effect of integration time on the rain rate and the cumulative distributions function (CDF) are also discussed.

2 MEASUREMENTS

The measurement site is at Department of Physics, the Federal University of Technology, Akure (FUTA), Nigeria. 3-year rain rate data collected at Akure (7.17 °N, 5.18 °E) between July 2012 and June, 2015 is used. The measurement was collected using an electronic weather station (Davis 6250 Vantage Vue). The precipitation data was collected using a self-emptying tipping spoon (with a resolution of 0.2 mm per tip), which is part of the Integrated Sensor Suit (ISS). The accuracy of the gauge is about ±1% at 1 litter/h with a measuring range of a minimum of 2 mm/h to a 400 mm/h. The instrument scans at an interval of one second and integrated over 1 minute. The availability of the gauge is about 99.2%, the remaining 0.8% unavailability is as a result of system maintenance. Rain rate of other integration times (5-min, 15-min, 30-min and 60-min) have been generated from the self-emptying tipping spoon data.

3 RAIN INTENSITIES WITH DIFFERENT INTEGRATION TIMES

The dynamic changes of point rain rate do not necessarily lead to dynamic changes in attenuation along the radio propagation link. As a result of the spatial averaging that occurs over the "active volume" of a radio link, studies have shown that the attenuation is underestimated, if the data were considered with large integration times [5, 9]. Hence, the use of 1-minute rain rate gives the best agreement with the available radio paths [10 -11].

3.1 Cumulative Distribution Functions (CDFs) of Rain Rate

The CDFs of rain rates of different integration times are generated by averaging the 1-minute rain rate data from the self-emptying tipping spoon data. Fig. 1 shows the cumulative distribution of rain rate for different integration times from 1-min to 60-min. It has been found that a power law exists between the equiprobable rain rates of two different integration times. Fig. 2 also presents the relationship between the rain rates of 1-minute integration time and the equiprobable rain rates integration times of 2, 5, 15, 30 and 60 min. Since most of the meteorological stations where rain rates can be obtained are in these long integration times there is a need to convert to the recommended integration time of 1-minute needed for the prediction of rain-induced attenuation. Therefore, Fig. 2 will be useful for obtaining 1-minute rain rate when rain rates are available at different integration times.

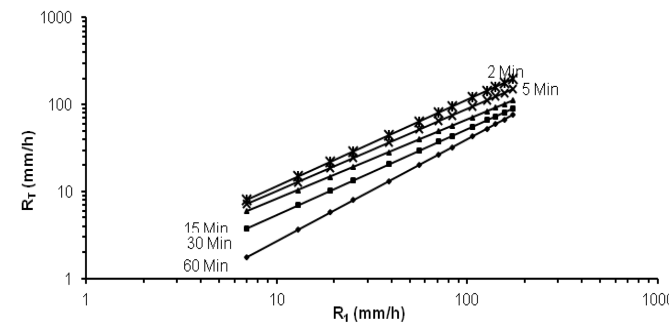

Fig. 2: Equal probabilities occurrence of equivalent 1-min rain rates for different integration times

The power law relation between 1-minute integration time and the equiprobable rain rates integration times is given by [5]:

$$R_\tau(P) = aR_T^b(P) \quad mm/hr \tag{1}$$

where R rate is the rain rate in mm/h. τ is the integration time at which the rain rate is required, T is the integration times at which the rain rate is available, P is the percentage of exceedance and the parameters a and b are the regression coefficients or converting coefficients.

The power law derived by using data over Akure with 1-minute and 5-minute can also be expressed as [3]:

$$R_{1-\min} = 1.815R_{5-\min}^{1.144} \tag{2}$$

The power law derived by using data over New Delhi with 10 s and 15 min by Sarkar *et al*, [12] was:

$$R_{10s} = 2.567R_{15-\min}^{0.852} \tag{3}$$

The results were compared with the results earlier obtained at another tropical station, Ile-Ife (7.5°N, 4.5°E) in Nigeria by Ajayi [6]. The following was found by them:

$$R_{10s} = 2.076R_{10-\min}^{1.011} \tag{4}$$

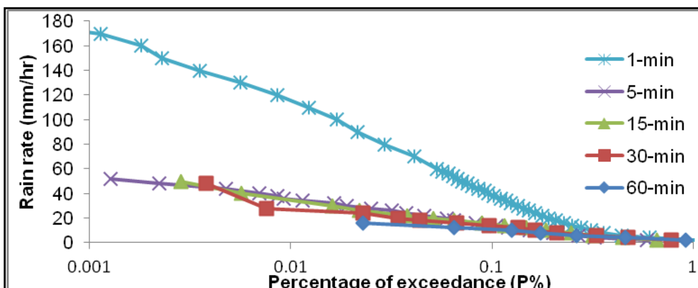

Fig.1: Cumulative distribution of rain rate at Akure for various integration times

The coefficients, a and b of the power law reported by Flavin,

[13] from the temperate stations in Europe, Canada and USA are also presented in Table 1. Results from the table show that the values of *b* of the stations from the temperate region are in agreement with the values of *b* in the tropical stations (Table 2). However, there is disagreement on the values between the tropical stations and temperate regions. The discrepancy could be attributed to the dominance of convective rain in the tropics, while stratiform rain is more prevalent in the temperate regions as earlier discussed by Ajayi and Ofoche [5]. Tables 2-3 give a typical coefficients *a* and *b* for required rain rates of 1 and 5 min integration time based on the present work.

TABLE 1
Coefficients of a and b for $R_\tau = aR_T^b$ for τ = 1-min [12]

T (min)	a	b
2	0.872	1.055
5	0.991	1.098
20	4.311	0.853

TABLE 2
Coefficients of a and b for $R_\tau = aR_T^b$ for τ = 1-min

T (min)	*a*	*b*
2	0.752	1.058
5	1.815	1.094
15	2.152	0.721
30	4.925	0.830
60	5.321	0.752

TABLE 3
Coefficients of a and b for $R_\tau = aR_T^b$ for τ = 5-min

T (min)	*a*	*b*
15	3.251	1.125
30	5.242	0.795
60	6.811	0.624

3.2 Behavior of conversion factor C_R and C_E

According to Ajayi and Ofoche [5] and Watson *et al*, [10], the conversion factors C_R and C_E for different integration times are considered as:

$$C_R(P) = \frac{R\tau}{R_1} \tag{5}$$

$$C_E(R) = \frac{E\tau}{E_1} \tag{6}$$

where $C_R(P)$ is the ratio of rain rates exceeded for a given percentage of time *P* as measured by the rain gauges with integration times τ-min and 1-min, $C_E(R)$ is the ratio of the exceedances for a given rain rate measured using the 1-min integration time. The result of $C_E(R)$ obtained in Akure for *T* = 5 min and t = 1 min was then compared with that obtained in Ile- Ife, Ogbomoso and some countries in Europe. The result is shown in Table 4. As shown in Table 4, there is a gradual decrease in the value of $C_E(R)$ with increasing rain rate for the European countries while that of Ile-Ife, Ogbomoso and Akure in Nigeria decreases rapidly with increasing rain rate. This suggests that C_E might be climate dependent as suggested in [6] which is also corroborated according to the value obtained for Akure. The value of C_R obtained in Akure is also compared with that obtained in [10] for some stations in Europe and that of Ile-Ife, as obtained in [5]. There is a good agreement for the results obtained in Ile-Ife. However, our 1 minute statistics are a bit higher than those obtained from the Ogbomosho data; at the same time. Although, Akure and Ogbomosho belongs to the same locality (rain forest part of the country), the main cause is the different number of the available year of rain rate data. The present study employed 3 years rain rate data while Ogbomosho was only 10 months rain rate data. On the average, our results are different from that obtained by Harden et al [1] and Watson et al.[10]. They reported high values of between C_R and C_E. The reason might be due to high occurrence of rainfall, caused by stratiform clouds encountered in temperate areas like Italy, UK and West Germany than in tropical areas.

The lower values of C_R and C_E obtained at Akure compared with those in temperate regions may also be due to the higher convective rainfall observed at these tropical stations. The difference in the C_E also suggests the tendency of the rain characteristics to be different over the European and tropical region. The values are depicted in Table 5.

4 Rain Rate Duration

The rain rate duration, particularly of high intensity, is important for estimating the period of severe fades and fade-outs of links. It also provides information on cell sizes if the speed of the rain cell is known [5, 14].

TABLE 4
VALUES OF $C_E(R)$ FOR τ=5-MIN AND 1-MIN

Source	Locations	Rainfall rate (mm/h)										Comments
		10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
Watson *et al*, [10]	Greece							0.61	0.51		0.34	2-yrs data from Kefallina
Watson *et al*, [10]	Italy			0.63	0.60	0.60		0.63			0.59	2-yrs data from Rome
Watson et al, [10]	West Germany		0.83	0.74	0.73							1-yr data from Darmstrdt
Harden *et al*, [1]	UK	0.78	0.72	0.71	0.69	0.60		0.43				5-yrs data from southern UK on a network of rain guage
Ajayi and Ofoche, [5]	Nigeria (Ile-Ife)	0.74	0.68	0.59	0.57	0.40	0.30	0.17	0.10	0.08		28-month data obtained at Ile-Ife using a fast response raingauge
Semire and Raji,[5]	Nigeria (Ogbomoso)			0.37			0.28			0.16		10-month data obtained at Ogbomoso using a rain guage
Present study	Nigeria (Akure)	0.48	0.32	0.15	0.11							3-yrs data using a raingauge of tipping bucket type

TABLE 5
VALUES OF $C_R(P)$ FOR τ = 1-MIN.NUMBERS IN BRACKETS INDICATE THE 1-MIN RAIN RATE

Source	Locations	*τ*[min]	Percentage of exceedance		Comments
			0.01	0.001	
Watson *et al*, [10]	Italy	5	0.80(100)		2-years data from Rome
		10	0.70(100)		
		60	0.42(100)		
Harden *et al*, [1]	UK	5	0.84(20)	0.82(60)	5-years data from southern UK from a network of rain guages
		10	0.77(20)	0.72(60)	
		60	0.59(20)		
Watson *et al*, [10]	West Germany	5	0.93(20)	0.90(40)	1-year data from Darmstadt
		10	0.81(20)		
Ajayi and Ofoche, [5]	Nigeria (Ile-Ife)	5	0.68(80)	0.64(130)	28-months data obtained at Ile-Ife
		10	0.52(80)	0.53(130)	
Semire and Raji [7]	Nigeria (Ogbomoso)	5	0.64(90)		10-months data obtained at Ogbomoso
		10	0.53(90)		
Present study	Nigeria (Akure)	5	0.33(110)		3-year data obtained at Akure
		60	0.25(110)		

The rain rate is estimated from the measured data for the period under study. This is shown in Fig. 3.

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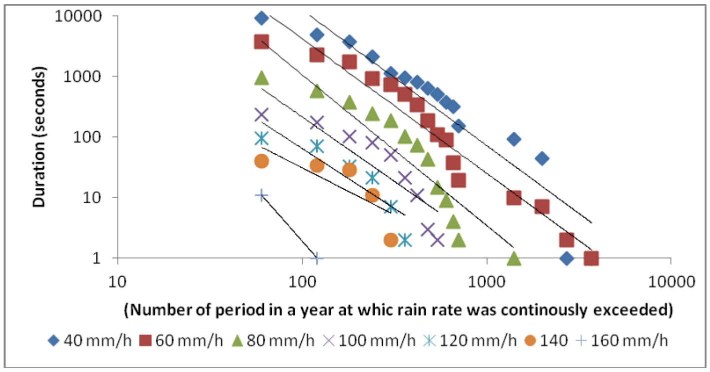

Fig 3: Duration of rain rate

Figure 3 shows that the rain rate of 40 mm/h, 60 mm/h, 80 mm/h, 100 mm/h, 120 mm/h, 140 mm/h and 160 mm/h is exceeding continuously once in a year for 60 min, 55 min, 30 min, 15 min, 7 min, 4 min and 2 min. It is important to know that such long duration, particularly of high rain rate is significant. It shows the period for which the links may be under deep fades or fade-outs. Service provider should adopt a proper measure, since such outages can affect customer confidence in their services.

5 RETURN PERIODS FOR SPECIFIC RAIN RATES

Return periods for specific rain rates have been studied from the rain rate data obtained within the study period. Figure 4 shows the average number of occasions in a year when rain rates of 40, 60, 80, 100, 120, 140 and 160 mm/h had return periods exceeding intervals in the range from 10 to 10^4 seconds. Return periods greater than 10^4 seconds were not considered, because emphasis has been placed on return periods within rain event. One of the interests of this paper is to study the return periods of various rainfall intensities during rainfall events in particular.

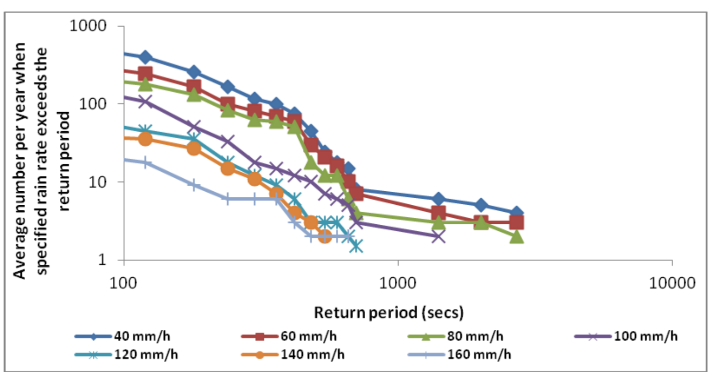

Fig. 4: Return period of rain rate

It can be seen in Fig. 4 that the rain rates ≤ 80 mm/h had a return periods of about one hour thirty minutes, while rain rates of 100 mm/h had return periods of 83 minutes and 120 mm/h showed return period up to 15 minutes. At 140 and 160 mm/h, the return periods of about 12 minutes were reached. It is noted that the rain rate exceeded at 0.01% of time as recommended by the ITU for radio communication purposes based on this study and previous results from this location is about 100 mm/h [3, 8], hence emphasis is also laid on this rain rate value in this work. It is therefore noted that at rain rate ≥ 100 mm/h, majority of the return period is less than 10^3 seconds, showing that the variations for such high rain rates are either within the individual rain cell or between adjacent rain cells within the mesoscale system. It could also be observed that in almost all the rain rates, return periods increased between 10 and 12 minutes, and stay high to about 30 minutes when there is a rapid fall between 30 and 2 hours. However, this phenomenon requires further studies to identify the rainfall characteristics responsible for it

6 CONCLUSION

3-year rain rate data collected at Akure between July 2012 and June, 2015 have been utilized to study the effect of integration time on cumulative distribution of rain rate for this tropical station. Values of equiprobable rain rate for different integration times for probabilities between the range of 0.01% and 1% have been employed to obtain a power law relationship and other relations between the rain rates at different integration times. The conversion factors C_R and C_F obtained at Akure are lower than those obtained for various locations in Europe and in Nigeria. The lower values of C_R and C_F obtained at Akure compared with those in temperate regions may be due to the higher convective rainfall observed at these tropical stations. The high values of C_R and C_F in the temperate regions may be explained as being due to high occurrence of rainfall, caused by stratiform clouds. These results show that different conversion factors are required for different locations even within the same climatic region for the conversion of rainfall rate measurements from one minute integration time to another for the estimation of microwave attenuation due to rainfall.

Results on rain rate duration also show that high rain rates of over 100 mm/h can be continuously exceeded for periods of the order of seconds. Such high rainfall rate with long durations can constitute serious outage problems on communication systems operating above 10 GHz in this region. The return periods of rain rates within continuous rain, indicate that return period is more for low rain while for heavy rain return periods are less. The majority of the return periods are as a result of rainfall rate variation within single cells and small mesoscale systems especially at the high rain rates.

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