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Article in *Telecommunications and Radio Engineering* · May 2020

DOI: 10.1615/TelecomRadEng.v79.i6.70

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1-MINUTE RAIN RATE DISTRIBUTION FOR COMMUNICATION LINK DESIGN BASED ON GROUND AND SATELLITE MEASUREMENTS IN WEST AFRICA

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West Africa is in the tropical region and it is characterized by intense rainfall. Rain is a significant factor causing signal degradation on microwave links due to its variability; it causes scattering, absorption, and refraction of electromagnetic waves. Experimental studies have shown that rainfall intensities above 64 mm/h at 0.01% in this region results in noticeable digital television signal fading, squelching and complete outages. Hence the need for estimating rain rate distribution across West Africa. This paper analyzed the rain rate from six countries in West Africa, namely Benin, Cameroon, Cote d'Ivoire, Ghana, Nigeria, and Togo. Three locations were selected in each country. Rain data were obtained from the Tropical Rain Measuring Mission-Precipitation Radar (TRMM-PR) and the Global Precipitation Measurement (GPM) missions, and Tropospheric Data Acquisition Network (TRODAN) weather stations in Nigeria. This study used ITU-R and Moupfouma models for the conversion of the 5-minute rain rate to 1-minute integration time at a probability of exceedance ranging from 1% to 0.001%. The cumulative rain rate distribution from the measured rain rate is presented alongside the predictions of the models. ITU-R and Moupfouma predicted similar results at 0.1% probability of exceedance. ITU-R overestimates the rain rate above 0.01% probability of exceedance. On the other hand, the Moupfouma models prediction plots at 0.01% overlap for all locations, indicating that there will be a signal loss at 0.01% probability of exceedance across these locations. The result shows that the 5-minute conversion provides satisfactory performance and suitable for estimating the 1-minute rain rate statistics required for propagation planning over West Africa.

KEY WORDS: *Rain rate, 1-minute, rainfall measurement, communication links, West Africa*

1. INTRODUCTION

The influence of the earth's atmosphere on electromagnetic waves propagation on the earth and space has become a continual source of concern in the performance of communication systems. This effect causes unrestrained disparities in signal characteristics such as phase and amplitude, which results in a decrease in quality of the signal transmission and a rise in the error rate of transmissions [1].

Degradation of signal due to scattering, absorption, and refraction of electromagnetic wave energy by raindrops is one of the critical impairments observed in radio propagation for satellite links operation above 10 GHz [2]. At constant speed, as frequency increases, the wavelength of the radio signal decreases to almost the size of the rain droplet, making it susceptible to rain attenuation. The factors determining rain attenuation on a microwave link are the rate of the exponential decay of the radio wave as it propagates through the volume of rain, change in polarization of the signal due to the uneven shape of the droplet and increase in the system noise temperature. These factors also describe the propagation of radio wave and precipitation and directly affects communication links performance [3,4].

The rainfall measurement is a weather parameter which shows a climatic variability over the African continent and particularly in West Africa [5]. It is, therefore, the main factor that enables us to differentiate the climates in the Tropics. From a climatic point of view, the West African region is defined by the mutual interaction of two important drivers: the Atlantic Ocean and the Sahara. Both temperature and precipitation as well as their annual cycle depend on how the air masses associated with the dry and hot desert interior and the humid ocean to the south and the west, interact. The intensity of precipitation associated with the monsoon in West Africa, its penetration inland, and its exact timing are of crucial importance for several human activities and satellite communication [6].

There is a ring of deep clouds that circle the equator, which is one of the most significant features of the planet. The meteorologists called this path of the ring "the Intertropical Convergence Zone" (ITCZ). West Africa falls within the ITCZ zone. The dynamic of the ITCZ progression is such that air masses from the trade-wind latitudes of each hemisphere converge toward this narrow band of intense convection, resulting in frequent precipitation [6]. The south-westerly trade wind ushers in a low-level seasonal circulation pattern called the West African monsoon (WAM), which represents the core factor of climate inconsistency in the region. In the Sahel region of West Africa, rainfall is limited to just one season. Sometimes, agriculture depends on the seasons as it varies yearly and monthly to plan for crop cultivation. It is, therefore, essential to study the nature and causes of the rainfall, especially in a region where agriculture represents 36% of their gross domestic product (GDP) and in line with the Sustainable Development Goals, SDGs 2 and 13 among others [7,8]. Also, reliable rainfall rate data are necessary for planning and design of satellite communication link, management of water resources, agricultural purpose, and flooding, as well as to assess the impact of climate change [9]. Omotosho et al. [9] proposed satellite observation of rainfall

networks as the best solution for adequate temporal and spatial coverage of rainfall in this region.

Efforts have been made by several researchers in analyzing the level of degradation of terrestrial and satellite signals. Few models have also been developed based on available rain data to relate rain rate to average specific rain attenuation. Some of the models presented by the International Telecommunication Union (ITU) include ITU-R Recommendation P.838-3 [10-12]. Although the degree of precipitation differs for different locations, hence the world is divided into 15 regions (rain zones) by the ITU recommendation Rec. ITU-R PN.837-5 [13] according to precipitation intensity. According to Diaz et al. [14] and Hodges et al. [15], higher rain attenuation prevails in the areas with higher rainfall.

Usually, attenuation is analyzed in terms of rainfall rate using a power-law relationship [16]. The power relationship is used to determine the rainfall rate from a link. Ojo et al. [17] and Ajayi and Ofoche [18] engaged both the Rice-Holmberg model [19], and Moupfouma and Martins model [20] to convert rain rate to the 1-minute equivalent for Nigeria. The results show that the cumulative distribution of rain rate is approximately 130 mm/h for high availability time requirement of 0.01% in the south-south region. On the other hand, Tattelman and Schar [21] made use of monthly mean temperature and precipitation, the number of days in the month with precipitation, and latitude to come up with the method for estimating 1-minute rainfall rates.

2. RAIN RATE PREDICTION MODELS

Rain rate models are used to predict the point rainfall-rate cumulative distribution of any location. Several such models exist. However, some of them have discrepancies, such as the number of stations and data availability. Not all the stations satisfy the 1-minute integration time requirement [22]; some require a relatively high density of short integration time [23].

Most researchers have made use of the rain rate distribution presented by the model developed by Moupfouma and Martin [20]. It is a model that approximates a log-normal distribution at a low rate and a gamma distribution at a high rate. The model is suitable for both tropical and temperate regions [24]. The Moupfouma model made use of Chebil and Rahman's model [25] as input for rain rate exceeded for 0.01% of the time ($R_{0.01}$). On the other hand, the ITU recommended model used the geographic coordinates to calculate the rain rate at a given location. ITU Recommendations P1144-10 [26] and P837-4 [13] are combined to obtain the rain rate (mm/h).

3. INSTRUMENTS AND METHODOLOGY

Five-year precipitation data collected from the Tropical Rain Measuring Mission-Precipitation Radar (TRMM-PR) satellite and Global Precipitation Measurement (GPM)

mission's Core Observatory were analyzed [27]. The precipitation data were used to determine the distribution of rain rate in six West African countries shown in Figure 1 from 2013 to 2017. Table 1 highlights the three locations selected in each country with their characteristics. Tropospheric Data Acquisition Network (TRODAN) data in Nigeria from 2013 to 2014 was employed for comparison. The TRODAN stations are centres of the National Space Research and Development Agency (NASRDA) [28]. The TRMM and GPM are American-Japanese joint earth satellite observatory missions. TRMM was launched in November 1997 and placed at an altitude of 350 km, later extended to 402.5 km. The TRMM was succeeded and improved upon by the GPM mission launched in 2014. Both missions, TRMM-GPM, were established to provide a comprehensive knowledge of the nature of precipitation, snow and radiation in the tropical regions of the earth [27,29].

4. DATA ANALYSIS

4.1 Rain Distributions

Data collected from the TRMM-GPM at the eighteen selected locations in West Africa, as presented in Table 1, were processed and analyzed. The monthly, yearly, 5-minute rain rate and the 1-minute rain distributions of the locations showing the average monthly rainfall accumulations during the observation period are as shown in Figs. 2-14.

TABLE 1: Site characteristics

Countries	Locations	Longitude (-°W/ +°E)	Latitude (°N)	Height a.s.l. (m)	Elevation Angle (θ)	Average Annual Rainfall (mm)
Ghana	Bawku	-0.2534	11.0464	247.6	57.9	992.807
	Tamale	-0.8631	9.4031	191.2	56.1	1682.23
	Accra	-0.3028	5.6243	91.9	51.8	1890.9
Nigeria	Kano	8.6455	11.9820	448.4	63.3	1374.56
	Abuja	7.2744	9.1094	478.1	58.2	2427.931
	Lagos	3.3475	6.5869	32.2	533.3	2498.43
Côte d'Ivoire	Tingrela	-6.5215	10.5204	362.5	57.1	2168.99
	Katiola	-5.12057	8.1464	291.8	54.9	1813.12
	Abidjan	-4.0976	5.3619	76.0	52.2	1779.88
Cameroon	Maroua	14.3368	10.7659	414	67.7	966.28
	Toubo	15.22	7.7954	545.3	60.4	2290.97
	Kumba	9.3930	4.6505	250.3	51.5	4892.3
Benin	Kandi	2.9250	11.1372	170.6	57.9	1680.04
	Djougou	1.6824	9.7355	44.9	56.6	2137.89

	Cotonou	2.3985	6.3802	5.5	52.5	1668.45
Togo	Dapaong	0.1208	10.9100	298.1	57.9	1690.84
	Kara	1.0858	9.5566	315.6	56.6	2238.91
	Lome	1.1627	6.1507	20.3	52.5	1080.8

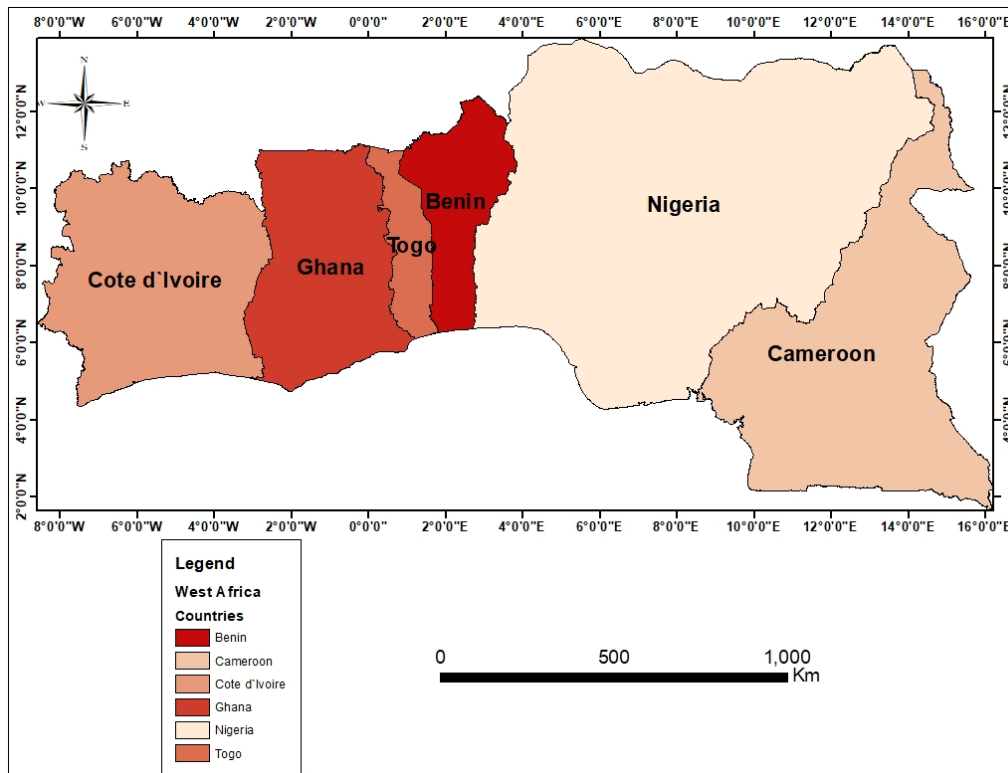


FIG. 1: Map of West Africa showing the selected six countries

5. RESULTS

Figures 2 and 3 and Table 1 revealed that the annual rainfall accumulation distribution in Cote d’Ivoire had a range between 1813.12 mm and 2168.99 mm, with Tingrela having the highest amount of rainfall. In Cameroon, the values ranged between 2290.17 mm and 4892.3 mm, with Koubaloum having the highest amount of rainfall. Similarly, the ranges are 1668 mm – 2137.89 mm, 992 mm – 1890.28 mm, 1080 mm – 2238 mm, and 1374 mm – 2498 mm for Benin, Ghana, Togo and Nigeria with Djougou, Bawku, Kara, and Lagos having the highest rainfall, respectively. The worst months,

being the period of the high amount of rainfall, were observed between July and August in Cameroon and July and October in the remaining five countries.

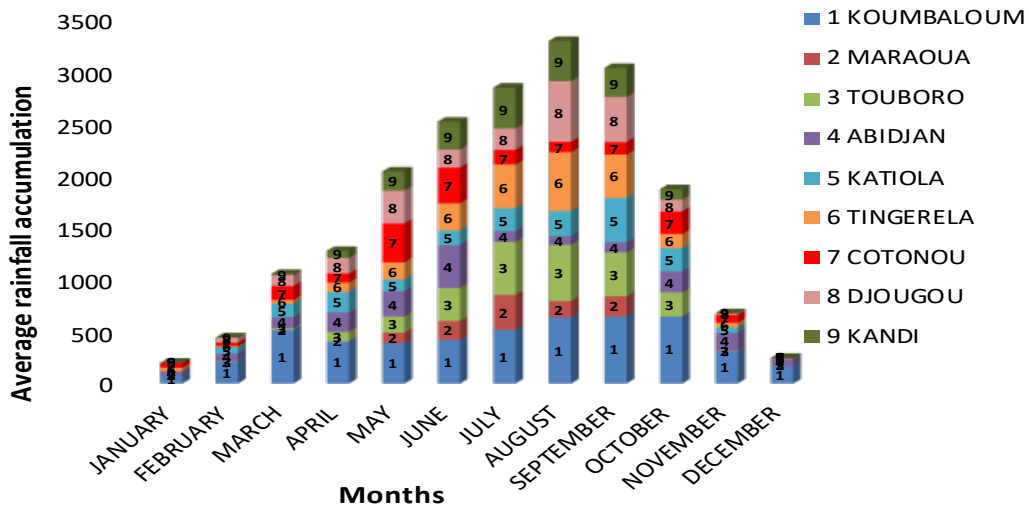


FIG. 2: Average monthly rainfall accumulation during the observation period

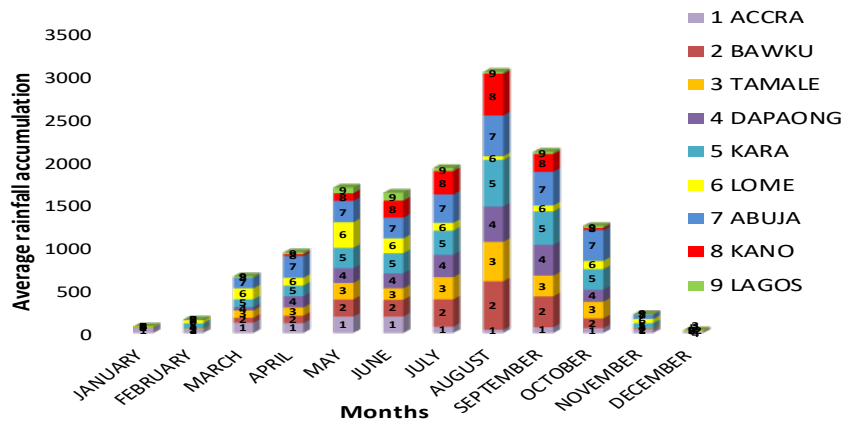


FIG. 3: Average monthly rainfall accumulation during the observation period

Figures 4-6 present the 5-minute integration time rain rate obtained from TRMM-GPM. 5-minute integration time was found to be very high at 0.001% across all locations; it fluctuated between 190 mm/h and 200 mm/h but low at 0.01% and 1%.

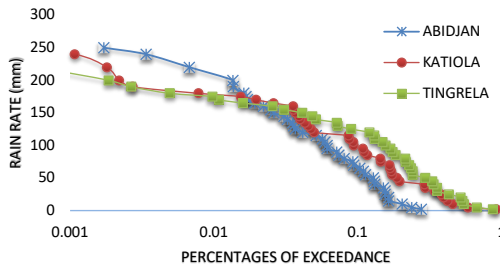


FIG. 4: 5-minutes rain rate distributions over Cote d'Ivoire

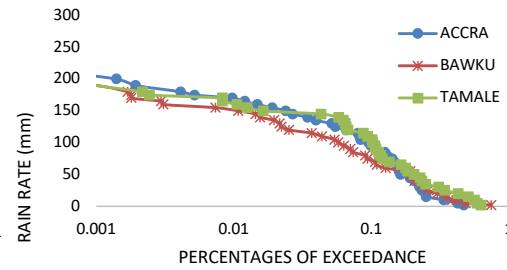


FIG 5: 5-minute rain rate distributions over Ghana

The disparity in cumulative rain rate distributions for the year 2013 to 2017 is presented for each of the six countries in Figs. 7-12. The rain rate calculated in terms of the probability of exceedance ranges from 0.0001% to 1.0%, which is equivalent to 99.9999% to 99% availability, using a 1-minute integration time for both Moupfouma and ITU-R models. The highest rain rate of 115 mm/h at 0.01% probability of exceedance in Kumbaloum is an indication of a high level of signal degradation at the location. Figures 7-12 show that Moupfouma predictions are higher than that of ITU-R at all probabilities of exceedance in Ghana, Cote d'Ivoire, Cameroon, and Benin. On the other hand, ITU-R forecasts are higher at probabilities of exceedance below 0.01% with values of 222 mm/h, 182 mm/h, and 170 mm/h in Lagos, Abuja and kano across Nigeria, and 165 mm/h, 180 mm/h, and 180 mm/h in Lome, Kara, Dapaong across Togo, respectively. The predicted values of Moupfouma model converged at 0.01% probability of exceedance at all locations. The convergence indicates that the rain rate would be identical across all the locations. By implication, electromagnetic waves would suffer similar level degradation across all the locations at 0.01% of probability of exceedance. Hence 0.01% point marks the transition from low rain rate with a high probability of exceedance regime to high rain rate with a low probability of exceedance regime.

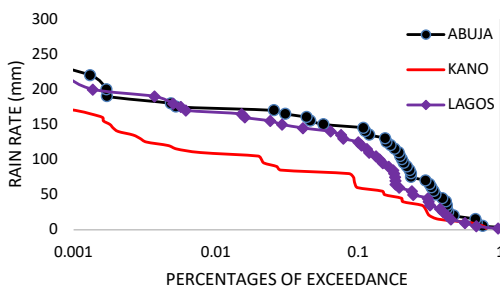


FIG. 6: 5-minute rain rate distributions over Nigeria

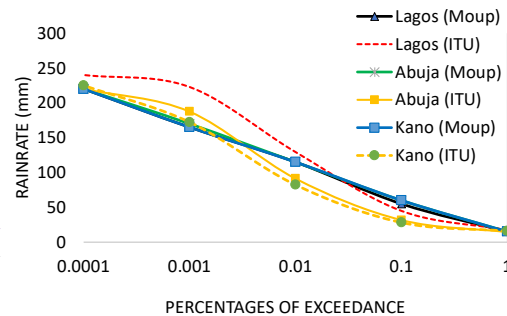


FIG. 7: 1-minute rain rate distributions over Nigeria

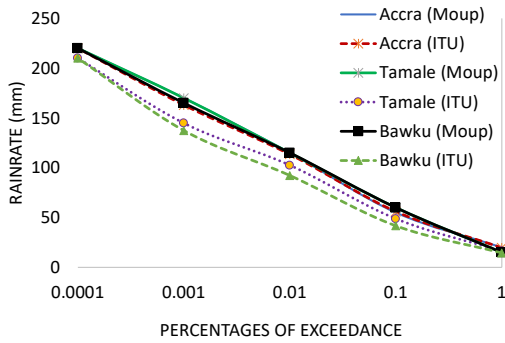


FIG. 8: 1-minute rain rate distributions over Ghana

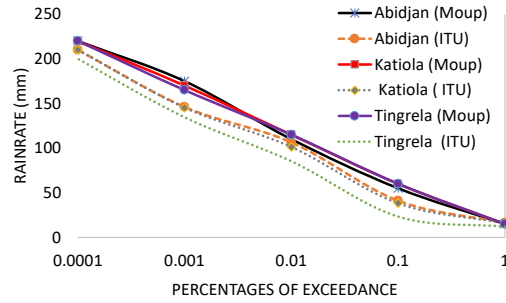


FIG. 9: 1-minute rain rate distributions over Cote d'Ivoire

Figure 13 presents the TRMM-GPM predicted rain rate compared with the in-situ TRODAN rain rate from 2013 to 2014 over Nigeria. Moupfouma predicted rain rate appeared similar to the measured from 1% to 0.01% probability of exceedance. The predictions by Moupfouma underestimates the rain rates at a higher probability of exceedance. Similarly, Moupfouma overestimates at a lower probability of exceedance. However, both measured and the predicted values exhibited a low degree of dispersion for Minna from 1% to 0.01%. For instance, at 0.01% the measured rain rate recorded 129 mm/h, 120 mm/h, and 111 mm/h in Lagos, Kano, and Minna, respectively, while Moupfouma predicted 115 mm/h across all the locations. On the other hand, both TRODAN and ITU R reported 129 mm/h over Lagos at 0.01% in Fig. 14, with a higher degree of dispersion at other probabilities across all the locations. Hence, ITU-R underestimates at high percentages of the probability of exceedance and overestimates at lower probability.

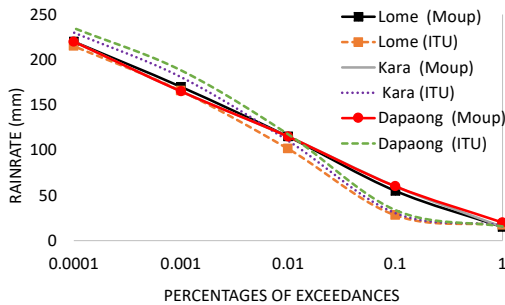


FIG. 10: 1-minute rain rate distributions over Togo

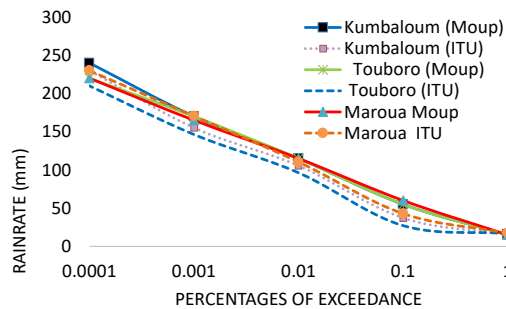


FIG. 11: 1-minute rain rate distributions over Cameroon

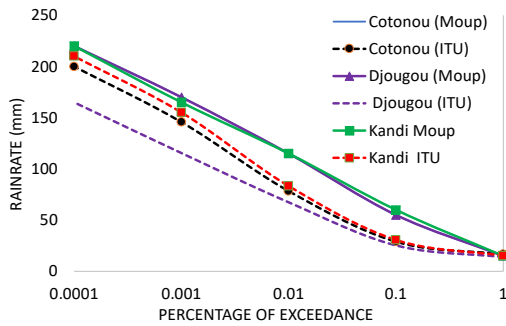


FIG. 12: Typical 1-minute rain rate distributions over Benin

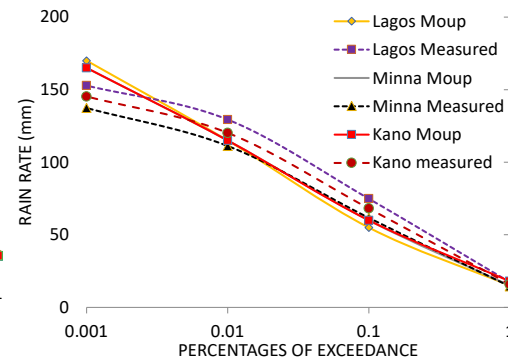


FIG.13: Comparison between in-situ and TRMM-GPM derived 1-minute rain rate distributions over Nigeria (Moupfouma model)

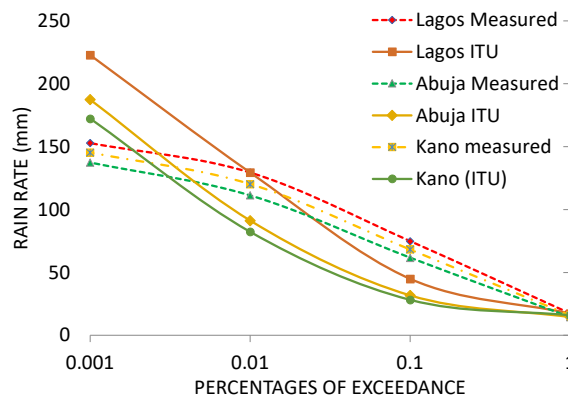


FIG. 14: Comparison between TRODAN and TRMM-GPM derived 1-minute rain rate distributions over Nigeria (ITU model)

6. CONCLUSIONS

The typical distribution of the statistics of 1-minute rain rate derived from the TRMM-GPM 5-minute rain rate across six West African countries using ITU-R and Moupfouma models were presented. Measured 1-minute rain rate from TRODAN was used to validate the ITU-R and Moupfouma models derived 1-minute rain rate across Nigeria. Both ITU-R and Moupfouma models underestimate rain rate at high probability of exceedance and overestimate at low probability of exceedance. However, Moupfouma predicted rain rates showed low degree of dispersion compared to ITU-R, which showed high degree of dispersion. The result shows that both models are not suitable for

estimating 1-minute rain rate statistics in West Africa, which is required for radio propagation links planning and design over West Africa.

ACKNOWLEDGEMENTS

Centre for Atmospheric Research (CAR), National Space Research and Development Agency (NASRDA) and National Aeronautics and Space Administration (NASA) are appreciated for their support to access the data used for this study.

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