CHAPTER 2

CHARACTERISTICS OF RAIN ATTENUATION AND RAIN INTENSITY

2.1 Weather and Climate in Tropics and in Southeast Asia

Scientists found that the climate in the tropics is influenced by an equatorial rain belt that exists and corresponds to the convergence of the tread winds around the world having the width of about 10 degree latitude. This equatorial rain belt is known as the Intertropical Convergence Zone (ITCZ) or the equatorial trough which could be seen by the meteorological satellite image. The latent heat in the ITCZ due to the highest concentration of sun shine, released within this band, and provides the energy that drives the global circulation of the atmosphere. The ITCZ moves between the north and south directions, varying with season, and follows the changes in the sun angle with relative to the equatorial plane. Over water, the migration of the ITCZ produces one or two rainy seasons in the tropical regions depending on the position of the ITCZ. The surface-heating on land and topography combined with the ITCZ produce a more complex pattern of wind convergence and monsoons. In tropical regions, rainfall is mainly convective in nature driven by the release of latent heat.

The weather and climate in Southeast Asia are mainly affected by a very large extent of the monsoon and the ITCZ which are the natural phenomenon of weather circulation. In addition to the monsoons and the ITCZ, some tropical storms, (e.g., depression, typhoon) have high potential to produce heavy rainfall and may cause severe flooding. ITU-R Report 836 [1988] divides rain climate zone of Southeast Asia into ITU-R Zone-N and ITU-R Zone-P. The ITU-R Zone-N or a tropical moderate climate has average annual rainfall accumulation of 1000 - 2000 mm/yr, while the ITU-R Zone-P or a tropical wet climate has annual rainfall accumulation of about 2000 - 5000 mm/yr. From June to October, the southwest monsoon, the ITCZ, and some tropical storms may establish over Southeast Asia and cause heavy rainfall in ITU-R zone-N (Indonesia, Malaysia, Singapore, Thailand). Heavy rainfall with heavy clouds may be observed in accordance with the monsoon regime. From November to April, the northeast monsoon and the ITCZ move down to the South and causes heavy rainfall in the ITU-R zone P (the southern path of the region) such as Indonesia, Malaysia, Singapore and the Thailand Peninsular. At the same time, the northern path of the region (Indo-china, Thailand) is relatively cold and dry. More details of the climate in Southeast Asia are described in Appendix A.

In Thailand, heavy rainfall occurs between May to October when the southwest monsoon and the ITCZ dominate the weather. As shown in Figure2.1, Thailand is located in both the ITU-R rain zone-N and zone-P, while Singapore and Indonesia are located in ITUR-zone P. An average annual rainfall accumulation throughout Thailand varies between 1000 - 5000 mm/yr while Singapore and Indonesia have higher rainfall accumulation in excess of 2000 mm/yr.

R.K. Crane [1990] mentioned that the complexity of rainfall mechanism in the tropics cause all rain attenuation models unsuccessful prediction, and significant error occurs at +/- 30 degree latitude, There are mainly three factors that impact on the error prediction:

1) too few rain climate zones to span the wide range of rain condition present in the equatorial region,
2) inadequate procedure of the prediction model for taking into account the natural occurrence of the vertical variations of specific attenuation,
3) due to the ITU-R prediction model using a universal curve (Log-normal) for the cumulative distribution of path attenuation in all regions.

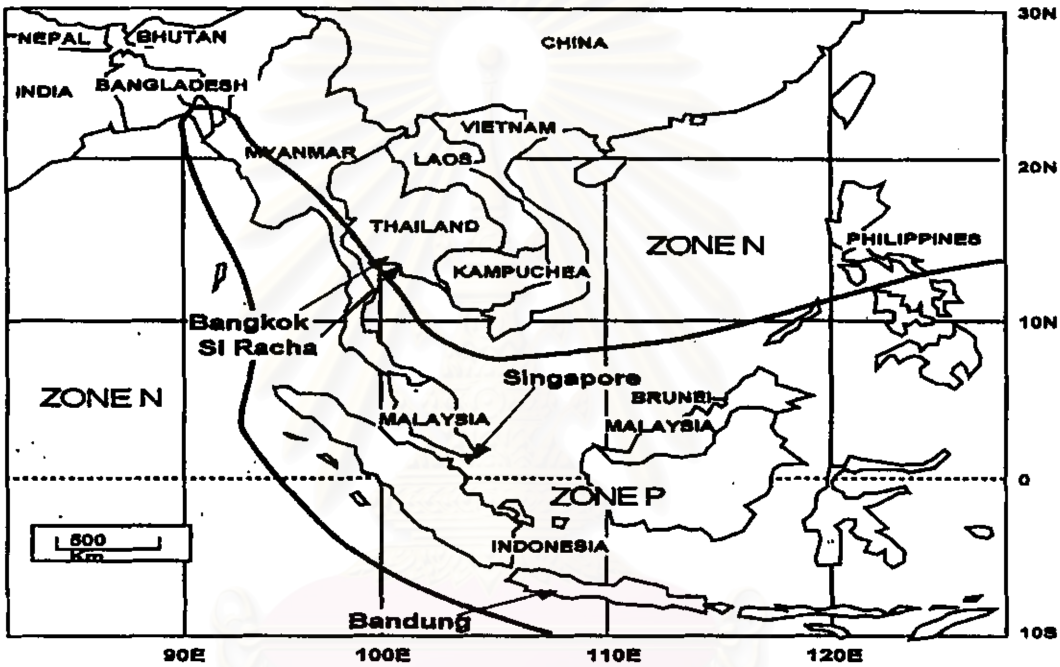

Figure 2.1 Map of four experimental sites in Southeast Asia [Indonesia (Bundung), Singapore, Thailand (Bangkok and Si-racha)], the ITU-R rain zone-N, and the ITU-R rain zone-P, K. S. McCormick [1996]

R.K Crane [1990], proposed 4 approaches to identify the rainfall-rate climate for the tropics. The first approach is to use the envelop position of the ITCZ. The second approach is to use the latitudinal dependent of average yearly rainfall accumulation. The third approach is to identify the region where the meteorological process has the same precipitation, The final approach is to use a similar region that has similar rainfall rate distribution.

ITU-R Rec.563-3 [1990] proposed rainfall-rate climate zone initially based on data analysis conducted in Canada and Europe and some recommendations taken from the Global model of R.K. Crane. ITU-R rain model modified the model using rainfall rate observation by many administrations. In addition, ITU-R provides contour maps of rainfall rate from the cumulative distribution of rainfall rate at 0.01% of a year to be used for ITU-R rain attenuation prediction model.

2.2 Rainfall Characteristic in the Tropics and in Southeast Asia

Rainfall in the tropics has more significant effect to radiowave propagation than other hydrometeors(ice, snow, cloud, etc.). It is well understood that rainfall in the tropics has very high rain intensity. In addition, the geometrical structure of the tropical rainfall is different from the temperate regions. Therefore, to accurately predict rain attenuation, it is necessary to have information on both the spatial and the temporal behavior of the rainstorms from long-term observation at particular locations. The lack of propagation experiments in the tropical regions brings about to the lack of understanding of the behavior of the tropical rainfall and rainstorms causing serious error prediction. To evaluate rain attenuation accurately, overall structures of rain not only the macro structure but also the micro structure must be taken into considerations.

K.A. Hughes [1990] characterized the propagation effect of the tropical regions into 3 specific characteristics as follows:

1) extensive desert region and warm maritime region can raise super refraction and ducting,
2) extensive region with very high rainfall causes very high attenuation, depolarization and scatters the microwave frequencies,
3) equatorial region in which the geomagnetic equator interferes the trans-ionospheric propagation at frequencies less than 10 GHz.

Due to a complex structure of rainfall, as shown in Figure 2.2, and its variation both in space and time, meteorologists classify rainfall in two types: a stratiform rain and a convective rain.

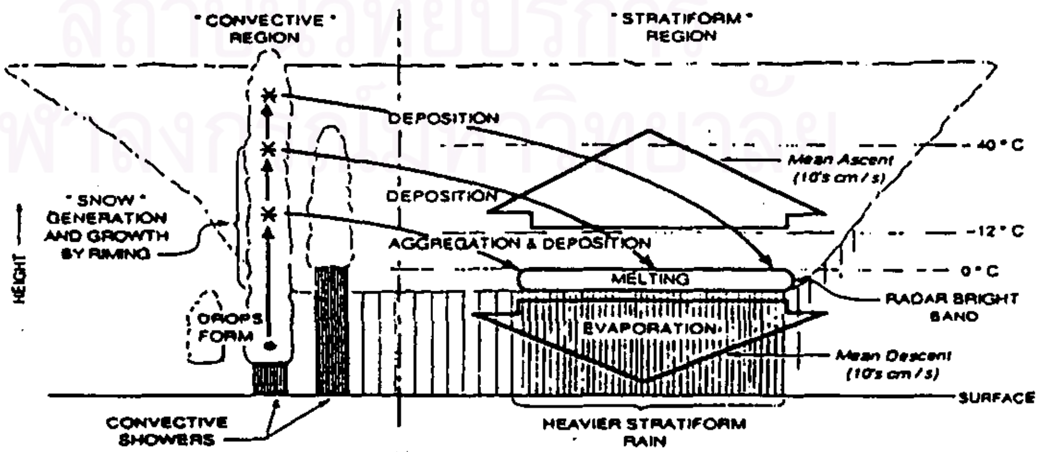

Figure 2.2 The model of a heavier stratiform rain and a convective rain, Robert A Houze [1990]

1) the stratiform rain has the formation of small ice particles usually in the upper troposphere layers. When the stratiform rain falls, these small particles join together to form bigger nucleus and become unstable. As they pass through the melting layer and extend from about 500 m to 1 km below the 0°C isotherm height, they turn into raindrops and fall down to the earth.

2) in case of the convective rain, small particles associated with clouds are formed below the 0°C isotherm. They are stirred up by the strong movement of air-masses caused by difference in the tropospheric pressure. In this process, water drops are created and grown in size until they fall to the ground.

The tropical rainfall are predominantly convective type and characterized by high rainfall rate occurring over limited extensions and falling at very short periods. During rainfall, a heavier stratiform structure develops and extends over wider areas with high rainfall rate and the convective structure embedded inside the stratiform structure. Studies of rain structures performed in previous decades indicated that rainfall observed in many regions have combined both a convective and a stratiform rain (see Figure 2.2) especially at the low latitude of +/- 15 degree.

Scientists characterize rain structures by space and time with variable structures, associated with many cells and many dimensions, that move horizontally with speed depending on the tropospheric wind. Rain cells are formed by a nucleus with high rainfall rate embedded in an extensive region with low rain intensity. The diameter of the nucleus is variable and inversely proportional to its intensity. Radar observations show that a typical size of rain cells with high rainfall intensity ranges from 2 to 5 kilometers. The lifetime of an individual rain cell is short between 10 to 20 minutes. Some observers found that a tendency of forming new rain cells adjacent to the existing cells which can cause rainstorm to last longer than the normal duration of individual rain cell.

The height of rain-cell is an important parameter for modeling attenuation along an earth-satellite path. It is generally agreed by many observers that for the stratiform rain, below the melting layer, raindrops start to fall at the height which is equal to 0°C isotherm. Above that height, rain is assumed to have the form of ice, snow, or melting snow. But for convective rain, the form of ice, snow, without melting layer, can reach the altitude of up to 10 kilometers.

The meteorologists usually deal with long-term averages of rainfall in hours, days, months, rather than the rapid variations of rainfall (rain intensity) obtained over extensive regions. But telecommunication engineers are only interested in the rapid variation of rainfall occurring in very short duration i.e., a second to some minutes. Therefore, many rainfall information available at a meteorological station may not be successfully applied for the radio propagation studies.

2.3 Types of Rain

The structure of rain is complex and not measurable in terms of their effect on radio wave. Scientists classified rain structures by rain's behavior into 4 types.

1) The stratiform rain has wide-spread structure and long lasting rainfall period with low-medium rainfall rate up to 25 mm/h. The stratiform rain is formed by cumulous clouds and by the coalescence mechanism of the Bergeron-Findeisen theory. This rain has some uniform structures with liquid rainfall at 0°c isotherm and the height above 4 - 6 km. It is normally found in the temperate regions at high latitude during spring and fall seasons.

2) The convective rain occurs because of the motion of vertical atmosphere. The convective flow occurs in a cell whose horizontal extent is several kilometers and extends to the height greater than 0° C isotherm. The cell may isolate or embed in a thunderstorm region. The convective rain may be divided into 2 types: a warm rain or a convective shower, and a severe thunderstorm rain. Warm rain has high rainfall rate and more concentrated in small areas. This rain is produced by the condensation-coalescence mechanism of the Bergeron-Findeisen theory. The thunderstorm rain or the very high convective rain has very high rainfall rate with thunder and lightning. This rain is usually generated by the cumulonimbus clouds which may extend to the height of more than 10 km.

3) The monsoon rain has a sequence of band of intense convection followed by interval of the heavier stratiform rain. The rain-band is typically 50 km across hundreds of kilometers which produces very heavy rainfall lasting for several hours.

4) The tropical storm or typhoon has relatively large region of rainfall extending over hundreds of kilometers. This tropical storm is classified by several spiral bands termination in region of intense rainfall surrounded by the central region (the eye of the storm). The rain-band contains region of intense convection and heavier stratiform.

2.4 Macrostructure of Rain

To study effects of rainfall to radiowave propagation, rain structures both the macro structure and the micro structure shall be understood. The macroscopic characteristics include a rain-cell size, a rain-cell distribution, a movement of rain-cell, and a height of the melting layers. The microscopic characteristics include a drop-size distribution, a drop density, a drop shape, a terminal velocity of the drop, and ice crystals.

1) The Horizontal Structure of Rain

Observation of rainfall rate by rain gauge is usually found that the short interval of high rainfall rate is imbedded in a longer interval of the light rain. Such observation is the typical of rainfall in all regions. The process of rainfall is non-stationary at time and space that lead to difficulty to evaluate rain attenuation prediction. Rain cells are usually clustered within a rain region or a meso-scale area. The satellite link operated at low elevation angle (<10 degree) and terrestrial link longer than 10 km may be affected by more than one rain cells.

For the broadcasting satellite service that serves many receiving stations simultaneously within a large coverage area, an understanding of statistical dependence of rain attenuation over a large area is required. Barbaliscia [1988] studied the joint probability of rain spread over 10 to 1,000 km using a point rainfall rate. Results shown that the statistical dependence of joint rainfall at 2 sites decreased with the increasing distance, and the distance separation of more than 600 km was found to be independent.

2) The Vertical Structure of Rainfall

In estimating rain attenuation and scattering, information on the vertical structure of rainfall is required. Previously, rain attenuation model proposed by ITU-R 618-2 [1992] assumed a uniform vertical and cylindrical model of rain cell extending from the ground up to the 0° C isotherm height. Due to the non-uniformity of rain both vertical and horizontal, the uniform rain attenuation model may be overestimated in heavy rainfall climate of the tropical regions.

Many observers found that a stratiform rain can be modeled into 3 distinct layers. The first layer starting from the ground to just below the transition height contains only liquid particles (raindrops). The second layer is narrow about 300 mm around the transition height and contains mainly melting snow particles, and also causes attenuation due to large volume of wet snow (see Dissanayake, McEwan, [1978]). The third layer is above the transition height containing only ice and snow with little attenuate radio wave below 60 GHz due to the small contents of small particles. Scientists also found that the value of the transition height of the stratiform rain is close to that of the ambient 0°C isotherm height when the vertical air motion is weak.

The convective rainstorm has more complex structure than the stratiform structure. In the convective rain, Houze [1981] found that strong vertical air motion exists resulting in large scale mixture of many different particles such as. supercool raindrops which can be found far above the 0° C isotherm height of convective rain.

3) Rain height and the 0°C isotherm height.

In the stratiform rain, ITU model assumes the transition height to be identical to the 0°C isotherm height. G.O. Ajayi and Barbaliscia [1989] found that the 0°C isotherm height has a very small variation in diurnal and yearly, while monthly variation is significant variation in the temperate zone but may be negligible in the tropic. On the extensive studies of Leitao [1984], G.O. Ajayi and Barbaliscia [1989], it appeared that the 0°C isotherm height during rain condition (h_{FR}) tends to be lower than the 0°C isotherm height measured during the summer month especially in the temperate region.

2.5 Microstructure of Rain

The microstructure of rainfall, essential for the radio propagation prediction, consists of a drop size distribution, a raindrop shape and orientation, and a terminal velocity of the raindrop.

1) The Rain Drop Size Distribution

The size, the shape and the orientation of the raindrop may vary within a storm. Many observations show that the drop size distribution is stable on average and changes with rainfall rate. The drop size distribution of Law & Parson [1943] was found useful for the estimation of attenuation and scattering of rain at frequencies up to 40 GHz. The small drops having diameter of less than 0.5 mm are not well modeled by Law and Parsons distribution due to the measurement error of very small drops. Many scientists found that the high concentration of small drops can be highly varied in many areas of the world; so that, the use of a single model of raindrop size distribution, for example; a negative exponential, a Log-normal distribution may not be adequate for all regions. G.O. Ajaji and R. Olsen [1990] studied the drop size distribution in Nigeria and found that the log-normal distribution is well fitted with a tropical climate. The study of drop size distribution in Malaysia by A.R. Tharek and Dim [1992] also found that the log-normal distribution was agreed with experimental data. But, in Singapore, T.S. Yeo, P.S. Kooi, M.S. Leong [1990], found that the negative-exponential drop size distribution was fitted with the Singapore area.

2) Drop shape and Orientation

Scientists found that due to the effects of earth's gravity and the surface's tension of water, falling drops are nearly spherical shape. The force of gravity provides the main orientation force of raindrops. The drop may vibrate and oscillate while falling. However, the shape is nearly oblate spheroid with the symmetry axis close to the vertical axis. The horizontal force due to a vertical wind gradient, may cause the mean orientation of raindrop to be canted by a few degrees. Pruppacher and Pitter [1971] modeled the drop shape as a function of the drop size distribution and observed on the laboratory. Results agreed with the shape predicted by Pruppacher and Pitter [1970].

3) Terminal Velocity

The terminal velocity of raindrops as a function of the drop size was reported by Gunn and Kinzer [1949]. The measurements were made in a quiet condition in the laboratory. The velocity of the drop depends on air-density and the height. The size of the drop and the liquid water content of the drop change little with the height. Since rainfall rate depends on the drop size and the terminal velocity of the drop; therefore, rainfall rate depend on the height. The attenuation varies by the rainfall rate, then the attenuation will vary little with the height where the radio link is located.

2.6 Rain Intensity Statistics

1) Rain Gauge Integration Time

The cumulative distribution of rain intensity over a long-term measurement is useful for the prediction of rain attenuation in the area that lack of the measured attenuation data. In radio propagation studies, a very short percentage time of rainfall rate (< 0.01%) is significant to develop the prediction model, but various rainfall data from the meteorological services cannot be used directly for the rain attenuation prediction.

A tipping-bucket rain gauge and a fast response rain gauge having a short integration time (less than 1 minute) are used in the radio propagation research. The ITU-R Rep. 563-4 [1990] recommended the integration time of $\leq$ 1 minute as appropriate for rainfall measurement and it also proposes the mean cumulative distribution, shown in Table 2.1, based on experiment data available before 1990. When the tipping-bucket rain gauge is used, the ITU-R recommends that measurement of time interval between successive tips is mainly suitable for the rainfall rate between 10-100 mm/h. For very high rainfall rate, a gauge and a recording system shall be specifically designed for precise operation.

2) Year-to-Year Variability of Rain Intensity Statistics.

Many of today's propagation models use the long-term cumulative distribution of point rainfall rate to design a terrestrial and a satellite communication systems. A single year rainfall rate may deviate from the long-term measurement from many years. Therefore, year-to-year variability information is also important to estimate the variation and the deviation from average value. Aresu [1989] studied yearly variation of annual statistics of rain attenuation in Italy over 10 years and found 20% of year-to-year variability higher than the average.

3) Statistics of Rainfall Event Duration

The statistical distribution of a duration of rainfall event that exceed the threshold is useful for the design of the radio microwave link above 10 GHz. Misme [1994], Yamada M. OGAWA, A. Furtuta and Yokoi. H [1978] indicated that the rainfall duration distribution was approximately a log-normal distribution. Measurement in Italy and in Greece by Fedi and Mello [1977] indicated that the median duration of rainfall event was inversely proportional to the valve of the rainfall intensity threshold.

2.7 Rain Intensity Predictions

The knowledge of rainfall rate (rain intensity) cumulative distribution is widely used as a fundamental tool for rain attenuation prediction. Estimation of rain attenuation can be derived from rainfall rate data available in certain areas of interest. Rainfall especially of high intensity (> 100mm/h) is difficult to measure accurately. For moderate rain intensity (< 50 mm/h), many scientists found that the cumulative distribution can be approximated by a log-normal distribution. Segal [1980] suggested that a power-law relationship can satisfactorily approximate the entire cumulative distribution over 5 mm/h. Morita and Higuti [1976] proposed a gamma distribution as an approximation to the rainfall rate distribution in Japan.

Analysis by F. Moupfouma [1982] suggested that the rainfall rate distribution was better described by a log-normal distribution at low rainfall rate and a gamma distribution at high rainfall rate. In addition Moupfouma, L. Martin, N. Spanjaard [1990] analyzed rainfall behavior at Donala in Cameroon and at Brazzaville in Congo located in the highest rainfall zone in the continental of Africa in 1986. They found that strong showers with high rain intensity due to convective rain occurring for a short period and over a limited areas. A stratiform rain has low-medium rain intensity (< 50 mm/hr) with long duration and high extent over a large area. They also found that the convective rain event is not isolated with the stratiform rain. In addition, rainfall at inland or on a mountain has significantly different behavior than rainfall in a coastal area.

The relationship of rain intensity and rain drop size can be defined as the volume of water falling per surface area given a specific time interval of minutes or hours. This rain volume depends on the raindrop size distribution and the velocity of raindrop given by (Moupfouma et al., [1990]) :

$$R = 4\pi \int n(a)v(a)a^3 da \qquad \text{-------------------------- (2.1)}$$

where

n(a) is the drop size distribution,

a is the radius of the raindrop in meter,

v(a) is the drop fall velocity in meter/second.

1) Rice & Holmberg Rain Intensity Distribution Model

The well-known rain intensity distribution model of Rice and Holmberg [1973] divides rainfall into two types: M_1 and M_2. The M_1 contains the high rainfall rates associated with thunderstorms and strong convective activity while the M_2 contains any rainfall rate excluded from M1. The total annual average rainfall accumulation M can be expressed by:

$$M = M_1 + M_2 \quad \text{mm}$$

and $\beta = M_1/M$

where

β is the ratio of convective rainfall accumulation to total rainfall accumulation. Rice and Holmberg proposed the double exponential equation to obtain the cumulative distribution of rainfall rate (R) as follows:

$$P(\%) = 100/8760 \cdot M\{0.03\beta \cdot \exp(-0.03R) + 0.2 \cdot (1-\beta) \cdot [\exp(-0.258R) + 1.86 \cdot \exp(-1.63R)]\} \text{-------}(2.2)$$

This equation is found very useful for the design of the millimeter waves in North America and Canada.

2) ITU-R Rain Intensity Distribution Model

ITU-R Rep.836 [1988] simplified the Rice & Holmberg model and established the 15 climate zones which are given in Table 2.1 for the world-wide application. The tropical regions fall in Zone M, N, P and Q and it indicates in Figure 2.3.

Table 2.1 Rainfall rate distribution in 15 ITU-R rainfall climate zone, ITU-R 836 [1988]

Rainfall rates in the 15 CCIR rainfall climatic zones (Table 1 of Reference 65)

Percentage of time	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q
1·0	<0·1	0·5	0·7	2·1	0·6	1·7	3	2	8	1·5	2	4	5	12	24
0·3	0·8	2·0	2·8	4·5	2·4	4·5	7	4	13	4·2	7	11	15	34	49
0·1	2	3	5	8	6	8	12	10	20	12	15	22	35	65	72
0·03	5	6	9	13	12	15	20	18	28	23	33	40	65	105	96
0·01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
0·003	14	21	26	29	41	54	45	55	45	70	105	95	140	200	132
0·001	22	32	42	42	70	78	65	83	55	100	150	120	180	250	180

Rainfall rates exceeded for the given percentage times in the various climatic zones

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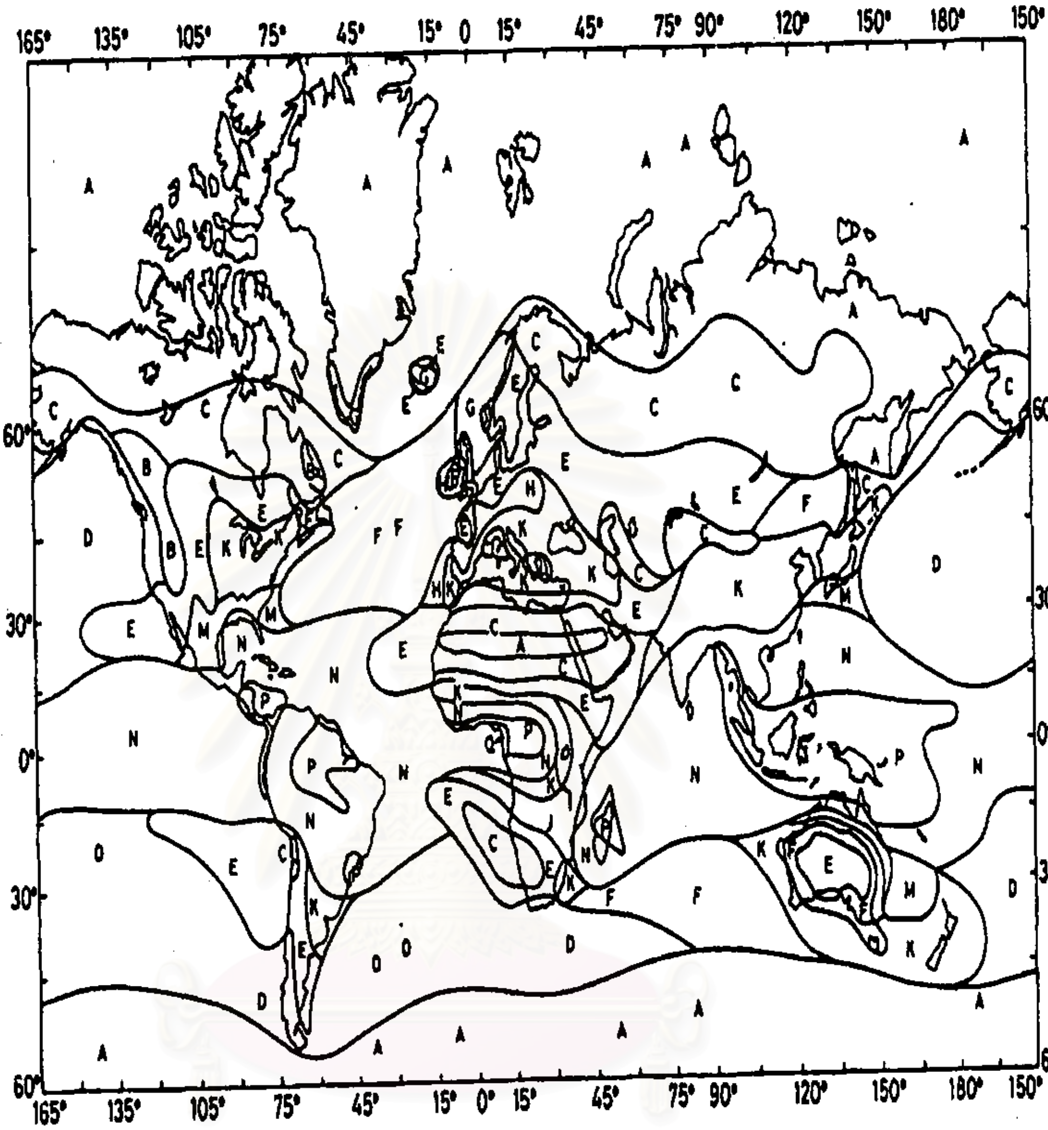

Rainfall climatic zones of the Earth as given by the CCIR (combined from References 28 and 65)
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Figure 2.3 Rainfall map corresponding to the 15 rainfall climate zone (A to Q), ITU-R 836 [1988]

2.8 Review of Rain Attenuation Studies

The nature of rain causing attenuation at frequencies above 10 GHz was first studied by H. Goldstein [1951] before the World War II. Early studies of rain attenuation were focused on the theoretical estimation of specific attenuation and scattering cross section as well as an experimental verification of the theoretical estimation of rain attenuation. R.G. Medhurst [1965] verified rain attenuation experiments that were performed before 1964 and his experimental observations did not agree with the theory. R.K. Crane [1971], carefully investigated experimental data compared with theoretical estimates and he found errors due to the rainfall measurement. At that time, most researchers agreed that good agreement can be obtained between the theory and the experiment when the experimental observation was well performed. Currently many works of rain attenuation studies are focusing on the construction of a suitable prediction models of rain attenuation suitable for all climate regions.

The theoretical model of rain attenuation was started by the computation of a specific attenuation. The specific attenuation (dB/Km) can be computed by the assumption of the homogeneous of raindrops with the drop's size assumed as a uniformly distributed along a propagation path. Then an introduction of a single scattering theory was applied to sum all the scattered field from each raindrop to all raindrop sizes distribution along the path. The drop size distribution for this calculation is identical to the drop size distribution observed at the earth surface. The general specific attenuation due to rain can be expressed by:

$$\alpha = 4.343 \int Q(r, \lambda, m) n(r) dr \qquad \text{------------(2.3)}$$

where

α in a specific attenuation (dB/Km),

$Q(r,\lambda,m)$ in a attenuation cross section of a raindrop,

r is a drop radius (meter),

λ is a ware length (meter),

m is a refractive index,

n(r) is the rain drop size distribution,

The extinction (attenuation) cross section for each spherical raindrop may be calculated by knowing the drop size distribution n(r)dr. For frequency below 2 GHz, the raindrop is much less than the wavelength and attenuation is mostly due to the absorption rather than scattering. Therefore, the specific attenuation may be estimated by the Raleigh approximation for scattering by sphere. However, at higher frequency, the extinction cross section can be calculated by the Mie [1908] scattering theory. Studies of H.R. Pruppacher and P. L. Pitted [1971] found that the falling water droplets in quiet condition are flatten on the bottom and round on the top. However, the spherical drop shape approximation is often used because it eases to calculate the scattering parameter, rather than the distorted spherical drop shape.

For the oblate-spherical drops shape, T Oguchi [1973] used the higher order approximation to calculate the attenuation and the phase rotation of radiowave due to the oblate spherical raindrop and used a drop shape distribution function which was observed for falling drops under quiet condition. R.K. Crane [1975] found that the variation in the specific attenuation due to variation of drop size distributions for a given rainfall rate is larger than the fluctuation of attenuation due to the effect of second-order parameter caused by drop shape; therefore, it may be ignored effects of the second-order for the prediction of attenuation.

The parameters to be calculated in the rain attenuation such as rain intensity, rain drop size distribution, show time and spatial variability which are non-deterministic (randomness) and cannot directly be predictable. Therefore most of rain attenuation analysis must rely on a statistical analysis to quantitatively evaluate the impact of rain on radiowave.

R.K. Crane [1971] analyzed the effects of multiple scattering and showed that the single scattering theory is applicable for rain at frequencies below 20 GHz. Many scientists try to verify and compare the theoretical estimation with the measurement. Since the theoretical estimation of rain attenuation was introduced, many experiments have been conducted by measuring attenuation along the propagation path and simultaneously observing the rainfall rate at a point on the ground. Then, the point-rainfall rates were transformed to the specific attenuation values (dB/km). Finally, average rain attenuation along the path may be calculated by multiplying the path length and some reduction factors with the specific attenuation.

R.G. Medhurst [1965] compared the theoretical estimation with the observed measured attenuation performed prior to 1964 and found disagreement with the observations. He proposed the empirical relationships between attenuation and path average rainfall that can be used instead of the theoretical relationship. However, R.K. Crane [1971] reviewed the experiments and he found some problems on rainfall observations. Many radar observations indicate that high rainfall is confined to small areas while light rainfall occurs in areas around intense rain cells. Radar observations suggested that average rainfall rate along the path cannot be adequately estimated unless a large number of rain gauges are used along the propagation path and rain gauge separation must significantly be smaller than the horizontal extent of the rain cells. R.K. Crane [1971] observed rain cells by L-band radar which often found that rain cells are smaller than 2 km. It is implied that the rainfall rate along the path may require many rain gauges spacing only several hundred meters along the path.

Statistical of rain attenuation is essential for a communication system design above 10 GHz. System design needs to know how often rain attenuation occurs in a year, and how long (in several minutes) it will exceed the system threshold and persist for some percentage time within a given year. Up to date, there are generally three prediction approaches to obtain that attenuation statistics.

The first approach is using a large number of long term-observation of attenuation data, usually in several calendar years. The long term attenuation and rainfall data may compile to the statistics on the probability of its occurrence. The longer the observation period, the more closer the attenuation statistics. These attenuation and rainfall statistics are called a cumulative distribution of attenuation, and a cumulative distribution of rain intensity (rainfall rate). Figure 2.4 shows an example of a cumulative distribution of attenuation in Bangkok and Si-racha, Thailand during March 1, 1994 - February 28, 1995.

The second approach is using empirical models i.e. ITU-R P.618-4 [1995] model associated with some meteorological data to calculate the statistics of rain attenuation. Most of the empirical approach were developed from measured data of the first approach and some meteorological data. In some areas, the long-term statistics of attenuation from the first approach is not available. Then the second approach can be applied.

The third approach is a semi-empirical method i.e. the Leitao and Watson [1986] model. This model used the knowledge of physical characteristics of rainstorms observed by the dual-polarization radar and introduced a scattering theory. This model worked well for the rain attenuation prediction in the European region.

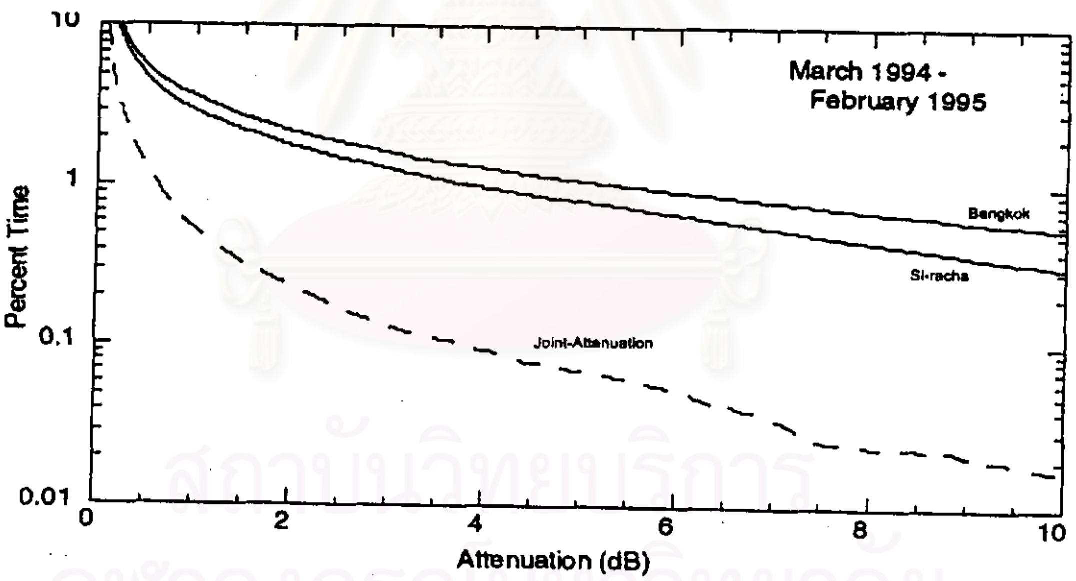

Figure 2.4 Annual cumulative distribution of Attenuation in Bangkok and Si-racha, Thailand. The dashed curve shows the joint attenuation distribution between Bangkok and Si-racha.

Currently, the empirical models to predict a distribution of attenuation and rain intensity are not directly useful in estimating attenuation distribution function for different locations especially in the tropics. In order to obtain the available attenuation statistics from available point - rainfall data, the path attenuation associated with the effective path length model may be required. The path average rainfall distribution could be transformed to the attenuation distribution using the effective path length concept and the theoretical relationship between rainfall rate and specific attenuation. The effective path length usually represents a single raincell. But for a low elevation angle operation, it much includes the probability of more than one cell occurring along the path.

Rain attenuation model normally uses a point-rainfall data at 1 minute integration time, then the point rainfall rate are transformed to specific attenuation data and the attenuation distribution function is created using an effective path length concept:

$$A(p) = \propto L_{eff}(p) \quad dB \quad \text{------------------------------}(2.4)$$

where:

$\propto$ is a specific attenuation (dB/km),

A(p) is a slant path attenuation at percentage time p % (dB),

Leff(p) is an effective path length at percentage time p % (km)

The specific attenuation proposed by R.L Olsen and D.V. Rogers [1978] has been found to be related with the rainfall rate (R) as

$$\propto = KR^{\Lambda} \quad dB/km \quad \text{------------------------------}(2.5)$$

where

K and Λ are parameters depending on frequency and polarization.

The values of K and Λ for the frequency range from 1 to 400 GHz were calculated by Fedi [1979], Maggiori [1981] with the oblate spheroids shape, at the temperature of 20^{0}C, the Laws and Parsons [1943] drop size distribution, the Gunn and Kinzer [1949] terminal velocity, and the refractive index values according to the model of Ray [1972].

2.9 Attenuation Prediction Models for the Tropics

Recently, many researchers found that the well-known ITU-R attenuation prediction model, using the uniform structure of a stratiform rain in the temperate regions, has seriously error estimated the rain attenuation in the tropics. Scientists found that an error estimation is mainly due to the concept of the model prediction using the stratiform rain having a uniform structure of rainfall. Up to date, a lot of studies are focusing on the modification of the ITU-R model to be suitable for the tropics. In the tropical regions, some scientists were developed the prediction model suitable for the tropics. These models are ITU-R 618-4 [1995], Dissanayake, Allnutt and Hidara[1997], CETUC [1993], M. Juy [1990].

2.10 Rain Attenuation Studies on Earth-satellite Path in the Tropics

Many scientists have been studying attenuation due to rain at frequencies above 10 GHz mainly in the temperate climates i.e. Europe, the United States, Canada, more than three decades. In Europe, the OLYMPUS satellite was deployed to study effects of hydrometores including cloud, hail, rain, fog, ice particles, on both Ku-band and Ka-band frequencies. The ITALSAT satellite was launched to study attenuation at frequencies of 20 GHz, 40 GHz, and 60 GHz. In addition, in the Unites States, the National American Space Agency (NASA) deployed the Advance Communication Technology Satellite (ACTS) to study the effects of radiowave propagation over north America and Canada. In Southeast Asia, rain attenuation studies are not widely performed. The joint cooperation between some countries in Southeast Asia (Indonesia, Singapore, and Thailand) and Canada to study the Ku-band rain attenuation along the earth-satellite part was reported by K.S. McCormick, et al., [1996]. Analysis of Rain Attenuation at low elevation angle was reported by N. Yoothanorm et al., [1997]. The joint study among INTELSAT, Eindhoven University of Technology, the Netherlands, and Surabaya Institute of Technology was performed at Surabaya in Indonesia during 1991-1993 by G. Brussaard, et al., [1993]. For the Ka-band (30/20GHz) rain attenuation study along an earth-satellite path in Southeast Asia is not yet performed due to the unavailability of the Ka-band beacon signals.

Recently the Ku-band rain attenuation studies in the tropical regions have significantly progressed. The extensive study of INTELSAT and other administrations used both radiometer and beacon measurements. Many countries in the tropics carried out rain attenuation studies including: Australia by Bowthorpe [1990], MS Pontes, L.A.R. Silva Mello and R.S.L. Souza [1990], Cameroon by D.K McCarthy, J.E. Allnutt, W.E Salazar, F Wanmi, M. Tchinda, T.D.G. Ndinayi, and C. Zaks [1990], Indonesia by P.J.I Maagt, S.I.E. Touw, J. Diik, G. Brussaarrd, and J.E. Allnutt [1993], Kenya by McCarthy, et al.,[1992], Nigeria by McCarthy, et al.,[1990], Peru by A.W Dissanayake, J.E. Allnutt, D.K. McCarthy [1989], R. Lekkla et. al., [1993] and R. Lekkla et. al, [1995].

Investigations of rainfall characteristics in the tropical regions were also reported by Moupfouma et al., [1990], Ajayi [1990]; Harris and Mimer, [1990]; Maciel and Assis,[1990], Ajayi and Babaliscia [1990], Ponies and Souza [1991], Crane [1990], R Lekkla et. al., [1993]. Crane [1990] reported that there is still a lack of measured rainfall intensity distributions in the tropical climates that is currently poorly defined.

Effective rain height is the main concern to develop the attenuation model. The progress of the effective rain height studies in the tropical regions was performed by Ajayi and Babaliscia [1990]. The rain height study in India with 11 GHz vertical and slant-path radiometers were reported by Raina, [1991]. M.S. Pontes et al., [1994] also performed the measurement of effective rain height in Brazil to verify their prediction model.

For attenuation prediction, many experimental researches in the tropics found that the well-known ITU-R prediction models underestimated the measured attenuation distribution. Dissanayake and Allnutt [1992] reported that rain attenuation prediction for the tropics can be improved by assuming the log-normal distribution to both rain intensity distribution and attenuation distribution. Pontes, et, al., [1992] reported that attenuation prediction in Brazil can be improved by better modeling of effective rain height and effective path length. In Indonesia, M Juy et al., [1990] proposed the modification of the ITU-R 564-3 [1986] model by using a log-square law distribution for the high rainfall areas of Indonesia. In Papua New Guinea, Bryant and Dugamari [1992] studied rain attenuation statistics at high elevation angles and it was possible to develop the prediction model by separating the effects of individual rain cells.

The following details are summarized activities of rain attenuation experiments along the earth-satellite paths in the tropical regions:

J.E Allnutt and S.A.J Upton [1985] performed rain attenuation measurement using the 11.6 GHz radiometric measurement in Hong Kong in 1980, at a latitude = 22° N, a longitude = 114°E, an altitude above sea level = 50 m, an elevation angle = 27.9° an azimuth angle = 253.2°. Result was found that 10.3 dB fading persisted about 0.1% of the time and 2.3 dB persisted about 1%. Measured attenuation distribution did not agree with the CCIR 564-2 model [1985] and it overestimated the measured attenuation distribution. Rainfall rate measurement was compared with the Rice and Holmberg model (β = 0.5 , M = 1200 mm/yr), which was described in section 2.7 and it was well agreed with the measured rainfall rate distribution.

D.K McCarthy, et, al., [1990] performed radiometric measurement in the sub tropical region of Douala, Cameroon at a Longitude = 9.7° E , a latitude = 4° N, an altitude = 15m, an elevation angle = 47°, an azimuth angle = 263.6°. Douala has average rainfall accumulation of 4,110 mm/yr and it is designated in the ITU-R Zone Q. The Dicke-Switches radiometer with a 1.8 m antenna and a tipping-bucket rain gauge collected rain attenuation and rain intensity statistics. The effective medium temperature (see details in chapter 3) was set up at 285° K. Result was compared with the ITU-R 564-3 [1986] model, and it underestimated the measured attenuation distribution. The measured rainfall distribution was found in good agreement with the Rice-Holmberg model when β equals 0.43 and M equals 3213 mm/yr.

D.K. McCarthy, J.E. Allnutt, W.E. Salazar, R.W. Sitati, M. Okoth, M.J. Mutungi, C.D. Odhiambo and C. Zaks [1990] conducted the 11.6 GHz radiometric measurement on the mountain of Nairobi, in Kenya at a Longitude = 36.7° E, a latitude =1.3° S, an altitude = 1800 m, an elevation angle = 56.9°, an azimuth angle = 83.8°. An average annual rainfall accumulation is 930 mm/yr with ITU-R zone-K. The effective medium temperature was set up at 285°K. Results of one year measurement showed less severe attenuation than the coastal area of the equatorial region. The ITU-R 564-3 [1986] seriously underestimated the measured attenuation distribution. For the rainfall measurement, the Rice & Holmberg model with β = 0.23, M= 1042 mm/yr, was well fitted with measured rainfall rate cumulative distribution.

DK McCarthy, J.E. Allnutt, W.Salazar, E.C. Omenta, B.R. Owolabi, T. Oladiran, G.O. Ajayi, T.I. Raji, and C.Zaks [1992] performed a radiometric experiment in the equatorial region of Ile-Ife, Nigeria at a longitude = 4.34° E, a latitude = 7.33° N, an altitude = 274 m, an elevation angle = 40.3°, and an azimuth angle = 257.25°. The average rainfall accumulation is 1400 mm/yr and it is designated between ITU-R zone N and zone P. The radiometer and the tipping-bucket rain gauge were installed more than one year. The effective medium temperature was calibrated at 285°K. Result indicated that attenuation about 10 dB exceeded > 0.1% of the time. The ITU-R 564-3, [1986] seriously underestimated the measured distribution. The cumulative rainfall distribution agreed well with the Rice & Holmberg Model when M = 1703 mm and β = 0.6.

A.W Dissanayake, et. al., [1989], conducted the 11.6 GHz radiometric measurement in the equatorial region of the Amazon Basin of Peru at Iguitos having a latitude (lat.)= 3.4° S a longitude (long.) = 285° E, an altitude (alt.) = 100m, during 1983 - 1984. Rainfall rate measurements were made by a tipping bucket rain gauge. Results were concluded that measured annual rainfall distribution at 0.01% = 115 mm/h, 0.1% = 55 mm/h and 1% = 6 mm/h. Rainfall result was found in good agreement with the Rice & Holmberg model given β = 0.6, and M = 2300 mm/yr. The measured cumulative distribution of attenuation was plotted against the log-normal distribution and it has a good agreement with the measured distribution while the ITU-R 564-3 [1986] underestimated the measured distribution.

MS Pontes, et. al., [1990] performed a 2-year measurement using 12 GHz radiometers together with the site-diversity measurement in Brazil - the equatorial and sub tropical of South America. During 1988-1990, the dual-slope radiometers and the tipping bucket rain gauges were installed at Belem (lat. =1.27°S, Long. = 48.3°, alt. = 24 m, el. = 70.3°), Manaus (lat. = 3°S, long. = 60°, alt. = 48m, el = 83°) and Rio de Janeiro (lat. = 22.5°S, long. = 43.3°, Alt. = 30m, el. = 53.52°). The effective medium temperature was calibrated at 285°K. Results indicated that the highest attenuation occurred in Belem, and Manaus (equatorial region) followed by Rio de Janeiro the sub-tropical. Measured results at Manaus and Belem, Rio de Janeiro were compared with 5 available models: Karasawa [1989], Gracia-lopez [1989], Laitao-Watson [1986], Boithias[1989], and CCIR Model [1990] and all models did not agree with the measured distribution.

2.11 Rain Attenuation Studies on the Earth-satellite Paths in Southeast Asia

In Southeast Asia, a number of countries i.e., Indonesia, Singapore, Thailand performed the rain attenuation studies on an earth-satellite (slant) path by some telecommunication entities and some educational institutions in the part decade. Results studies can be summarized as follows:

In Indonesia, M.Juy, R. Maurel. M. Rooryck, I.A. Nugroho, T. Harman [1990], conducted rainfall rate measurement at 6 places on the archipelago of Indonesia. Two-year results were reported at Padang on the west cost of Sumatra (lat.= 1° S, long. = 100.2° E, alt. = 200 m, ITU-R zone-P) and Tamahmerah in the Iryan Jaya (New Guine) (lat = 6.1° S, long., = 140.2° E, altitude = 19 m, ITU-R zone-P). Padang has average annual rainfall accumulation = 4764 mm/yr. Heavy rainfall occurs during the period of the northeast monsoon (October - December). Tamahmerah has average annual rainfall accumulation = 4577 mm/yr of which the location has no effect by the monsoon. The tipping bucket rain gauge provides a 1 minute integration time with a well-design for measuring very high rainfall rate. Measured rainfall distributions at two sites indicated very similar results whether the site separation is more than 4,000 Km. The measured rainfall rate that exceeded 0.01% of the time of both sites equals 135 mm/h and 150 mm/h. However, the measured rainfall rate distribution did not agree with the log-normal distribution.

In Indonesia, M.Juy, R. Maurel. M. Rooryck, I.A. Nugroho, T. Harman [1990], measured the slant-path rain attenuation at Padang with a latitude = 1°S, a longitude = 100.2° E and a altitude = 200 m in the Sumatra Island of Indonesia. The beacon signal at 11.198 GHz from the INTELSAT V (60° E) satellite was received at an elevation angle of 43.3° over 2 years. Results were found that at 0.1% of the time, attenuation of 14.3 dB (year-1) and 10.6 dB (year-2) were occupied. In addition, the ITU-R 564-3 [1986] underestimated the measured distribution lower than 1% of the time and overestimated the measured attenuation higher than 1% of the time. M Juy suggested the modification of the ITU-R model using the square-low distribution that can be fitted to the measured distribution. For rainfall rate measurement, the CCIR model underestimated the measured distribution higher than 0.01%, and it also overestimated the measured distribution lower than 0.01%. He concluded that the ITU-R used the Log-normal distribution for both attenuation and rainfall distributions that may not be suitable for the tropical regions.

In Indonesia, P.J.I Maagt, et. al., [1993] performed the joint beacon and radiometric measurement of 12 GHz rain attenuation at Surabaya at a latitude = 7.3°S, a longitude = 112.8°E in Indonesia over a 3-year period. The 11.198 GHz beacon signal was received from the INTELSAT V satellite at 174° degree longitude, with an elevation angle = 14.1° for year 1 experiment and 20° for year 2 and 3 experiments. The study of the effective medium temperature of the radiometer was also performed. Results were found that the measured attenuation with the effective medium temperature of 290° Kelvin was closed to the attenuation value measured by the beacon receiver. Attenuation at 20.5 dB, 16.1 dB, and 14.5 dB were occupied at 0.1% of the time for the first year, the second year, and the third year respectively. Comparing the measured attenuation distribution among the ITU-R 618-2 [1992] model, the ITU-R 564-3 [1986] model, and the ITU-R 564-4 [1990], it was found that all ITU-R model did not agree with the measured distribution. In addition the ITU-R 564-4[1990] and ITU-R 618-2 [1992] seriously underestimated.

In Indonesia, R Lekkla, et. al.,[1995], performed a three-year measurement of the 12 GHz rain attenuation using a dual-slope radiometer and a tipping bucket rain gauge, in Bundung (lat. = 6.9° S, long. = 107.6°E, alt. = 870 m, el. = 15° and ITUR-zone P) about 200 km from Jakarta to the West. The effective medium temperature was calibrated at 290° K. Result, shown in Figure 2.5, indicated that 8-10 dB attenuation exceeded 0.1 % of the time. The ITU-R 618-2 [1992] was found underestimation of the measured distribution. The rainfall distribution curves appeared between the ITUR-zone P and zone N.

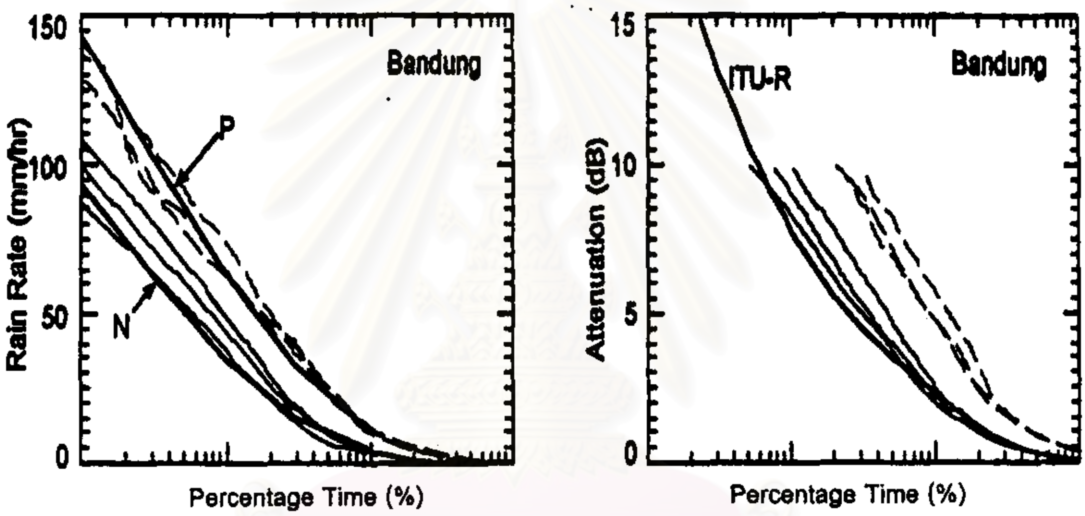

Figure 2.5 Cumulative distribution of rainfall rate and attenuation compared with the ITU-R model. Lekkla et, al., [1995].

In Thailand, R. Lekkla, et, al., [1995], conducted 12 GHz rain attenuation studies at low elevation angle in Bangkok (lat. = 13.5°, long. = 100.3°E, alt. = 30m, el. = 8° and ITUR-zone N) and Si-racha (lat. = 13.3°, long = 100.5°, alt. = 54m, el. = 7.4° and ITU-R zone-N). The dual-slope radiometer and a tipping bucket rain gauge were used to collect attenuation and rainfall data. The effective medium temperature was calibrated at 280° K. Results, shown in Figure 2.6, indicated that 10 dB attenuation exceeded 0.1 % of the time of all years. With site separation 80 km, between Bangkok and Si-racha, It was clearly shown that both cumulative distribution of attenuation and rainfall rate have similar distribution statistics. The ITU-R 618-2 [1992] model underestimated the measured distribution of both sites. The ITU-R rainfall zone-N seemed to agree well with the measured rainfall distribution.

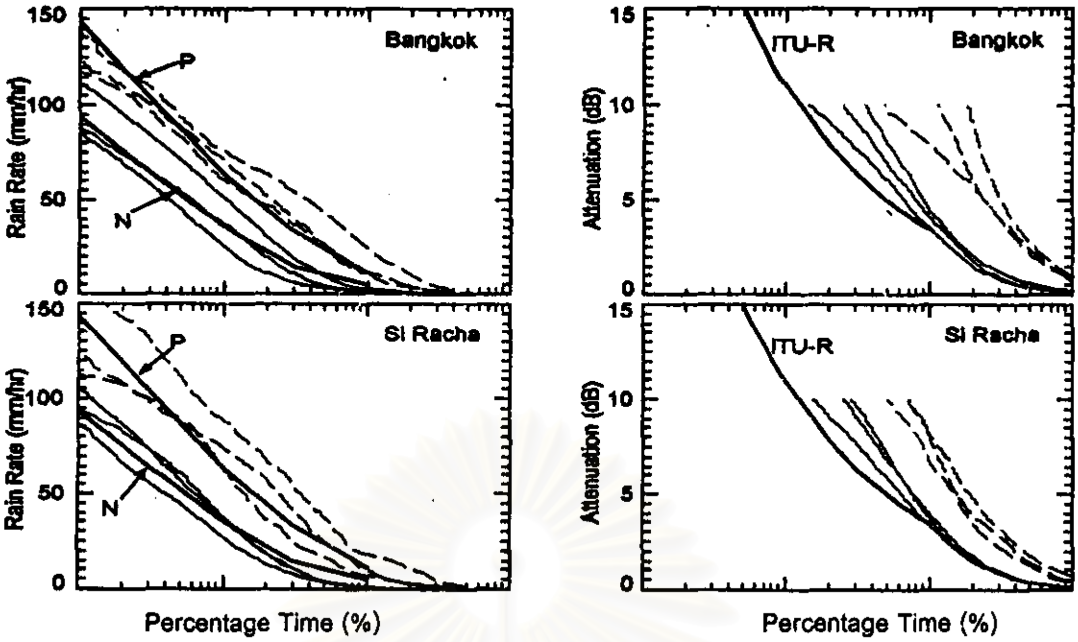

Figure 2.6 Cumulative distribution of rainfall rate and attenuation compared with the ITU-R model, R. Lekkla, [1995]

In Thailand, R. Lekkla, P. Prapinmongkolkarn, P. Hetrakul, K.S. McCormick [1995] analyzed site diversity data measured in Bangkok and Si-racha over a three-year period (1992-1995). Results, shown in Figure 2.7, indicated that the site diversity configuration with 80 km separation provides outstanding performance and it may be suitable for the high link margin system above 99.9% especially for the earth station operating at relatively low elevation angle less than 10 degree.

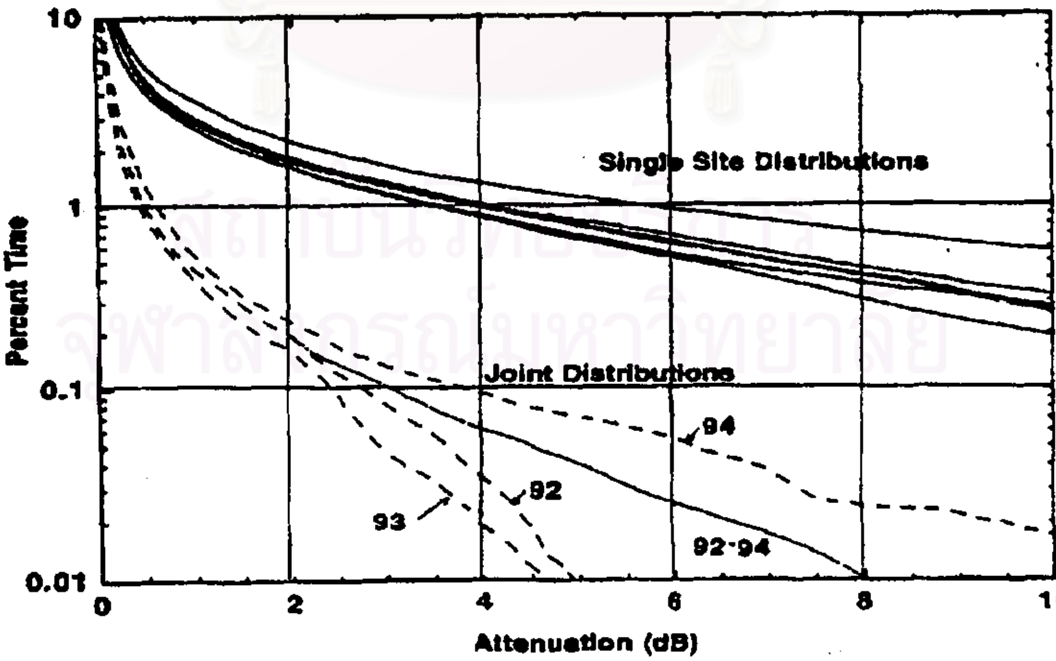

Figure 2.7 The Joint Cumulative distribution of attenuation between Bangkok and Si-racha R. Lekkla [1995]

In Thailand, N. Yoothanorm, et al., [1997] analyzed 12 GHz rain attenuation operated at low elevation angles in Bangkok and Si-racha. Results were found that attenuation distributions statistics had small year-to-year variation, but significantly large month-to-month variation. The attenuation distributions in rainy season was higher than the cold and dry season.

In Singapore, R Lekkla et al., [1995], presented a three-year result of 12 GHz rain attenuation measurement (lat. = 1.3° N, long. = 103.9°E, alt. = 20 m, el. = 39.4° , and ITU-R zone P) The dual-slope radiometer which the effective medium temperature was calibrated at 290° K and a tipping bucket rain gauge were installed from March 1992 to February 1995. Result, shown in Figure 2.8, indicated that at least 10 dB rain fade exceeded 0.1 % of the time. The ITU-R 618-2 [1992] seriously underestimated the measured attenuation distribution. Results of measured rainfall distribution occurred between the ITUR-zone P and zone N.

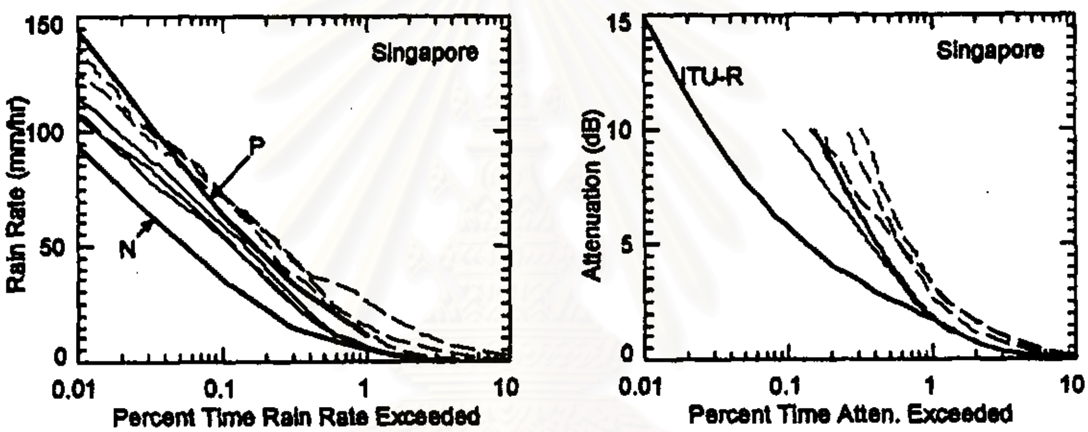

Figure 2.8 Cumulative distribution of rainfall rate and attenuation compared with the ITU-R 618-2 [1992] model. R. Lekkla et., al., [1995]

2.12 Concluding Remarks

In this chapter, we have reviewed the characteristics of rainfall (macro and micro structures) in the tropics and in Southeast Asia as well as rain intensity statistics and rain intensity predictions. We also review rain attenuation studies on the Ku-band earth-satellite in Southeast Asia. Various experimental studies were compared with the well-known attenuation ITU-R prediction models i.e. ITU-R 564-3 [1986], ITU-R 564-4 [1988], and ITU-R 618-2 [1992]. All prediction models underestimated the measured attenuation distribution in the tropics and in Southeast Asia. In addition the ITU-R 837 [1988] rain intensity prediction disagreed with the measured data in the tropics. Rice & Holmberg rain intensity model seems to agree well with the measured rainfall data.

One of the main reasons for the serious error prediction of ITU-R is due to the concept of the model developed from the startiform rain that work very well with the temperate regions but fail in the tropical regions which rainfall is usually convective in nature. In addition the lack of rain attenuation studies in the tropical region and the lack of long term measured data are not sufficient to develop a suitable model for the tropics. Therefore, the studies (measuring, analyzing, and modeling) of rain attenuation in the tropics and Southeast Asia must be urgently performed.