COMPARISON OF RAIN ATTENUATION MODELS FOR TROPICAL CLIMATE

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LIST OF SYMBOLS

λ	latitude of the earth station[deg]
H_s	altitude of the earth station[km]
θ	elevation angle of the link[deg]
f	frequency of the link[GHz]
k and α	the regression coefficients for specific attenuation
$R_{\mathrm{p}}(p)$	point rainfall rate distribution of an average year in the site of the earth station[mm/h]
$R_{0.01}$	point rainfall rate at 0.01% of the time of an average year in the site of the earth station [mm/h]
h_R	average effective rain height [km]
$H_0(p)$	average yearly distribution of the effective rain height [km]
A and β	the coefficients for worst month
L_{eff}	effective path length through rain [km]
$A_{0.01}$	attenuation exceeded for 0.01% of an average year [dB]
A_p	attenuation to be exceeded for other percentages of a average year [dB]
M	the average annual total rainfall depth, mm
P	percentage of time

γ	specific attenuation [dB/km]
A	total attenuation [dB]
H_ε	effective rain height [km]

PERBANDINGAN MODEL-MODEL PELEMAHAN OLEH HUJAN UNTUK IKLIM TROPIKA

ABSTRAK

Pengaruh hujan atas perambatan gelombang radio pada frekuensi lebih daripada 10 GHz adalah penting pada komuikasi satelit, terutamanya di kawasan tropikal yang mempunyai keamatan hujan yang tinggi. Pengukuran kadar hujan dan pelemahan selama tiga tahun (dari 1 Januari 2006 hingga 31 Disember 2008) telah dijalankan di Nibong Tebal, Kampus Kejuruteraan Universiti Sains Malaysia (USM) (Garis lintang: 5.17^{0}N and Garis bujur: 100.4^{0}E). Taburan bertokok satu minit kadar hujan, pelemahan hujan dan bulan yang paling buruk telah dianalisis dengan data-data yang disukat di USM dan dibandingkan dengan model-model ramalan yang sedia ada. Nilai untuk pekali bulan yang paling buruk, A and β yang diusulkan oleh model International Union Telecommunication (ITU-R) bulan yang paling buruk adalah tidak sesuai untuk Malaysia yang terletak di kawasan tropikal. Kajian tentang pelemahan hujan tentu telah dijalankan di USM. Nilai pekali regresi untuk pelemahan hujan tentu yang diperoleh daripada ITU-R didapati tidak sesuai digunakan untuk ramalan pelemahan hujan di Malaysia. Perbandingan antara model satu minit kadar hujan and pelemahan hujan telah dilakukan untuk kawasan-kawasan tropikal seperti Bangkok and Fiji. Kebanyakan model ramalan tidak memberi ramalan yang baik di kawasan yang kadar hujannya tinggi. Untuk perbandingan satu minit kadar hujan, model Moupfouma ialah model yang paling baik [Real Mean Square (RMS) kurang daripada 10%] pada kadar hujan yang rendah, sederhana and tinggi pada kebanyakan kawasan tropikal yang diuji. Model Kitami Institute of Technology (KIT) ialah model yang paling buruk dan memberi

RMS yang tinggi dalam perbandingan pada kebanyakan kawasan tropikal yang diuji. Untuk perbandingan pelemahan hujan, model ITU-R ialah model yang terbaik pada kebanyakan kawasan tropikal yang diuji; manakala, model Gracia-Lopez ialah model yang terburuk dan tidak sesuai digunakan di kawasan tropika.

COMPARISON OF RAIN ATTENUATION MODELS FOR TROPICAL CLIMATE

ABSTRACT

The influence of rainfall on radio wave propagation at frequencies above 10 GHz is essential for satellite communication, especially in tropical regions as a result of the high intensity rainfall. Besides, annual and worst month's cumulative statistics are needed to give the detailed insights for system design. A three years (from 1st January 2006 until 31st December 2008) rainfall rate and rain attenuation measurement was conducted in Nibong Tebal, Engineering Campus of Universiti Sains Malaysia (USM) (Latitude: 5.17^{0}N and Longitude: 100.4^{0}E). The cumulative distributions of one-minute rain rate, rain attenuation and worst month statistics analyzed from the USM measured data are presented and compared with existing prediction models. The values of coefficient of worst month, A and β obtained suggests that the global value proposed by International Union Telecommunication (ITU-R) worst month model is not suitable for Malaysia which is located in the tropical region. The regression coefficients of rain specific attenuation that provided by ITU-R are not suitable used in predicting rain attenuation at Malaysia. The comparison of one-minute rain rate and rain attenuation models has been done for tropical regions such as Bangkok and Fiji. Most of the existing prediction models do not perform well in high rain rate regions. For one-minute rain rate comparison, the Moupfouma model is the best model and shows a good agreement [Real Mean Square (RMS) value is less than 10%] to the measured data for low, medium and high rain rates at most of the measurement sites. The Kitami Institute of Technology (KIT) simplified model is the worst model and exhibited gave high RMS value in comparison at most of the measurement sites. For rain attenuation comparison, the ITU-R model is the best model for most of the

tropical sites; however, the Garcia-Lopez model is the worst model and not suitable for use in the tropics.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The ever-increasing exhaustion of the frequency spectrum for satellite communications due to the continual expansion of the available services and the demand for new technologies requires the use of increasingly higher frequencies, well above 10 GHz**,** for new systems and services (Pontes, *et. al*., 2003). The effects of the earth's atmosphere such as rain attenuation, gaseous absorption, cloud attenuation, melting layer attenuation, tropospheric scintillations, and low-angle fading on radio waves propagation between earth and space platforms are a constant concern in the design and performance of space communication systems. Propagation of the electromagnetic waves through the atmosphere at these frequencies is heavily affected by precipitation, which causes, among other effects, strong attenuation of the transmitted signal. These propagation impairments are more critical in tropical and equatorial zones compared to temperate zones (Dissanayake, *et. al*., 1997).

Rain attenuation is the dominant atmospheric impairment for satellite communication systems operating with high availability at any frequency above 10GHz. Rain attenuation depends on the temperature, size distribution, terminal velocity and shape of the raindrops. At such high frequency, the sizes of falling raindrops are close to a resonant sub-multiple of the signal wavelength. The droplets, hence, are able to absorb, scatter and depolarise the radio waves passing through the earth's atmosphere (Crane, 1996, Ippolito, 1986). Variations in water vapor along a path cause variations in signal strength. Absorption and scattering by rain at frequencies above 10GHz can cause a reduction in transmitted signal amplitude (attenuation), which in turn reduce the reliability, availability and performance of the communications link (Omotosho, *et. al.*, 2009). In the tropical and equatorial climates, with heavy rainfall periods and thunderstorms, this situation becomes drastic and may result in interruption of the earth-space link, rendering the services unavailable (Felix, *et. al*., 2006). This phenomenon is known as outage time where the amount of time during which the satellite system performance will be below the design threshold value and it will not be usable. To overcome this problem, one-minute rain rate and rain attenuation need to be studied and use to calculate the expected amount of rain attenuation to prevent the unavailability or outage time from occurring. The knowledge of rain attenuation statistics for the frequency of operation at a particular location is very useful for the planning and engineering for reliable communication system (Ajayi, 1996, Kumar, *et. al*., 2008). The considerable average worst month from year to year and within individual years is important in planning of satellite earth-link design.

When considering parameters affected by propagation impairments factor, it is necessary to specify the parameters on a statistical basis, which are usually specified in percentage of time. This percentage of time is normally described as the percentage of time in a month, in a year or the parameter equals to or exceeds a certain value so that the link margin can be established. Link margin is the additional transmitter power required to overcome the signal fade (Mandeep, 2006).

In satellite communication links**,** two important parameters, link availability and link margin, should be determined. However, two issues arise, how much link margin and which method for improving link availability should be provided to meet criteria of service. These two parameters are important in designing reliable satellite communication systems (Hasanuddin, *et. al*., 2003). Therefore, the information of one-minute rain rate, worst month and rain attenuation statistics is useful to solve the issues above.

Rain attenuation can be directly obtained from the measurement of beacon receiver or radiometer (Dissanayake, *et. al*., 1997, Pan, *et. al.*, 2001, Matricciani, *et. al.*, 2008, Ong, *et. al.,* 1997). Satellite beacon is the common method that used to measure the received power. Beacon receivers are commonly used to measure signal attenuation. Beacon measurements contain uncertainties because of spacecraft platform that will cause proper motion in its geostationary orbit and the interaction of this motion with the earth terminal antenna pattern will lead to diurnal fluctuation in the received signal (Stutzman, *et. al*., 1994). However, after removing as far as possible satellite and earth-station-induced effects, there still remains a significant variation in the perceived clear-sky level over daily, seasonal and annual period within the data (Pan, *et. al*., 2006). To ensure the accuracy of the beacon measurements, propagation measurements are the important factor in verifying modeling accuracy.

The primary aim of a rain attenuation prediction method is to achieve acceptable estimates of the attenuation acquired on the signal due to rain. The calculation of rain attenuation prediction related to a given rain rate or else to a given percentage of time (Moupfouma, 2009). Hence, the unavailability of time for reliable communication systems in a year (outage time) has to be kept at 0.01% of time. It corresponds to 99.99% of time availability of one year.

The accurate knowledge of rain rate statistics for the location of interest used as input to prediction methods allows the evaluation of the statistical behavior of rain attenuation. ITU-R recommends the use of rain rate cumulative distribution functions with one-minute integration time in order to derive rain attenuation cumulative distribution functions (Capsoni, *et. al.*, 2008). Ajayi and Ofoche (1983), Rice and Holmberg (1973), and Karasawa and Matsudo (1991) had earlier reported that the use of one-minute rain rate gives the best agreement with the ITU-R stipulations for the design of microwave radio links.

With realization that the rain process and rain rate statistics change seasonally, the ITU-R recommended the use of a worst month statistic. Some communication services such as television broadcasting require the link to operate with a specified outage in the worst month. Typically, an outage of 1% is tolerated in the worst month (Allnutt, 1989).

Many researchers have developed models that can be used to estimate one-minute rain rate distributions. Since majority of the studies on Earth-space propagation have been conducted in Europe and the United States, the existing prediction models may not be sufficiently accurate to characterize the effects of attenuation in tropical and equatorial climates (Mandeep, 2008). Most of the prediction models have primarily focused upon regions in the higher latitudes such as United State and Europe countries (Zhou, *et. al.*, 2000). When those models are applied to tropics, the performances are lower than accepted and the results of these researches indicate poor agreement between the measured and predicted rain attenuations. In the temperate region, rain is mostly stratiform structure which is generally ‘light’ with relatively large rain-cell diameters. However, in the tropical region, rain at times is from convective rain-cells, with relatively small diameters (Bryant, *et. al.*, 2001) often resulting in ‘heavy’ down pours for short periods (Ramachandran, *et.al.*, 2006) .

ITU-R considers that there is a need to calculate the attenuation due to rain from knowledge of rain rate. The method for predicting the rain attenuation is based on the relationship between the specified attenuation and rain rate established through the modeling of the rain shape, rain size, temperature and terminal speed of the raindrops. Rain attenuation is calculated by integrating the specific attenuation along the propagation path. The calculation of specific attenuation requires a cumulative distribution of one-minute rain rate (ITU-R, 2005).

Measurement of one-minute rain rate and rain attenuation were conducted in Universiti Sains Malaysia (USM), (100.4^0E 5.17^0N), Nibong Tebal, Malaysia. This system consists 0.5 mm tipping bucket rain gauge, data logger, a central computer and a satellite beacon receiver. The collected rainfall data were converted into real time data by computer software that was installed by Post-PARTNERS (Pan Pacific Regional Telecommunication Network Experiment and Research by Satellite Japan) named ‘Kisyo’. ‘Kisyo’ is a data acquisitions and logger program.

1.2 Objectives of the Research

In this thesis, the following goals will be achieved:

1. To determine the worst month and specific attenuation analysis with data collected in USM.
2. To utilize the existing rain rate and rain attenuation models for comparison among tropical climate.
3. To determine the most appropriate rain rate and rate attenuation model for used in tropical climate.

1.3 Organization of the Thesis

There are five chapters in the thesis. Chapter 1 introduces the importance of rain rate and rain attenuation research in order to establish a reliable satellite communication link in the tropical and equatorial regions.

Chapter 2 states the theory of rain rate and rain attenuation that are used in deriving rainfall models. This chapter also explains the one-minute rain rate models, rain attenuation models and ITU worst month model.

Chapter 3 describes the measurement setup of rainfall and beacon signal data collection system. The operation of the tipping bucket rain gauge and the beacon receiver are explained. The calibration of the instruments used and the uncertainties of the measurement accounted for from the measurement site are stated.

Chapter 4 shows the result and discussion of the research. The atmospheric dynamics on the satellite beacon measurement has been studied. The confidence level of the measured data is calculated by the given equation and the confidence intervals of the measured data are shown in graphical form. The USM measured data were compared with the existing one-minute rain rate models, ITU worst month model and rain attenuation models. The rain rate and rain attenuation data from other tropic regions were compared with the existing models. The models were compared in terms of percentage errors and Root Mean Square (RMS) values.

Chapter 5 concludes by summarizing the results of the statistical analysis done for the data collected. The recommendations for future work are proposed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Communications system design requires the development of a link budget between the transmitter and receiver that provides an adequate signal level at the receiver's demodulator to achieve the required level of performance and availability. The performance of a link is usually defined for time percentages in excess of 99% over periods of at least a month (Timothy, *et. al.*, 2003).

Rain produces significant attenuation on radio waves of frequencies above 10 GHz. Rain rate and rain attenuation predictions are one of the essential steps to be considered when analyzing a microwave satellite communication links. Raindrops absorb and scatter radio wave, leading to signal attenuation and reduction of the system availability and reliability. The severity of rain impairments increase with frequency and vary with the regional locations (Ojo, *et. al*, 2008). The effect of rain on microwave and satellite communications is more serious in the tropical areas than in the temperate areas. The tropical and equatorial regions experience extremely heavy rainfall during monsoon season.

The most effective way of obtaining the cumulative rainfall distribution is through direct measurement. However, due to the shortage of the required rainfall data at certain locations, rainfall models need to be introduced to predict the rain rate and attenuation at location of interest (Mandeep, *et. al*., 2003; Panagopolus, *et. al.*, 2003; Ahmad, *et. al*., 2004).

This chapter reviews rainfall models that will be used in computing the cumulative distribution of the models. The main objective is to study some statistical models for annually prediction rainfall from ground meteorological measurements.

2.2 Rainfall in Tropical and Equatorial Regions

In the tropical and equatorial region, meteorologists have classified rain precipitation in three categories. First is convective rain that arises because of vertical atmospheric motions resulting in vertical transport and mixing. The convective flow occurs in a cell whose horizontal extent is usually several kilometers. The cell usually extends height greater than the average freezing level at a given location because of the convective upwelling. The cell may be isolated or embedded in a thunderstorm region associated with passing weather front. Convective rainfall is heavier and the drops are larger. Convective precipitations are generally identified with intermittently strong vertical velocities (>1± 1 ms^{-1}) and high rainfall rates (>5mm/h) (Mandeep, 2006). The Figure 2.1 shows convective rain situations.

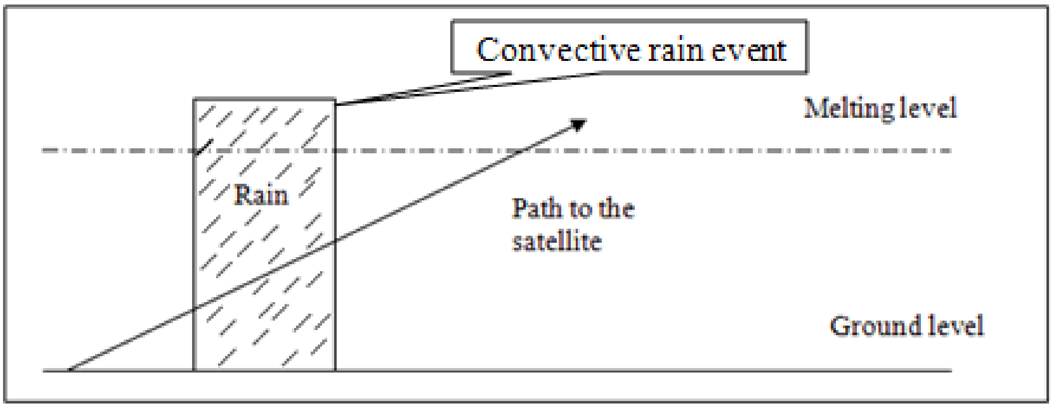


Figure 2.1 Convective rain situations

Secondly stratiform precipitations that is resulted from the formation of small ice particles in the upper growing nuclei becomes unstable and as they pass through the melting layer extending from 500m to 1 km below the 0^0 C isotherm turns into raindrops and falls down to the earth surface (Ajayi *et. al*, 1996). Raindrop growth in a stratiform cloud is slow, so its rain consists of small drops. Stratiform precipitation areas are characterized by, small velocities (<1± 1 ms^{-1}) and low rainfall rates (<5mm/h). Figure 2.2, shows that the widespread system of stratiform rain completely covers the path to the satellite from the ground up to the melting layer.

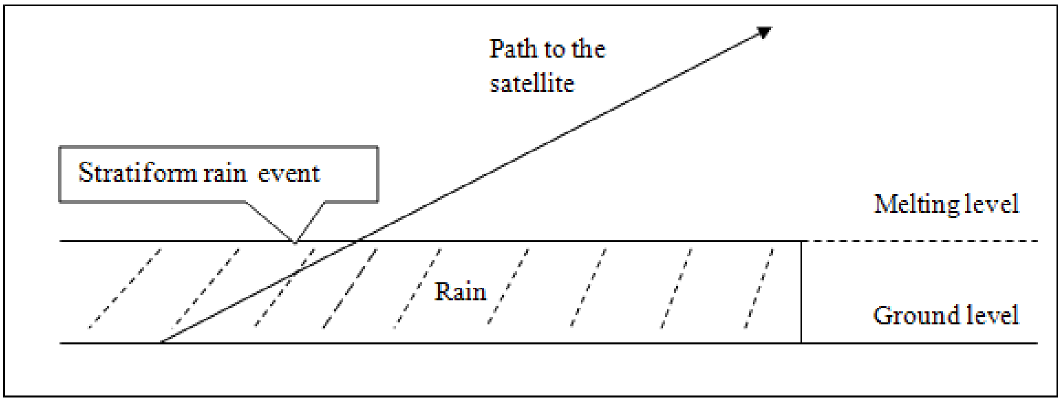


Figure 2.2 Stratiform rain situations

Finally tropical cyclonic storms (hurricanes) which are typically 50 to 200 km in diameter, move at 10 to 20 km/h, extend to melting layer heights up to 8km and have high rain rates. This cyclonic rainfall is produced by horizontal convergence of moist air in a circular area of low pressure where the maximum vorticity exists. This storm usually last between one to five days, which contrast with the short life span of individual convection cells

In the temperate climate, rain is mostly of stratiform structure which is generally 'light' with relatively large rain-cell diameters. However, in the tropical climates, rain at times is from convective rain-cells, with relatively small diameters often resulting in 'heavy' down pours for short periods. The precipitation observed over the globe often are a combination of the two rather than simply one or the other

(Ramachandran, *et. al*). Basically, convective precipitation depends on how much condensed water is carried to and detrained at the tops of the updrafts, thus escaping precipitation. Stratiform precipitation depends on the amount of condensate detrained at the tops of the convective updrafts, and the parameterized conversion of cloud water/cloud ice to rain/snow. Stratiform rainfall generally occurs more frequently in the tropics, yet convective rainfall accounts for most (~70%) of the cumulative rainfall, because its intensity is so much higher.

2.3 The Importance of Rain Rate

Rainfall rate is an important parameter for a microwave link because it enables the attenuation due to rain to be determined. An important parameter in rain attenuation studies is the rain rate for 0.01% of the time or $R_{0.01}$. Design and system engineers use this value to construct communications system such that the link is available for 99.99% of the time.

The rain rate is calculated by measuring the time interval between each rainfall increment. When there is rainfall within the archive period, the highest measured value is reported. When no rainfall occurs, the rain rate will slowly decay based on the elapse time since the last measured rainfall.

Rain rate is measured by rain gauge, the most common of which is a tipping bucket. The long term behavior of rainfall rate is described by a cumulative probability distribution or by a cumulative distribution function. The cumulative distribution function for rain rate is commonly referred to as an exceedance curve. This gives the percentage of time (usually the percentage of 1 year) that the rain rate exceeds a given value (Timothy, *et. al*, 2003).

One – minute rain rate statistics are required to setup a communication link. The prediction of satellite link attenuation is generally based on the point rainfall rate for 0.01% of the year (Bryant, *et. al.*, 2001). Almost all rain attenuation prediction methods, including ITU-R require 1-min rain rate data as meteorological data of the place concerned. For the empirical methodology, an appropriate distribution of 1- min rain rate is needed for the site under studied in order to predict accurate rain attenuation for the location. This input is sometime provided by meteorological and environmental agencies, universities, and independent researchers (Ojo, *et. al*, 2008).

Rain displays significant spatial and temporal variation along a horizontal path and procedures are required to statistically estimate the instantaneous rain rate along the path. Because of no physical theory that exists to calculate the surface point rain rate distribution, the rain rate distribution is empirical and developed from available long-term observation of rain accumulation. A complete description of the rain-rate process must include information on year-to-year variability. The rain-rate distribution itself would contain this information if the number of independent rain-rate samples in each year were known. The rain-rate statistic of interest in attenuation modeling is the “instantaneous” rain rate that can be related to the number density of raindrops of different sizes distributed along the propagation path. Generally, the rate of interest is the one minute average rain rate. The temporal correlation of the rain process ensures that adjacent one minute average samples of rain rate are not independent. Therefore, an additional model for year-to-year variability must be utilized. Observations of single-year empirical distributions obtained at a single location over a several year period suggest a lognormal variation in distribution values at specified rain rates or at specified annual probabilities of occurrence (Crane, 1980).

2.4 Prediction of Rain Attenuation using Rain Rate

The power-law form of rain specific attenuation is very convenient and has been used in calculating rain attenuation statistics. A fundamental quantity in the calculation of rain attenuation statistics is the specific attenuation γ (attenuation per unit distance). The power-law form of rain specific attenuation, γ is commonly used. The power-law equation express the relationship between point rain rate R and specific attenuation, γ, the attenuation measured over 1 km

$$\gamma = k\,(R)^{\alpha} \text{ dB/km} \tag{2.1}$$

where k and α are regression coefficients which depends on DSD, temperature, frequency and polarization of radio wave, where the non-spherical shape of rain drop take effect of the polarization dependence, the vertical polarized waves attenuated less than those are horizontal polarized (ITU-R, 2005).

From ITU-R recommendation P-838-3, for linear and circular polarization, and for all path geometries, the coefficients in equation 2.1 can be calculated from the values in Table 2.1 using the following equations:

$$k = [\, k_H + k_V + (\, k_H - k_V\,)\cos^2\theta \cos 2\tau\,]/2 \tag{2.2}$$

$$\alpha = [\, k_H\,\alpha_H + k_V\,\alpha_V + (k_H\,\alpha_H - k_V\,\alpha_V\,)\cos^2\theta \cos 2\tau\,]/2k \tag{2.3}$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal ($\tau = 45^0$ for circular polarization).

Rain attenuation can be predicted accurately if the rain is precisely described all the way along the path. Path attenuation is an integral of all individual increments of rain attenuation caused by the drops encountered along the path. This is physical approach to predict rain attenuation. However, rain cannot be described accurately along the path without extensive meteorological database, which does not exist in most regions of the world (Timothy *et. al*., 2003). Because of it, most prediction models therefore resort to semi empirical approaches.

The effective path length is the length of a hypothetical path obtained from radio data dividing the total attenuation by specific attenuation exceeded for the same percentage of time.

$$A(\text{dB}) = \gamma(\text{dB/km}) \times L_{\text{eff}} \ \ \text{km} \tag{2.4}$$

Where L_{eff} is effective path length and γ is specific attenuation.

The semi empirical approach is based on two factors:

i. The rain rate at a point on the surface of the earth is statistically related (over a period of at least a year) to the attenuation encountered along the path to a satellite;
ii. The actual path length of the path through the rain medium can be adjusted in such a way that the effective path length, L_{eff} is developed over which the rain can be considered to be homogeneous.

To calculate the effective length path, the calculation L_{eff} that used in the SAM (Simple Attenuation Model) model has been referred and adopted. The effective path length can be found from measured slant path attenuation and rain rate by identifying and tabulating corresponding values of $A(p)$ and $R(p)$ with p as a parameter. However, it is much more convenient to calculate the effective path length from an effective rain height which can be expressed by equation 2.5 and 2.6. Effective rain height is a fictitious altitude at which all rain suddenly ceases. In stratiform rain, with $R \leq 10$ mm/h, the effective rain height, H_e is constant and equal to H_i and the effective path length is equal to path length, L in equation 2.5. H_i is the zero degree isotherm height which depends on the latitude of the earth station.

$$L = (H_e - H_o)/\sin\theta \tag{2.5}$$

where H_o is rain height and θ is elevation angle.

In convective rainstorms, when $R > 10$ mm/h, the effective rain height, H_e depends on the rain rate, R because strong storms push rain higher into the atmosphere, lengthening the slant path. However, the rain rate is not uniform with altitude, so a modified value of effective path length must be used

$$L_{eff}\,(\text{km}) = \frac{1 - \exp[-\alpha\beta \ln(R/10)\, L \cos\theta]}{\alpha\beta \ln(R/10) \cos\theta} \tag{2.6}$$

Where θ is elevation angle and the empirical constant β = 1/22 and α =1/14.

Based on empirical data, the following expressions for effective rain height, H_e were derived

$$H_e = \begin{cases} H_i & \text{km} \quad R \leq 10 \text{ mm/h} \\ H_i + \log(R/10) & \text{km} \quad R > 10 \text{ mm/h} \end{cases} \tag{2.7}$$

The effective path length L_{eff} depends on the actual path length, L_s and the reduction factor , r_p and its expressed (Ponte *et al.*, 1995, and Lin, 1979) as

$$L_{eff} = L_s * r_p \text{ km} \tag{2.8}$$

The r_p depends on the spatial distribution of rain rate and accounts horizontal variations of the rain along a path. The purpose of the reduction factor is reducing the point rain rate to the path averaged rain rate or to reduce the actual path length filled with uniform point of rainfall.

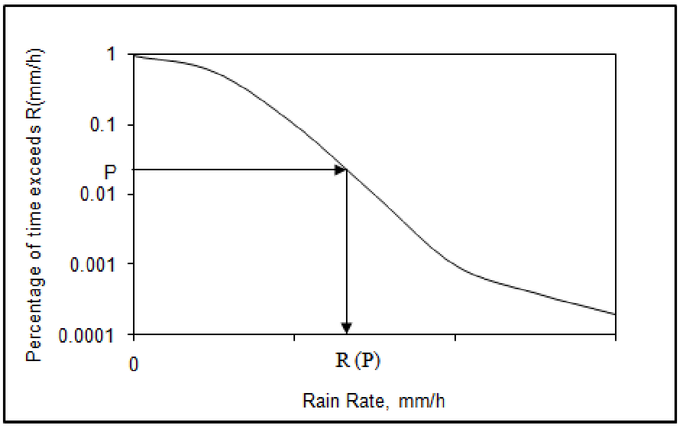
Table 2.1 Regression coefficients for estimating specific attenuation in equation (2.1). (Recommendation ITU-R P.838-3, 2005)

Frequency (GHz)	k_H	α_H	k_V	α_V
11	0.01772	1.2140	0.01731	1.1617
12	0.02386	1.1825	0.02455	1.1216
13	0.03041	1.1586	0.03266	1.0901
14	0.03738	1.1396	0.04126	1.0646
15	0.04481	1.1233	0.05008	1.0440
16	0.05282	1.1086	0.05899	1.0273
17	0.06146	1.0949	0.06797	1.0137
18	0.07078	1.0818	0.07708	1.0025
19	0.08084	1.0691	0.08642	0.9930
20	0.09164	1.0568	0.09611	0.9847
21	0.1032	1.0447	0.1063	0.9771
22	0.1155	1.0329	0.1170	0.9700
23	0.1286	1.0214	0.1284	0.9630
24	0.1425	1.0101	0.1404	0.9561
25	0.1571	0.9991	0.1533	0.9491
26	0.1724	0.9884	0.1669	0.9421
27	0.1884	0.9780	0.1813	0.9349
28	0.2051	0.9679	0.1964	0.9277
29	0.2224	0.9580	0.2124	0.9203

2.5 Prediction of Rain Attenuation using Equiprobability Method

The procedure for finding equiprobable values of rain rain and rain attenuation is shown in Figure 2.3. For a given time P, the rain rate is read off the rain rate statistics and rain attenuation is read off the rain attenuation statistics.

Attenuation and rain rate values so paired are called equal-probability values. The disadvantage of this approach is outweighed by the improved accuracy obtained by extrapolating to both low and high time percentages, where the rain rate measurements are somewhat suspect (Timothy *et. al*., 2003).



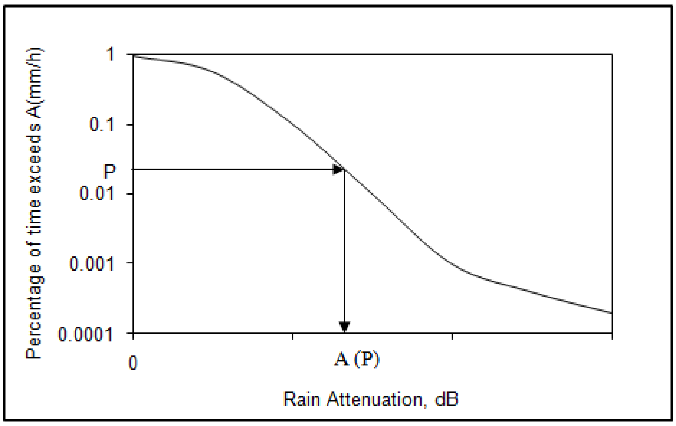


Figure 2.3 Procedure for finding equal-probability value of rain rate, R and attenuation, A.

2.6 Worst Month Statistics

The ITU-R P. 841-4 (2005) considered that

a) for design of radio communication systems the required statistics of propagation effects pertain to the worst-month period of reference;

b) the reference statistics for many radio meteorological data and propagation prediction methods is “the long-term average annual” distribution;

c) consequently there is a need for a model that provides for the conversion of the “annual” to the “worst-month” statistics.

The worst-month analysis plays an important role in satellite-earth link design where there is a need to know the design margin that must be met in any particular month of the year. Worst-month statistics can be applied to quantities such as rain attenuation, rain rate and cross polarization (Yagasena and Hassan, 2000). For a period of 12 consecutive calendar months, the worst month statistic is obtained by selecting the worst performance (highest probability of occurrence) among all months of data at each annual occurrence level (Stutzman, *el at*., 1984).

The worst-month and annual statistics is related by the following ratio:

$$Q = X/Y \tag{2.9}$$

where X is the average worst-month probability and Y is the average annual probability for the same threshold. Q is a function of the occurrence level and the climatic region. Similar climatic regions will have similar values of Q. Q may also be expressed by a power law relation of the form

$$Q=AY^{-\beta} \tag{2.10}$$

The ITU has recommended values of A = 2.82 and β = 0.15 for global planning purposes.

Some communications services, particularly those that involve broadcasting (e.g. television), require the link to operate with a specified outage in the worst month. Typically, an outage of 1% is tolerated in the worst month. The ratio between the attenuation experienced in a worst month to that exceeded in an average year depends on the probability level selected and the climate (Allnutt, 1989).

2.7 One-minute Rain Rate Models

2.7.1 Rice and Holmberg Rainfall Rate Model

The Rice and Holmberg model is based on the calculation of cumulative time statistics of point rainfall rate in United States and it has been derived from a broad database. This model divided the rainfall into two types to permit the prediction of rainfall rate statistic from the total rainfall accumulation measured in an average year. The two types are mode 1 rain (M_1) and mode 2 rain (M_2). Mode 1 contained the high rainfall rates associated with strong convective activity and thunderstorms. Mode 2 was simply everything else. The total average rainfall accumulation M was therefore

$$M = M_1 + M_2 \quad \text{mm} \tag{2.11}$$

A coefficient β was postulated that was equal to the ratio of the convective rainfall or the thunderstorm rain to the total rainfall accumulation, namely

$$\beta = M_1 / M \tag{2.12}$$

Let $q_{1t}(R)$ and $q_{2t}(R)$ be the probability that a rainfall rate, R(mm/h) is exceeded by mode 1 and mode 2 rain respectively and let T_{1t} and T_{2t} be the total number of hours that there is more than 0.254 mm of rain in a t-min period. Then the number of hours

T_t of rainy t-min periods for which a surface point rainfall rate, R(mm/h) is exceeded is the sum of contributions from the two modes

$$T_t = T_{1t}q_{1t}(R) + T_{2t}q_{2t}(R) \quad \text{hours} \tag{2.13}$$

Also the percentage of an average year during which t-min average rainfall exceeds R (mm/h) is given by T_t (R) / 87.66. The exponential expressions used for q_{1t} and q_{2t} are given as

$$q_{1t} = \exp(-R / \overline{R_{1t}}) \tag{2.14}$$

$$q_{2t} = 0.35 \exp(-0.453074\, R / \overline{R_{2t}}) + 0.65 \exp(-2.857143\, R / \overline{R_{2t}}) \tag{2.15}$$

where

$$\overline{R_{1t}} = M_1 / T_{1t} \quad \text{mm/h} \tag{2.16}$$

$$\overline{R_{2t}} = M_2 / T_{2t} \quad \text{mm/h} \tag{2.17}$$

$\overline{R_{1t}}$ and $\overline{R_{2t}}$ can be derived as

$$\overline{R_{1t}} = A_1 + B_1 \ln[C_1 \exp(-30/(t+10)) + 1/(t+10)] \quad \text{mm/h} \tag{2.18}$$

where

$$A_1 = 1 + 65.67864 \exp[-\beta M / 8766] \quad \text{mm/h} \tag{2.19}$$

$$B_1 = 13.457 \exp[-\beta M / 8766] \quad \text{mm/h} \tag{2.20}$$

$$C_1 = 0.00704 \tag{2.21}$$

$$\overline{R_{2t}} = \frac{(1-\beta)M}{24\, D\, [0.165 + 0.77 \exp(-120/t) + A \exp(-B/t)]} \quad \text{mm/h} \tag{2.22}$$

where

$$B = 1443.95 \ln[8.26136 (365.25/D - 0.9408)] \tag{2.23}$$

$$A = \exp(B/1440) / 8.26136 \tag{2.24}$$

$$D = 1 + M/8 \tag{2.25}$$

When t=1 minute then the more general formula that is given by Rice and Holmberg can be written as

$T_1(R) = M\{0.03\beta \exp(-0.03R) + 0.2 (1-\beta)[\exp(-0.258R) + 1.86 \exp(-1.63R)]\}$ hours (2.26)

The value of β can be obtain from Figure 2.4.

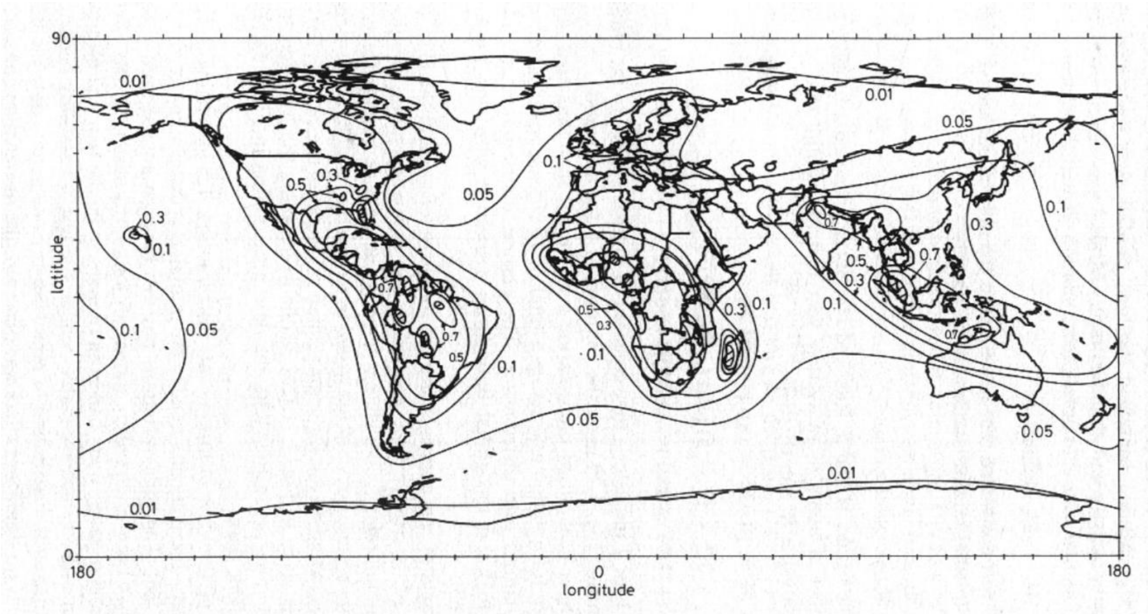


Figure 2.4 Contours of the coefficient β for use in Rice-Holmberg model (Rice & Holmberg)

2.7.2 Dutton and Dougherty Rainfall Rate Model

The Dutton and Dougherty (1974) (D-D) rain model is the further extension of Rice-Holmberg rainfall prediction model. These extension describe the variation of rainfall with location in Europe and it utilizes the same input parameters with Rice-Holmberg (R-H) model, M (average annual total rainfall depth, mm), β(ratio of thunderstorm rain to total rain) and D (average number of days for which precipitation is greater or equal to 0.25mm). The D-D modification to the R-H model facilitates error analysis of the predicted distribution and simplifies procedures for estimating rain rates for a specific percentage of a year. The author has also presented a method for calculating β for a specific location and also for estimating year-to-year variations.

$$D = 0.07656M - 83.632\beta + 62.523 \quad (2.27)$$

where

$$\beta = \beta_o \{ 0.25 + 2\exp[-0.35(1 + 0.125M) / U]\} \quad (2.28)$$

and $\beta_o = 0.03 + 0.97 \exp[-5 \exp(-0.004M_m)]$

where

U is the average number of "Thunderstorm days" expected during an average year.

M_m is the highest monthly precipitation observed in 30 consecutive years.

β can also be found from Figure 2.5.

If P(t) is the percentage of an average year for t-minutes of the rainfall rate, R(mm/h) is expected to exceed, then for $t \leq 60$-minutes,

$$P(t) = \begin{cases} K\, T_{1t} \exp(-R/R_{1t}) & R > 30\text{mm/h} \quad (2.29) \\ K\, T_{st}\, \overline{\exp}\, (-^{4}\sqrt{R} / R_{st}) & 5 \leq R \leq 30 \text{ mm/h} \quad (2.30) \\ K[T_{1t} + T_{2t}] \exp(-R/R_t^1) & R < 5\text{mm/h} \quad (2.31) \end{cases}$$

where, K = 0.0114 provides a conversion from hours to percent of hours in an average year of 365.24 days or 8766 hours.

For t > 60 minutes

$$P_t(R) = \begin{cases} K\, T_{1t} \exp(-R/\overline{R_{1t}}) & R \geq R_c \\ K[T_{1t} + T_{2t}] \exp(-R/R_t^1) & R < R_c \end{cases} \tag{2.32}$$

$\overline{R_{1t}}$, T_{2t} and R_t^1 are linear combinations of M, β and D for given value of t. The expressions are given below.

$$\overline{R_{1t}} = a_{1t} M + a_{2t} \beta + a_{3t} D + a_{4t} \pm S_1 \tag{2.33}$$

$$T_{2t} = b_{1t} M + b_{2t} \pm S_2 \tag{2.34}$$

$$R_t^1 = b_{3t} M + b_{4t} \beta + b_{5t} D + b_{6t} \pm S_3 \tag{2.35}$$

The parameter for a_{1t}, a_{2t}, a_{3t}, a_{4t} , S_1, b_{1t}, b_{2t} , S_2, b_{3t} , b_{4t} , b_{5t} , b_{6t} , S_3 are given in Table 2.2.

Table 2.2 Coefficients of the D-D Model for t-minutes rainfall

quantity	coefficients	t = 1 min	t = 5 min	t = 30 min	t = 60 min	t = 360 min	t = 1440 min
$\overline{R_{1t}}$	a_{1t}	0.0	−0.015782	−0.0084347	−0.0053345	−0.0018022	0.0
	a_{2t}	0.0	14.313	7.4519	4.6086	1.7116	0.0
	a_{3t}	0.0	0.19983	0.10638	0.067053	0.022986	0.0
	a_{4t}	34.1329	18.278	12.276	9.2075	2.1793	1.00038
	S_1	0.2823	0.0683	0.0411	0.0285	0.0060	−0.0
T_{2t}	b_{1t}	0.30045	0.30045	0.32633	0.49168	1.3139	1.8209
	b_{2t}	207.05	207.05	224.89	338.84	904.18	1254.9
	S_2	25.0338	25.0338	27.1901	40.9674	109.381	151.7197
R_t	b_{3t}	3.5329×10^{-4}	-6.6457×10^{-4}	−0.0013234	-4.9893×10^{-4}	-1.7799×10^{-4}	-6.2620×10^{-8}
	b_{4t}	0.24476	1.4071	2.3183	1.1401	0.49868	0.30220
	b_{5t}	0.0033902	0.016705	0.025179	0.011940	0.0045351	0.0023186
	b_{6t}	1.2807	0.44634	−0.17309	0.19847	0.083186	0.11520
	S_3	0.0915	0.0915	0.0884	0.0604	0.0240	0.0166

$$T_{1t} = \beta M / \overline{R_{1t}} \tag{2.36}$$

R_c is defined by common point $R = R_c$ in equation 2.32 as

$$R_c = R_{1t} R_t^1 / (R_{1t} - R_t^1) \ln [(T_{1t} + T_{2t}) / T_{1t}] \tag{2.37}$$

Since the 5 to 30mm/h range can be expected to straddle R_c for most climatologically circumstances, T_{st} and R_{st} can be found via the boundary conditions,

$$T_{st} \exp(-\sqrt[4]{30} / R_{st}) = T_{1t} \exp(-30 / \overline{R_{1t}}) \quad (2.38)$$

$$T_{st} \exp(-\sqrt[4]{5} / R_{st}) = (T_{1t} + T_{2t}) \exp(-5 / R_t^1) \quad (2.39)$$

2.7.3 KIT (Simplified) Rainfall Rate Model

This simplified KIT (Kitami Institute of Technology) model is based on average annual total rainfall and the thunderstorm ratio and it is possible to estimate the 1 min rain rate distribution for an arbitrary percentage of time. The author has used the Dutton and Dougherty (D-D) method for calculating β(ratio of thunderstorm rain to total rain) for a specific location

$$\beta = \beta_o \{ 0.25 + 2\exp[-0.35(1 + 0.125M) / U]\} \quad (2.40)$$

where $\beta_o = 0.03 + 0.97 \exp[-5 \exp(-0.004M_m)]$

U is the average number of "Thunderstorm days" expected during an average year.

M_m is the highest monthly precipitation observed in 30 consecutive years.

β has a strong influence on the rainfall rate for small percentage of time while M (average annual total rainfall depth, mm) has a strong influence on the rainfall rate for large percentage of time. If the value for U and M_m is unavailable, β can be obtained from Figure 2.5. Therefore the equation is expressed as

$$R_p = a_p M^{bp} \beta^{cp} \quad \text{mm/h} \quad (2.41)$$

$$\log(a_p) = 0.1574155x^4 + 1.348171x^3 + 3.528175x^2 + 1.479566x - 2.302276 \quad (2.42)$$