CHAPTER 8

DIURNAL VARIATIONS OF RAIN ATTENUATION

8.1 Introduction

Some satellite applications such as Direct broadcasting services that rely on the prime-time interval, satellite operators must concern on the high attenuation period within a day from the day-to-day (diurnal) variation of rain attenuation statistic. If statistics of long-term diurnal variations of rain attenuation are known, it may be possible to relocate the essential traffic to avoid the high attenuation period and/or utilizes the power control technique to compensate attenuation only in that high fading period. Then, the satellite capacity and the earth station transmitted powers may utilize more efficiently.

This Chapter presents results study of the diurnal variation of rain attenuation and rainfall statistics in Southeast Asia over a three year period. Data were analyzed to obtain the conditional probability distribution and the measured cumulative distribution of attenuation every 2 hours.

8.2. Data Analysis

Rain attenuation and rainfall rate data to be analyzed in this paper were taken from March 1992 to February 1995. Table 8.1 summarizes the total observation hours of each year (Total hours), percent of attenuation of each year and all 3 years.

To obtain the diurnal variation of rain attenuation, the probability theorem needs to be introduced. The diurnal variations of rain attenuation is the density function of the conditional probability of attenuation in each observation period or a number of hours. The conditional probability of attenuation occurring in each i'th hour can be expressed by

$$P(Hi\backslash Y) = P(Hi,Y)/P(Y) \quad \text{------------------------}(8.1)$$

where

i is the selected interval number (0708LT,0910LT,...,0506LT)

Hi is the event of attenuation exceeding the threshold in i'th interval

Y is the event of attenuation exceeding the threshold in 24 hours,

P(Hi,Y) is the joint probability of event Hi and event Y,

P(Y) is the probability of event Y.

From a long-term observation, the diurnal variation of attenuation in each i-hour interval can be expressed by

$$P(Hi\backslash Y) = \frac{T(A \geq \alpha \text{ dB, in i Hours})}{T(A \geq \alpha \text{ dB, in 24 Hours})} \quad \text{------------------(8.2)}$$

where

$T(A \geq \alpha$ dB, in i Hours) and $T(A \geq \alpha$ dB in 24 Hours) are the total accumulation time that the measured attenuation (A) exceeds α dB in each i'th duration and 24 hours.

In this analysis, each interval equals to 2 hours period and the number of a cumulative distribution equals to 12 curves which can make it easy to compare the measured and the predicted curves. The 2-hour diurnal curves (conditional probability distribution) can be obtained from each daily data by dividing all daily time-interval into each 2-hour interval, starting from 0700-0800LT to 0500-0600LT local time (LT), and observing the measured attenuation exceeding the threshold of 2, 4, 6, 8 and 10 dB. The local time in Southeast Asia is 7 Hour + GMT time.

Table 8.1 Total observation hours (Total hours), The percent of measured attenuation exceeding the threshold P(Y).

	Bangkok				Si-racha			
Atten. (dB)	Year-1 (1992)	Year-2 (1993)	Year-3 (1994)	3-years (92-94)	Year-1 (1992)	Year-2 (1993)*	Year-3 (1994)	3-Years (92-94)
Total Hours	7,796.4 (89%)	7,813.92 (89.2%)	6,412.32 (73.2%)	22,022.6 (84%)	8,409.6 (96%)	5,983.08* (68.3%)	7,884.0 (90%)	22,276.6 (84.7%)
2 dB	1.689%	1.881%	2.075%	1.881%	1.6%	1.631%*	1.648%	1.62%
4 dB	0.898%	1.041%	1.177%	1.040%	0.859%	0.895%*	0.922%	0.879%
6 dB	0.548%	0.636%	0.795%	0.658%	0.515%	0.548%*	0.618%	0.560%
8 dB	0.325%	0.415%	0.554%	0.427%	0.322%	0.383%*	0.412%	0.372%
10 dB	0.195%	0.264%	0.4%	0.282%	0.196%	0.268%*	0.288%	0.250%
	Bundung				Singapore			
Year	Year-1 (1992)	Year-2 (1993)	Year-3 (1994)	3-years (92-94)	Year-1 (1992)	Year-2 (1993)	Year-3 (1994)	3-Years (92-94)
Total Hours	7,243 (82.7%)	8,490 (97%)	8,415 (96%)	24,148 (92%)	7,835.0 (89.4%)	8057.0 (92%)	7,914.0 (90.3)	23,806 (90.5%)
2 dB	1.324%	1.168%	0.940%	1.144%	0.895%	1.119%	1.028%	1.014%
4 dB	0.644%	0.491%	0.425%	0.520%	0.498%	0.650%	0.533%	0.560%
6 dB	0.346%	0.232%	0.184%	0.254%	0.318%	0.440%	0.313%	0.357%
8 dB	0.177%	0.118%	0.081%	0.125%	0.213%	0.303%	0.198%	0.238%
10 dB	0.155%	0.104%	0.070%	0.110%	0.200%	0.285%	0.182%	0.222%

* Loss of data in April - July 93

8.3 The Diurnal Variation of Rain Intensity and Rainfall

The diurnal variation of rain intensity P(Bi\Z) can be defined in similar ways as the diurnal variation of attenuation. It is the total accumulation time of each measured rain intensity (R) exceeding the threshold (γ) in the selected interval, divided by the total accumulation time in 24 hours as expressed by:

$$P(Bi\backslash Z) = \frac{T(R > \gamma, \text{ in i interval})}{T(R > \gamma, \text{ in 24 hours})} \quad \text{------------(8.3)}$$

Where:

Bi is the event of rain-intensity (R) exceeding the threshold (γ)

P(Bi\Z) is the diurnal variation of rain intensity

In practice, the P(Bi\Z) is not easily to obtain from the meteorological data bank. Only a 1-hour rainfall data is widely measured by many meteorological stations all over the world. It is possible to use that 1-hour rainfall data to obtain the diurnal variation of rainfall for predicting rain attenuation in a given hour. The diurnal variation of rainfall P(Ri\Z), different from the diurnal variation of rain-intensity P(Bi\Z), is the conditional probability of the amount of rainfall in each i hour interval given that the probability of rainfall in all observation period is known. It can be expressed by:

$$P(Ri\backslash Z) = P(Ri,Z)/ P(Z) \quad \text{------------------(8.4)}$$

where

Ri is the event of rainfall in the i'th interval,

Z is the event of rainfall in 24 hours,

P(Ri,Z) is the joint probability of rainfall between event Ri and event Z,

P(Z) is the probability of rainfall in observation period.

From the measured data, the diurnal variation of rainfall can be obtained by:

$$P(Ri\backslash Z) = \frac{\text{Total rainfall accumulation in each i-hour interval (mm)}}{\text{Total rainfall accumulation in observation period (mm)}} \quad \text{---------(8.5)}$$

Figure 8.1 shows results of the diurnal variation of rain intensity P(Bi\Z) of 10, 25 mm/h in Bangkok over three years compared among the measured diurnal variations of rainfall P(Ri\Z) measured by the tipping bucket rain gauge (measured rainfall) and 1-hour rainfall data of a meteorological station of Bangkok (meteo. Rainfall). It is indicated that there are good correlations (COR > 0.9) among all measured rainfall data that may lead to the development of the prediction model by using 1-hour rainfall data to predict cumulative distribution of attenuation in any hour.

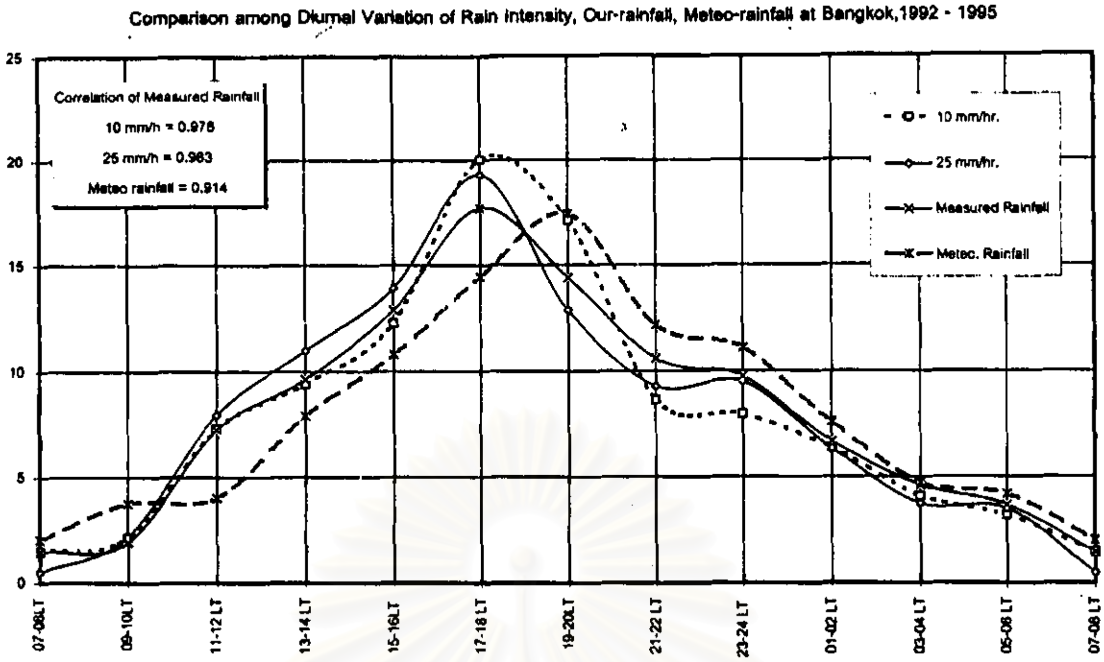

Figure 8.1 Comparison among diurnal variation of rain intensity, measured rainfall, meteorological rainfall at Bangkok

Figure 8.2 shows the measured diurnal variation pattern of rainfall P(Ri/Z) in Southeast Asia over 3-years by the tipping bucket rain gauge. It shows remarkable different pattern between the coastal areas (Bangkok, Si-racha, and Singapore) and the mountainous area (Bundung). The convective rain is mainly occurred in Bundung in the afternoon (1300LT to 1700LT) local time. Singapore shows high probability of rainfall in the morning to afternoon (0700LT - 1500LT) while Bangkok shows the highest rainfall in the evening prime-time (1700LT - 1900LT). Si-racha does not show a distinct pattern and rainfall may occur any hour of the day. Three year results implied that rainfall in Bundung is mainly convective in nature while rainfall in Bangkok and Si-racha and Singapore may be influenced by both convective rain and a stratiform rain.

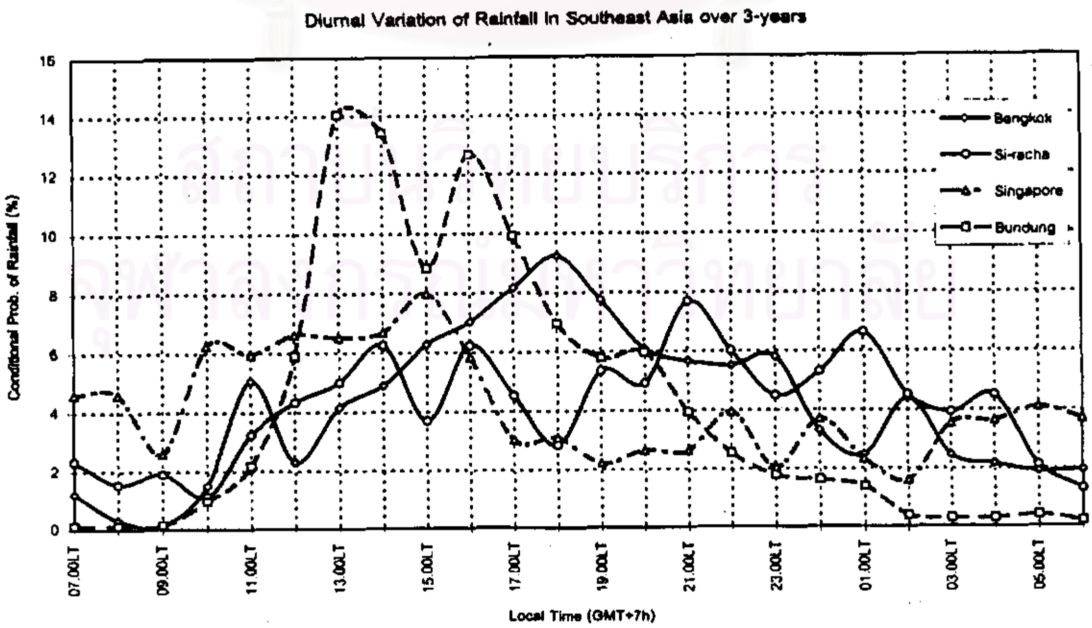

Figure 8.2 Diurnal Variation of rainfall in Southeast Asia over 3-years

8.4 Result Analysis

Results of yearly diurnal variation of attenuation are shown in figure 8.3 - 8.18. The vertical axis indicates the percent conditional probability of attenuation exceeding the threshold. In Figures 8.3 - 8.18, the horizontal axis shows the local time (GMT +7 hour) divided into each 2-hour interval. All percent value attenuation of each year and all years are shown in Appendix D (Percent of diurnal variation of attenuation).

1) Yearly Diurnal Variation of Attenuation in Bangkok

As shown in Figure 8.3 (year-1), attenuation is most likely to occur in the evening to late midnight during 1700LT-0200LT(70%). The 10 dB diurnal pattern shows the largest variation with the coefficient of variation (COV) of 88.23%, while the 2 dB pattern tends to show the smallest variation (COV = 55.12%). In addition, the 10 dB pattern shows the highest probability of occurrence at 1900LT-2000LT(20%) and 0100LT-0200LT(20%), while the 4-8 dB patterns show the highest probability of occurrence at 1700LT-1800LT. All attenuation patterns show the smallest occurrence in early morning to noon (0300LT-1200LT). It can be clearly seen in Figure 8.3 that the high attenuation patterns show a large variation than the low attenuation pattern. This is due to the low attenuation occurred in any hour more frequently than high attenuation. Attenuation may occur in any two hours with the high probability of attenuation falling in the night time than in the day time.

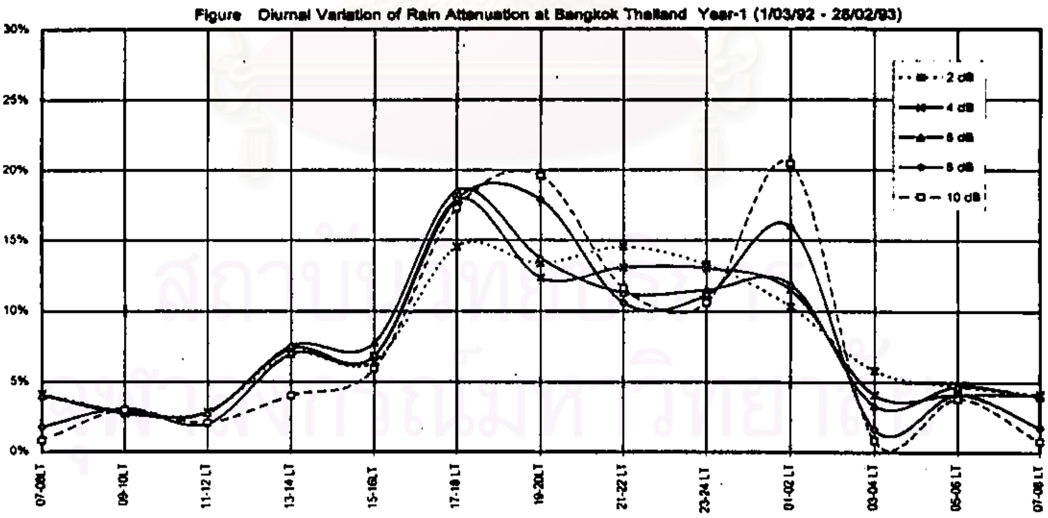

Figure 8.3 Diurnal variation of attenuation in Bangkok, Thailand, year-1(1992)

As shown in Figure 8.4 of (year-2), It is clearly indicated that both high and low attenuations are most likely to occur in the late afternoons and early evenings between 1700LT-2000LT(42%). It is remarkable to indicate that the higher attenuation shows more larger variation (COV = 83.85%) than the lower attenuation (COV = 55.64%) with the maximum peak at 1700LT-

1800LT while the less occurrence of all attenuation fall between midnight to noon (23.00LT-12.00LT). The high attenuation pattern shows higher kurtosis (3.536) than the lower attenuation pattern (3.029). The 2 dB and 10 dB patterns show a positive correlation of 0.8586. Again, results of year-2 measurement can support the implication of attenuation behavior in Bangkok having the high probability of occurrence in the night time and low probability in the day time.

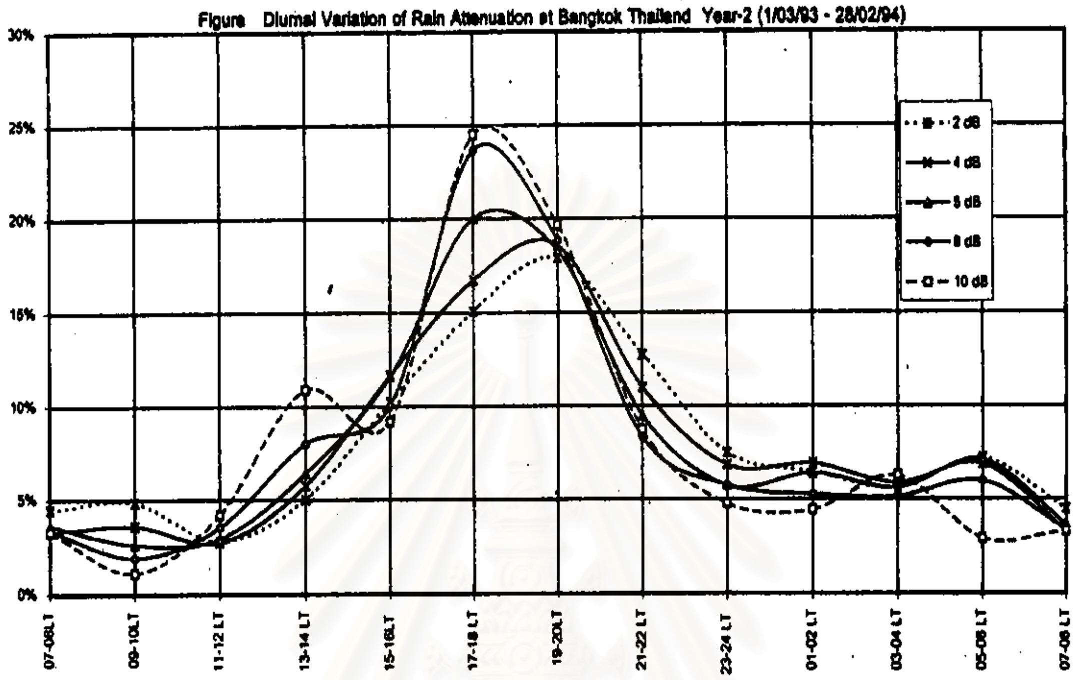

Figure 8.4 Diurnal variation of attenuation in Bangkok, Thailand, year-2(1993)

As shown in Figure 8.5 (year-3), all attenuation retain the most probability of occurrence in the evening (1700LT-2400LT) having the peak occurrence at 1900LT-2000LT(23%). The high (10 dB) attenuation still shows larger variation (COV = 88.51%) than the low (2 dB) attenuation (COV = 68.24%). All attenuation patterns show a good correlation coefficient of 0.940.

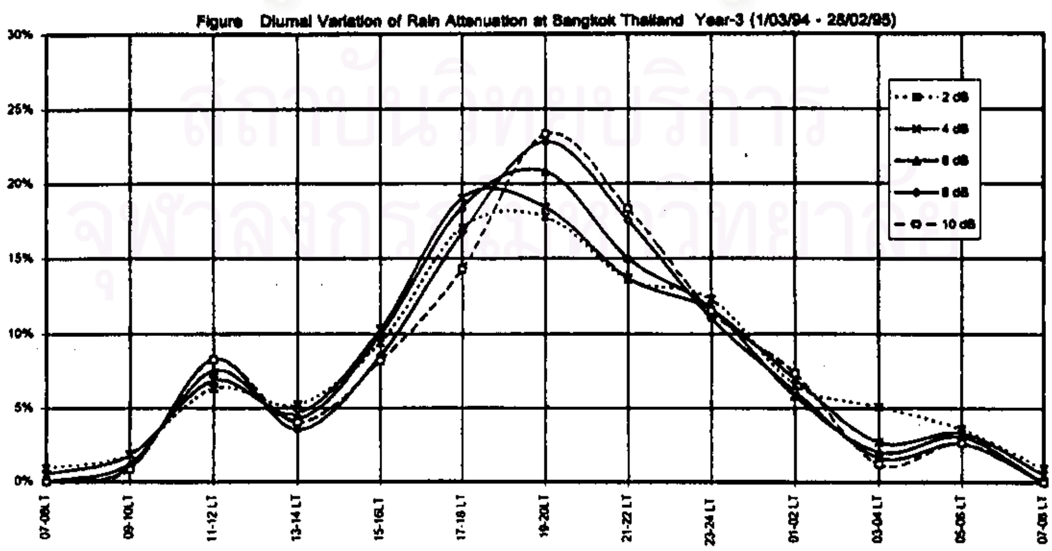

Figure 8.5 Diurnal variation of attenuation in Bangkok, Thailand, year-3(1994)

Table 8.2 Analytical results of diurnal variation of attenuation at 2 dB and 10 dB of Year-1, Year-2, Year-3, and all 3-Years, and results of 3-year diurnal variation of rain intensity at 25 mm/h and 100mm/h in Bangkok and Si-racha.

Bangkok

Year	Year-1 (1992)		Year-2 (1993)		Year-3 (1994)		3-Years		3-Years	
Details	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	25 mm/h	100 mm/h
Total (sec)	474320	54972	529288	74504	479108	92352	1482708	221826	262799	8984
Minimum (sec.)	13418	448	15268	812	4446	0	48590	2882	3856	53
Maximum (sec)	69030	11244	96932	17922	85360	21534	245714	46684	52647	1779
Mean (sec)	39526.6	4581	44107.3	6208.66	39925.6	7696	123559	18485.5	21899.9	582
Median (sec)	31888	2735	37051	4036	31075	7183	100758	15730	20061.5	345
Std. Deviation	21790.3	4042.27	24545.4	5206.20	27247.5	6811.97	69664.2	14420.2	15161.4	582.67
Kurtosis	-1.7293	-1.13871	0.68436	1.29905	-0.9667	-0.1056	-0.8632	-0.1841	0.18964	-0.18377
Skew-ness	0.29970	0.69693	1.16421	1.39394	0.52014	0.81154	0.69882	0.87418	0.8852	0.97801
COR	0.8282		0.8586		0.9400		0.9656		0.5324	
COV	55.12%	88.23%	55.64%	83.85%	68.24%	88.51%	56.38%	78.00%	69.3%	100%

Si-racha

Year	Year-1 (1992)		Year-2 (1993)		Year-3 (1994)		3-Years		3-Years	
Details	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	25 mm/h	100 mm/h
Total (sec)	487090	59638	351426	57884	467898	81928	1336414	199450	227191	6799
Minimum (sec.)	20090	1950	1086	0	7114	0	41820	4908	6764	0
Maximum (sec)	80580	10732	91978	17700	93526	20002	266084	44140	31714	1173
Mean (sec)	40590	4969.833	29285.5	4823.66	38991.5	6827.33	111367	16620.8	18932.5	566.583
Median (sec)	36921	4474	22647	3279	36499	6071	91618	13933	20039.5	448
Std. Deviation	15464	2965.839	24694.8	4966.22	27270.2	6040.65	64700.7	11736.3	8059.79	469.639
Kurtosis	3.6994	-0.38944	3.02982	3.53620	-0.0285	0.89446	1.75722	1.67067	-1.0368	-1.9951
Skew-ness	1.6144	0.814343	1.54092	1.68192	0.76596	1.07636	1.26632	1.35975	-0.1708	0.124198
COR	0.6290		0.9141		0.9382		0.9258		0.5650	
COV	38.09%	59.65%	84.32%	102.8%	69.93%	88.46%	58.09%	70.60%	42.57%	82.88%

Singapore										
Year	Year-1 (1992)		Year-2 (1993)		Year-3 (1994)		3-Years		3-Years	
Details	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	25 mm/h	100 mm/h
Total (sec)	252366	56592	342606	87358	292802	51784	252366	56592	-	-
Minimum (sec.)	2796	104	15608	2800	7186	772	2798	104	-	-
Maximum (sec)	57912	17484	57912	17484	51306	11024	57912	17484	-	-
Mean (sec)	21030.5	4716	28550.5	7279.83	24400.33	21030.5	21030.5	4716	-	-
Median (sec)	14478	2178	25576	6220	20895	3555	14478	2178	-	-
Std. Deviation	21516.3	5967.58	14321.5	4711.8	15804	3235.75	21516.3	5967.58	-	-
Kurtosis	-0.603	1.53	1.08	1.6	-0.992	-0.369	-0.603	1.53	-	-
Skew-ness	0.924	1.62	1.42	1.59	0.68	1.012	0.92	1.62	-	-
COR	0.944		0.910		0.929		0.945		-	
COV	97.5%	126.5%	50%	64%	64%	75%	97.5%	126%	-	-
Bundung										
Year	1992		1993		1994		1992-1994		1992-1994	
Details	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	2 dB	10 dB	-	-
Total (sec)	345302	40460	356974	32026	284774	21210	987050	28038	-	-
Minimum (sec.)	0	0	0	0	92	0	92	0	-	-
Maximum (sec)	100270	13696	122350	11208	73980	7206	73980	28038	-	-
Mean (sec)	2877.52	3371.67	29747.83	2668.33	23731.2	1767.5	82254	7808	-	-
Median (sec)	12370	2311	12549	926	16027	85	35854	3543	-	-
Std. Deviation	34328	4366.13	37339	3566	26906.1	2712.42	96796	10231.6	-	-
Kurtosis	0.39	1.74	2.38	1.809	-0.25	0.002	0.593	0.54	-	-
Skew-ness	1.2	1.5	1.52	1.47	1.004	1.23	1.22	1.33	-	-
COR	0.91		0.994		0.957		0.97		-	
COV	119%	129%	125%	133%	113.3%	153%	117%	131%	-	-

Remark COV(Coefficient of Variation), COR(Correlation Coefficient)

2) Yearly Diurnal Variation of Attenuation in Si-racha.

Figure 8.6 of year-1 shows a large diurnal variation of attenuation providing three peaks: (1) early afternoon (1300LT-1400LT) with 20%, (2) late evening (2100LT-2200LT) with 12%, (3) after midnight (0300LT-0400LT) with 12%. It is notable that all attenuations occur most frequently at early afternoon (1300LT-1400LT). The 10 dB attenuation pattern shows much larger variation (COV=59.65%) than the 2 dB attenuation patterns (COV=38.09%), and both have low correlation coefficient of 0.629.

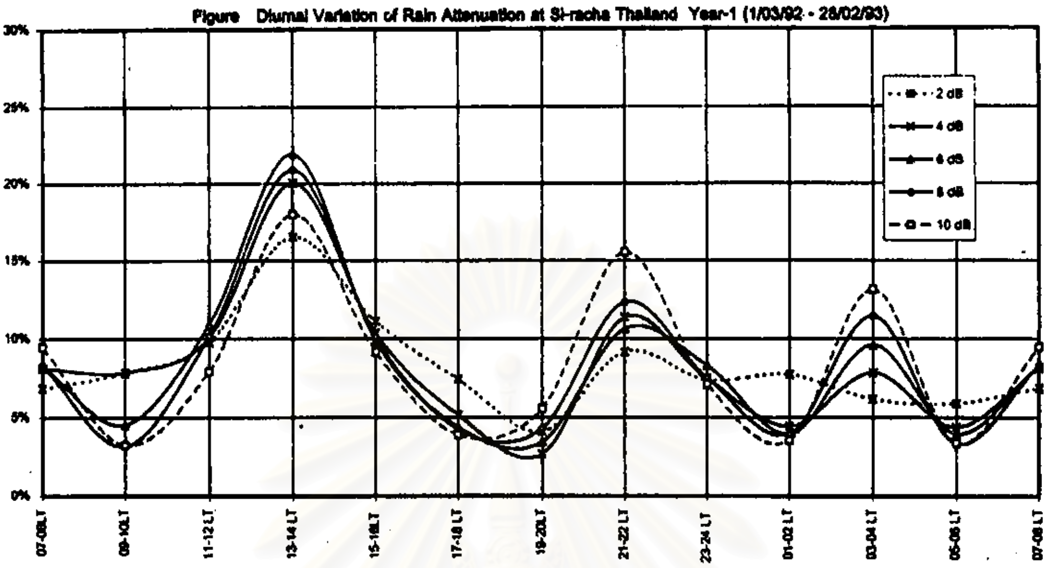

Figure 8.6 Diurnal variation of attenuation in Si-racha, Thailand, year-1(1992)

As shown in Figure 8.7 of year-2, all attenuation patterns show a good correlation (COR ≥ 0.914) and having the highest percentage time occurring in the early afternoon at 1300LT-1400LT(28%). Compared with year-1, year-2 pattern shows some similar diurnal variations and having the same peak percentage time at 1300LT-1400LT and 2100LT-2200LT.

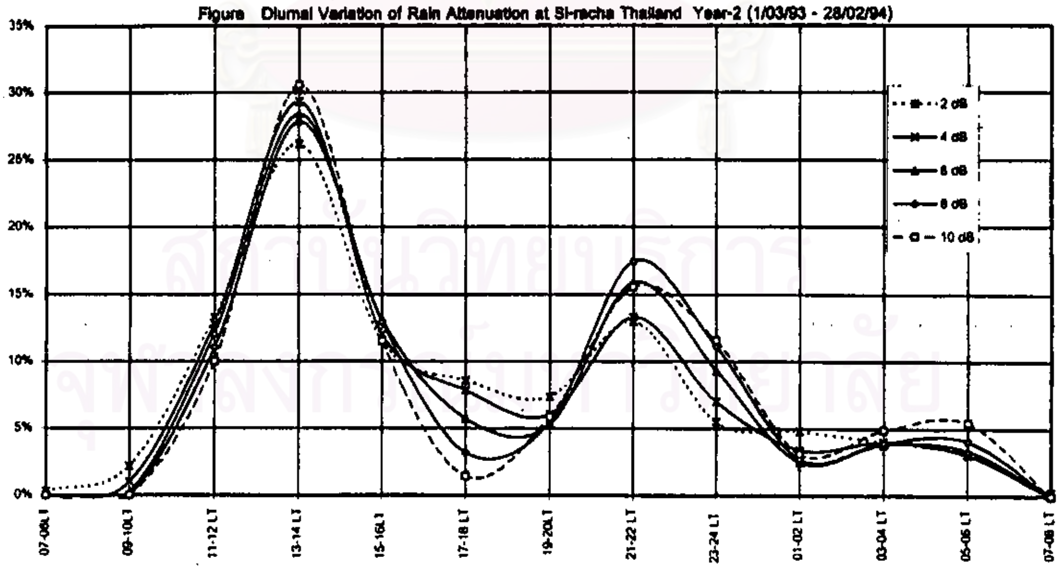

Figure 8.7 Diurnal variation of attenuation in Si-racha, Thailand, year-2(1993)

In Figure 8.8 of year-3, all attenuation patterns have the most frequent occurrence again in the early afternoon (1300LT-1600LT) the same as year-1 and year-2. The attenuation patterns of year-3 show some different patterns from year-1 and year-2; but, both patterns still maintain the same maximum occurrence at 1300LT-1400LT. There is a good correlation between 2 dB and 10 dB patterns with correlation coefficient of 0.9382.

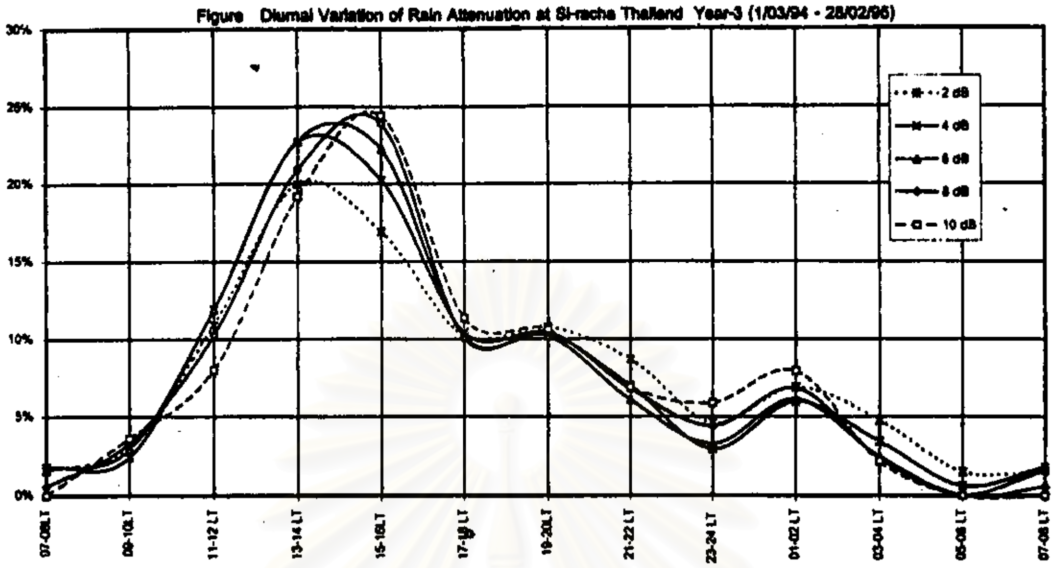

Figure 8.8 Diurnal variation of Attenuation in Si-racha, Thailand, year-3 (1994)

3) Yearly Diurnal Variation of Attenuation in Singapore

As shown in Figure 8.9 (year-1), attenuation starts in early morning 0300-0400LT and it gradually increases in the afternoon with the peak attenuation during 1300-1600LT. Both low and high attenuation show the largest variation with the coefficient of variation (COV) of 97% and 126% respectively. All attenuation patterns show the smallest occurrence in the evening to midnight (1700LT-0200LT). It can be clearly seen in Figure 8.9 that both high and low attenuation show a very good correlation (COR=0.944)

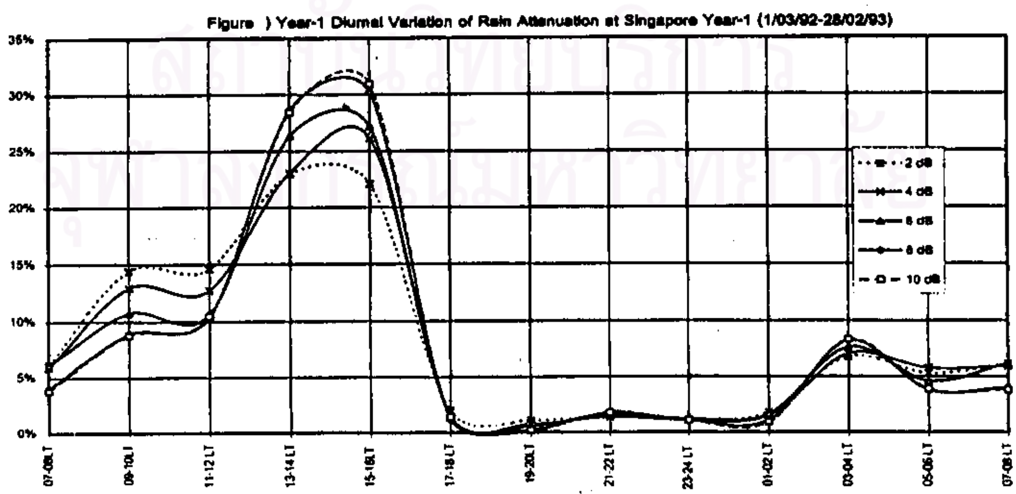

Figure 8.9 Diurnal variation of Attenuation in Singapore Year-1 (1992)

As shown in Figure 8.10 (year-2), it is clearly indicated that both high and low attenuation are most likely to occur in the early afternoon between 1300LT-1600LT (same as year-1 pattern). The high attenuation and the low attenuation do not show remarkable variation and they still show a good correlation (COR=0.91). The year-2 pattern shows similar pattern with year-1 pattern, but there are some percent attenuation occurrences > 5% falling in the evening to early morning.

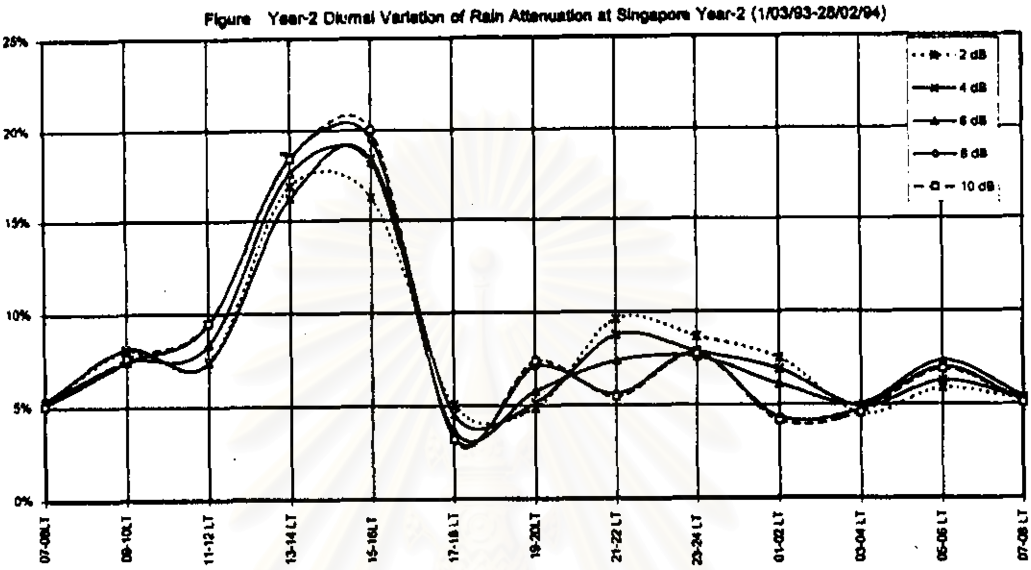

Figure 8.10 Diurnal variation of Attenuation in Singapore Year-2 (1992)

In figure 8.11 (year-3), there is some different patterns compared with year-1 and year-2 patterns. The peak attenuation moves to the 1100-1200LT with more percent attenuation falling in the morning (0700-0800LT). There is still a good correlation between the low and the high attenuation with COR= 0.93.

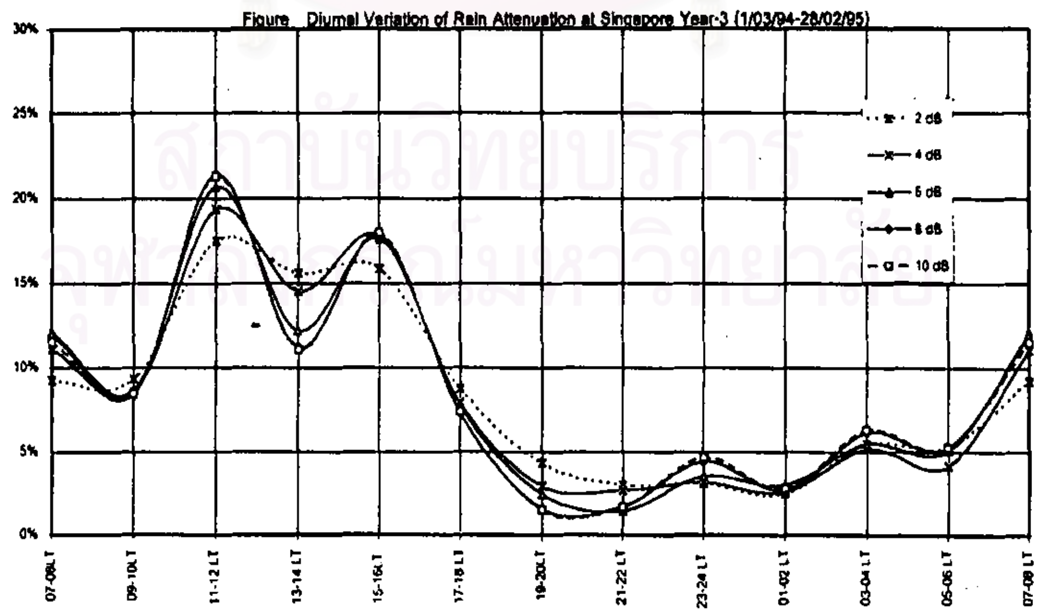

Figure 8.11 Diurnal variation of Attenuation in Singapore Year-3 (1994)

4) Yearly Diurnal Variation of Attenuation in Bundung, Indonesia

Figure 8.12 (year-1) shows the most outstanding pattern that all attenuations mostly occur in the day time, but less occur in the night time. Both low and high attenuations have relatively large variation (119%, 129%) and have a good correlation coefficient (0.91). During 00.00-0600LT, almost no attenuation occurs.

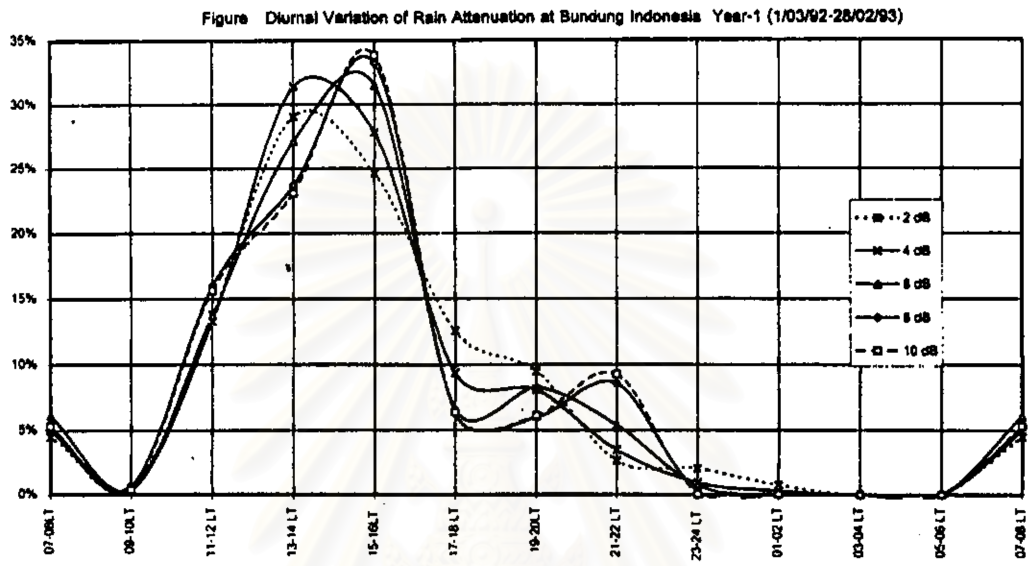

Figure 8.12 Diurnal variation of Attenuation in Bundung Year-1 (1992)

Figure 8.13 (year-2) shows similar pattern with year-1 pattern, the highest probability of attenuation occurrence is still concentrated in the daytime at 1300-1400LT, but no attenuation occurs in the night time after midnight. It is remarkably indicated that both high and low attenuation patterns show excellent correlation (0.994) and relatively large variation (125%, 133%).

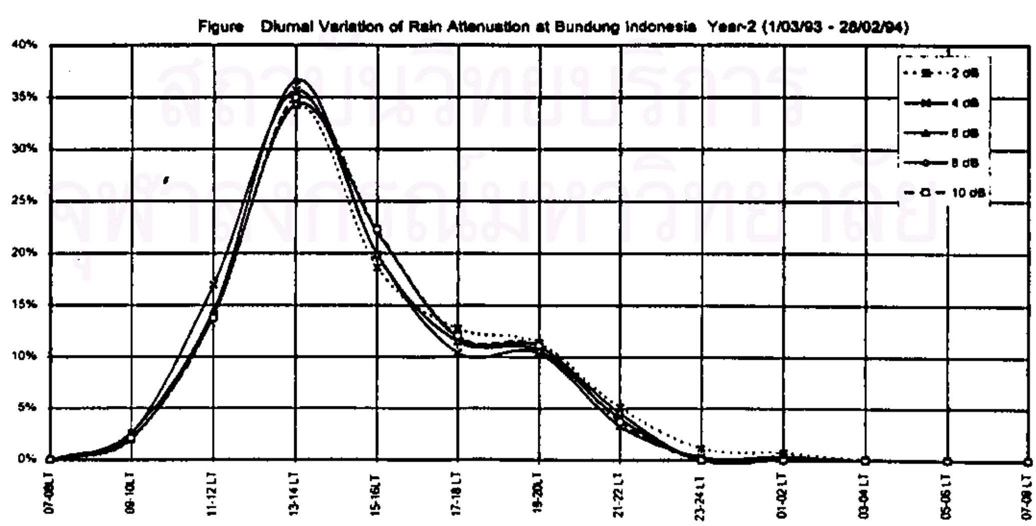

Figure 8.13 Diurnal variation of Attenuation in Bundung Year-2 (1993)

Figure 8.14 (year-3) again shows similar pattern with year-1 and year-2 patterns. The highest probability of attenuation still occurs in the early afternoon, but almost no attenuation shows in the night time. It is again clearly indicated that both low and high attenuations show excellent correlation (0.97) and having relatively large variation (117%, 131%).

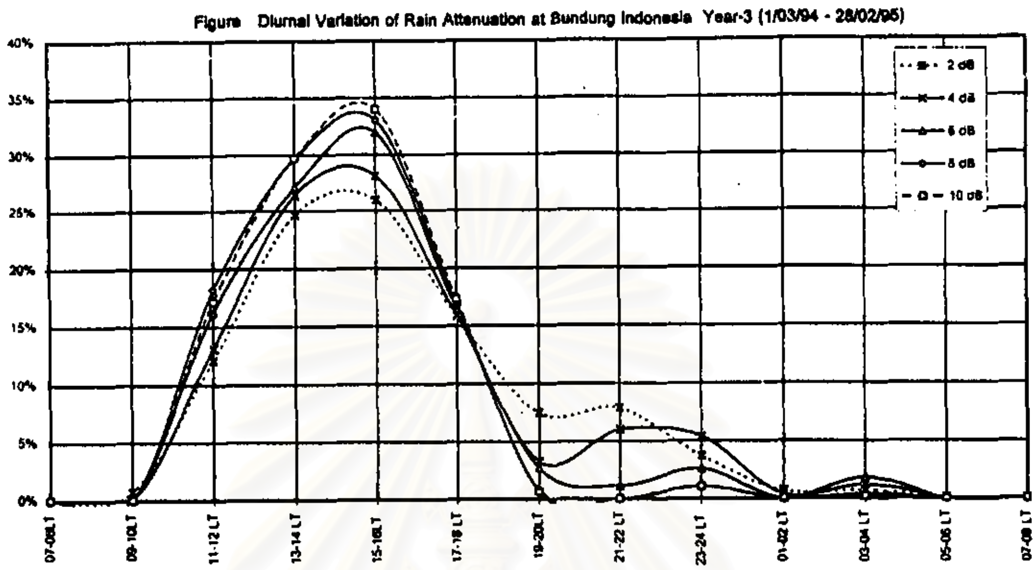

Figure 8.14 Diurnal variation of Attenuation in Bundung Year-3 (1994)

8.5 Diurnal Variation of Attenuation and Rainfall Over 3-years.

Figures 8.15 - 8.18 illustrate the diurnal variation of attenuation and rainfall at every 2 hour interval over 3 years in Bangkok, Si-racha, Singapore and Bundung respectively. The dash curve shows the plot of the diurnal variation of rainfall obtained by the tipping bucket rain gauges with 1 hour integration time. The correlation coefficients between all attenuation curves and each rainfall curve are also shown in the Figures. The percent of conditional probability of 6 dB attenuation and rainfall for each 2-hour interval are summarized in Table 8.3.

Table 8.3 The percent (%) of conditional probability of 6 dB attenuation P(Hi\Y) and Rainfall P(Ri\Z) in Bangkok (BK (6 dB)), Si-racha (SR (6 dB)) Singapore (SP (6 dB)) and Bundung (BD (6 dB)).

Name	07-08LT	09-10LT	11-12LT	13-14LT	15-16LT	17-18LT	19-20LT	21-22LT	23-24LT	01-02LT	03-04LT	05-06LT
BK(6 dB)	2.49	2.24	4.56	6.05	10.00	19.19	17.97	11.28	9.61	7.89	3.72	5.01
SR(6 dB)	3.51	2.79	11.62	24.00	15.56	7.01	6.58	10.24	6.64	4.43	5.31	2.32
SP(6 dB)	8.43	9.79	14.01	16.52	15.45	4.64	3.75	4.53	5.17	4.44	6.66	6.66
BD(6 dB)	0.00	1.08	15.02	31.03	28.53	11.04	7.84	3.98	1.00	0.00	0.48	0.00
BK-Rainfal)	1.44	1.90	7.25	9.63	12.90	17.7	14.40	10.60	9.75	6.68	4.60	3.66
SR-Rainfall	3.86	2.93	7.27	12.10	10.60	7.00	9.38	13.12	11.35	10.67	8.05	3.48
SP-(Rainfal)	6.03	8.25	14.3	14.70	15.7	9.43	5.39	6.00	4.47	3.15	6.26	6.13
BD-Rainfal)	0.20	1.30	8.3	27.80	21.30	16.40	11.81	7.10	3.31	1.78	0.60	0.50

1) Diurnal Variation of Attenuation and Rainfall in Bangkok

Figure 8.15 remarkably indicates that all attenuation curves have the peak mostly concentrates in the evening (1700LT-2000LT). The high attenuation curves (8 - 10 dB) show a larger variation than the lower curves (2 - 4 dB). The correlation between the 2 dB curve and the 10 dB curve is 0.96, and there are some good correlation coefficients (0.87 - 0.92) between all attenuation curves with the rainfall curve. Three year results imply that the rainfall in Bangkok is relatively high. and the diurnal variation of attenuation in Bangkok are mainly affected by both a convective rain, having the high probability of rainfall concentrated in the afternoon, and a stratiform rain having probability of rainfall in any hour.

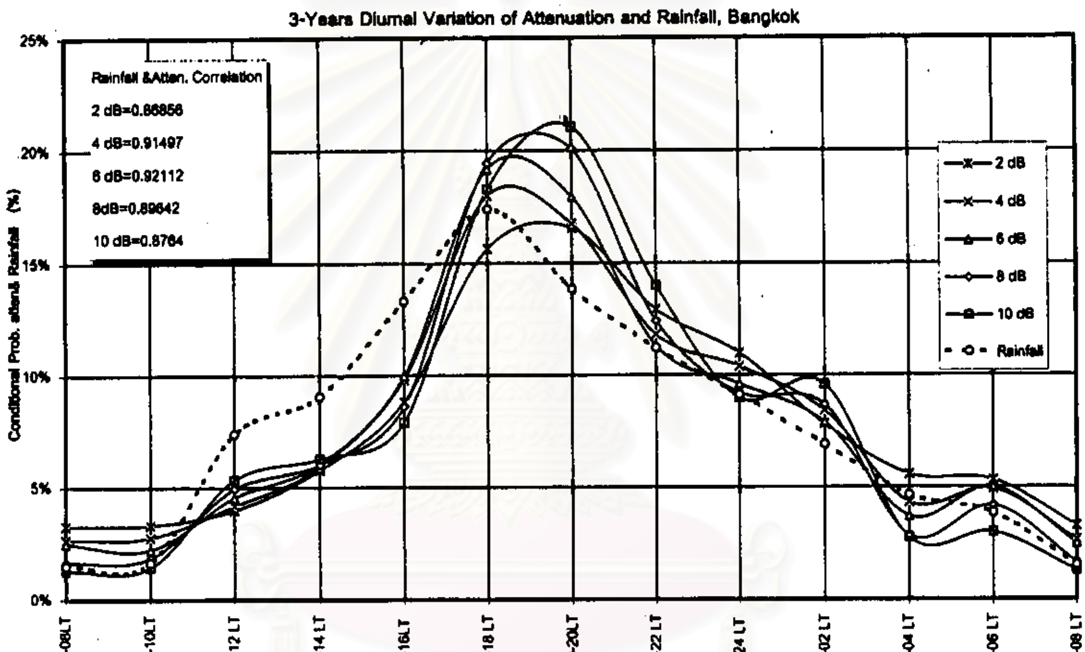

Figure 8.15 Comparison of diurnal variation of attenuation and rainfall, over 3-years, Bangkok, Thailand

The non-parametric Kolmogorov-Smimov test also performs with all data. It is found that the normal distribution with mean=7 (1900-2000LT) and a standard deviation 2.7 are well fitted measured data of Bangkok.

It is often seen that during the southeast monsoon, heavy clouds with high humidity are formed around the southwest of Bangkok and then move along the monsoon wind and combine with the warmer air in Bangkok causing frequent rainfall in the evening.

2) Diurnal Variation of Attenuation in Si-racha.

Figure 8.16 shows a 3-year average of the diurnal variation pattern of attenuation and rainfall. It shows significant difference from the Bangkok pattern even if the site separation is only 80 km. All curves have the peak in the early afternoon (1300LT-1400LT). The 10 dB curve shows the largest variation while the 2 dB curve tends to spread over a large interval. There is not a good correlation between the attenuation curves and the rainfall curve (COR= 0.52-0.67). Three-year results may be expected that rainfall in Si-racha is high and does not show an outstanding behavior of convectivity that has the percent rainfall peak in the afternoon. But attenuation shows the percentage peak in the early afternoon which is not corresponding with rainfall pattern.

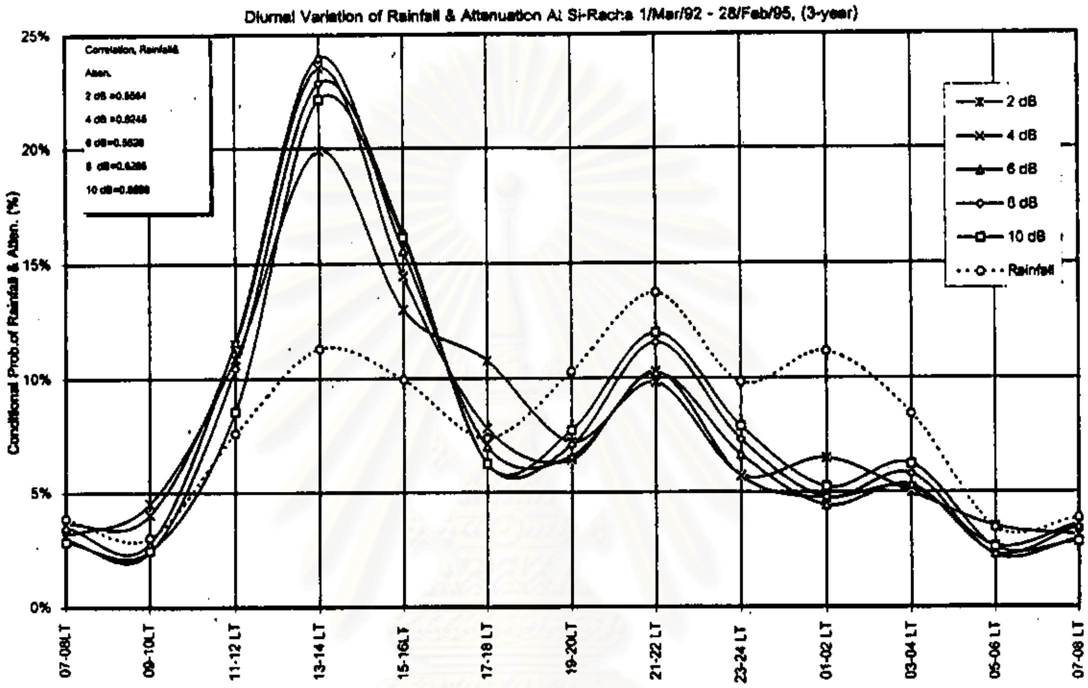

Figure 8.16 Comparison of diurnal variation of attenuation and rainfall over 3-years, Si-racha, Thailand

The Kolmogorov-Smimov was tested to find the suitable distribution to be fitted with all data, but it can not find any suitable distribution for Si-racha data.

Results of Si-racha may be expected that the low elevation angle introduces a large uncorrelation of rainfall and attenuation due to multiple rain-cells that may pass through the slant path. Si-racha is located in the coastal area influenced by both a convective and a startiform rains. It is usually observed that during the southeast monsoon heavy clouds are formed in the Gulf of Thailand and fall along the radiometer slant path in the afternoon

3) Diurnal Variation of Attenuation at Singapore.

Figure 8.17 shows 3-year average of the diurnal attenuation pattern in Singapore. All curves start to increase from early morning (0300LT) to the maximum percentage at 1500-1600LT. It is remarkable to show that both low and high attenuations are highly correlated (COR = 0.945) which is implied the most heavy rainfall in Singapore. All attenuation patterns have a very good correlation with a rainfall pattern (COR = 0.95 - 0.97). The Kolmogorov-Smimov was tested and it can not find any suitable distribution for Singapore data.

Diurnal Variation of Rainfall & Attenuation in Singapore, (1/03/92 - 28/02/95) 3-year

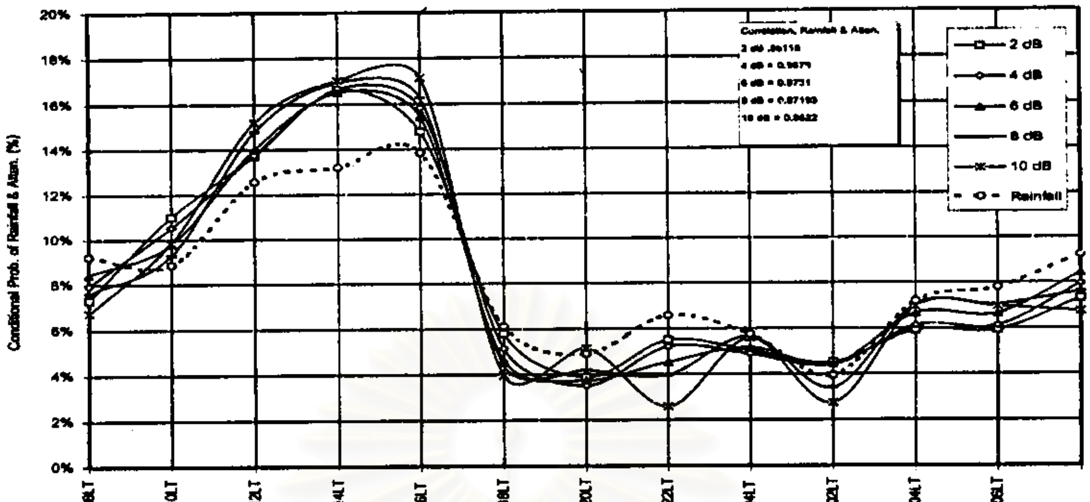

Figure 8.17 Comparison of diurnal variation of attenuation and rainfall, over 3-years, Singapore

Three years results imply that rainfall in Singapore (a coastal area) is influenced by both a convective and a heavier startiform rain with high rain intensity. Startiform rain may occurs at any hour while a convective rain is highly concentrate in the afternoon.

4) Diurnal Variation of Attenuation in Bundung.

In Figure 8.18, both low and high attenuation curves show very high correlation (0.97) having the peak in the afternoon (1300LT-1600LT). Almost no attenuation and rainfall occur between midnight to morning (0100LT-0800LT). All attenuation patterns have a very good correlation with a rainfall pattern (0.97) Three-year results imply that rainfall in Bundung (a mountainous area) is mainly influenced by a convective rain with very high rain intensity.

Diurnal Variation of Rainfall and Attenuation at Bundung, Indonesia 1/Mar/92 - 28/Feb/95 (3-year)

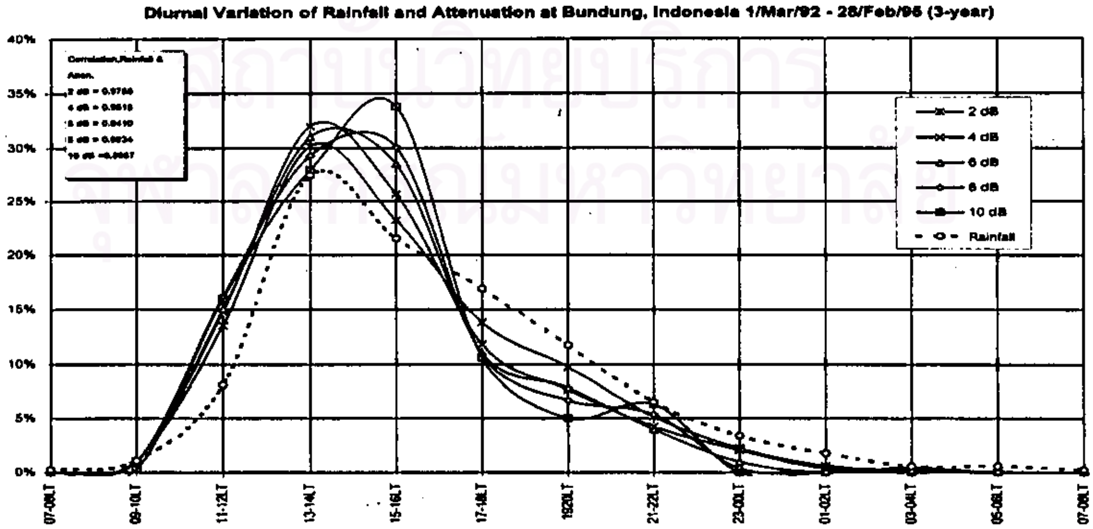

Figure 8.18 Comparison of diurnal variation of attenuation and rainfall, over 3-years, Bundung, Indonesia

The Kolmogorov-Smimov was tested, but it can not find any suitable distribution for Bundung data. Bundung is located at 870 mm height in the valley surrounded by mountains. It is relatively warm in the day time, but cold in the nigh time. High convectivity of atmosphere mostly occurs in the day time causing a convective rain, but almost no rain in the night time.

Three-year results concluded that the diurnal variation pattern of rain attenuation is mainly influenced by the environmental conditions i.e., geographical location, building, local winds. The mountainous area tends to produce more convective rain with high rainfall and high attenuation in the afternoon while the coastal area tends to produce both convective rains with heavy rainfall occurring in the afternoon to evening and a heavier stratiform rain occurring in any hour.

8.6 Year-to-Year of Diurnal Variation and of Rain Attenuation

Table 8.4 shows the comparison among four diurnal variations of attenuation at 6 dB threshold. BK92, Bk93, BK94 represent the percentage of 6 dB attenuation occupying each interval for Bangkok while the SR92, SR93, SR94, SP92, SP93, SP94, and BD92, BD93, BD94 represent the diurnal variations of 6 dB of Si-racha, Singapore and Bundung respectively. The "MAX" represents the percentage maximum different valve between year-1, year-2, and year-3 values of each interval. Figure 8.19 shows the plot of the "MAX" valves of each 2-hour interval. The Bangkok curve shows the smallest year-to-year variation with average variation of 4.08% followed by Bundung (5.06%), Si-racha (6.18%) and Singapore (6.65%). The maximum different variation is 14.20% belonging to Singapore at 1300-1400L, but the smallest percent variation (0%) occurs in Bundung during 0100-0600LT when no attenuation occurs. Three-year results concluded that the diurnal variation pattern of attenuation is not significantly deviated from year-to-year.

Table 8.4 Year to Year variation of diurnal variation of attenuation in Southeast Asia at 6 DB

[illegible]	[illegible]	[illegible]	[illegible]	1314LT	1516LT	[illegible]	1920LT	2122LT	2324LT	[illegible]	[illegible]	[illegible]	[illegible]
BK92	4.00%	2.90%	2.77%	7.56%	7.77%	18.54%	13.72%	11.29%	11.49%	11.91%	3.34%	4.71%	100.00%
BK93	3.75%	2.69%	3.04%	6.56%	11.87%	20.49%	18.72%	7.43%	5.88%	6.53%	5.75%	7.26%	99.97%
BK94	0.00%	1.25%	7.55%	4.27%	10.00%	18.46%	20.82%	15.02%	11.69%	5.85%	2.04%	3.05%	100.00%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	49.14%
SR92	8.28%	4.57%	10.90%	21.94%	9.87%	4.42%	3.50%	10.61%	8.31%	3.98%	9.61%	3.99%	99.98%
SR93	0.00%	0.25%	12.13%	28.43%	13.16%	5.75%	5.28%	15.90%	9.37%	2.51%	3.84%	3.39%	100.01%
SR94	1.62%	2.93%	11.91%	22.85%	22.25%	10.16%	10.20%	6.09%	3.31%	6.11%	2.47%	0.11%	100.01%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	74.16%
SP92	6.17%	10.77%	10.66%	26.40%	27.21%	1.30%	0.58%	1.64%	1.26%	1.68%	7.70%	4.61%	99.98%
SP93	5.41%	7.46%	8.34%	17.64%	18.19%	3.67%	5.80%	7.39%	7.58%	6.13%	5.07%	7.33%	100.00%
SP94	12.11%	8.66%	20.69%	12.20%	17.66%	7.72%	2.45%	1.42%	3.52%	3.00%	5.52%	5.06%	100.01%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	79.85%
BD92	6.41%	0.45%	13.76%	27.12%	31.47%	6.65%	8.28%	5.42%	0.72%	0.00%	0.00%	0.00%	100.28%
BD93	0.00%	2.65%	14.51%	36.65%	19.90%	11.52%	10.70%	4.06%	0.00%	0.00%	0.00%	0.00%	99.99%
BD94	0.00%	0.00%	16.23%	27.09%	31.95%	16.92%	2.71%	1.14%	2.61%	0.02%	1.83%	0.00%	100.50%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60.61%

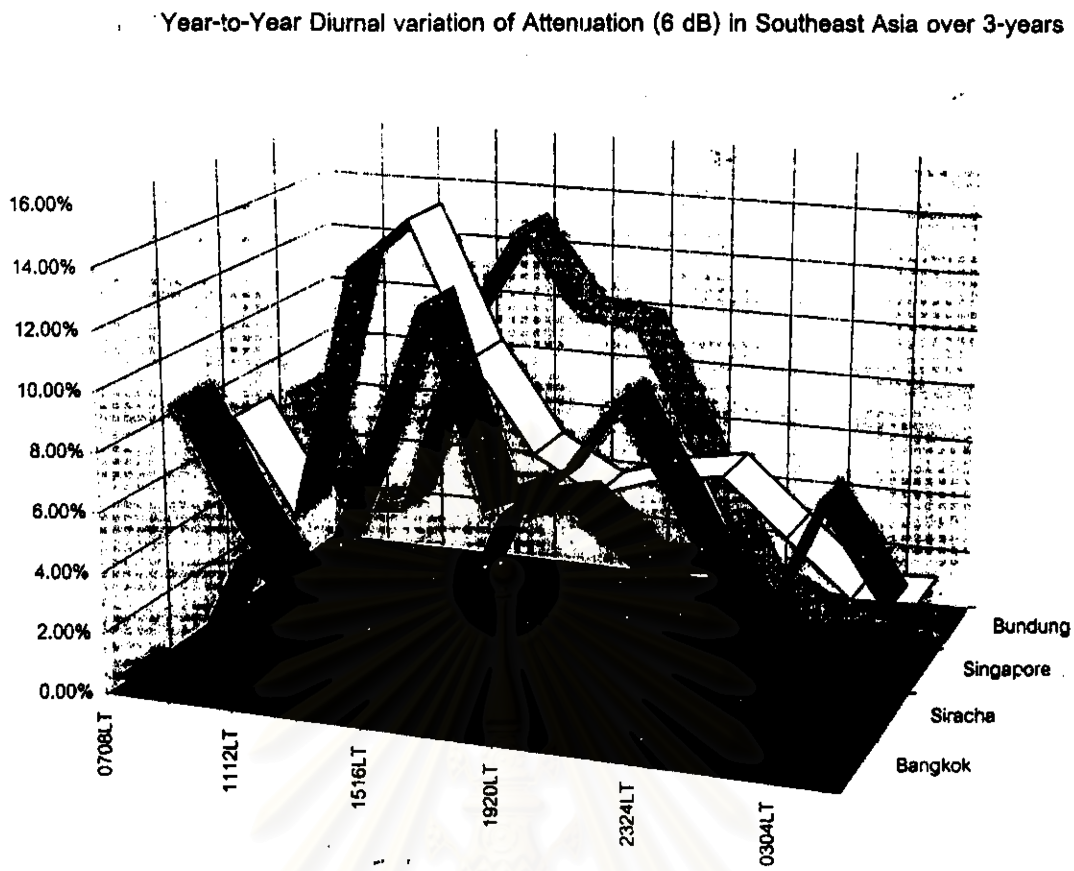

Figure 8.19 Year-to-Year diurnal variation of attenuation (6 dB) in Southeast Asia 3-years

8.7 Site-to-Site Diurnal Variation of Attenuation in Southeast Asia.

Three year measurement at four locations clearly indicated that the diurnal variation of attenuation is highly dependent on the environmental conditions i.e., buildings, a geographical location, a coastal area, a mountainous area. For example, Bangkok has a lot of buildings and rain usually falls in the evening due to the high convectivity usually occurring in the late afternoon when heavy clouds with high humidity move from the Southwest along the monsoon wind and combine with the warm air in the afternoon resulting high probability of rainfall in the evening.

Si-racha site is located on the hill (54 meters above sea level) near the Gulf of Thailand. The radiometer slant-path's is passing through a small valley. In rainy seasons, sea breeze and southwest monsoon wind carry high humidity from the sea to form heavy stratiform clouds and then introduce heavy rainfall along the radiometer's slant-path in the early afternoon. Three-year measurements confirmed that the local environments are strongly influenced on the diurnal variation pattern of attenuation. It is not surprised that why the diurnal variation pattern in Bangkok and Si-racha are significantly different even if the site distance is only 80 kms.

The diurnal variation pattern of Bundung in mountainous area is different from the coastal area (Bangkok, Si-racha, Singapore). Both attenuation and rainfall show the outstanding pattern of the convective behavior that almost no rain occurs in the night time.

8.8 Comparison of the Diurnal Variation of Attenuation and Rain Intensity

Diurnal variation of various point-rain intensity P(Bi\Z) of 10, 25, 50, 75, and 100 mm/h in Bangkok during March 1,1992 - February 28,1995 is shown in Figure 8.20 (Bangkok) and Figure 8.21 (Si-racha). In Bangkok, result shows that very high rain intensity patterns (75-100 mm/h) mostly occur at 1500LT-1600LT while the low-moderate rain intensity patterns (10-25 mm/h) mostly occur at 1700LT-1800LT. All rain intensity patterns tend to fall in the afternoon and early evening and very high rain intensity pattern (100 mm/h) shows much larger variation (COV ≥ 82.88%), than low-moderate rain intensity pattern (COV = 42.57%). This is due to the characteristics of rainfall that low rain intensity tends to occur more frequently than the high rain intensity and the low-moderate rain intensity duration occurs much longer than heavy rain intensity duration. The correlation between 10 mm/h and 100 mm/h rain intensity show low correlation (COR= 0.5650).

In Si-racha, the diurnal variation of rain intensity shows a relatively large variation, and especially the 100 mm/h pattern shows the most largest variation (COV = 82.88%).

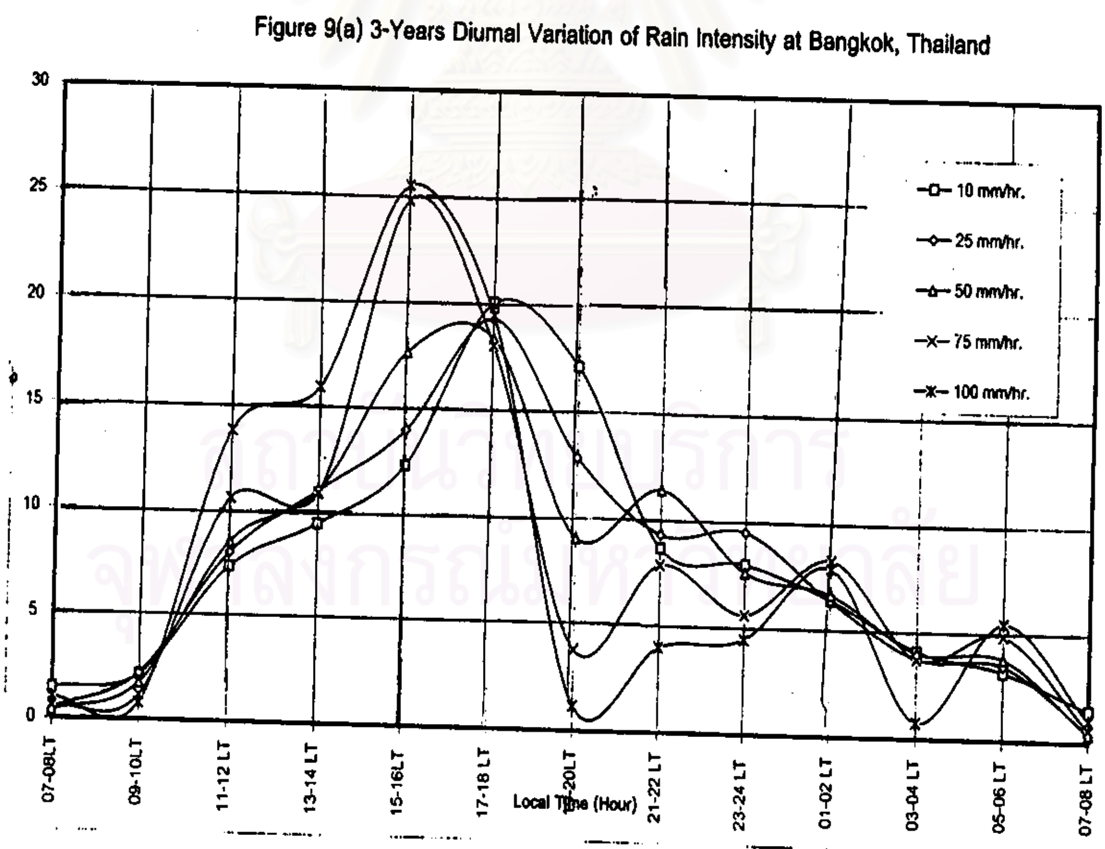

Figure 8.20 Diurnal variation of rain intensity in Bangkok, Thailand over 3 years

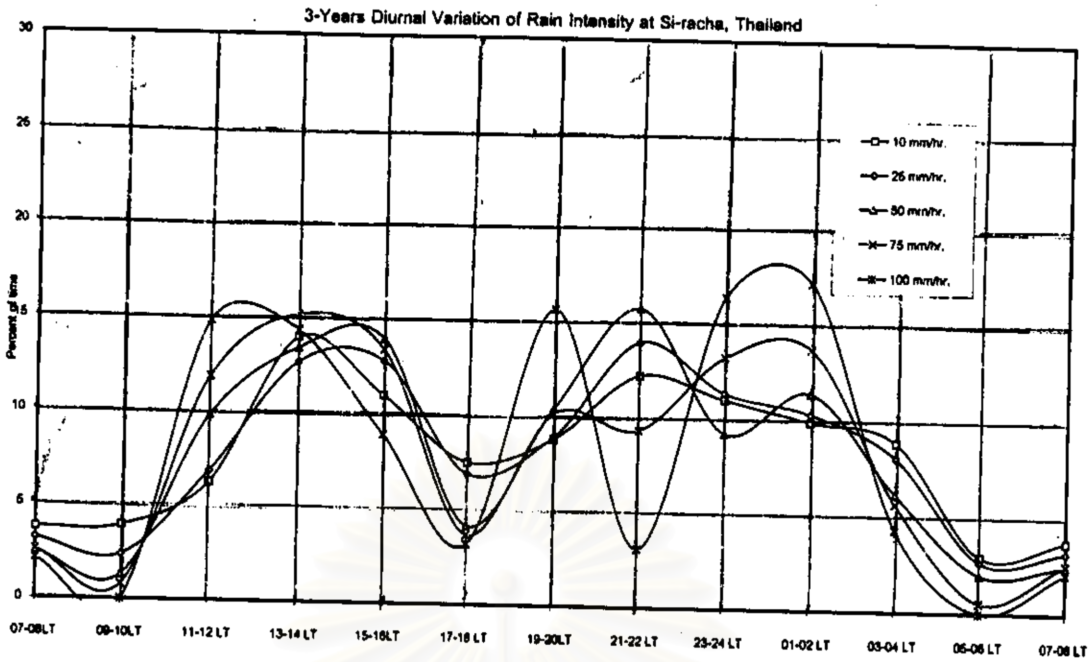

Figure 8.21 Diurnal variation of rain-intensity in Si-racha, Thailand over 3 years.

8.9 Two-hour Cumulative Distribution of Attenuation

Figures 8.22 - 8.33 illustrate the cumulative distribution of attenuation of each 2-hour interval P(Hi) starting from 0708LT, 0910LT, ..., 0506LT. The cumulative distribution in Bangkok shown in Figure 8.22 (year-1), Figure 8.23 (year-2), Figure 8.24 (year-3), in Si-racha shown in Figure 8.25 (year-1), Figure 8.26 (year-2), Figure 8.27 (year-3), in Singapore shown in Figure 8.28 (year-1), Figure 8.29 (year-2), Figure 8.30 (year-3), in Bundung shown in Figure 8.31 (year-1), Figure 8.32 (year-2), Figure 8.33 (year-3). There are three groups of curves in each figure namely: the solid line which represents 0708LT, 0910LT, 1112LT, and 1314LT; the dashed line which represents 1516LT, 1718LT, 1920LT, 2122LT, and the dotted line which represents 2324LT, 0102LT, 0304LT and 0506LT respectively. In all curves, the cross (X) symbol represents an average cumulative distribution of attenuation P(Y) of each threshold between 2 - 10 dB.

The average P(Y) curve can be obtained by:

$$P(Y) = P(Y,H_{0708LT}) + P(Y,H_{0910LT}) + \ldots + P(Y,H_{0506LT}) \quad \text{------------------(8.6)}$$

$$= \sum_{i=0708LT}^{0506LT} P(Y \backslash Hi)P(Hi) \quad \text{------------------(8.7)}$$

where

P(Y,Hi) is the joint probability distribution of event Y and event Hi

P(Y|Hi) is the conditional probability of event Y given that event Hi is known,

P(Hi) is the probability of attenuation exceeding the threshold interval i or the

2-hours cumulative distribution of attenuation.

Figures 8.22 -8.24 clearly indicate that each average cumulative distribution P(Y) fallen in the middle of the 2-hour curves P(Hi). The uppermost curve belongs to the 1718LT and 1920LT curves having the peak probability of occurrence P(Hi\Y). The lowermost curve belongs to the 0708LT curve having the minimum probability of occurrence. Figures 8.25 - 8.27, show the 2-hour curves P(Hi) of Si-racha. It remarkably shows that the 1314LT curve is located at the uppermost while the 0708LT curve is located at the lowermost curve. The slope and position of the curves are corresponding to the diurnal variation of attenuation P(Hi\Y). Figures 8.28 - 8.30, show all 12 curves of Singapore. The average P(Y) curve is located among the P(Hi) curve. The uppermost curve (1314LT) is also corresponding to the P(Hi\Y). Figures 8.31 - 8.33, show all curves of Bundung. There is relatively difference among each curve. This is due to a large variation of the diurnal variation pattern P(Hi\Y). The uppermost and the lowermost curves are corresponding to the diurnal variation P(Hi\Y). Three year results imply the possibility to develop a statistical model of P(Hi) using the joint probability in equation (8.7).

8.10 Concluding Remarks

Results of the diurnal variation of attenuation ITU-R Zone N and Zone-P during 3 year period can be concluded as follows:

(1) The diurnal variation pattern of attenuation is highly dependent on the environmental conditions i.e., buildings, geographical location, local winds (monsoons, sea breeze, mountain winds) but uncorrelation with distance.

(2) The diurnal variation pattern of attenuation in Southeast Asia has high probability of occurrence in the daytime rather that the nighttime with the peak occurring in the afternoon between 1300LT - 1800LT.

(3) There is significant difference between the coastal area and the mountainous area in which the convective rain mostly occurs in the mountainous area. However, in the coastal area, a convective rain associated with a startiform rain both occur.

(4) Three-year observation found a small year-to-year diurnal variation (4-6% average).

(5) The good correlation (>0.9) between the low and high attenuation may imply the heavy-type of rainfall in Southeast Asia.

(6) The good correlation (> 0.9) between attenuation patterns and rainfall patterns may be possible to develop the more short-term attenuation prediction model.

Results of analysis recommend that for the broadcasting satellite systems (Direct to home, Direct PC, etc.) that require a large coverage service area, the knowledge of diurnal attenuation distribution may not significantly improve high benefits, unless those systems are applied in a small specific area such as a city, a province. It is due to the diurnal attenuation significantly relies on environmental conditions. However, it can be further developed the diurnal attenuation model, described in Chapter 9, using the knowledge of diurnal variations of rainfall P(Ri/Z) from one hour rainfall data that available in many meteorological data banks.

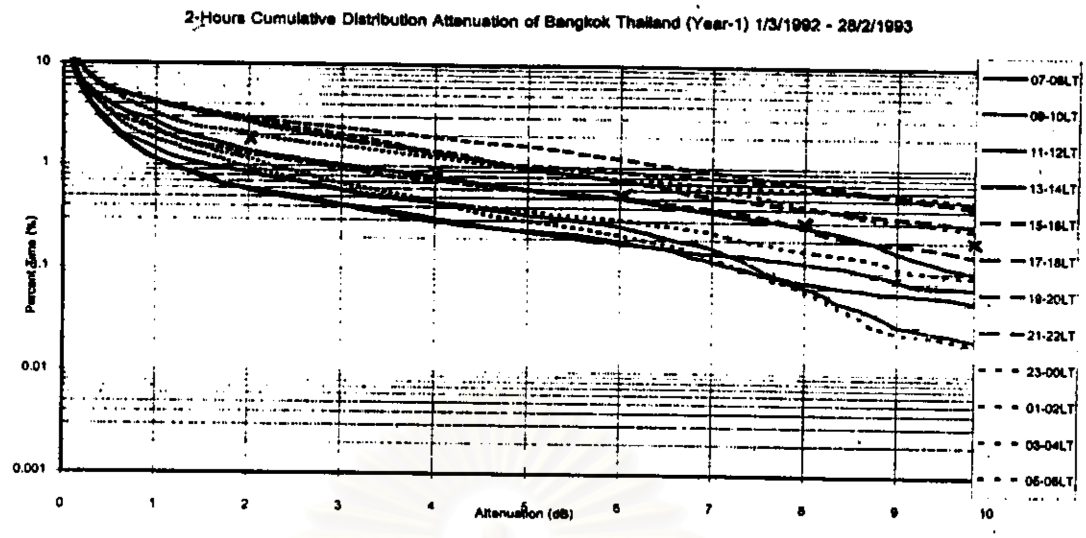

Figure 8.22 2-hours cumulative attenuation distribution of Bangkok (year-1)

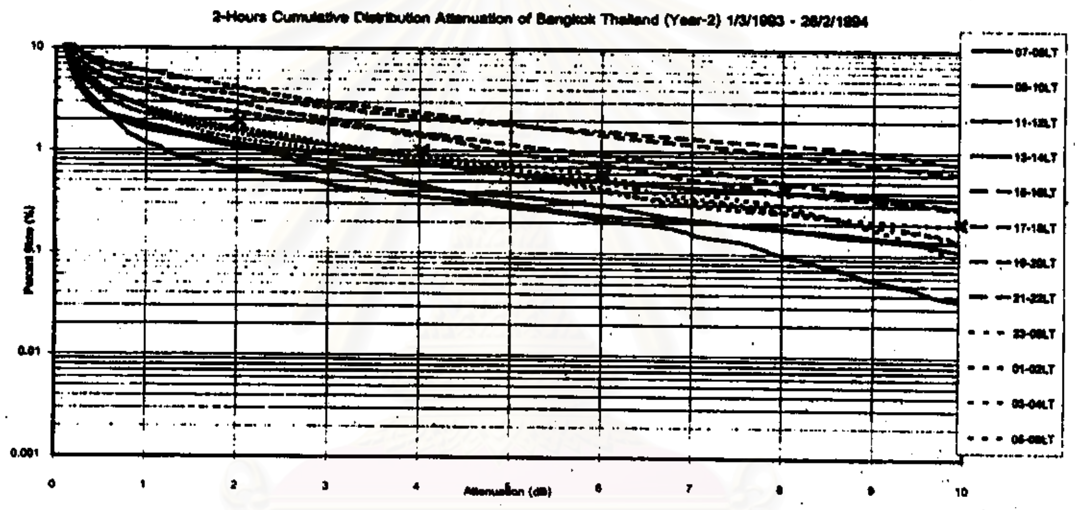

Figure 8.23 2-hours cumulative attenuation distribution of Bangkok (year-2)

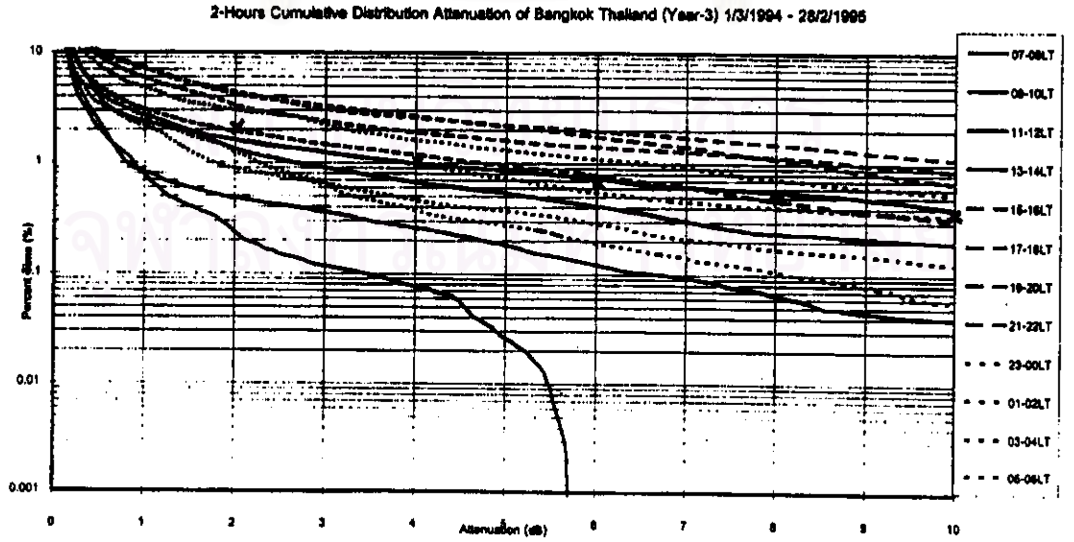

Figure 8.24 2-hours cumulative attenuation distribution of Bangkok (year-3)

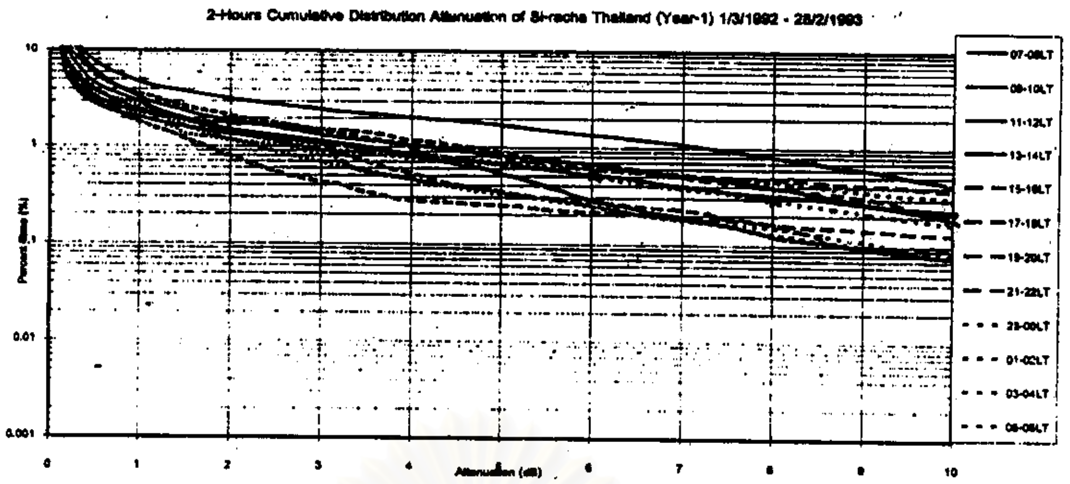

Figure 8.25 2-hours cumulative attenuation distribution of Si-racha (year-1)

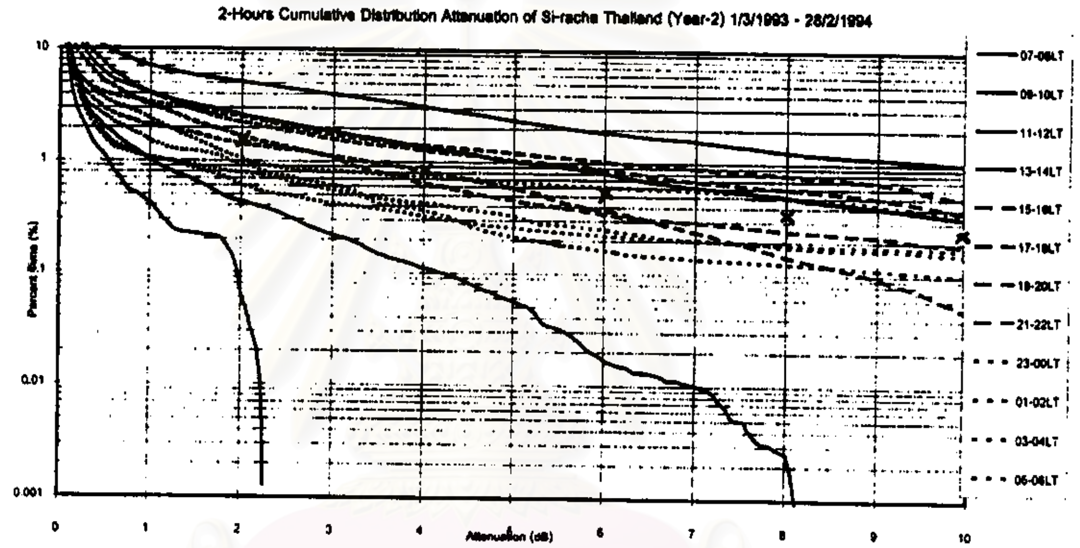

Figure 8.26 2-hours cumulative attenuation distribution of Si-racha (year-2)

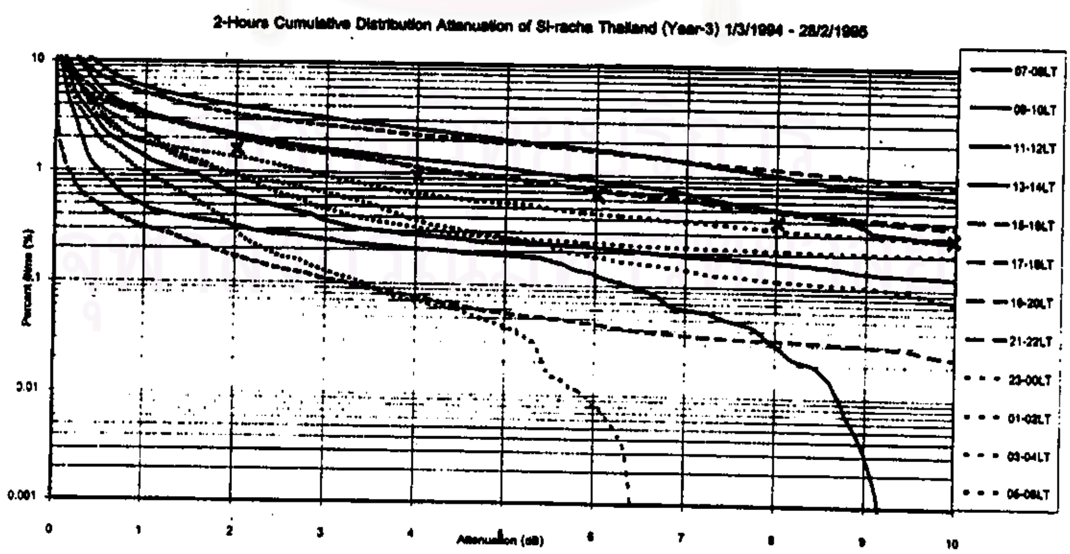

Figure 8.27 2-hours cumulative attenuation distribution of Si-racha (year-3)

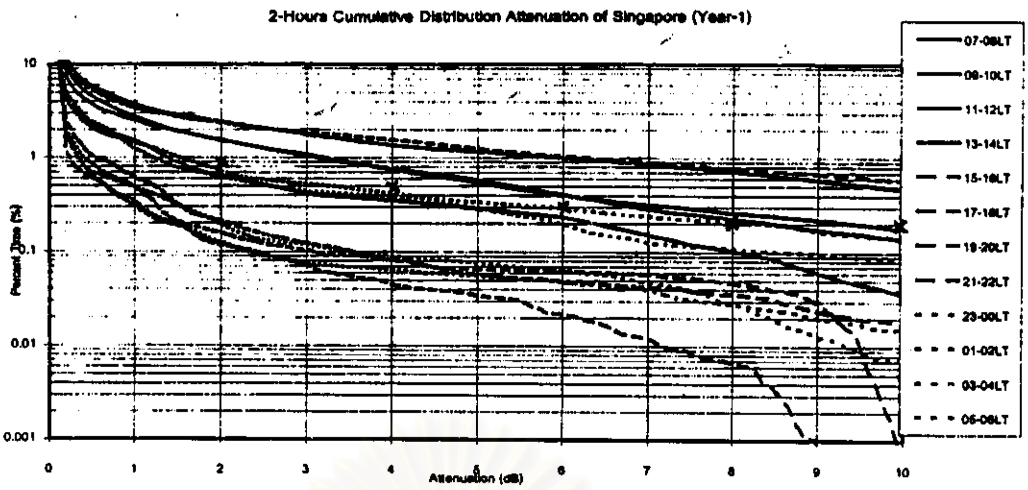

Figure 8.28 2-hours cumulative attenuation distribution for Singapore (year-1)

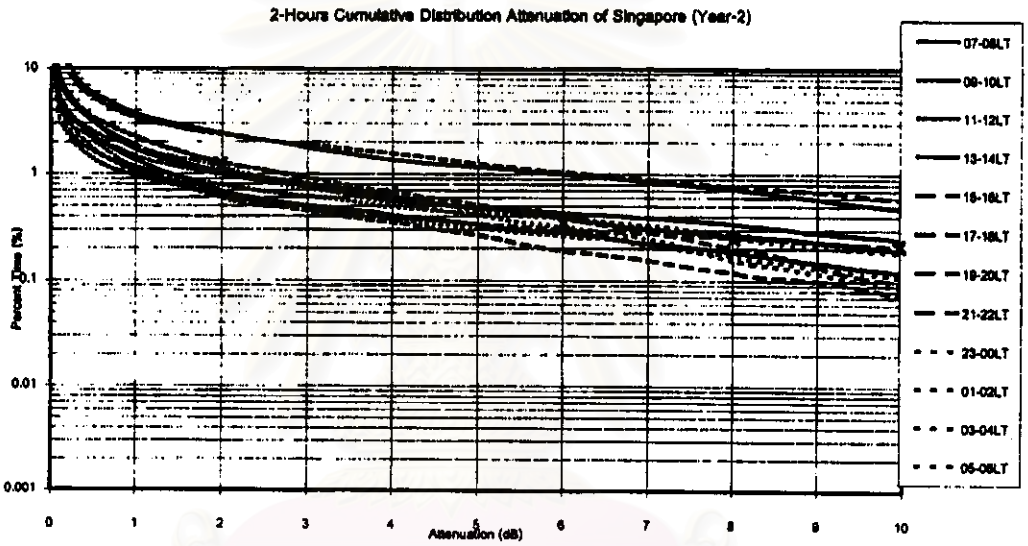

Figure 8.29 2-hours cumulative attenuation distribution of Singapore (year-2)

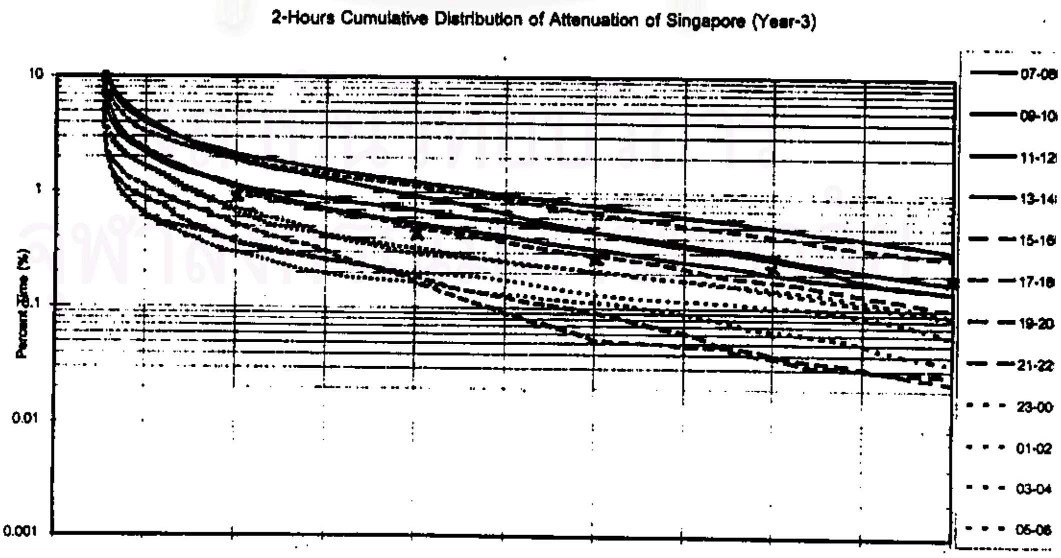

Figure 8.30 2-hours cumulative attenuation distribution of Singapore (year-3)

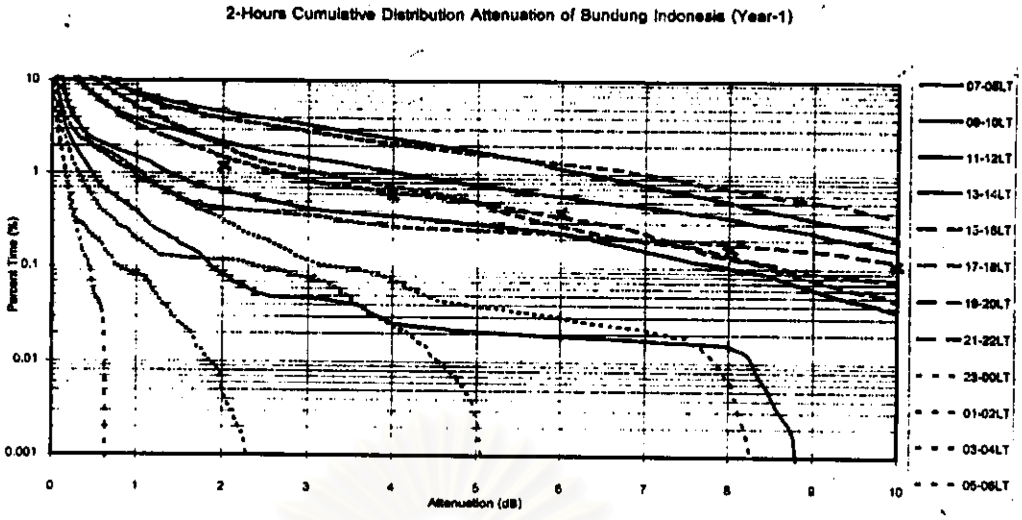

Figure 8.31 2-hours cumulative attenuation distribution of Bundung (year-1)

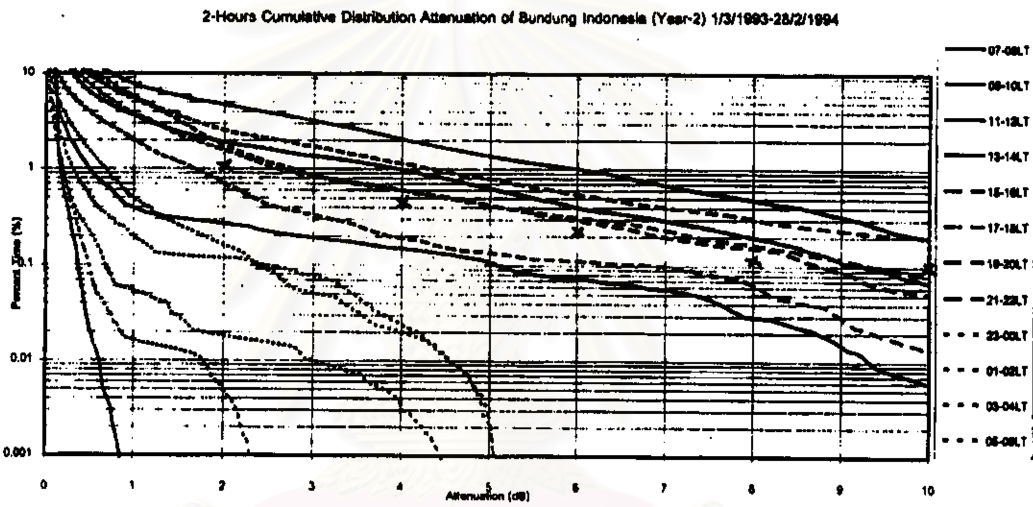

Figure 8.32 2-hours cumulative attenuation distribution of Bundung (year-2)

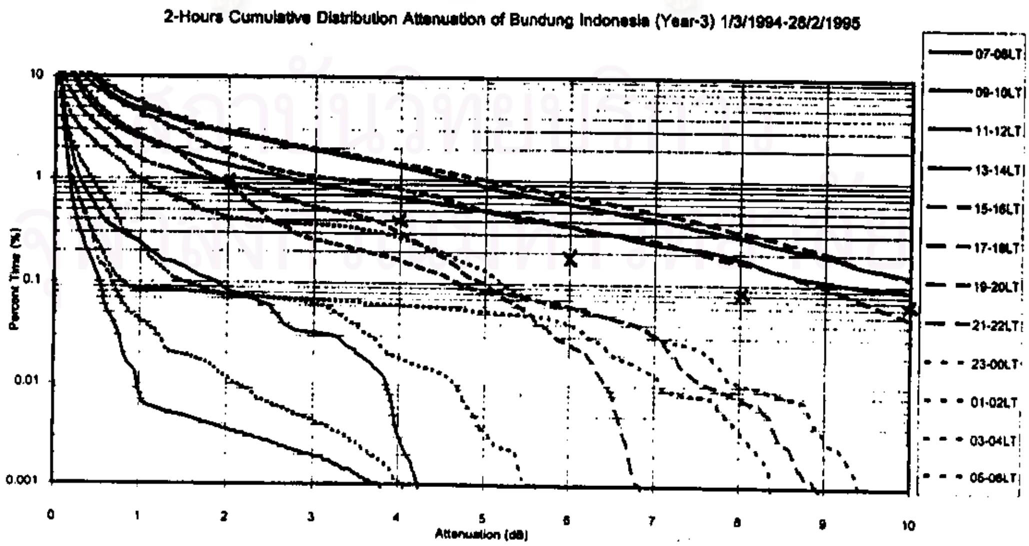

Figure 8.33 2-hours cumulative attenuation distribution of Bundung (year-3)