Progress In Electromagnetics Research M, Vol. 49, 1–8, 2016

Cumulative Distributions of Rainfall Rate over Sumatra

Marzuki[1, *], Hiroyuki Hashiguchi[2], Toyoshi Shimomai[3], and Walter L. Randeu[4]

Abstract—The microwave radio links above 5 GHz suffer from attenuation due to precipitation. The need for employing higher frequencies has therefore encouraged research into rain attenuation due to precipitation. The natural variations of tropical precipitation occur in a wide range of time-scales, so does probably the behavior of radio communication links. This paper examines the variations of cumulative distribution of rainfall in Sumatra from an optical rain gauge measurement with a near continuous record of operation over eleven consecutive years (2002–2012). The worst month statistics were also examined and all results were compared with the ITU-R model. Of some natural variations of rainfall rate investigated, the diurnal variation had the most significant effect on the cumulative distribution of rainfall rate. The ITU-R model overestimated the rainfall rate for the first half of the day (00:00–11:59 LT) whereas it underestimated the rainfall rate until 0.01% of time for the second half of the day (12:00–23:59 LT) before the model starts to overestimate. The ITU model overestimated 52.85% of rainfall rate at 0.01% of time for the first half of the day and underestimates 7.59% for the second half. Considerable differences between the recorded data and the ITU-R model for the annual, seasonal, and intreaseasonal variations are only significant at small time percentage ($\leq$ 0.01%). The relationship of worst month statistics was also slightly different from the ITU-R model. This result reinforces the previous studies on the limitation of the ITU-R model for the tropical region.

1. INTRODUCTION

Electromagnetic wave propagation of high frequency links is strongly attenuated by rain, particularly in communication systems operating at frequencies above 5 GHz. Therefore, rain attenuation is the major concern for telecommunication system designers. Rain attenuation of line of sight or satellite link systems, can be estimated when the statistic of point rainfall rate of the location of interest is available. Integration time, average cumulative distributions and worst-month distributions are among important rainfall rate statistics for modeling the rain attenuation. Once such statistical measures are available, the designer can predict the percentage of time during which the attenuation due to rain is significant within an average year, the future link performance and the availability of communication services [1].

The prediction method recommended by the International Telecommunication Union Radiocommunication Sector (ITU-R) is widely used to estimate the rain attenuation. However, when the method is applied to the tropical regions, the inaccuracy of these empirical formulaes have been reported by many investigators [2–6]. In addition to the lack of rainfall and attenuation data, the inaccuracy of the ITU-R model for the tropical region may be due to the variability of precipitation in this region. Tropical precipitation varies in a wide range of time-scales, in comparison with the temperate region. Therefore, it is worthwhile to conduct more study on the characteristics of tropical rainfall. This paper presents the cumulative distributions of rainfall rate over Sumatra in term of natural variation of precipitation in the region. The data are from an optical rain gauge measurement with a near continuous record of operation over eleven consecutive years (2002–2012) at Kototabang (KT), west Sumatra (0, 20°S,

---

Received 30 April 2016, Accepted 3 June 2016, Scheduled 30 June 2016

* Corresponding author: Marzuki (marzuki@fmipa.unand.ac.id).

[1] Department of Physics, Andalas University, Padang, Indonesia. [2] Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Japan. [3] Interdisciplinary Faculty of Science and Engineering of Shimane University, Japan. [4] Institute of Microwave and Photonic Engineering, Technical University of Graz, Austria.

100, 32°E; 864 m above sea level). This study can be additional reference for ongoing effort to improve the rain attenuation models for the telecommunication system design in the tropical rainfall.

2. DATA AND METHODOLOGY

An Optical Rain Gauge (ORG) has been installed at KT since 2002. The instrument is part of the Equatorial Atmosphere Radar (EAR) facilities, sampling rain rate every 1 minute. We analyzed the rain rate with a near continuous record of operation over eleven consecutive years (2002–2012). The number of observation days for each year are 295 (2002), 356 (2003), 352 (2004), 355 (2005), 333 (2006), 264 (2007), 362 (2008), 359 (2009), 353 (2010), 361 (2011) and 305 (2012). The availability of data on monthly basis was given in Fig. 1. The percentage indicates the ratio of monthly recorded samples to the total number of samples that would have been recorded had no measurement failures occurred during a given month. It can be seen that the availabilities of data during 2002, 2006, 2007 and 2012 are lower than 80%. Therefore, the data during these years were excluded in the analysis.

Sumatra's tropical rainfall variation occurs in a wide range of time-scales. Peak of rainfall is observed during 12:00–24:00 local time (LT) and 00:00–12:00 LT in the inland region of Sumatra Island and the offshore region of the Indian Ocean [7], respectively. This characteristic is also obvious from the long-term rainfall record (Fig. 2). Such diurnal cycle of precipitation results in the diurnal cycle of raindrop size distribution and influences the rain attenuation modeling of this region [8]. Thus, the diurnal variation of attenuation statistics have to be considered for the fade margin design [9]. Therefore,we grouped the data into 00:00–11:59 and 12:00–23:59 LT, over 12-hour interval.

Second precipitation variation, which is analyzed, is the intraseasonal variation in response to Madden Julian Oscillation (MJO). The MJO is the major oscillation in tropical weather on weekly to monthly timescales (30–60 days) that can be characterized as an eastward moving super cloud cluster and rainfall near the equator [10]. Ratio of total rainfall during active to inactive MJO phase is about 1.2, but the ratio of rain data is about 1.6. Thus, convective storms are more intense but shorter

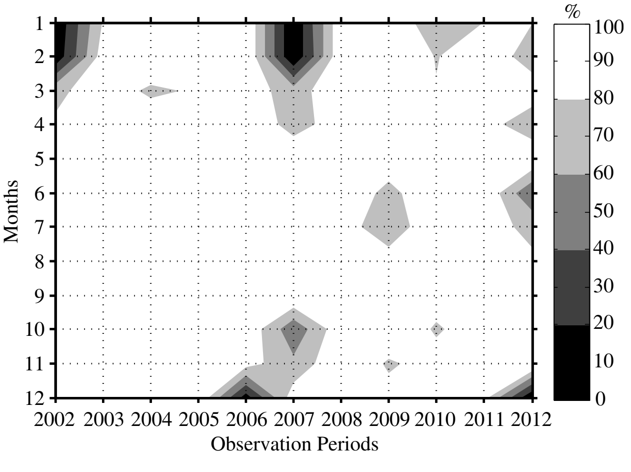

Figure 1. Availability of the data on monthly basis. The percentage indicates the ratio of monthly recorded samples to the total number of samples that would have been recorded had no measurement failures occurred during a given month.

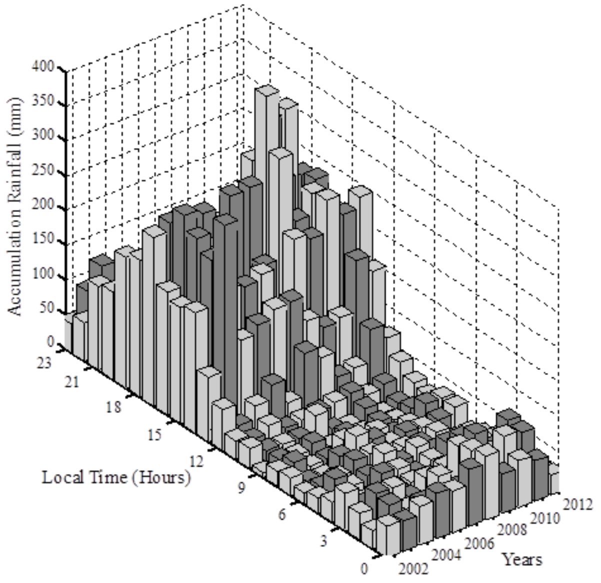

Figure 2. Total rainfall on diurnal basis from 2002–2012.

duration during the inactive MJO phase than during active one [11]. Therefore, we classified the data into active and inactive MJO phases. The amplitude and phase of the MJO were determined by using the Realtime Multivariate MJO index [12]. The index that has amplitude greater than one was assumed as strong MJO, and conversely it was defined as weak MJO. The strong MJO index was classified into two phases, i.e., active and inactive (suppressed) as in [11].

Sumatra is located in the Asian monsoon climate region [13]. Sumatra receives more rainfall during the southwesterly monsoon (SW) [7]. To examine the cumulative distribution of rainfall on seasonal basis, we divided a year into four monsoons, i.e., pre-SW (April–May), SW (June–September), pre-northeast (NE) monsoon (October–November) and NE (December–March) [13].

3. RESULTS

3.1. Variation of Cumulative Distribution of Rainfall

Figure 3 shows the cumulative distribution of rainfall rate in Sumatra for several selected years compared with the ITU-R model [14]. The discrepancy is obvious when the rain rate becomes large or time percentage becomes small. The rainfall rate of 0.01% and 0.001% percentage time from our experiment during 2011 has the largest value, namely, 102.68 and 153.26 mm/hr, respectively, in comparison with 95.05 and 148.33 mm/hr from the ITU-R model. Such high values are also observed in Malaysia in which 0.001% time rainfall rate is 140.0–218.0 mm/h [15]. Sumatra is close to Malaysia so that the climatology of rainfall for Indonesia is almost similar to Malaysia.

The cumulative distribution of rainfall in Sumatra may be also influenced by El Nino/Southern Oscillation (ENSO). Theoretically, during El-Nino, western part of Pacific including Indonesia receives less rainfall, and vice versa for La-Nina year [16]. To observe the effect of ENSO, we divided the years into several ENSO conditions based on the index proposed by the National Oceanic and Atmospheric Administration (NOAA). Annual rainfall of some normal years such as 2003 and 2008 are higher than La-Nina years such as 2010 and 2011 (Table 1). Thus, higher total rainfall during La-Nina was not clearly observed from point rainfall data at KT. However, intense rainfall at KT is more dominant during La-Nina years than other ENSO periods indicated by larger rainfall intensity for small time percentage (Fig. 3). Lack of annual and seasonal variation of rainfall in Sumatra is probably due to the local convective and the orographic effect that can be caused by the complex topography of Sumatra Island [13].

The cumulative distribution of rainfall rate on a diurnal basis is depicted in Fig. 4. The bolded solid line is the cumulative rain rate distribution at KT obtained from the ITU-R model [14]. It is clearly

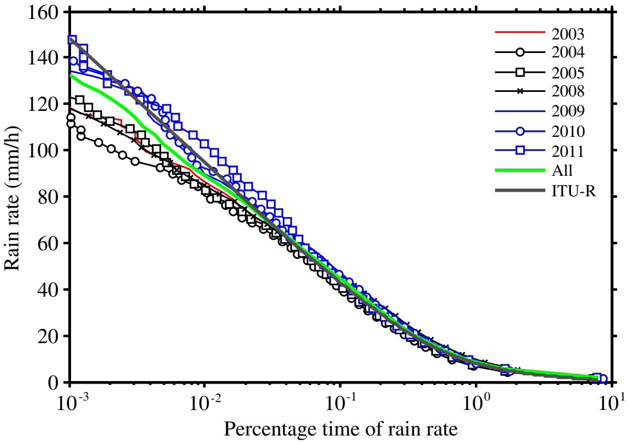

Figure 3. Cumulative distribution of rainfall rate at Kototabang on a yearly basis for several years from 2002 to 2012, compared with the ITU-R prediction [14].

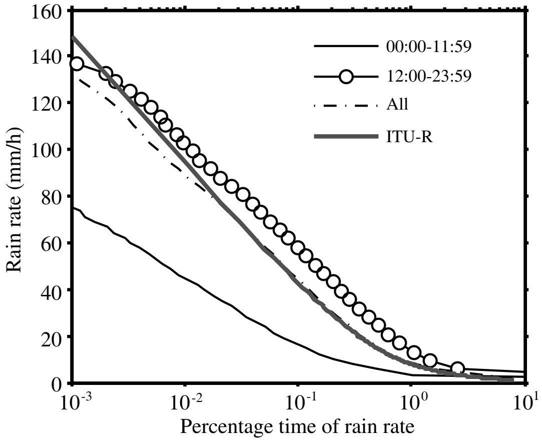

Figure 4. Cumulative distribution of rainfall rate at Kototabang on a diurnal basis from 2002 to 2012, compared with the ITU-R model [14].

Table 1. Rainfall rate of several percentage times on a yearly basis for several years from 2002 to 2012, compared with the ITU-R prediction [14]. Total rainfall is in unit of mm/year and N of ENSO status indicates normal, ME indicates moderates El-Nino, ML indicates moderate La-Nina and WL indicates weak La-Nanina.

Remark	Total rainfall	ENSO	1%	0.10%	0.01%	0.001%
ITU-R	-	-	8.01	42.97	95.05	148.33
2003	2498.79	N	8.18	43.94	86.42	120.61
2004	1985.16	ME	6.48	40.28	82.47	113.74
2005	2164.36	N	7.11	41.21	82.82	121.55
2008	2770.18	N	9.64	45.44	84.64	117.88
2009	2367.55	ME	8.23	46.95	89.73	139.34
2010	2327.80	ML	8.01	45.78	93.20	139.44
2011	2325.75	WL	8.55	43.74	102.68	153.26
All	-	-	8.51	44.46	89.18	132.81

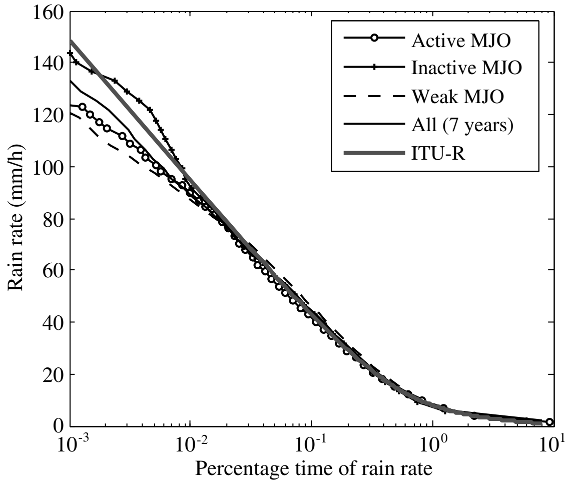

Figure 5. Cumulative distribution of rainfall rate at Kototabang on a intraseasonal basis from 2002 to 2012, compared with the ITU-R prediction [14].

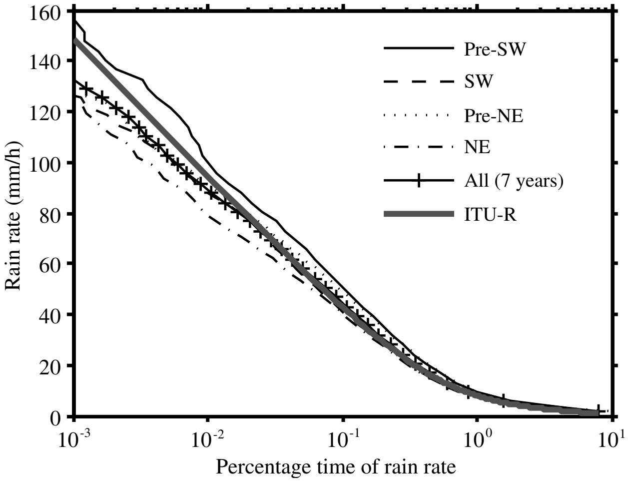

Figure 6. Cumulative distribution of rainfall rate at Kototabang on a seasonal basis from 2002 to 2012, compared with the ITU-R prediction [14].

seen that rain at KT primarily occurs in the afternoon as also obvious from Fig. 2. During the first half of the day (00:00–11:59 LT), the rainfall rate of 1, 0.1, 0.01, and 0.001% percentage time from our experiment are 3.64, 16.25, 44.82, 75.29 mm/h, respectively. These values are much lower than those of ITU-R model (Table 1). On the other hand, during the second half of the day (12:00–23:59 LT), they are 13.61, 57.61, 102.26 and 132.04 mm/h, respectively. The rainfall rate of 0.001% percentage time from our experiment is slightly lower than the ITU-R model but other percentages are higher. Rainfall rate statistics are used in the rain attenuation prediction model. The ITU rain attenuation prediction method is based on 0.01% of rainfall rate parameter. It can be seen that the ITU model overestimates 52.85% of rainfall rate at 0.01% of time for the first half of the day and underestimates 7.59% for the second half.

Figure 5 shows the cumulative distribution of rainfall on an intraseasonal basis. It can be seen that during the inactive MJO phase, the rainfall rate is higher than during the active phase, for the same percentage, particularly for small time percentage. During the active phase, the 1, 0.1, 0.01, and 0.005% percentage time rainfall rates from our experiment are 8.20, 41.74, 89.52 and 101.17 mm/h, respectively. The values for the inactive phase are 7.55, 43.98, 92.05, and 119.43 mm/h. The distribution of rainfall during active and inactive MJO phases are not much different from that of weak MJO phase and are in fairly good agreement with the value estimated by the ITU-R model (Table 1). At small time percentages, the cumulative distribution of measured rain rates during the inactive MJO phase is slightly higher than during the active phase, consistent with the previous study [11]. For example, the rainfall rate of 0.005% percentage time for inactive and active MJO phases are 119.43 and 101.17 mm/h, respectively.

The cumulative distribution of rainfall rate on a seasonal basis is depicted in Fig. 6. Pre-SW monsoon has the highest rainfall rate for all time percentages. The 1, 0.1, and 0.01% percentage time rainfall rates from our experiment for Pre-SW are 9.23, 50.95 and 99.62 mm/h, respectively. These values are slightly higher than those of ITU-R model (Table 1). On the other hand, NE monsoon has the lowest rainfall rate for all time percentages. The 1, 0.1, and 0.01% percentage time rainfall rates for NE monsoon are 7.52, 40.42, and 79.19 mm/h, respectively. These values are slightly lower than those of ITU-R model.

3.2. Worst Month

Worst month statistics is important for the design of radio telecommunication systems, especially if the system has to fulfill quality criteria in any month of the year. The concept of worst month statistics can be found in the ITU-Recommendation [17]. The annual worst month of 12 consecutive months is calculated by selecting the worst performance at each annual occurrence level among all months. Suppose X_{ij} is the probability of exceeding for a threshold level j in the ith month. The worst month at level j is determined by taking the highest X_{ij} among all 12 months, suppose called by X_{hj}. The worst month probability distribution for particular year consists of all X_{hj} values for the various j levels. The calendar month to which each X_{hj} belongs may vary from one level j to the next. For multiple year data, the average annual worst-month probability is formed by taking the average of the individual annual worst-month probabilities for each level j [18].

The average worst month statistic probability (X) and the average annual statistics (Y) can be governed by the following equation:

$$Q = X/Y, \tag{1}$$

where Q is a function of the occurrence level and the climatic region. Q may be expressed by the power law of the form [19]

$$Q = AY^{-\beta}. \tag{2}$$

To relate X and Y, Eq. (2) can be written as

$$X = AY^{1-\beta}. \tag{3}$$

The ITU-R recommends the values of $A = 2.85$ and $\beta = 0.13$ for global planning purposes. In case of the worst month and annual statistics are expressed as percentages rather than probabilities, then $A = 3.0$ and $\beta = 0.13$.

Figure 7 shows a composite curve of rain rate exceedance for worst month. The relationship between the annual rain rate exceedance to the worst month rain rate exceedance is shown in Fig. 7(a) and is expressed by

$$P_a = 0.63 P_w^{1.18}, \quad r^2 = 0.998 \tag{4}$$

where P_a is the annual rainfall rate exceedance and P_w the worst month rainfall rate exceedance.

Figure 7(b) shows the Q factor as a function of annual percentage of rain rate exceedance. Q was found to follow the power law of the form:

$$Q = 1.39 Y^{-0.24}, \quad r^2 = 0.962 \tag{5}$$

It can be seen that the Q factor for the rainfall rate at KT is different from the value proposed by the ITU-R for global planning purpose. Moreover, it is also different from the recommended value for Indonesia, i.e., $A = 1.7$ and $\beta = 0.22$ [19]. Coefficient of A in Sumatra is lower than the ITU-R model, not only for composite curve but also for yearly data (Table 2). On the other hand, the worst-month statistics for Malaysia is $A = 1.68$ and $\beta = 0.07$ [20]. Although the cumulative distribution of rainfall rate in Sumatra is similar to Malaysia, the worst-month statistics is different. This indicates that the characteristics of temporal rainfall variability in Indonesia may be different from Malaysia [21]. Furthermore, the regional variation of the rainfall in Indonesia is also significant [7, 22].

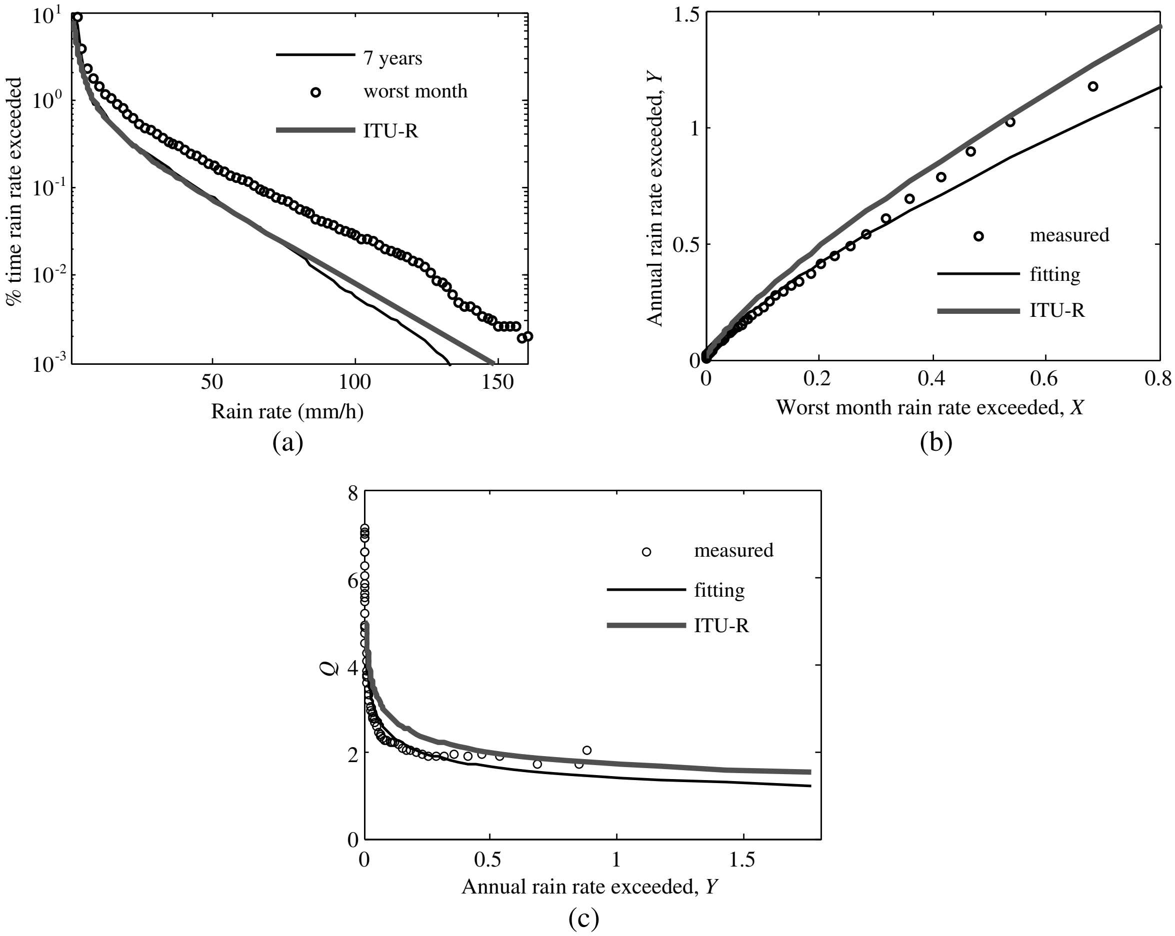

Figure 7. Annual and worst month cumulative distribution of rainfall rate at Kototabang for the period from 2002 to 2012, compared with (a) the ITU-R [14] and the ITU-R of worst month [19], (b) seven years averaged annual rainfall exceedance against worst month attenuation exceedance and (c) Q factor as a function of annual percentage of rainfall exceedance along with the ITU-R model [19].

Table 2. Coefficient of worst month statistics of rainfall rate at Kototabang compared with the ITU-R model.

Remark	A	β
2003	1.04	0.25
2004	1.52	0.19
2005	1.03	0.26
2008	1.54	0.22
2009	1.59	0.24
2010	1.22	0.31
2011	1.31	0.26
All	1.39	0.24
ITU-R	1.70	0.22

4. CONCLUSIONS AND FUTURE WORKS

The result shows that the cumulative distribution of rainfall rate in the tropical region is strongly influenced by some variabilities. Such variabilities limit the accuracy of the ITU-R model. The ITU-R model overestimates the measured rainfall rate for the first half of the day (00:00–11:59 LT) whereas it underestimates the measured rainfall until 0.01% of time for the second half of the day (12:00–23:59 LT) before the model starts to overestimate. ITU model overestimates 52.85% of rainfall rate at 0.01% of time for the first half of the day and underestimates 7.59% for the second half. Considerable differences between the recorded data and the ITU-R model for the annual, seasonal, and intreaseasonal variations are only significant at small time percentage ($\leq 0.01\%$). The relationship of worst month statistics is also slightly different from the one proposed by the ITU-R model. Thus, the variability of tropical precipitation should be kept in mind when modeling the radio communication links in the tropical region such as for the fade margin design. The current result is only from one point rainfall and more study must be done to apply the rainfall variability into the ITU-R model. Therefore, the distribution of one-minute rain rate in Indonesia derived from the Tropical Rainfall Measuring Mission (TRMM) satellite data is being analyzed and will be published in subsequent papers.

ACKNOWLEDGMENT

Optical Rain Gauge (ORG) and other EAR facilities at Kototabang are supported by Grant-Aid for Scientific Research on Priority Areas funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

REFERENCES

1. Moupfouma, F. and L. Martin, "Modelling of the rainfall rate cumulative distribution for the design of satellite and terrestrial communication systems," *Int. J. Satellite Commun.*, Vol. 13, 105–115, 1995.
2. Manabe, T., T. Ihara, J. Awaka, and Y. Furuhama, "The relationship of raindrop-size distribution to attenuation experiments at 50, 80, 140, and 240 GHz," *IEEE Trans. Antennas Propag.*, Vol. 35, 1326–1330, 1987.
3. Yeo, T. S., P. S. Kooi, M. S. Leong, and S. S. Ng, "Microwave attenuation due to rainfall at 21.225 GHz in the Singapore environment," *Electron. Lett.*, Vol. 26, No. 14, 1021–1022, 1990.
4. Yeo, T. S., P. S. Kooi, and M. S. Leong, "A two-year measurement of rainfall attenuation of CW microwaves in Singapore," *IEEE Trans. Antennas Propag.*, Vol. 41, No. 6, 709–712, 1993.
5. Zhou, Z. X., L. W. Li, T. S. Yeo, and M. S. Leong, "Analysis of experimental results on microwave propagation in Singapore's tropical rainfall environment," *Microwave Opt. Technol. Lett.*, Vol. 21, No. 6, 470–473, 1999.
6. Obiyemi, O. O., J. S. Ojo, and T. S. Ibiyemi, "Performance analysis of rain rate models for microwave propagation designs over tropical climate," *Progress In Electromagnetics Research M*, Vol. 39, 115–122, 2014.
7. Mori, S., J. I. Hamada, I. M. Yudi, M. D. Yamanaka, N. Okamoto, F. Murata, N. Sakurai, H. Hashiguchi, and T. Sribimawati, "Diurnal land-sea rainfall peak migration over Sumatera island, Indonesian maritime continent, observed by TRMM satellite and intensive rawinsonde soundings," *Mon. Weather Rev.*, Vol. 132, No. 8, 2021–2039, 2004.
8. Marzuki, T. Kozu, T. Shimomai, W. L. Randeu, H. Hashiguchi, and Y. Shibagaki, "Diurnal variation of rain attenuation obtained from measurement of raindrop size distribution in equatorial Indonesia," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 4, 1191–1196, 2009.
9. Fiebig, U.-C. and C. Riva, "Impact of seasonal and diurnal variations on satellite system design in V band," *IEEE Trans. Antennas Propag.*, Vol. 52, No. 4, 923–932, 2004.
10. Madden, R. A. and P. R. Julian, "Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific," *J. Atmos. Sci.*, Vol. 28, 702–708, 1971.

11. Marzuki, H. Hashiguchi, T. Kozu, T. Shimomai, Y. Shibagaki, and Y. Takahashi, "Precipitation microstructure in different Madden-Julian oscillation phases over Sumatra," *Atmos. Res.*, Vol. 168, 121–138, 2016.
12. Wheeler, M. C. and H. H. Hendon, "An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction," *Mon. Weather Rev.*, Vol. 132, No. 8, 1917–1932, 2004.
13. Kozu, T., K. K. Reddy, S. Mori, M. Thurai, J. T. Ong, D. N. Rao, and T. Shimomai, "Seasonal and diurnal variations of raindrop size distribution in Asian Monsoon region," *J. Meteor. Soc. Japan. Ser. II*, Vol. 84A, 195–209, 2006.
14. Radiowave Propagation Series, I.T.U., "Characteristics of precipitation for propagation modelling," Recommendation ITU-R P.837-5, International Telecommunications Union, Geneva, 2007.
15. Omotosho, T. V., J. S. Mandeep, M. Abdullah, and A. T. Adediji, "Distribution of one-minute rain rate in Malaysia derived from TRMM satellite data," *Ann. Geophys.*, Vol. 31, 2013–2022, doi:10.5194/angeo-31-2013-2013, 2013.
16. Hendon, H. H., "Indonesian rainfall variability: Impacts of ENSO and local air-sea interaction," *J. Clim.*, Vol. 16, No. 11, 1775–1790, 2003.
17. Radiowave Propagation Series, I.T.U., "The concept of worst month," Recommendation ITU-R P.581-2, International Telecommunications Union, Geneva, 1990.
18. Chebil, J. and T. A. Rahman, "Worst-month rain statistics for radio wave propagation study in Malaysia," *Electron. Lett.*, Vol. 35, 1447–1449, 1999.
19. Radiowave Propagation Series, I.T.U., "Conversion of annual statistics to worst-month statistics," Recommendation ITU-R P.841-4, International Telecommunications Union, Geneva, 2005.
20. Ting, T. T. and J. S. Mandeep, "Analysis of worst-month relationship with annual rain attenuation in Malaysia," *Research Journal of Applied Sciences, Engineering and Technology*, Vol. 7, No. 7, 1453–1455, 2014.
21. Aldrian, E. and R. D. Susanto, "Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature," *Int. J. of Climatology*, Vol. 23, No. 12, 1435–1452, 2003.
22. Marzuki, H. Hashiguchi, M. K. Yamamoto, S. Mori, and M. D. Yamanaka, "Regional variability of raindrop size distribution over Indonesia," *Ann. Geophys.*, Vol. 31, 1941–1948, doi:10.5194/angeo-31-1941-2013, 2013.