Investigation of spatial variations of rainfall rate using radar data

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Investigation of Spatial Variations of Rainfall Rate using Radar Data

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
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Summary

Due to the need for an understanding of the rain structure and the effect of rainfall on the high frequency wireless communication links, several issues related to the characters of rainfall rates and rain attenuation in Singapore are studied. This will enable the development of a comprehensive rain attenuation model.

The characteristics of a 2-dimensional Plan Position Indicator (PPI) rainfall rate database produced by meteorological RADAR system are studied. The discrepancies between the statistics of this database and that of the commonly adopted one-minute integrated rain data formats are analyzed. A simple framework for calibrating the PPI rain data to its one-minute counterparts is suggested based on the investigations. Highly accurate results are observed from this calibration.

A 2-dimensional rainfall rate visualization model is developed using the calibrated PPI rainfall rate database. Simulation of the characteristics of point rainfall rate and path rain attenuation at five satellite ground stations around Singapore is carried out using this 2D model. The simulation results are analyzed and presented. The following aspects related to the rainfall in Singapore are covered: the spatial and temporal variation of rainfall, the rain attenuation along Ku-band links, the path reduction factor in rain attenuation predictions, and the use of site diversity in combating rain attenuation in Singapore.

Some preliminary efforts are devoted to the design and development of a 3-dimensional rainfall rate visualization model for Singapore. The proposed 2-dimensional implementation of 3-dimensional data interpolation shows great potential for improving the efficiency of processing large-size databases. A prototype of volumetric data viewer is developed and tested. The experiences gained in these works will be beneficial to the successors of the study.

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Chapter 1

Introduction

1.1 Motivation

Nowadays, satellite technology plays an increasingly important role in long-distance communications. With its fast booming in applications, there is a growing demand for the satellite systems with larger capacity and higher reliability. However, the currently used frequency bands in the satellite communications are already overcrowded due to this growth in the service demand. Therefore, there is a worldwide interest in pursuing higher frequency bands (e.g. Ka-, Ku-band) for the satellite communications systems. In practice, the rain attenuation along the satellite link is one of the most critical factors that can cause serious deterioration to the performance of satellite systems operating in these high frequency bands. The rain volume along the propagation path can absorb the transmitted power as well as scatter the signal in random directions, and hence causes degradation to the received signal level. Moreover, it also depolarizes wireless signal, resulting in interference between channels with different polarizations. The effect of rain attenuation is of great importance to tropical countries like Singapore, where high intensity rainfalls are often experienced.

In order to understand the behavior of rain attenuation along satellite links, extensive studies had been carried out by researchers all over the world. These studies normally require the rainfall rate and rain attenuation information collected from actual satellite systems, which are usually neither cost efficient nor time efficient. Thanks to the great improvement in computer technology over the past a few decades, computer simulations has become a good alternative in the studies of the effects of rain on satellite links. With the commercially available high speed computers, the rainfall rate or rain attenuation databases, which requires years of data collection from

actual links, can be obtained through simulation in merely a few days or even a few hours. Moreover, the results from those well-developed simulation routines can produce remarkably high agreement with that collected from practical systems. Hence, the high speed, high accuracy simulations of the effects of rain on the satellite communication systems are becoming more and more popular in the design and analysis of contemporary satellite systems. Therefore, in this study, comprehensive models of rain structure in Singapore will be developed based on the rainfall rate database provided by the Meteorological Service of Singapore (MSS), and studies on the variations of rainfall rate and rain attenuation in the country are to be carried out through computer simulations with these rainfall rate models.

1.2 Scope and Objective

The main objective of this study can be described as the following:

- To understand the nature of the rainfall rate database collected from the Meteorological Weather Doppler RADAR (MWDR) system of MSS, and to modify the data if necessary so as to make it compatible to the commonly adopted rain data regulations.
- To develop comprehensive rainfall rate visualization models base on the RADAR rain database.
- To perform systematic simulations with the rain models developed to study the characteristics of various aspects of the point rainfall rate and path rain attenuation in Singapore.

1.3 Organization of the Thesis

This thesis consists of six chapters. In the next chapter, some backgrounds about this study are introduced. This includes the evolution of RADAR meteorology (Section 2.1) and satellite technology (Section 2.2), the effects of the rain attenuation on microwave communication links (Section 2.3), the use of site diversity techniques to combat rain attenuation (Section 2.4), the review of commonly used techniques in

the 3-dimensional data visualization (Section 2.5), and finally the programming language adopted in this study (Section 2.6). These topics are then briefly reviewed in the last section of the chapter (Section 2.7).

The following three chapters (Chapters 3 to 5) document the main efforts in this study. In Chapter 3, a simple framework for calibrating the RADAR rain database that is utilized in the investigations of the effect of rain on microwave links is proposed. Firstly the main features of the PPI RADAR rain database to be calibrated are introduced in this chapter (Section 3.1). Then the main motivations behind the calibration are explained (Section 3.2), followed by the descriptions of the specifications of the databases utilized in the development of the calibration method (Section 3.3). The main procedures of the calibration are then described (Section 3.4). Finally, the effort devoted to the calibration of PPI rain data is summarized (Section 3.5). Chapter 4 focuses on the development of a 2-dimensional rainfall rate model. In this chapter, the detail algorithms of program modules developed for the model are explained (Section 4.1). Then the model is applied to the simulations on the characteristics of point rainfall rate and path rain attenuations in Singapore, and the results are analyzed (Section 4.2). A brief summary is presented at the end of the chapter (Section 4.3), which highlights the main conclusions drawn from the study. Chapter 5 introduces a 3-dimensional rainfall rate visualization model developed. It starts with the specifications of the raw reflectivity database to be used in the modeling (Section 5.1). Then the main features of the 3D model is suggested (Section 5.2). Some preliminary work done on this 3D model is described in the following section (Section 5.3), followed by the summary of the chapter (Section 5.4).

The last chapter (Chapter 6) will state the main conclusions drawn from this study, followed by the recommendations on the future directions for related topics.

Chapter 2

Backgrounds

2.1 RADAR systems

A brief history of the RADAR systems

Generally speaking, a RADAR system refers to a combination of hardware and software equipments which is capable of detecting distant objects (targets) by analyzing the reflected high frequency electromagnetic waves backscattered from the objects. Modern RADAR systems are able to determine the size, radial velocity, shape and many other characteristics of the target objects. Nowadays, meteorological RADAR has become the most popular instrument in the modern operational weather services around the world, due to its strong capability in remotely detecting and tracking of the movement of precipitations, as well as in observing internal structure of the various meteorological events (e.g. thunderstorms, tornados).

The term RADAR stands for “RADio Detecting And Ranging” of objects. Although the acronym was first introduced by S.M. Tucker and F.R. Furth of the U.S Navy in 1940, the concept of RADAR technology can be traced back to the beginning of the 20th century. In the year 1900, Nikola Tesla had explained the similarity of the reflection of both the electromagnetic and sound waves when obstacles are encountered in the propagation. Hence, he proposed the feasibility of determining the relative position and the movement of the obstacles from the reflectivity. Later in 1917, he had further elaborated this idea by proposing the principles in details such as the frequency and power levels to be employed. A milestone in the history of RADAR technology was set in Germany in 1904, when Christian Hulsmeyer patented a device named “telemobiloscope”, which is a transmitter-receiver system utilizes

radio echoes to detect metallic objects. This invention is the first precursor of the realization of the concept of RADAR. Later in the 1920s, some key experiments were conducted by researchers from both the Great Britain and the U.S. In December 1924, British researchers E.V. Appleton and M.A.F. Barnett verified the existence of the reflecting layer (ionosphere) in the sky using frequency modulation (FM) continuous waves (CW). By examining received wave reflected from the sky and that from the direct ground transmission at the distant receiver, the height of the ionosphere can be determined. Although this experiment did not refer to the detection of an actual particle in space, it still can be considered as the demonstration of the technique of radio wave ranging. Previous to Appleton and Barnett, A.H. Taylor and L.C. Young from the U.S. Naval Aircraft Laboratory had also conducted an experiment in 1922, in which the reflected VHF waves from various objects were successfully detected. In their later memorandum, they stated the possibility of utilizing high frequency radio waves to detect and track enemy vessel at a much greater distance. These efforts have fostered the fast booming of the development of RADAR technology in the 1930s. In this remarkable decade, extensive efforts were diverted to this area all over the world. This is partially because of the growing threat of the military conflict around world. Due to its obvious advantage in the detection and location of vessels and aircrafts in the warfare, a number of countries have conducted their researches simultaneously. In 1935, R.A. Watson-Watt and A.F. Wilkins successfully demonstrated the detection of aircraft by means of the reflected radio wave from it. This convincing experiment has immediately caught the attention of the British military authorities and eventually led to the deployment of RADAR networks in Britain. During the wartime, advance in the design and manufacturing of faster and more lethal aircrafts had triggered the intense interest in improvement of the RADAR technology. By the end of World War II, RADAR systems had been greatly developed and widely utilized around the globe. For the detailed description of the works of the pioneers in the field, please refer to the great texts by Sword [1] and Atlas [2].

Shortly after the war, the advanced technologies in the previously military fields soon found their applications in the commercial domain. Due to its obvious advantages in detecting precipitations and arrivals of storms of distance away, RADAR systems had acquired great interest in the area of meteorology. Many novel

inventions had been incorporated into the RADAR system, and remarkable improvements had been made at all components of the system. A great advance in the RADAR technology was the application of Doppler shift principle in the RADAR networks, which was first developed in the WWII. The Doppler Effect observed at the reflected signal from the moving objects had made it possible to determine the radial velocity of the target. The Doppler RADARs based on this effect are widely utilized in the area of weather forecasting nowadays. An in depth explanation of the Doppler shift principle and its applications in the Doppler RADAR systems can be found in the text by Doviak and Zrnic [3]. Another remarkable advance of the RADAR technology is the incorporation of polarization analysis in the RADAR systems. According to Bringi [4], over the traditional single-polarization RADAR systems, the dual-polarization technique offers significant advantages in (a) improving the quality of the RADAR data by distinguishing reflectivity from non-meteorological objects (e.g. bird and insects), (b) differentiating different types of precipitation (e.g. rain or hail), and (c) improving rainfall rate estimation. Great efforts were devoted to the topic by Bringi and his colleagues. The detail theory and application of this technique are thoroughly elaborated in another publication of them [5].

Theories in RADAR Meteorology

In order to exploit the full potential of the RADAR systems in the meteorological applications, it is essential to have a better understanding of the theories behind the operations of the systems. Therefore, in this section those useful theories related to the RADAR meteorology are revised and elaborated.

(a) A Simple Form of the RADAR Equation

The RADAR equation relates the received power at the receiver of the RADAR system to the characteristics of both the RADAR system itself and the target object. It is a convenient tool of understanding the operations of the RADAR. A simple form of it can be derived in a few steps as follows:

When the RADAR transmits a pulse of energy P_t into the surrounding area, the energy is equally distributed into the region. The resultant power density (S) at a distance R from the transmitter can be determined by,

$$S = \frac{P_t}{4\pi r^2} \quad (2.1)$$

This equation is for an isotropic antenna which dissipates the power uniformly to the space around it. However, in the real RADAR systems, directive antennas are usually employed. Hence, a gain g is experienced in the direction of the RADAR beam. Therefore, Equation (2.1) can be amended as:

$$S = \frac{P_t \cdot g}{4\pi r^2} \quad (2.2)$$

Assume that the RADAR beam hits a target with an effective cross sectional area to the RADAR beam of σ along the propagation. Then the power intercepted and reradiated by the target will be given by,

$$P_\sigma = \frac{P_t \cdot g}{4\pi r^2} \cdot \sigma \quad (2.3)$$

Therefore, at the receiver site, the received power can be determined by,

$$P_r = \frac{P_t \cdot g}{(4\pi)^2 r^4} \cdot \sigma \cdot A_e \quad (2.4)$$

where A_e is the effective area of the antenna at the receiver. It can be expressed by means of the antenna gain and the wavelength of the RADAR, which is give by,

$$A_e = \frac{g \cdot \lambda^2}{4\pi} \quad (2.5)$$

Substituting Equation (2.5) into (2.4), the simplified RADAR equation which expresses the reflected power from a target object can then be denoted as

$$P_r = \frac{P_t \cdot g^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 r^4} \quad (2.6)$$

In the case of a spherical target (e.g. rain drops), the effective cross sectional area of the object is determined by diameter D of the object (Note that the larger the size of the drop the more it deviates from spherical shape). However, the relationship between them is not unique. This relationship is dependent upon the relative size of the object to the wavelength of the RADAR beam. Since most of the objects in a meteorological event (e.g. raindrop, hail, etc.) are relatively small (i.e. $D/\lambda < 0.1$) compared to the wavelengths of weather RADAR systems (at the level of centimeters), the relationship between σ and D is given by,

$$\sigma = \frac{\pi^5 \cdot |K|^2 \cdot D^6}{\lambda^4} \quad (2.7)$$

where $|K|^2$ is determined by the refractivity of the material of the target. This equation is applicable in the case of a single target. The real RADAR systems, on the other hand, examine the precipitation over a volume. Therefore, the reflected power to the RADAR is a composition of that from a large number of individual point targets. The overall cross sectional area of this volume can be determined by simply summing those of the individual objects as.

$$\sigma_t = \sum_{i=1}^n \sigma_i \quad (2.8)$$

With this Equation (2.8), the problem of determining the reflected power from a rain volume can be simplified to that of an equivalent point rain target as

$$P_r = \frac{P_t \cdot g^2 \cdot \lambda^2 \cdot \sum_{i=1}^n \sigma_i}{(4\pi)^3 r^4} \quad (2.9)$$

which yields a simple form of RADAR equation in the case of precipitation detection.

(b) RADAR Reflectivity

In order to utilize the Equation (2.9) in the practical weather RADAR systems, it is necessary to have the knowledge of the actual number and size of the raindrops in the volume, which is usually not possible. Therefore, a parameter RADAR reflectivity (η)

is defined to describe the total backscattering cross sectional area per unit volume. It is defined as,

$$\eta = \frac{1}{V} \cdot \sum_{i=1}^n \sigma_i = \int_0^\infty \sigma(D) \cdot N(D) \cdot dD \quad (2.10)$$

where V is the sample volume scanned by RADAR and $N(D)$ is the size distribution function of the particles. In the case of RADAR meteorology, the individual backscattering cross sectional area σ_j takes the form in Equation (2.7). Therefore, substituting this equation into (2.10) yields,

$$\eta = \frac{\pi^5 \cdot |K|^2}{\lambda^4} \cdot Z \quad (2.11)$$

where Z is the reflectivity factor of the RADAR and takes the form,

$$Z = \int_0^\infty N(D) \cdot D^6 \cdot dD \quad (2.12)$$

The sample volume V is determined as,

$$V = \pi \cdot \frac{r \cdot \theta}{2} \cdot \frac{r \cdot \varphi}{2} \cdot \frac{h}{2} \quad (2.13)$$

where θ and φ are horizontal and vertical beam width of the RADAR signal, and h is pulse length of the beam which is given by,

$$h = c \cdot \tau \quad (2.14)$$

where τ is the pulse duration and c stands for the speed of light. However, in the practical systems, the beam pattern is not well behaved as described in Equation (2.13). Hence, a factor of $\ln(2)$ is applied to cope with it, and the modified volume is given by,

$$V = \frac{\pi \cdot r^2 \cdot \theta \cdot \varphi \cdot c \cdot \tau}{8 \cdot \ln(2)} \quad (2.15)$$

Another factor that needs attention is the attenuations along the propagation path of the RADAR beam. This attenuation can occur anywhere, the atmosphere, the cloud and the waveguide, to name a few. Therefore, a factor l is added to account for all

these losses. By substituting Equations (2.11), and (2.15) into (2.9), the RADAR equation can be described again in terms of Z :

$$P_r = \frac{\pi^3 \cdot P_t \cdot g^2 \cdot |K|^2 \cdot \theta \cdot \phi \cdot c \cdot \tau \cdot l}{2^{10} \cdot \ln(2) \cdot r^2 \cdot \lambda^2} \cdot Z \quad (2.16)$$

(c) The Z-R Relationship

As described above, the reflectivity Z is related to the raindrop size distribution (DSD) function $N(D)$ of a unit rain volume (Equation (2.12)). Therefore, it is of great importance to study and formulate well the behavior of the DSD in order to improve the accuracy of RADAR meteorology. In the past few decades, a lot of effort was put on the development of various DSD models, e.g. the Laws-Parsons model [6], the M-P model [7], and the Joss-thunderstorm and Joss-drizzle models [8], etc. Marshall and Palmer [7] suggested an exponential distribution function based on their empirical study, which is given by,

$$N(D) = N_0 \cdot \exp(-\Lambda \cdot D) \quad (2.17)$$

where N_0 has the value of $8000 \text{ (m}^{-3} \text{ mm}^{-1}\text{)}$, and Λ is related to rainfall rate by,

$$\Lambda = 4.1R^{-0.21} \quad (2.18)$$

This Marshall and Palmer (M-P) model is the most popular raindrop size distribution model in the field of meteorology. However, large variations in the DSD are often observed at different locations, with different precipitation types, and so on [9]. Therefore, a rich collection of DSD models are proposed with various factors for different climate conditions.

Since the DSD is directly related to the intensity of rainfall, the above discussion implies that there should be a connection between the rainfall rate R and reflectivity factor Z . This relationship is well studied in different meteorological conditions from experimental DSDs, and therefore, a variety of Z-R models were proposed. Battan [10] has listed more than 60 experimentally determined models, most of which takes the form of a power law equation:

$$Z = aR^b \quad (2.19)$$

where parameters a and b are to be determined locally. Currently the most commonly accepted values for these parameters are derived from the M-P DSD model described above, which is given by,

$$Z = 200R^{1.6} \quad (2.20)$$

This model is widely adopted in the operational weather services around the world, including the Meteorological Services of Singapore (MSS). Since the study of the DSD and Z - R relationship is beyond the scope of the study, this popular M-P model is utilized in the analysis.

2.2 Satellite Communications Systems

Generally speaking, a satellite communication system refers to a wireless communication system which utilizes the satellite as a repeater. It consists of two major segments: the space segment (the satellite) and the ground segment (earth stations). Satellite communication engineering is a subtle combination of the disciplines of radio wave propagation, antenna technology, orbital mechanics, modulation and digital coding, etc (Pratt et. al. [11]). Dues to its great advantages in long distance communications, the satellite communication system has been widely used in various segments of the communications industry nowadays.

A Brief History of Satellite Communications

The idea of satellite communications was firstly introduced by the British science fiction writer, Sir Arthur C. Clarke. In his pioneer note [12] in 1945, he originated the idea of using the synchronous space relays (satellites) in long distance wireless communication around the world. He also raised the exciting assumption that three satellites spaced 120 degrees apart in the synchronous orbit can cover the whole world (with some overlaps). This great idea was not considered seriously in the following years until John R. Pierce from AT&T's Bell Telephone Laboratories elaborated in 1954 the utility of a communication "mirror" in space, a medium-orbit "repeater" and

a 24-hour-orbit "repeater". The milestone in the development of the satellite communication system was the launching of the Sputnik I by Russia in 1957. This event had triggered the fast development of the rocket technology which made it possible to put the satellite into the space orbits. The first communication satellite ever launched into space were ECHO I and II, by AT&T on August 12, 1960, and January 25, 1964, respectively. From then on, satellite technology had experienced a fast development in both the military domain and the commercial market. Today, satellite communication system has become one of the most popular implementation of long distance communications around the world. A more detailed elaboration of the historical events in the evolution of satellite technology can be found in the texts by Pratt et. al. [11] and Evans [13].

The Architecture of Satellite Communications Systems

A satellite communications system consists of two major components:

(a) The Satellite

The satellite itself is also known as the space segment. It is composed of several separate functional subsystems, namely the Power Subsystem, the Attitude and Orbit Control Subsystem (AOCS), the Telemetry, Tracking, and Command Subsystem (TT&C), and the Communication Subsystem (Transponder). The key segment among the subsystems mentioned above is the transponder, which is in charge of receiving, processing and retransmitting the useful information between ground stations. It normally includes the receiving antenna to pick-up signals from the ground station (uplink transmission), a broad band receiver, an input multiplexer, and a frequency converter which is used to reroute the received signals through a high powered amplifier for downlink. The functionality of the satellite varies with different applications depending on its usage. In the case of telecommunications, the primary task of the satellite is to receive signals from a ground station and send them down to another ground station located at a considerably large distance away from the first ground station. This relay action can be two-way, as in the case of a long distance phone call. Another use of the satellite is as with the case of television broadcasts.

The ground station's uplink, received by the satellite is broadcast through numerous downlinks over a wide region, so that it may be received by many different customers possessing compatible equipment. Still another use of satellites is for remote sensing purpose. These satellites are equipped with cameras or various sensors, and they merely downlink any information it picks up from its vantage point. A text by Martin [14] gives a thorough summary of the technical details of the most modern communication satellites as well as the ones which date back to early stages of the history of satellite systems.

(b) The Ground Station

A ground station is any transmitting or receiving system that sends signals to or receives signals from a satellite. Similar to the satellites, the ground station also consist of several subsystems, including, the Antenna, the Power/Low-noise Amplifiers, the Frequency Converters, the Modulation/Demodulation Units, the Multiplexing Units, and the Control and Monitoring Units. As it is indicated in the definition, the ground station's job is two-folded. In the case of an uplink, or transmitting station, terrestrial data (in the form of baseband signals), is passed through a baseband processor, an up converter, a high powered amplifier, and a parabolic dish antenna up to an orbiting satellite. In the case of a downlink, or receiving station, it works in the reverse fashion to that of the uplink, ultimately converting signals received through the parabolic antenna from the satellite to the baseband signal.

Ka-Band Satellite Systems

In the past a few decades, extensive research on the wave propagation in earth-space links have paralleled the fast booming of the applications of satellite systems in the commercial market. A recent trend in the development of the satellite communications systems is that, due to the growth in the demand for higher data-rate and larger capacity direct-to-user (DTU) wireless services and the shortage of usable lower frequency bands (L-, S- or C-band, etc.), researchers are motivated to pursue the satellite systems in the higher frequency bands. Therefore, for over 30 years, the

technologies of supporting satellite system operating in and beyond the Ka-band (20-30 GHz) has become a hot topic in the field. Ever since the late 1970's, parallel studies on the ka-band technology had been conducted mainly in the U.S. [15], Europe [16] and Japan [17]. In 1977, the launch of the Engineering Test Satellite-Two (ETS-II) was the milestone of the research on ka-band in Japan. The experiments conducted with this satellite involved the ka-band frequency for the first time in the country. Since then extensive experiments had been carried out with the domestic communications satellites. In Europe, the researches on the Ka-band satellite communications were mainly conducted on two collaborative satellites: (a) the experimental telecommunication satellite OLYMPUS (operational from mid-1989 to mid-1993) from the European Space Agency (ESA), and (b) the ITALSAT (launched in 1991) from Italian Space Agency (ISA). With these two space units, studies were carried out on a variety of issues associated with the ka-band signal propagations. The effort on the same topic in the U.S. was mainly directed to the development of the Advanced Communications Technology Satellite (ACTS), which was launched in 1993. The ITALSAT and the ACTS had successfully demonstrated the feasibility of the Ka-band technology to meet the requirements of the modern communication systems, and therefore, built the strong confidence to the technique. A good survey on the general issues about the Ka-band satellite systems can be found in the works of Gargione et. al. [18].

One problem associated with the propagation of radio waves in the Ka-band is the excessive attenuation due to atmospheric absorption and rain along the path. These effects are well studied worldwide through the measurement from the OLYMPUS [19] [20], ITALSAT [21], [22] and ACTS [23] [24] [25]. Special interest on this topic was observed in Singapore, where serious rain attenuation is often experienced because of the abundance rainfall in the country. Therefore, much effort had been diverted to this topic by local researchers [26] [27] [28]. However, a great obstacle was faced in these studies, which is the shortage of reliable databases of the measured attenuation along slant-path ka-band links in the region. Fortunately, a good alternative is provided by using computer simulations. Therefore, in this study, simulations of rain attenuation are to be implemented by using a 2-dimensional rainfall rate model.

2.3 Rain attenuation

In practice, there are several factors that can affect the performance of radio wave communication systems in the atmosphere; such as the absorption of the power by the atmospheric gases, the water vapor and the liquid in the form of cloud or precipitation. Among these deduction factors, rain attenuation causes the most signification signal loss to the communication links operating at high frequency bands (above 10 GHz). Generally speaking, the rain attenuation refers to the degradation of the signal level of electromagnetic waves due to the rainfall along the propagation path. When the radio wave signal passes through a rain cell, each raindrop will scatter the signal in random directions, and hence, give rise to attenuations to the signal. This will reduce the fade margin of the wireless communication system and lead to the degradation of the link availability. Hence, there is a practical demand for a reliable rain attenuation prediction model. Extensive efforts were devoted to this topic by researchers all over the world. These efforts have led to a rich collection of theoretical and empirical models for rain attenuation estimation. Among them are some popular ones such as the ITU-R models [29] [30], the Crane-global model [31] and the Crane two-component model [32]. For an exhaustive elaboration of the effect of rain on wireless communication links, refer to the text by Crane [33].

The effects of rain on wireless communication links are specially important for tropical countries like Singapore, where high rainfall intensity is often observed. Therefore, the study of the characteristics of the rain attenuation in the local climate has drawn great attention from researchers. In NTU, for instance, experiments were conducted since the late 1990's with beacon receivers operating at Ku-band, and the attenuation statistics were analyzed and compared with various prediction models from ITU-R [34] [35]. Their investigation suggests that the ITU-R recommendations on earth-space links do not suit the local climate very well. A more detailed analysis was presented in the thesis by Zhu [36]. Similar results were also observed in the experiments by other researchers [27] [37], and amendments were made to the prediction models to fit the local conditions. In this thesis, the experiments on the effect of rain attenuation in Singapore will be conducted through computer simulation, and the simulation results will be studied and compared with the ITU-R predictions. Modifications to these models are also proposed based on these analyses.

The ITU-R model

(a) Terrestrial Line of Sight Links

The ITU-R models designated to the prediction of rain attenuation in Line-of-Sight [29] and Earth-Space [30] links refer to a collection of procedures for the estimation of long-term statistic of the rain attenuation in these situations. They both start from the calculation of the specific rain attenuation (γ_R) [38]. It uses a power law equation to describe the relationship between the specific rain attenuation and the point rainfall rate (R),

$$\gamma_R = k \cdot R^\alpha \quad (2.21)$$

where factors k and α are frequency dependent, and can be determined by:

$$k = [k_H + k_V + (k_H - k_V) \cdot \cos^2 \theta \cdot \cos 2\tau] / 2 \quad (2.22)$$

$$\alpha = [k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cdot \cos^2 \theta \cdot \cos 2\tau] / 2k \quad (2.23)$$

where θ refers to the elevation angle of the communication link and τ is the polarization tilt angle of the electromagnetic wave relative to the horizontal ($\tau = 45^\circ$ for circular polarization.). The k_H , α_H and k_V , α_V in the equations represent the values of k and α for the linear polarizations: H – Horizontal and V - Vertical. These values can be obtained from a look up table (Table 1).

Table 1. Regression coefficients for estimating specific attenuation

Frequency (GHz)	k_H	k_V	α_H	α_V
1	0.0000387	0.0000352	0.9122	0.8801
1.5	0.0000868	0.0000784	0.9341	0.8905
2	0.0001543	0.0001388	0.9629	0.9230
2.5	0.0002416	0.0002169	0.9873	0.9594
3	0.0003504	0.0003145	1.0185	0.9927
4	0.0006479	0.0005807	1.1212	1.0749
5	0.001103	0.0009829	1.2338	1.1805
6	0.001813	0.001603	1.3068	1.2662
7	0.002915	0.002560	1.3334	1.3086
8	0.004567	0.003996	1.3275	1.3129
9	0.006916	0.006056	1.3044	1.2937
10	0.01006	0.008853	1.2747	1.2636
12	0.01882	0.01680	1.2168	1.1994
15	0.03689	0.03362	1.1549	1.1275
20	0.07504	0.06898	1.0995	1.0663
25	0.1237	0.1125	1.0604	1.0308
30	0.1864	0.1673	1.0202	0.9974
35	0.2632	0.2341	0.9789	0.9630
40	0.3504	0.3104	0.9394	0.9293
45	0.4426	0.3922	0.9040	0.8981
50	0.5346	0.4755	0.8735	0.8705
60	0.7039	0.6347	0.8266	0.8263
70	0.8440	0.7735	0.7943	0.7948
80	0.9552	0.8888	0.7719	0.7723
90	1.0432	0.9832	0.7557	0.7558
100	1.1142	1.0603	0.7434	0.7434
120	1.2218	1.1766	0.7255	0.7257
150	1.3293	1.2886	0.7080	0.7091
200	1.4126	1.3764	0.6930	0.6948
300	1.3737	1.3665	0.6862	0.6869
400	1.3163	1.3059	0.6840	0.6849

An alternative way of a quick estimate of values of k and α at frequencies other than listed in Table 1 is through the curves depicted in Figure 1.

(a) Variation of k

(b) Variation of α

Figure 1. Graphical illustration of coefficients for estimating specific attenuation

With the knowledge of the specific attenuation, the long-term statistics (normally referred to as the annual characteristics) of the rain attenuation along wireless link can be predicted. The normal approach is firstly determine the attenuation exceeded for 0.01% of time:

$$A_{0.01} = \gamma_{0.01} \cdot L_{eff} \quad (2.24)$$

The specific attenuation $\gamma_{0.01}$ here is calculated from Equation (2.21) with the point rainfall rate $R_{0.01}$ which exceeds the same percentage of time within the year. Then the estimated rain attenuation exceeded for the percentage of time other than 0.01% (e.g. 0.001%, 0.1% etc.) can be determined by either (links located in latitudes equal to or greater than 30°):

$$\frac{A_p}{A_{0.01}} = 0.12 \cdot p^{-(0.546+0.043 \log p)} \quad (2.25 \text{ a})$$

or (links located in latitudes below 30°):

$$\frac{A_p}{A_{0.01}} = 0.07 \cdot p^{-(0.855+0.139 \log p)} \quad (2.25 \text{ b})$$

The L_{eff} in Equation (2.24) refers to the effective path length, over which the path/line rainfall rate is assumed to be constant. It can be related to the actual length of the propagation path L by,

$$L_{eff} = L \cdot r \quad (2.26)$$

where r denotes the path reduction factor. It is usually determined theoretically from:

$$r = \frac{1}{1 + \frac{L}{L_0}} \quad (2.27)$$

where L_0 is given by,

$$L_0 = 35 \cdot e^{-0.015 R_{0.01}} \quad (2.28)$$

This formula is valid for $R_{0.01} \leq 100$ mm/hr, while in the case of $R_{0.01} \geq 100$ mm/hr, the value 100 mm/hr is used in place of $R_{0.01}$.

(b) The Earth-Space Link

The estimation of rain attenuation along slant path links is slightly more complicated than the LOS case. A schematic plot of a typical earth-space link is as shown in Figure 2.

Figure 2. Effect of rain on slant-path communications links

The first step of predicting the rain attenuation along earth-space communication links is to determine the effective height of the rain volume, which can be looked up from the global rain height map in the ITU-R recommendation [39].

Then the slant-path length is obtained by,

$$L_s = \frac{(h_R - h_s)}{\sin \theta} \quad \text{for } \theta \leq 5^\circ \quad (2.29)$$

or,

$$L_s = \frac{2(h_R - h_s)}{(\sin^2 \theta + \frac{2(h_R - h_s)}{R_e})^{1/2} + \sin \theta} \quad \text{for } \theta > 5^\circ \quad (2.30)$$

where h_s stands for the height of the antenna above the sea level, R_e is the effective earth radius and θ represents the elevation angle.

The horizontal projection of the path is calculated from:

$$L_G = L_s \cdot \cos \theta \quad (2.31)$$

With the knowledge of the projected path length, the path reduction factor for the slant path communication links is then determined by a variation of equation (2.27),

$$r = \frac{1}{1 + \frac{L_G}{L_0}} \quad (2.32)$$

Then the rain attenuation along the earth-space link can be determined at 0.01% and other percentage of times from the equations (2.24) and (2.25).

A particular issue needs to be noticed in this model is the determination of the path reduction factor. According to Ong et. al.[40], the ITU-R model (Equations (2.27) and (2.32)) tends to underestimate the path reduction factor in the local climate, i.e. the predicted effective path lengths are normally shorter than the empirical results. Therefore, amendments to the model were suggested for the Singapore climate. The verification of their suggestions with computer simulations is to be stated in a later chapter of this thesis. A more in-depth study was carried out by Goddard and Tan [41], in which various issues (frequency, path length and time percentage) related to the path reduction factor were investigated. In an earlier publication, Goddard had conducted with Thurai an experiment that utilizes the RADAR collected reflectivity database to determine the path reduction factor [42]. Their work is a very good guidance to the author in the simulations of path reduction factor in this study which also made use of RADAR rain database.

2.4 Site Diversity Systems

In order to solve the problem of excess attenuation due to the rain along satellite communication links, various technologies were proposed and investigated by researchers and system engineers. These mitigation techniques mainly fall into three categories (Panagopoulos et. al. [43]):

- *Adaptive Power Controlling* Adjust the transmitting power to accommodate the changes of the fading along the communication path [44] [45].
- *Signal Processing* Modify the encoding and decoding algorithms to improve the capability of the signal against the fading [46].
- *Diversity* Utilize multiple transmit/receive paths (Site Diversity) or time slots (Time Diversity) to compensate the attenuations [47].

One of the most popular methods to combat the rain attenuation is site diversity. A site diversity satellite system consists of two or more spatially separated ground stations, and hence, provides separate propagation paths to the signal. In practice, the two ground station diversity system is of the most concern. Figure 3 depicts the plan view of the ground stations of a site diversity system.

Figure 3. Plan view of a site diversity system

The basic assumption of the site diversity systems is that the rain attenuation will not significantly affect the two different propagation paths simultaneously (Hogg [47]). Hence, by switching to the ground station with the higher received signal level at all time, the effect of rain attenuation will be reduced significantly. This concept is illustrated in Figure 4.

Figure 4. Combined signal level in site diversity systems

As shown in Figure 4, the received signal from site 1 and site 2 are not attenuated simultaneously, hence, the combined signal from these two sites has a much better performance against the rain attenuation.

The commonly used figure of merit that measures the performance of the site diversity systems are the Diversity Improvement Factor (I) and the Diversity Gain (G). These two concepts can be explained by a simple plot in Figure 5.

Figure 5. Illustration of improvement factor and diversity gain

As illustrated in Figure 5, the diversity improvement factor measures the improvement in the time percentages exceeded for a specified level of rain attenuation. It is given by,

$$I = \frac{p_1}{p_2} \quad (2.33)$$

where p_1 and p_2 are the respective time percentages of the single-site and diversity systems at the same level of rain attenuation.

The diversity gain, on the other hand, measures the decibel difference between the rain attenuations in the diversity system and the single-site system for a specified percentage of time. It is determined by,

$$G = A_1 - A_2 \quad (2.34)$$

where A_1 and A_2 refer to the rain attenuation of the single-site system and diversity system, respectively, which has a same percentages of time exceeded in the attenuation statistics.

Currently in the literature, there are many prediction models available for the estimation of the improvement in performance of the diversity systems over the single-site systems. These models were developed from either the empirical analysis (e.g. the models by Goldhirsh [48], Allnutt and Rogers [49], Hodge [50], and the ITU-R model [30]) or the physical investigations (e.g. the model by Matricciani [51]). The well accepted ITU-R model calculates the diversity improvement factor by:

$$I = \frac{1}{(1 + \beta^2)} \left(1 + \frac{100\beta^2}{p_1}\right) \approx 1 + \frac{100\beta^2}{p_1} \quad (2.35)$$

where p_1 is the single-site time percentage, and β is a parameter depending on link characteristics. The approximation in the equation is acceptable since β^2 is generally small. β can be determined by an empirical relationship:

$$\beta^2 = 10^{-4} \cdot d^{1.33} \quad (2.36)$$

where d refers to the distance (in km) between the diversity sites.

The diversity gain in the ITU-R model takes the form of the product of several gains contributed from different aspects of the spatial arrangement of diversity sites:

(1) Gain contributed by the spatial separation:

$$G_d = a(1 - e^{-bd}) \quad (2.37)$$

where:

$$\begin{aligned} a &= 0.78A - 1.94(1 - e^{-0.11A}) \\ b &= 0.59(1 - e^{-0.1A}) \end{aligned} \quad (2.38)$$

The term A in (2.38) refers to the rain attenuation (dB) for the single site.

(2) Gain contributed by the frequency:

$$G_f = e^{-0.025f} \quad (2.39)$$

where f is the frequency in GHz.

(3) Gain contributed by the elevation angle:

$$G_{\theta} = 1 + 0.006\theta \quad (2.40)$$

where θ is the elevation angle in degrees.

(4) Gain contributed by the base-line:

$$G_{\psi} = 1 + 0.002\psi \quad (2.41)$$

where ψ refers to the angle (degrees) made by the azimuth of the propagation path with respect to the baseline between sites, chosen such that $\psi \leq 90^\circ$.

The net diversity gain can be determined then by taking the product of the above gains:

$$G = G_d \cdot G_f \cdot G_{\theta} \cdot G_{\psi} \quad (2.42)$$

The technology of site diversity is of great interest to the researchers in Singapore, which is a small island with frequent intensive precipitations. Timothy et. al. [52] studied the performance of site diversity systems and verified the feasibility of the prediction models with the locally obtained data. It was evident in their study that, even for countries with very limited territory such as Singapore, remarkable performance of site diversity technique still can be achieved. In this study, this conclusion is further affirmed by the results from simulations on the site diversity systems in Singapore by means of a 2-dimeiosnal rainfall rate model.

2.5 Weather RADAR Data Visualization and Interpolation

The fast booming of RADAR technology in weather surveillance and forecasting has triggered a worldwide interest on the topic of real-time acquisition and visualization of the meteorological data from the weather RADAR system. The main obstacles in the realization of this idea are the size and structure of the RADAR database to be utilized. As the meteorological RADAR systems scan and retrieve the weather data from the surrounding volume repeatedly with very high speed, a very vast amount of database is usually produced, which put a formidable challenge to

acquire, store, process and visualize the data in real-time. Moreover, since the raw data in the RADAR systems is collected from the region from curvilinear scans, the RADAR database is thus organized in conical coordinate systems. This feature of the database causes extra difficulties to the visualization of the data, and therefore, additional processing is required to modify the database so as to make it compatible to the commonly used data visualization algorithms. Furthermore, in order to better comprehend the metrological data, additional context information such as the local terrain and landmarks also has to be rendered, which puts even heavier burden to the visualization system. Therefore, besides the great improvement in the graphics hardware, extensive efforts had been put on the development of more efficient software algorithms to speed up the RADAR data visualization. The most commonly encountered problems associated to the topic often falls in the categories of developing more efficient algorithms in (1) volumetric data rendering and (2) 3-dimensional data interpolation. These two topics will be elaborated in the following sections.

Volumetric Data Visualization

Generally speaking, there are three commonly applied approaches in the visualization of volumetric databases:

- 1) *Slicing and Dicing* where the 3 dimensional databases are displayed in a 2-dimensional manner as a series of slices. This technique consumes less processing power than other techniques, and therefore it is normally very fast. An example of slicing view of a volumetric database is depicted in Figure 6.

Figure 6. 3D visualization realized by slicing and dicing

- 2) *Isosurfacing* where the volumetric data are rendered in a series of isosurfaces. An isosurface refers to the contouring surface in the volume which consist of the data points having the same value (isovalue). In the case of rainfall visualization, the data points with the same rainfall rates are rendered the same color such that the areas with critical rainfall rates can be easily spotted in the rain volume. Isosurfacing give a good overall feel of the 3D shape of the data. However, since only a limited number of isosurfaces can be shown simultaneously, the inside pattern of the volume are normally difficult to understand. An example of isosurfacing view of a rain volume is as illustrated in Figure 7. The surfaces with different values are rendered in different colors and the transparency levels are differentiated such that the inner surfaces could be seen through the outer ones.

Figure 7. 3D visualization realized by isosurfacing

- 3) *Volumetric Visualization* where each data point is directly rendered with respect to its value, while the intensities are added together in some fashion, e.g. the higher the data value, the more opaque it would be, and the lower the data value, the more transparent. This is the most direct approach among all the 3D data visualization techniques. Since every data point has to be rendered, more computation power is also required than other techniques. An example of the volumetric visualization of rainfall rate data is illustrated in Figure 8. As shown in the figure, the color of each data point represents the intensity of rainfall at the spot in the 3D space. With proper scheme of transparency, the value of the inner data points can be easily recognized through the outer data.

Figure 8. 3D visualization realized by volumetric rendering

The applications of 3D visualization on the weather RADAR data probably starts from the late 1980s, when great blueprints of computer graphics systems dedicated to the field of meteorology was designed [53]. In the early years of this technology, only slicing and dicing approach is possible due to the limited computation power of the hardware. In the following decades, with the remarkable improvement in the computer hardware, the more direct approaches in the realization of 3D visualization are possible. Therefore, the applications of the slicing and dicing technique, due to its drawback of losing much useful information, are usually limited to coarse visualization of relatively simple 3D shapes. Since then extensive efforts have been put on the development of various techniques to directly visualize the 3D data and to improve the rendering speed and accuracy of the visualization. Several examples of the popular volume rendering algorithms are explained and compared in the works by Meibner et. al. [54].

An example of the isosurfacing approach in the visualization of Doppler RADAR data can be found in a case study by Gerstner et. al. [55], where a multiresolution algorithm was proposed to improve the visualization efficiency by adaptively extracting and rendering isosurfaces from the volumetric database to meet the various requirements of the user in the level of resolutions. This method is further elaborated in a separate publication [56]. Djurcilov and Pang [57] had also developed a visualization system based on the isosurfacing approach. In their works, the problem associated with the large amount of missing data in the RADAR databases was

addressed and possible solution was proposed. A group in GUV center of Georgia Institute of Technology has also devoted their efforts to the development of a real-time Acquisition-Display model of the weather RADAR system [58], in which the direct volumetric visualization technique was utilized. In their works they have emphasized the essentiality of context information such as terrain, buildings and other static objects [59]. Similar works were also done in various countries [60] [61] [62] around the world.

3D Data Interpolation

In the design of the real-time acquisition-visualization systems of weather RADAR data, an often encountered problem is associated with the curvilinear nature of the RADAR scan (Figure 9). As stated before, the RADAR systems collect the meteorological data from sweeps around the region in various elevation angles. Therefore, the raw data from the RADAR systems are usually given in a conical coordinate system. Although the 3D data in this system can still be visualized directly by means of techniques such as the mesh-wire approach, it is more convenient, however, for most of the data visualization techniques (e.g. the isosurfaceing and volumetric rendering) to deal with data in a regularly gridded Cartesian coordinate system. Moreover, the meteorological data in the polar system would be hard to match the Cartesian grids of the terrain information. Therefore, proper interpolation has to be performed to convert the original conically organized RADAR database into Cartesian coordinate system before it can be visualized.

Figure 9. Curvilinear scan of meteorological RADAR

The basic idea of this interpolation is to consider the data points in the conical system as a set of scattered data in the Cartesian coordinate system, and then perform the regular 3-dimensional interpolation technique on the data to produce the cubical database. A number of interpolation algorithms are applicable in this situation, such as the direct trilinear method, the Shepard method [63], the radial basis function method [64], etc. A good survey on these methods can be found from the work by Lodha and Franke [65]. It should be noted that these relatively simple algorithms normally do not have any measure of the interpolation errors. Therefore, proper error estimations should be accompanied with the application of these methods. More precise methods such as Kriging [66] can provide a much better estimations of the missing data with no change to the existing data values. However, these methods usually consume great computation power. Therefore, a trade-off between the interpolation efficiency and accuracy are normally faced when choosing among the interpolation algorithms. In the case of meteorological database, the enormous size of the data from the RADAR system normally makes it not feasible to apply the complicated interpolation methods due to the limitation of the hardware. Therefore, the simple approaches are often utilized.

In the development of the 3D rainfall rate visualization model in this study, the direct volumetric rendering approach is adopted in the visualization of the rain data. Moreover, the simple trilinear interpolation schemes are studied, and a modified version of this method is applied. Details of these studies are to be elaborated in Chapter 5 of this thesis.

2.6 Interactive Data Language (IDL)

The programming language used in this project is the Interactive Data Language (IDL). It is a high level programming language utilizing the IDL programming platform developed by the Research Systems Inc (RSI). It is one of the best applications available for providing the strong capabilities of both data analysis and data visualization. Many predefined and well developed mathematics and physics functions are included in this language. Hence, it is advantageous because it is easy to begin with and requires little effort on developing the mathematical models, etc. The

program modules written in IDL are in .PRO format. The IDL software version used in this study is version 5.3.

2.7 Summary

In this chapter, the background knowledge of the topics related to this study has been reviewed. In the first section, several issues about the RADAR meteorology have been introduced. The evolution of the RADAR technology was firstly summarized, followed by the theories of RADAR meteorology which are essential to this study. The following section dealt with the topic of satellite communication systems. The brief history of the satellite technology was firstly reviewed. The general architecture of typical satellite communications system was then described, followed by the recent trend of pursuing higher frequency bands (Ka-band and beyond) of the modern satellite systems. The third topic introduced in this chapter refers to the effect of rain on wireless communication links. The well accepted ITU-R model of predicting rain attenuation along the Line-of-Sight and Earth-Space links were explained in details. The site diversity technology used to combat excessive rain attenuation was investigated in the next section of the chapter. An in-depth elaboration of the commonly used model of predicting the diversity gain (G) and diversity improvement factor (I) were presented. The following section briefly reviewed the popular techniques in the contemporary weather RADAR data visualization and interpolation. The last topic introduced in this chapter is the IDL programming platform utilized. This platform provides a rich collection of convenient tools which greatly helps the author in the development of the program modules in this thesis. The review of the issues in this chapter has provided the author with not only a much better understanding of the useful backgrounds, but also a clearer idea of obstacles to be faced in this study. Therefore, a strong foundation of this thesis has been built by these efforts.

Chapter 3

Calibration of RADAR Rain Data

As described in the previous chapters, rain attenuation is a vital factor that affects the performance of wireless communication systems operating in the high frequency bands. Therefore, a comprehensive understanding of the characteristics of rainfall and rain attenuation will be of great importance for both the academic studies and commercial system planning. Traditionally, the statistics of rainfall rate are normally collected from large networks of rain gauges and that of the rain attenuation are obtained from actual wireless links, both of which are quite costly and time consuming. Fortunately, the situation is much improved with the worldwide boom in RADAR technology. Meteorological RADAR provides a much cheaper way of obtaining rainfall rate information over a large area. Its advantages of large coverage and high resolution make it very attractive to utilize the RADAR rain databases in the simulations on the effect of rain attenuation along communication links. Therefore, in this study, a two dimensional rainfall rate model based on the RADAR rainfall rate database is to be developed.

Since the main purpose of developing this rainfall rate models is to study the characteristics of the point rainfall rate and rain attenuation along terrestrial communication links, the database utilized in the development has to be compatible to the commonly accepted data format in researches on the topic. Unfortunately, the RADAR rain database to be employed does not meet this requirement. This is because most rain attenuation prediction methods (e.g. the ITU-R model) require rainfall rate statistics with one minute integration time for certain range of time percentages. However, the rainfall rate statistics obtained from the RADAR systems normally do not agree with that of the one-minute systems. Therefore, it is necessary to calibrate the RADAR rain data with the rain statistics with one minute integration time before applying it to rainfall rate models. Hence, a simple framework of converting RADAR

rain statistics to the equivalent one-minute rain rates was developed and proposed in another publication of the author [67]. In this chapter, this calibration method is to be further elaborated.

3.1 The PPI Rain Database

The database to be utilized in the development of the 2D rainfall rate model is a collection of Plan Position Indicator (PPI) rainfall rate images produced by the S-band Meteorological Doppler Weather RADAR (MDWR) system from Meteorological Service of Singapore (MSS). The antenna of the MDWR system is located at 103°58'12" E; 1°21'4"N, which is adjacent to the Changi Airport of Singapore. The PPI images are in GIF format. Each of them displays the instantaneous rainfall rate data at the time when the meteorological RADAR is scanning the surrounding region at 1° elevation. The time interval between two successive readings is around 4 minutes. There would be about 340 PPI rain images produced in a typical day. An example of these rainfall rate images is depicted in Figure 10.

Figure 10. PPI rainfall rate image from MSS

As shown in Figure 10, the rain data is arranged in the RADAR rain map in a 2 dimensional array of the size 598×598 pixels corresponding to a region with the full range of 140×140 km² around Singapore. Hence, each pixel on the map represents an area of the size 234×234 m². The color of each pixel indicates the heaviness of rainfall at the spot, and the actual value of rainfall rates can be looked up in the color bar beside the map. It is important to note that in order to reduce the size of the PPI database, the RADAR system has already quantized the continuous rainfall rate values into 16 levels, each represented by a color in the RADAR rain map. Therefore, in order to restore the rain data, the colors in the map have to be “de-quantized”. In this study, the average values of these 16 rainfall rate levels are picked to be the representative of the whole range. These values are listed in Table 2 together with the corresponding colors.

Table 2. Color codes in PPI rainfall rate images

Level	Color	Rainfall Rate (mm/hr)	Average Value
1		0.05 ~ 0.10	0.075
2		0.10 ~ 0.25	0.175
3		0.25 ~ 0.5	0.375
4		0.5 ~ 0.75	0.625
5		0.75 ~ 1	0.875
6		1 ~ 2	1.5
7		2 ~ 3	2.5
8		3 ~ 4	3.5
9		4 ~ 8	6
10		8 ~ 12	10
11		12 ~ 20	16
12		20 ~ 30	25
13		30 ~ 50	40
14		50 ~ 100	75
15		100 ~ 150	125
16		> 150	180

3.2 Origins of the Discrepancies

The differences between the rain statistics from the PPI RADAR data describe above and the one-minute rain data collected from rain gauge systems mainly originates from two problems.

1) Instantaneous vs. Integrated

As describe in the previous section, the RADAR system collects the rain data on the instantaneous basis, meaning that the rainfall rate obtained from the Doppler weather RADAR is the instantaneous rainfall rate when the RADAR beam scans through the rain volume. On the other hand, the rainfall rates in the one-minute system are the integrated rain rates within a one minute time span measured at one point or location. Therefore, the rain data from the two systems normally does not agree with each other. This problem can be illustrated by the graph in Figure 11.

Figure 11. Instantaneous vs. integrated

The curve in Figure 11 depicts the variation of the rainfall rate in a one minute period. Suppose that the weather RADAR scans through this rain volume at the 10th second, the resultant rainfall rate reflected to the RADAR system will be 100 mm/hr. On the other hand, the one-minute rainfall rate is the mean value of the rainfall within this minute, which is 70 mm/hr. Therefore, significant discrepancy can be caused between the rain rates from the two systems.

2) Discrete vs. Continuous

This problem refers to the difference in the temporal continuity of the database from the two systems. As explained before, the time interval between two successive PPI rain images is around 4 minutes. Therefore, the RADAR database is discrete in time. On the other hand, the data of the one-minute system is continuous from minute to minute. This nature causes further differences between the RADAR rain statistics and that of one-minute system. This concept can also be described in a graph in Figure 12.

Figure 12. Discrete vs. continuous

This graph depicts the variation of the one-minute rainfall rate in a rain event with 16 minutes time span. The crosses on the curve represent the rainfall rates sampled by the Doppler RADAR in every 4 minutes. In order to predict the rainfall rate in between two successive samples of the RADAR database, a linear interpolation is carried out. Apparently, this process enlarges the differences between two systems.

Besides the two problems described above, there are other factors which also contribute to the discrepancies between the PPI rain rates and one-minute rainfall, e.g. the ensemble averaging over the effect of drop size distribution (DSD) in the radar pulse volume and the usage of long-term statistical approximated Z-R relationship (Equation (2.19)) in the rain rate determination, etc.. Therefore, it is necessary to calibrate the RADAR rain data before applying into the rainfall rate visualization model. Hence, the differences between the rain statistics from both the RADAR and

one-minute systems are investigated and a framework of calibrating the RADAR rain rates with one-minute rainfall is proposed in this study

3.3 Database Specifications

In order to study the characteristics of the rainfall rates from the two systems, the databases from both of them which are overlapped in time are required. Currently in NTU, there are two databases with one year time span which meet this requirement. The specifications of these databases are described separately as follows.

1) The One-minute Integration Time Rain Gauge Data

The one-minute integration time rainfall rate database used in the calibration was collected from two tipping bucket rain gauges located at two sites in the NTU campus. These two sites are 171 meters apart and located on the rooftops above the Main Lecture Theater (MLT, 103°40'56" E and 1°20'33" N) and the South Spine (S2, 103°40'50" E and 1°20'32" N) respectively. The resolution of the rain gauges is 0.1 mm per tip, i.e. each tip registered per minute corresponds to 6 mm/hr of rainfall. This database covers the full 12 months of year 2000. According to [68], the rain gauges worked reasonably well in the year, despite that some losses of data occurred at the site MLT due to the equipment faults. Table 3 presents the availability of this database.

Table 3. Availability of one-minute rain gauge data

Months	Data Availability (%)	
	MLT	S2
Jan, 2000	100	100
Feb, 2000	100	100
Mar, 2000	58.06	100
Apr, 2000	83.33	100
May, 2000	100	100
Jun, 2000	100	100
Jul, 2000	100	100
Aug, 2000	100	100
Sep, 2000	100	100
Oct, 2000	100	100
Nov, 2000	100	100
Dec, 2000	100	100
year 2000	95.12	100

2) The Doppler RADAR Data

NTU has purchased a collection of PPI rainfall rate maps from MSS for research purposes. This set of data covers a period of 22 months, from January, 2000 to October, 2001. Due to the hardware problems of the Doppler RADAR and the corruption of the storage medium, a portion of the database is not retrievable. The availability of the subset of the year 2000 in this database is listed in Table 4. It is reported that the availability of the subset is considerably high (above 90%) in most of the months, except for December (78%) due to the data corruption.

Table 4. Availability of RADAR data

Months	Data Availability (%)
Jan, 2000	99.48
Feb, 2000	92.80
Mar, 2000	99.05
Apr, 2000	95.56
May, 2000	95.12
Jun, 2000	99.27
Jul, 2000	97.04
Aug, 2000	99.16
Sep, 2000	97.54
Oct, 2000	91.30
Nov, 2000	98.38
Dec, 2000	77.95
Year 2000	95.22

3.4 A Framework of Converting RADAR Rain Rate Statistics to Equivalent One-minute Integration Time Rain Rates

1) Comparison of RADAR and One-minute Rain Rate Statistics

The two sites where the one-minute rainfall rate data were collected are located in two pixels which are adjacent to each other on the PPI rain maps. To study their yearly characteristics, the cumulative distribution functions (CDF) of the rainfall rate data from the two systems are investigated. The CDF is defined as the function of percentage of time within a certain period of time when a specific rainfall rate is exceeded. It is a statistical measure that describes the rain characteristics at a location.

The CDF of the two data systems are calculated at the two sites and depicted in the subplots of Figure 13. In each graph, the RADAR rain distributions are plotted together with its counterparts with one minute integration time.

(a) MLT

(b) S2

Figure 13. Comparison between rain statistics from RADAR and one-minute systems

As illustrated in the plots, there are obvious discrepancies between the two set of rain rate statistics. For the percentages of time greater than 0.003%, the RADAR rain data falls below the one-minute rain rates, while for the percentage less than 0.002%, the RADAR data tends to be over that of the one-minute dataset.

2) Procedures of Calibration

To convert the RADAR rain rates to its equivalent one-minute rain rates, we firstly examine their yearly cumulative distribution functions. Table 5 lists the rainfall rate values of the two databases at the percentages of time of 0.003, 0.03, 0.1, 0.3 and 1% in the year 2000. In CCIR Report 563-4 [69], Singapore has been designated to the climate rain zone P (Tropical Wet Climates) among the 15 zones (A to Q) defined. Several characteristics of the rain, including the yearly rain distribution, are developed for each of these rain zones. Therefore, the ITU-R rain rates of rain climate zones P (tropical wet climate) and N (tropical moderate climate) are also presented and compared with the local statistics.

Table 5. Equiprobable rainfall rates (R_r : RADAR rainfall rate, R_l : one-minute rainfall rate)

Percentage of Time (%)		0.003	0.01	0.03	0.1	0.3	1
MLT	R_l (mm/hr)	152.63	126.15	99.95	66.64	26.96	9.24
	R_r (mm/hr)	179.24	93.59	27.72	12.54	3.89	0.89
S2	R_l (mm/hr)	147.28	120.52	98.47	66.261	27.45	9.55
	R_r (mm/hr)	141.57	39.84	25.62	12.78	4.09	0.91
ITU-R	Zone P	200	145	105	65	34	12
	Zone N	140	95	65	35	15	5

It is observed that the one-minute rainfall statistics are well bounded by the rain distributions defined for the zones P and N by ITU-R. One the other hand, the RADAR rain rates falls far below the values of zone N for most of the times (except for 0.003% of time). The rainfall rates from the two systems listed in Table 5 which yield the same cumulative probability in the year are so called the equiprobable rainfall rates. With these equiprobable rainfall rates, we can interpolate the one-minute rainfall rate values which correspond to the representative rain rates of the 16

rain levels in the RADAR database. The ratios between them (R_l/R_r) are also generated. They are presented in Table 6.

Table 6. Conversion ratios from RADAR rain data to one-minute rain data

Level	Rain Range	Average Rain Rate	MLT		S2		Average R_l/R_r
			R_l	R_l/R_r	R_l	R_l/R_r	
1	0.05 ~ 0.10	0.075	5.59	74.53	5.59	74.53	74.53
2	0.10 ~ 0.25	0.175	5.81	33.20	5.82	33.26	33.23
3	0.25 ~ 0.5	0.375	5.95	15.87	5.96	15.89	15.88
4	0.5 ~ 0.75	0.625	7.49	11.98	7.58	12.13	12.06
5	0.75 ~ 1	0.875	9.12	10.42	9.28	10.61	10.51
6	1 ~ 2	1.5	12.3	8.20	12.06	8.04	8.12
7	2 ~ 3	2.5	18.76	7.50	18.86	7.54	7.52
8	3 ~ 4	3.5	24.64	7.04	24.34	6.95	6.99
9	4 ~ 8	6	40.26	6.71	38.79	6.47	6.59
10	8 ~ 12	10	56.48	5.65	55.36	5.54	5.59
11	12 ~ 20	16	77.22	4.83	75.92	4.75	4.79
12	20 ~ 30	25	93.69	3.75	95.83	3.83	3.79
13	30 ~ 50	40	110.06	2.75	120.86	3.02	2.89
14	50 ~ 100	75	120.57	1.61	135.54	1.81	1.70
15	100 ~ 150	125	133.16	1.07	143.79	1.15	1.11
16	> 150	180	161.75	0.90	155.38	0.86	0.88

It is evident in Table 6 that the relationships between the two databases are quite consistent at the two sites. Therefore, they were averaged to produce a set of calibration ratios (listed in the last column of the table) to be utilized in predicting the one-minute rain statistics from the RADAR rain rates. As the calibration ratios are applied, a set of calibrated rainfall rate values of the 16 rain levels of the RADAR database is produced and listed in Table 7.

Table 7. Calibration of RADAR rainfall rates

Level	Rain Range	Average Rain Rates	Calibration ratios	Calibrated Rain Rates
1	0.05 ~ 0.10	0.075	74.53333	5.59
2	0.10 ~ 0.25	0.175	33.22857	5.81
3	0.25 ~ 0.5	0.375	15.88	5.96
4	0.5 ~ 0.75	0.625	12.056	7.54
5	0.75 ~ 1	0.875	10.51429	9.20
6	1 ~ 2	1.5	8.12	12.18
7	2 ~ 3	2.5	7.524	18.81
8	3 ~ 4	3.5	6.997143	24.49
9	4 ~ 8	6	6.5875	39.53
10	8 ~ 12	10	5.592	55.92
11	12 ~ 20	16	4.785625	76.57
12	20 ~ 30	25	3.7904	94.76
13	30 ~ 50	40	2.8865	115.46
14	50 ~ 100	75	1.7074	128.06
15	100 ~ 150	125	1.1078	138.48
16	> 150	180	0.880917	158.57

3) Evaluation of the Calibration Method

The rain rate statistics predicted from the calibrated RADAR data are compared with the measured one-minute rain rates in Figure 14.

(a) MLT

(b) S2

Figure 14. Comparison between rain statistics from one-minute and calibrated RADAR systems

Since the same set of rain data, which the calibration ratios were obtained from, is used, it is expected that the predicted one-minute rain statistics should have quite close fits to the measured rain rates. As depicted in Figure 14, the results agree with the expectation very well at both of the two sites. The equiprobable rain rates of the predicted and measured one-minute rain statistics are listed in Table 8 together with the characteristic rainfall rates defined for the ITU-R rain climate zones P and N.

Table 8. Equiprobable rainfall rates of the calibrated RADAR data

Percentage of Time (%)		0.003	0.01	0.03	0.1	0.3	1
MLT	R1	152.63	126.15	99.95	66.64	26.957	9.2412
	Rr	157.81	117.86	95.176	60.559	24.53	9.2421
S2	R1	147.28	120.52	98.471	66.261	27.454	9.5461
	Rr	143.51	117.39	95.043	61.176	27.223	9.3318
ITU-R	Zone P	200	145	105	65	34	12
	Zone N	140	95	65	35	15	5

It can be observed that the predicted rain distributions are quite close to that of the measured one-minute rain data at the percentage of times of 0.003, 0.01, 0.03, 0.1, 0.3 and 1%. They also fall between the bounds of ITU-R zones P and N.

In order to study the consistency between the calibrated RADAR rain data and the one-minute rain data, the amounts of rainfall in each of the twelve months of the year 2000 are investigated. Since only the one-minute database at the MLT site has a resolution down to the unprocessed minutely data level, while that of the S2 site consisted of a collection of processed rain distributions, the analysis of the monthly rain amount is only possible at the MLT site. Therefore, the following studies will be focused to this site. The total amount of rainfall in each month obtained from the calibrated RADAR rainfall rate and the one-minute rainfall rate databases are compared in the bar chart depicted in Figure 15.

Figure 15. Monthly amount of rainfall in the year 2000 at MLT

As shown in the chart, the amount of rainfall of the calibrated RADAR rain database shows a high consistency with that of the one-minute rain data in most of the months with the exception of three months: March, October and December. Investigations showed that these discrepancies are mainly contributed by the defects of the database. As listed in Table 3, the availability of the one-minute database in March of year 2000 was at a low of 58.06%. This loss of data causes the amount of rainfall for the one-minute database to drop way below the calibrated RADAR system in the same month. Similar situation is observed in December, where the availability of RADAR rain data is at a low of 77.95%. The situation in the month of October is slightly more complicated: an extremely high rain event was observed in the RADAR

database on Oct, 5th, which lasted for an unrealistically long period of time (approx. 7 hours). More than half (270 mm) of the total rainfall in October of the RADAR database was contributed by this rain event. However, this event was not found in the one-minute database in the corresponding period. Therefore, it is concluded that this unrealistic rain event is probably due to the malfunction of the RADAR on the day. In order to mitigate the effect of the erroneous months on the calibration process, these months were removed from the database and calibration is carried out again with the 9-month subset of the databases from the two systems. A new set of calibration ratios is then generated.

To further evaluate the performance of the calibration method, the correlation between the RADAR rainfall rates and one-minute rainfall rates are looked into on 26 days which contained most of the high rainfall rate rain events of the year. Figure 16 depicts the variation of hourly rainfall rate from the two databases on a typical rainy day.

Figure 16. Comparison between hourly rainfall rates from RADAR system and one-minute system

As illustrated in the figure, the variation of the hourly rainfall rate of the calibrated RADAR database is quite consistent to the one-minute rain data on the same day, which gives rise to a 0.9997 correlation between the two data series. However, the mean value of the correlation of hourly rainfall rate for all the 26 days is only 0.892,

revealing that the overall consistency is not as good as expected. It is suggested by the supplier of the RADAR database (MSS) that this inconsistency might be due to the misalignment between the RADAR map and the physical map, i.e. the pixel in the PPI images may not be aligned with the physical location on the map as is indicated. Therefore, the relationship between the hourly rainfall rate of the one-minute database and that of the 25 pixels around the current pixel (including the current pixel) are studied. The schematic illustration of the area studied is depicted in Figure 17. The average hourly correlations between the data from the two systems are calculated at each pixel and listed in Table 9.

Figure 17. Adjacent pixels around MLT

Table 9. Averaged correlations between hourly RADAR rainfall rate and one-minute rainfall rate

x/y Coordinate	x-2	x-1	x	x+1	x+2
y+2	0.903	0.922	0.884	0.908	0.878
y+1	0.896	0.923	0.892	0.907	0.883
y	0.896	0.923	0.892	0.907	0.883
y-1	0.916	0.938	0.919	0.882	0.884
y-2	0.917	0.934	0.921	0.894	0.889

The x and y in Table 9 represents the coordinates of the current pixel in the RADAR rain map. As shown in the table, the best correlation between the two databases is

0.938, which occurs at the pixel with the coordinates (x-1, y-1) in the RADAR rain map. Hence, the procedures of calibration described above are carried out again at this pixel and a new set of calibration ratios is produced.

Table 10 compares the three sets of calibration ratios obtained, including (1) the calibration ratio obtained from the current pixel (x, y) using all 12 months of data; (2) the calibration ratio obtained from the current pixel (x, y) using 9 months of data with the 3 erroneous months eliminated; and (3) the calibration ratio obtained from the pixel with the best correlation among the 25 pixels tabulated in Table 9 (x-1, y-1) using 9 months of data.

Table 10. Comparison between calibration ratios

Level	Average Rain Rates	Pixel (x, y)		Pixel (x-1, y-1) 9 months
		12 months	9 months	
1	180	0.880	0.933	1.00
2	125	1.107	1.157	1.345
3	75	1.707	1.671	2.104
4	40	2.887	2.900	3.450
5	25	3.790	3.878	4.179
6	16	4.786	4.971	5.287
7	10	5.592	5.885	6.544
8	6	6.588	7.065	7.140
9	3.5	6.997	8.341	8.240
10	2.5	7.524	8.400	8.457
11	1.5	8.120	9.962	9.835
12	0.875	10.514	11.929	11.868
13	0.625	12.056	11.260	11.738
14	0.375	15.880	15.906	15.915
15	0.175	33.227	33.670	33.616
16	0.075	74.533	74.975	74.976

The comparison among the 3 sets of calibration ratios shows high consistency from each other. This provides a certain degree of confidence for the calibration method and the results obtained so far. It should also be noted that, the calibration ratio of the 2 sets obtained at the current pixel (x,y) are quite similar, implying that the effect of the three erroneous months on the calibration is not so significant as expected.

The RADAR rain data is recalibrated using the set of calibration ratio from the pixel with the best correlation (last column in Table 10). The resultant rain statistics of the 9 months in year 2000 produced by the recalibrated RADAR data is then compared with the measured one-minute rain rate as plotted in Figure 18.

Figure 18. Comparison between re-calibrated RADAR rain statistics and one-minute statistics

It is observed that the recalibrated RADAR rain data produces a good match to the one-minute rain data measured in the same period. This is further elaborated in Table 11, which lists the rainfall rate values of the two databases at some typical percentage of times.

Table 11. Comparison between re-calibrated RADAR rain rates and one-minute rain rate at typical percentages of times

% Of Times	R _i	R _r
0.003	157.81	138.00
0.01	125.13	124.65
0.03	100.51	99.50
0.1	68.99	65.44
0.3	30.10	28.84
1	9.90	9.70

3.5 Summary

In this chapter, a simple framework of predicting one-minute integration time rainfall rate statistics from the meteorological RADAR rain databases has been proposed. The prediction results showed close fit to the measured one-minute rain distributions. From the analysis of the prediction results, it can be concluded that the calibration of RADAR rain data with one-minute rain data is not a trivial matter and is of significant importance. In order to perform an accurate calibration, certain issues have to be resolved. For example, despite the good fit produced by the calibrated RADAR rain data to the desired one-minute rain statistics, the 9 months' time span of the database is not sufficient to show the long term validity of the calibration method. Therefore, as a natural continuation, further work should be carried out on the testing of the method with databases of a longer time span. Moreover, the alignment of the RADAR rain map and the physical map has to be examined to ensure a good match for the point of interest. This might be very complicated as each point on the map has to be matched to its corresponding point based on the maximum correlation value. Another promising extension of this topic is to investigate the monthly variations of the conversion ratios which might lead to a general guideline of applying the method with different seasons of the year.

Chapter 4

The 2-Dimensional Rainfall Rate Model

In this chapter, a 2-dimensional rainfall rate visualization model based on the PPI RADAR database described in Chapter 3 will be introduced. Studies on the rainfall rate and rain attenuation using this 2D model are to be carried out and some sample results are to be analyzed.

4.1 The Algorithms of the 2D Rainfall Rate Model

The main tasks of the 2D rainfall rate visualization model can be described as:

- 1) To extract the rainfall rate data from a series of GIF formatted pictures, and store the data into data files for future usage.
- 2) To implement the simulations for the point rainfall rate (R) and/or path rain attenuation (A) using the extracted rain data.
- 3) To display and export the simulation results into proper output files.

Since the database utilized in the model is a collection of the rainfall rate images (about 340 images per day), an essential step is to read in the images one by one to extract the data stored in them. However, the IDL language has a characteristic such that it is much more powerful when working with data formatted in arrays rather than working in loops, i.e. it is more efficient to arrange the collection of data into a data matrix before it is processed by IDL programs. Therefore, in order to improve the efficiency of the program, it is necessary to implement some preprocessing on the rain rate data before doing any data analysis or simulation. Hence, the 2D model has two subroutines: “*Preprocessing*” and “*Simulation*”. In the following sections, the functionality of these subroutines will be explained in detail.

4.1.1 Preprocessing

The subroutine “*Preprocessing*” reads in the rain data stored in the images and process it so as to obtain a data file which contains the complete set of rain data for one day. This process can be described by a simple chart in Figure 19.

Figure 19. Functionality of the subroutine of preprocessing

A program module was developed in IDL to implement the tasks described above. The basic functional module in the program is capable of processing one day’s data at a time. Then it is extended to process as long as one year’s data by adding in proper controller modules. The basic program module works in three main steps:

Reading The rain data images are to be read into memory and the color-coded data in the RADAR rain maps are to be translated into actual rainfall rates and formatted into data matrices.

Concatenating The series of rainfall rate data matrices of a day are to be concatenated to form a single data matrix.

Exporting The data matrix produced in the previous step is to be exported into a data file for future applications.

The algorithms of each of these stages are to be explained separately as follows.

(a) Reading

At this stage, the PPI images are read into the program in time sequences controlled by a simple loop statement. Since the most informative portion of these PPI rain images is the 598×598 pixels RADAR map as shown in Figure 20, it is firstly cropped from the image and converted into a 598×598 matrix.

Figure 20. RADAR rain map cropped from PPI image

As discussed in Chapter 3, the “de-quantization” of the color-coded rainfall rate data in the PPI images is carried out by picking the mean value of each level to be the representative rainfall rate which is related to the corresponding color in the map. The color codes in the RADAR rain maps can be interpreted to the actual rainfall rate through the lookup table in Table 2.

(b) Concatenating

After the rainfall rate data is recovered from the PPI images, they are ready to be concatenated to form a three dimensional matrix which contains the complete set of rainfall rate data for the day. As described before, the size of the rainfall rate map is 598×598 . Therefore, the dimensions of the matrix are $598 \times 598 \times N$, where N represents the number of PPI images available in the day. The value of N in a typical day is around 340 images.

(c) Exporting

In this step, the data matrix is stored into a data file in HDF format for further usages. HDF stands for Hierarchical Data Format and has a standard .hdf extension for all the data files generated in this format. It is a multi-object file format which provides a convenient way of sharing scientific data in a distributed environment. It is platform-independent and can be recognized and properly interpreted by most of the program development platforms. The choice of this data format in this program is because IDL provides a collection of convenient macros in HDF data compression, storage and recovery. Therefore, the output data file with this format consumes the optimal storage space and moreover, can be recovered with virtually no extra time cost.

The completed program flow of the subroutine “*Preprocessing*” is summarized in the flowchart depicted in Figure 21.

Figure 21. Flowchart of preprocessing

4.1.2 Simulation

This subroutine mainly deals with the retrieval of the data produced by preprocessing and the implementation of simulations according to the user demand. The program is capable of implementing simulations on two subjects: (i) the characteristics of the rainfall rate (R) at a certain location, and (ii) the path rain attenuation (A) along a terrestrial communication link. Similar to the module of preprocessing, the basic functional modules of the simulation program also operate on daily basis. To implement a longer term (monthly or annual) analysis, the diurnal

rainfall rate or rain attenuation data is concatenated to form the monthly or annual database, which is then processed to produce the corresponding long term statistics.

Simulation for Point Rainfall Rate

The main purpose of simulating the point rainfall rate is to obtain the information about either the short-term (instantaneous) or long-term (cumulative) characteristics of the rainfall at a certain location. The instantaneous rainfall rate shows the variation of rain intensity against time. It is incorporated in the diurnal analysis of the point rainfall rate of the program because it reveals the characteristics of precipitation in different parts of a day. This analysis is significant because nowadays, many communication services have a fluctuating demand during a day. For instance, the designer of the digital TV broadcasting services requires the knowledge of the characteristics of the diurnal variations of the rainfall rate and rain attenuation so as to avoid degradation of the quality of services at the peak hours. Since the instantaneous information of rain is not as significant for a longer time span as for a day, this analysis is not included in the monthly and yearly simulations. An example of instantaneous rainfall rate plot is depicted in Figure 22, which shows the variation of rainfall rate along a day with a heavy rain event in the afternoon.

Figure 22. Plot of instantaneous rainfall rate

The cumulative characteristics of the rainfall rate, on the other hand, reveal the long-term trend of the rainfall rate at the spot. The commonly used figure that describes this property is the cumulative distribution function (CDF) of the rainfall rate. It is defined as the probability function within a certain time span, when a threshold value (in this case, the rainfall rate R) is exceeded:

$$F(R) = P(r \geq R) = \frac{t_{exc}}{T_{total}} \quad (4.1)$$

where P represents the probability function. t_{exc} refers to the amount of time (in minutes) when the point rainfall rate is higher than R , while T_{total} is the total amount of time (e.g. T_{total} equals to 1440 for a day and $1440 \times 365 = 525600$ for a non-leap year, etc). This concept can be illustrated by Figure 23.

Figure 23. Calculation for cumulative distribution functions

As shown in Figure 23, a heavy rain event appears in the afternoon of Feb, 14th, 2000. The amount of time when the rainfall rate exceeded a 100 mm/hr threshold in the day can be determined from the graph as $t_{exc} = 6$ (mins). Therefore, the probability of rainfall rate exceeded 100 mm/hr is determined as:

$$F(100) = \frac{6}{1440} = 0.417\%$$

Similar procedure is carried out for other rainfall rate values and the CDF can then be generated.

The program module developed for the simulation on point rainfall rate works in a few steps:

(1) Data Acquisition

The first step is to retrieve the preprocessed rainfall rate database. The data file generated from preprocessing is loaded and the data stored in the file is restored. Then the subset of rainfall rate data at the specific location is extracted.

(2) Interpolation

As described in the earlier chapters, the time interval between two successive PPI data is around 4 minutes. However, most rain attenuation prediction models (e.g. the ITU-R model) require the rain database with one-minute integration time. Therefore, the rainfall rates within the 4 minutes void need to be predicted from the available data. This is done through a simple linear interpolation in the program. This process is described by the graph in Figure 24.

Figure 24. Illustration of linear interpolation

As illustrated in Figure 24, the RADAR system samples a rain event at the 0th, 4th, 8th, 12th and the 16th minute. In order to predict the rainfall rate in between two

successive readings, straight lines are drawn to connect the available rainfall rates. Then rain intensity can be interpolated from these lines. Therefore, a continuous one-minute rainfall rate database is predicted from the discrete PPI database through the linear interpolation.

(3) Calculation

After the linear interpolation, the CDF of the rainfall rate at the location is calculated through Equation (4.1) stated before. The plot of the cumulative rain distribution function in a typical year is depicted in Figure 25.

Figure 25. Plot of cumulative distribution function of rainfall rate

(4) Output File Generation

The final stage of the program is to visualize the simulation results through a pop up window, and the selected results are exported into output files according to user's demand.

The completed cycle of the program flow of this module is depicted in Figure 26.

Figure 26. Flowchart of simulation for point rainfall rate

Simulation for Path Rain Attenuation

The motivation behind the simulation for path rain attenuation is quite similar to that of the point rainfall rate, except that the objective is to obtain the statistics of the collective rain attenuation along a sequence of points instead of the rainfall rate at a single point. The rain attenuation is predicted from the rainfall rate data by utilizing the ITU-R model described in Section 2.3. The basic assumption behind this prediction is that the each pixel along the link is treated as a rain cell with uniform rainfall rate. Therefore, the specific rain attenuation at the i^{th} pixel can be calculated as,

$$\gamma_i = k \cdot R_i^\alpha \quad (4.2)$$

where R_i is the rainfall rate at the pixel, and coefficients k and α are frequency dependent factors. The total rain attenuation along the path can then be calculated as:

$$A = \sum_1^n \gamma_i \cdot l \quad (4.3)$$

where n is the total number of pixels along the path. The l in the equation represents the distance the signal has traveled within the pixel. In this program, this distance is adaptively determined by the azimuth angle (α) of the link with respect to the side lines of the pixel, chosen such that $\alpha \leq 45^\circ$. It is calculated by,

$$l = \frac{L}{\cos \alpha} \quad (4.4)$$

where L represents the length of the side lines of each pixel, which is 234 meters in the PPI rain maps. This can be illustrated graphically by Figure 27 below.

Figure 27. Determine the path length

As shown in Figure 27, four communication links are established from pixel *A* to four other pixels in the map. Links *A-B1* and *A-B4* aligned in the east-west and north-south directions, which yield 0° and 90° azimuth angles. Therefore, the path lengths of these two links in each pixel are taken to be $l_{A-B1} = l_{A-B4} = L = 234\text{m}$. The link *A-B3* aligns in the diagonal direction, with an azimuth angle of 45°. Hence, the path length in each pixel is set to be the diagonal distance of the pixel, which is $l_{A-B3} = 331\text{m}$. The case of link *A-B2* is slightly complicated because the same segment of communication link sometimes passes through two adjacent pixels (as illustrated in Figure 28). In this case the program will pick the rainfall rate value from the pixel which contains longer portion of the length, and it is assumed that the whole segment of path length passes through the pixel.

Figure 28. Path length with other azimuth angles

The structure of the program module for rain attenuation simulation is quite similar to that of the point rainfall rate. Some additional modules are incorporated to estimate rain attenuation from rainfall rate through the algorithm stated above. The flowchart of this program is depicted in Figure 29.

Figure 29. Flowchart of simulation for path rain attenuation

For the ease of the user to work with the program modules developed, Graphic User Interfaces (GUI) were generated to interact with the users and collectively control the individual functional program cells. The user manuals of these GUIs are included in

Appendix A of the report, which provide the hands-on guides to the detailed operations of them.

4.2 Application of the 2D Rainfall Rate model

As described previously, a variety of applications in the research and commercial fields are expectable from a well developed 2-dimensional rainfall rate model. In the following a few sections, investigations on the characteristics of point rainfall rate and path rain attenuation in Singapore are to be implemented by means of the 2D model developed, and the sample results are analyzed and commented.

4.2.1 Simulation on Point Rainfall Rate

The high intense rainfall can severely affect the availability of the wireless communication systems operating in high frequency bands. Therefore, a comprehensive understanding of the rain characteristics (e.g. rainfall rate, drop size distribution, etc.) is of great importance in the predictions of the rain attenuation along communication links. This is especially true for countries like Singapore, where heavy rainfall event occurs very often through out the year. There are many aspects in the studies of the rain characteristics that researchers normally pay attention to: the rainfall rate, the raindrop size distribution, the amount of rain, etc. The traditional way of obtaining the information of rainfall rate and rain amount is through the rain gauge networks, which normally requires a large amount of labor, equipment and time. On the other hand, with the 2-dimensional rainfall rate model developed, these statistics can be easily acquired through computer simulation. In this section, the rain statistics at several locations in Singapore are to be simulated, and the variation of yearly, monthly and daily rain characteristics are to be analyzed from the simulation results. The RADAR PPI rain data utilized in the study covers the completed twelve months of the year 2000. Therefore, all the analysis and conclusion drawn in the section are stuck to this period.

The statistics of the point rainfall rate are simulated at 5 representative locations in Singapore. The first site located at the Main Lecture Theater (MLT, site A) in the campus of Nanyang Technological University (NTU); while the other four sites refer to the four satellite earth stations of the Singapore Telecom (SingTel), namely the Bukit Timah (BT, site B), Sentosa (SEN, site C), Seletar (SEL, site D) and Tampines Telepark (TAM, site E). These five locations are highlighted in an outlined map of Singapore in Figure 30.

Figure 30. Five representative sites in Singapore

(1) Yearly Distribution of Point Rainfall Rate

The simulated rainfall rate data at the five sites were processed to produce the yearly cumulative distributions functions of the rainfall rates. These distributions are plotted in the semi-log paper in Figure 31. Also presented is the rainfall rate distribution of the rain climate zone P designated to Singapore by CCIR.

Figure 31. Yearly distribution of rainfall rates at five sites in Singapore

It is observed in the plots that at most of times the rainfall rate distributions around Singapore are below the value specified by CCIR (except for the sites Bukit Timah and Sentosa in the interval of 0.05% to 0.3% of times). This implies that the designated zone P tends to over-estimate the rainfall rates of the local climate in the simulated period. Table 12 shows the rainfall rates at each site with percentages of times of 0.003, 0.01, 0.03, 0.1, 0.3 and 1% exceeded in the year.

Table 12. Yearly distributions at typical percentages of times at five sites in Singapore

% of Time	NTU	BT	SEN	SEL	TAM	CCIR Zone P
0.003	137.96	158.56	158.56	126.69	95.80	200
0.01	115.46	118.92	117.52	115.46	94.76	145
0.03	94.76	96.01	96.92	94.76	76.57	105
0.1	57.43	71.41	71.41	63.69	55.92	65
0.3	23.35	31.53	35.77	32.69	29.64	34
1	8.20	8.78	11.02	9.14	9.40	12

In a recent modification of the ITU-R recommendation P837-4 [70], the rain rates exceeded for 0.01% of the average year over the world is given in a global precipitation map. The value designated to Singapore is 120 mm/hr, which is quite closed to the simulation results at most site except Tampines. This brings certain level of confidence on the reliability of the simulation scheme.

Also observed from the simulation results is that the heavy rain events occurred more frequently at the sites Bukit Timah and Sentosa (central and southern Singapore, respectively) in the simulated period. The lowest distribution, in contrast, occurs at the site Tampines, which is located at the eastern portion of the territory. This variation of rain characteristics from site to site suggests that the site diversity technology might be feasible in the country to combat the excessive rain attenuation along communication links. This technology is to be investigated in depth in a later section (Section 4.2.4) of this chapter.

It is noted that the rainfall rate distribution at the site Tampines falls far below its counterparts at the other four sites, which is seemingly suspicious. By the completion of this thesis, the author is still collaborating with the MSS to find out the origins of this discrepancy. One possible explanation for this phenomenon is the “clutter effect” of the weather RADAR systems. Clutter refers to the RF echoes returned from targets which are by definition not of interest to the RADAR operators. In the case of the weather RADAR system, these faulty echoes normally refer to the reflection from natural or man-made objects such as ground, hill, sea and buildings, etc. The clutter effect is especially significant for the blockages close to the antenna of the RADAR. This is because for the low elevation scans of the RADAR system, even low altitude objects may cause faulty echoes when they are close to the antenna of the RADAR. This effect can be illustrated graphically as shown in Figure 32.

Figure 32. The clutter effect

The clutter effect can be overcome by superimposing a ground map of the surrounding of RADAR antenna (clutter map) to the reflections, and eliminating all echoes appear to originate from the ground blockages. This process tends to

deemphasize the reflections from the near-antenna region and therefore, may cause the underestimation of the precipitation in the region. Since the Tampines site in the study is much closer to the antenna of the Doppler RADAR system (approx. 3 km) than the other sites, its rain distributions are more vulnerable to the clutter effect. A possible solution for this problem is to place an auxiliary RADAR in distance to the main RADAR system such that an alternative reading can be provided in the region which is prone to clutter effect.

(2) Seasonal Variation of Rainfall Rate

It is reported that the characteristics of rainfall in Singapore normally experiences significant variation in different months of a year. The annual climate change in the country follows a clear monsoonal pattern. The Northeast Monsoon dominates the country from around December to March, followed by a short inter-monsoon season in April and May. Then the Southwest Monsoon starts from around June and lasts for about four months until September. A similar inter-monsoon period prevails for around two months before the next Northeast Monsoon season. There are no obvious dry or wet seasons in Singapore, and rainfall is abundant throughout the year. The MSS has summarized the general characteristics of the rainfall in these four seasons in the Table 13.

Table 13. Monsoon seasons in Singapore

Season	Northeast Monsoon	Pre Southwest Monsoon	Southwest Monsoon	Pre Northeast Monsoon
Months	Dec – Mar	Apr – May	Jun – Sep	Oct – Nov
Wind	Northeast	Light and Variable	Southwest/Southeast	Light and Variable
Rain Character	Frequent afternoon showers in Dec and Jan. Spells of widespread moderate to heavy rain occur and last for 1 to 3 days at a stretch. Relatively drier in Feb till early Mar	Afternoon and early evening showers often with thunder	Isolated to scattered late morning and early afternoon showers. Early morning “Sumatra” line squalls are common.	Scattered shower with thunder in the late afternoon and early evening.

The monthly pattern of rainfall suggested by MSS is justified by the simulation results from the 2D model. The simulated rainfall rate data is analyzed in monthly basis at the five sites. It is observed that the rain statistics varies a lot from month to month, and different sites have different high rain rate months in the simulated period. These high rainfall months are summarized in Table 14.

Table 14. High rainfall rate months at five sites in Singapore

Sites	High Rainfall Rate Months
NTU	Feb, Jun
Bukit Timah	Feb, Apr
Sentosa	Apr, Oct
Seletar	May
Tampines	Feb, Oct

It is observed that heavy rainfall prevails most of the parts of Singapore in the months of February, April and October. Moreover, most high intensity rains occurred at the transition periods (Apr, Jun, Oct, etc.) between seasons. Therefore, these months which often experience heavy rainfalls are picked as the representative of the four seasons and compared in the subplots of Figure 33. The rain distributions at the five sites around Singapore in the same season are also cross compared in the graphs depicted in Figure 34. As illustrated in the plots, during the Northeast Monsoon (Dec to Mar), heavy rainfall appears quite often over the central and western parts of Singapore. The Southwest Monsoon season (Jun to Sep), on the other hand, causes excessive rainfall in the western and southern portion of the territory. In the Pre-Southwest Monsoon season (Apr to May), heavy rainfall prevails the central and southern areas of the country. In contrast, the Pre-Northeast monsoon season is relatively dry, which casts heavy rainfall only in the south of Singapore. Since only one year's data was analyzed, these observations still require further verification with databases with longer time span.

(a) NTU

(b) Bukit Timah

(c) Sentosa

(d) Seletar

(e) Tampines

Figure 33. Seasonal Variation of rain distribution in Singapore

(a) Northeast Monsoon Season

(b) Pre-Southwest Monsoon Season

(c) Southwest Monsoon Season

(d) Pre-Northeast Monsoon Season

Figure 34. Comparison of rain distributions in each season at five sites

(3) Diurnal Variations of Rainfall Rate

As stated before, the diurnal characteristics of rainfall rate are essential for the design of communications systems with a fluctuating demand with different times of a day. To study the diurnal variation of the rainfall rate in Singapore, the total number of minutes when heavy rainfall ($\geq 50\text{mm/hr}$, which causes more than 5 dB/km of specific attenuation to Ka-band signal) occurred within each of the 24 hours in a day is obtained and accumulated throughout the year. The diurnal variation of the high rainfall minutes in the hours are then averaged among the five sites and plotted in a bar chart in Figure 35. The results for the individual sites are depicted in the subplots in Figure 36. In these figures, the x-axis shows the 24 hours within a day, while the y-axis depicts the total number of minutes with heavy rainfall within the corresponding hour of the day. It is observed that most of the heavy rainfall occurred in the daytime (from 6 am to 6 pm). Moreover, the afternoon (1 pm. to 6 pm.) tends to be more prone to serious rain attenuation caused by heavy rainfall than any other times of the day. The numbers of minutes with heavy rainfall in this period are above 60 minutes,

which correspond to 0.011 % of time in the year. The peak hour for high intensity rains is 3 pm. in the afternoon, which experienced 111.6 minutes (0.021 % of time in the year) of heavy rainfall.

Figure 35. Averaged number of minutes with heavy rainfall in each hour

(a) NTU

(b) Bukit Timah

(c) Sentosa

(d) Seletar

(e) Tampines

Figure 36. Number of minutes with heavy rainfall in each hour at five sites in Singapore

Further investigation reveals that the diurnal pattern of heavy rainfall also changes with different seasons of the year. The high rainfall rate minutes in the four seasons are averaged among the five sites and plotted in the subplots in Figure 37, while the detailed plots for each of the five sites are presented in Appendix B. It is evident that the seasonal change of the diurnal rain characteristics agrees reasonably well with the general description stated in Table 13 by the MSS. According to the simulation results, the seasonal trend of the diurnal variation of rainfall can be summarized as in Table 15.

Table 15. Peak hours of heavy rainfall in different seasons

Season	Month	Period of heavy rainfall	Peak Hour/No. of Minutes
Northeast Monsoon	Dec to Mar	2 pm. to 6 pm	3 pm. / 71.8 mins (0.041% of time)
Pre Southwest Monsoon	Apr to May	7 am. to 4 pm.	4 pm. / 24.8 mins (0.028% of time)
Southwest Monsoon	Jun to Sep	5 am. to 9 am. & 1pm. to 6 pm.	8 am. / 31.6 mins (0.018% of time)
Pre Northeast Monsoon	Oct to Nov	1 pm. to 6 pm.	2 pm. / 28.8mins (0.033% of time)

(a) Northeast Monsoon Season

(b) Pre-Southwest Monsoon Season

(c) Southwest Monsoon Season

(d) Pre-Northeast Monsoon Season

Figure 37. Number of minutes with heavy rainfall in each hour in different seasons

4.2.2 Simulation on Path Rain Attenuation

The simulations for the path rain attenuation are carried out at the same five sites studied in the pervious section. At each site, the statistics of rain attenuation are obtained along four representative communication links (5 km each) to the four geometrical directions around the spot. The test links operate with a frequency of 11 GHz (Ku-band) and horizontal polarization. Figure 38 depicts the schematic description of the simulation scheme at the sites.

Figure 38. Scheme of simulation on terrestrial path rain attenuation

(1) Yearly Distribution of Rain Attenuation

The yearly distributions of the four paths around each site are plotted in semi-log graphs presented in Figure 39. Also presented in the figures are the rain attenuation distributions predicted from the ITU-R model described in Section 2.3. The $R_{0.01}$ utilized in the ITU-R predictions is the actual rainfall rate exceeded for 0.01% of times at the corresponding sites (Table 12).

(a) NTU

(b) Bukit Timah

(c) Sentosa

(d) Seletar

(e) Tampines

Figure 39. Yearly distributions of rain attenuation at five sites in Singapore

As illustrated in the plots in Figure 39, remarkable variations of distributions are observed in the rain attenuation along different directions at each site. This variation is especially significant at the sites of Bukit Timah and Tampines. The yearly distributions diverge a lot at the lower percentages of times, implying that the rain attenuation around these sites varied significantly in the simulated period. This divergence is probably due to the sizes of the rain cells are relatively small compared with the length (5 km) of the paths simulated. Extremely low attenuation was experienced along the Path 2 (East path) at the site Tampines. The distribution of rain attenuations in this link falls far below its counterparts in the other directions. As described in the part (1) in Section 4.2.1, since this link points to the direction of the RADAR antenna, this phenomena may also due to the clutter removal process of the RADAR system.

It is also observed that, except for the path 2 at the Tampines site, the predicted rain attenuation distributions fall below the simulated statistics at most of the percentage of times. The predicted and simulated rain attenuations exceeded for 0.01% of time in

the year are listed in Table 16. It is noted that the predicted $A_{0.01}$ from the ITU-R model is lower than the simulated in most of the situations, implying that the ITU-R model underestimate the effect of the rain attenuation in the local climate. This phenomenon is to be investigated and elaborated in details in a later section (Section 4.2.3).

Table 16. Comparison between simulated and predicted $A_{0.01}$

	NTU	Bukit Timah	Sentosa	Seletar	Tampines
Path 1	17.70	17.83	18.86	17.08	15.94
Path 2	17.35	16.08	19.51	19.66	7.94
Path 3	16.78	21.76	18.11	18.83	15.34
Path 4	17.19	22.10	16.28	17.06	18.15
Predicted	15.96	16.56	16.32	15.96	12.87

(2) Seasonal Variation of Rain Attenuation

Similar to the observations in the monthly trend of point rainfall rate, rain attenuation along the same link also experiences great variation in different months of the year. The highest and lowest (at 0.01% of time in the year) rain attenuation months are obtained and summarized in Table 17. Note that the “High” and “Low” tags in the table stand for the months experienced the highest and lowest rain attenuation at 0.01% of time in the year, correspondingly.

Table 17. Months with the highest and lowest rain attenuations

	NTU		Bukit Timah		Sentosa		Seletar		Tampines	
	High	Low	High	Low	High	Low	High	Low	High	Low
path1	Mar	Dec	Feb	Jan	Apr	Jul	Feb	Dec	Feb	Sep
path2	Oct	Dec	Feb	Jan	Oct	Sep	Oct	Nov	Dec	Nov
path3	Oct	May	Oct	May	Oct	Jan	Mar	Dec	Oct	Sep
path4	Oct	Dec	Oct	Jan	Apr	Jul	Feb	Dec	Apr	Sep

The findings listed in Table 17 agree well with the trend of high rainfall rate months observed in the analysis of seasonal rainfall rate characteristics. Therefore, the same four representative months are picked in each season and their distributions in the four paths at site NTU are plotted in Figure 40. Similar plots of the other four sites are included in the Appendix C. It is observed that severe rain attenuation occurred more frequently in the months of February, April and October than in other months around Singapore.

(a) Northwards path

(b) Eastwards path

(c) Southwards path

(d) Westwards path

Figure 40. Seasonal Variation of rain attenuation along the four paths around NTU

(3) Diurnal Variation of Rain Attenuation

The general pattern of the diurnal variation of the rain attenuation along communication links in Singapore is synthesized from the simulation results at the five sites. At each site, the averaged number of minutes of excessive rain attenuation (≥ 15 dB, corresponding to the $A_{0.01}$ predicted from the ITU-R model) in each hour was obtained among the four links simulated. Then the mean value of the high attenuation minutes of the five sites was utilized in the analysis of the trend of change of the rain attenuation with different hours of a day. The average number of minutes in each hour when high attenuation was experienced in the year 2000 is plotted in a bar chart depicted in Figure 41.

Figure 41. Averaged number of minutes with severe rain attenuation in each hour

As illustrated in the chart, high rain attenuation events occurred more often in the afternoon (1pm to 5pm) than any other periods of the day. The peak hour appears to be 3pm, when an average of 24.6 minutes of excessive rain attenuation was experienced. The rain attenuation in different seasons of the year also showed distinctive patterns. Figure 42 presents the high rain attenuation minutes in each hour in the four seasons in Singapore. The seasonal characteristics of diurnal variations of rain attenuation are summarized in Table 18. It is noted that the peak hours of rain attenuation coincide with that of the point rainfall rates (Section 4.3.1 part (3)), affirming the high correlation between heavy rainfalls and excessive rain attenuations.

Table 18. Peak hours with excessive rain attenuation in different seasons

Season	Month	Period of excessive attenuation	Peak Hour/No. of Minutes
Northeast Monsoon	Dec to Mar	3 pm. to 5 pm	3 pm. / 18.6 mins (0.011% of time)
Pre Southwest Monsoon	Apr to May	3 am. to 4 pm.	3 am. / 4.8 mins (0.005% of time)
Southwest Monsoon	Jun to Sep	4 am. to 9 am. & 1pm. to 6 pm.	8 am. / 4.0 mins (0.002% of time)
Pre Northeast Monsoon	Oct to Nov	1 pm. to 2 pm.	1 pm. / 10.2mins (0.012% of time)

(a) Northeast Monsoon Season

(b) Pre-Southwest Monsoon Season

(c) Southwest Monsoon Season

(d) Pre-Northeast Monsoon Season

Figure 42. Number of minutes with severe rain attenuation in each hour in different seasons

4.2.3 Path Reduction Factor

The observations in analysis of yearly distributions of rain attenuation suggested that the ITU-R model tends to underestimate the effect of rain attenuation in the local climate. The predicted $A_{0.01}$ falls below the simulation results in most of the cases. Therefore, in order to amend the model to fit the local conditions, a collection of simulations on the path rain attenuation were carried out at the five sites adopted previously. The variation of the path reduction factor ($r_{0.01}$) is studied from the simulation results. At each site, the simulation of path rain attenuation is implemented

with eight path lengths in each of the four directions. The working frequency is 11 GHz (Ku-band) with horizontal polarization. The simulation scheme is summarized in Table 19.

Table 19. Summary of simulation on path reduction factor

Sites	NTU, Bukit Timah, Sentosa, Seletar, Tampines
Path Lengths (km)	2, 5, 8, 10, 12, 15, 18, 20
Frequency (GHz)	11
Polarization	Horizontal

With the simulated yearly distributions of rain attenuation at each site, the simulated path reduction factor ($r_{0.01sim}$) can be calculated from a variation of the ITU-R model (Equation (2.24)) stated in Section 2.3:

$$r_{0.01sim} = \frac{A_{0.01sim}}{k \cdot R_{0.01}^{\alpha} \cdot L} \tag{4.5}$$

The simulated path reduction factors are averaged over the four paths at each site and compared with its counterparts predicted from the ITU-R model ($r_{0.01predicted}$) in Table 20. It is noted that the ITU-R predicted path reduction factor is invariant with the rain statistics ($R_{0.01}$) when $R_{0.01}$ exceeds 100 mm/hr. Therefore, the rainfall rate statistic ($R_{0.01}$) utilized in the predictions is set to 100 mm/hr. This is reasonable because the simulated $R_{0.01}$ exceeds 100 mm/hr at four out of five sites in Singapore, except for Tampines (94.8 mm/hr).

Table 20. Comparison between predicted and simulated path reduction factors

L (km)	$r_{0.01predict}$	$r_{0.01sim}$				
		NTU	BT	SEN	SEL	TAM
2	0.788	0.780	0.833	0.654	0.752	0.788
5	0.603	0.651	0.707	0.672	0.686	0.692
8	0.495	0.597	0.621	0.636	0.611	0.670
10	0.437	0.563	0.585	0.603	0.557	0.646
12	0.391	0.524	0.556	0.560	0.523	0.619
15	0.343	0.501	0.513	0.511	0.487	0.583
18	0.302	0.465	0.467	0.478	0.459	0.541
20	0.279	0.445	0.438	0.459	0.438	0.510

The simulated path reduction factors at the five sites are then averaged and compared with the predictions from the ITU-R model in Figure 43.

Figure 43. Variation of path reduction factor with distance

The above results showed obvious discrepancies between the predicted and simulated path reduction factors. The differences are smaller in the short range links and tend to be enlarged with the growth in path lengths. At most of times the prediction from the ITU-R model falls below the simulation results, implying that this model underestimates the seriousness of the attenuation by rain in the communication links in Singapore. Therefore, a few possible amendments to the ITU-R model are proposed to fit the local climate. These methods are to be explained separately in the following sections.

(1) The direct approach (Linear Approach)

In this approach, the direct relationship between the simulated and the predicted path reduction factors are firstly analyzed. The ratio between the simulated and predicted path reductions factors ($r_{0.01sim}/r_{0.01theory}$) are calculated at the simulated path lengths and plotted in Figure 44.

Figure 44. Ratio between simulated and predicted path reduction factors

It is observed that the curve showed clear linearity over the simulated path lengths. Therefore, a multiple, which increases proportionally with the path length, to the original ITU-R model is inspired by this characteristic. The modified model takes the general form of:

$$r = \frac{aL + b}{1 + L/L_0} \quad (4.6)$$

where a and b are coefficients to be determined from the empirical results. Linear curve fitting was carried out and the resultant coefficients are obtained as $a = 0.037$ and $b = 0.948$. Therefore, the ITU-R model of $r_{0.01}$ can be modified as:

$$r = \frac{0.037L + 0.948}{1 + L/L_0} \quad (4.7)$$

The predicted path reduction factors with the modified model are again compared with the actual simulation results in Figures 45, while the prediction errors ($E_{predict}$) are calculated and listed in Table 21. Also presented are the relative errors ($E_{relative}$) of the prediction, which is calculated by:

$$E_{relative} = \frac{E_{prediction}}{r_{0.01sim}} \times 100\%$$

(4.8)

Figure 45. Re-predicted $r_{0.01}$ with the linear approach

Table 21. Prediction error of the linear approach

L (km)	2	5	8	10	12	15	18	20
$r_{0.01predict}$	0.807	0.685	0.614	0.576	0.545	0.513	0.487	0.471
$r_{0.01sim}$	0.761	0.682	0.627	0.591	0.556	0.519	0.482	0.458
$E_{prediction}$	0.046	0.003	-0.013	-0.015	-0.011	-0.006	0.005	0.013
$E_{relative} (\%)$	6.1	0.5	-2.0	-2.6	-2.0	-1.1	0.9	2.9

It is observed that most of the relative errors are within the 3% error bound. Moreover, the modified model works better in the long path length links than in the short range communication links.

(2) The indirect Approach (Exponential Approach)

The key idea of this indirect approach is to modify the path length L before it is employed in the ITU-R model. The general form of this model is basically a variation of the ITU-R model taking the form:

$$r = \frac{1}{1 + L^a / L_0} \quad (4.9)$$

In a work of Ong et al. [40], the exponent a was suggested to be 0.9 in Singapore. In our study, this factor is obtained by:

$$a = \frac{\log(L')}{\log(L)} \quad (4.10)$$

Where L' refers to the simulated path length calculated from the simulated $r_{0.01sim}$ by:

$$L' = \left(\frac{1}{r_{0.01sim}} - 1 \right) \times L_0 \quad (4.11)$$

The variation of a against path length are depicted in Figure 46.

Figure 46. Variation of a with path length

It is evident that the factor a varies significantly at the short range region while it tends to stabilize at distances longer than around 8km. Therefore, the average value of a in the range of path lengths from 8 km to 20 km is used in the amended ITU-R model, which is given by:

$$r = \frac{1}{1 + \frac{L^{0.7351}}{L_0}} \tag{4.12}$$

The re-predicted path reduction factors are then compared with the simulation results in Figure 47. The prediction errors are again listed in Table 22 together with the relative prediction errors.

Figure 47. Re-predicted $r_{0.01}$ with the exponential approach

Table 22. Prediction error of the exponential approach

L (km)	2	5	8	10	12	15	18	20
$r_{0.01\text{predict}}$	0.819	0.701	0.630	0.588	0.554	0.516	0.482	0.462
$r_{0.01\text{sim}}$	0.761	0.682	0.627	0.591	0.556	0.519	0.482	0.458
$E_{\text{prediction}}$	0.058	0.019	0.003	-0.003	-0.002	-0.003	0	0.004
$E_{\text{relative}} (\%)$	7.5	2.8	0.4	-0.4	-0.4	-0.5	0	0.9

It is clear that this approach works quite well in the long distance communication links than in the short range links. Similar to that of the direct approach, the relative prediction errors are well bounded by the $\pm 3\%$ error bounds. The overall performance of this approach is better than the direct method.

Although in general both of the two methods worked quite well with the database of year 2000, significant variations of the simulated path reduction factors are still observed from site to site. Therefore, more simulations at different sites on the territory are still required to reveal the spatial characteristics of the method. Moreover, although the ITU-R model suggests that the prediction of $r_{0.01}$ is invariant with frequency of the link, some preliminary simulations had shown remarkable difference between path reduction factors in difference frequency bands. Hence, future investigation on this topic is recommended.

4.2.4 Site Diversity

A site diversity system, as described in Section 2.4, normally requires diversity earth stations to be sufficiently far apart so as to achieve best performance (in terms of diversity gain). Therefore, the feasibility of this technique in countries with quite limited terrestrial extent, such as Singapore, is always questionable. The simulation results in the previous sections, on the other hand, had shown great variation of yearly and monthly distribution of both rainfall rate and rain attenuation among different sites in Singapore. Therefore, simulations are carried out to study the merit of site diversity in the local climate by means of the 2D rainfall rate model developed, and the applicability of the technique is to be suggested in this section.

One problem associated with the rainfall rate model to be employed in the simulation is that it is 2-dimensional. Therefore, it is capable of simulating the effect of rainfall along any terrestrial Line-of-Sight (LOS) links on the map. In the satellite communication systems, on the other hand, the signal propagates along a slant path. Therefore, to employ the data in the study of the performance of satellite site diversity, we have to simplify the 3-dimensional problem into the 2D space. In this study, the attenuation due to rain is studied along the horizontal projections of the satellite links. The basic assumption behind this simplification is that the rainfall rate is invariant in the vertical direction. Therefore, when the wireless signal propagates through the slant-path, it experiences the same rainfall rate as its horizontal projection passes through the corresponding projection area on the PPI rain map.

The simulations are implemented at the five sites in Singapore in the year 2000 with the center frequency of Ku-band (11 GHz). A simple 2-site diversity system is studied with one station fixed at NTU, i.e. the performances of the diversity systems are evaluated with respect to the non-diversity rain attenuation statistics at NTU. Since Singapore is quite close to the equator, only the two paths with western and eastern extensions are of importance to the GEO satellite systems and therefore studied at each site. The path lengths of the simulated links are 5 km, which mimic the horizontal projection of the earth-space path with 45° of elevation with a typical rain height of 5 km. Table 23 depicts the planning of the simulations implemented.

Table 23. Summary of simulation on site diversity technology

Site	NTU	Bukit Timah	Sentosa	Seletar	Tampines
Latitude (N)	103°40'56"	103°47'5"	103°50'11"	103°50'11"	103°56'32"
Longitude (E)	1°20'33"	1°20'36"	1°14'49"	1°23'46"	1°21'12"
Distance from NTU (km)	--	11.3	20.1	18.1	28.8
Azimuth	90°, 270° (relative to North)				
Path Length (km)	5				
Frequency (GHz)	11 (Ku-band)				
Polarization	Horizontal				

To quantitatively evaluate the performance of the site diversity systems in Singapore, the distribution of combined attenuation in the diversity systems consisting of NTU and each of the other four sites are obtained. These distributions are

compared with the non-diversity systems in the subplots in Figures 48 and 49, corresponding to the two azimuth angles simulated at each site.

(a) NTU-BT System

(b) NTU-SEN System

(c) NTU-SEL System

(d) NTU-TAM System

Figure 48. Cumulative distributions of combined attenuation of the westward links

(a) NTU-BT System

(b) NTU-SEN System

(c) NTU-SEL System

(d) NTU-TAM System

Figure 49. Cumulative distributions of combined attenuation of the eastward links

Tables 24 and 25 list the diversity gains of the diversity system with respect to the non-diversity NTU link at some typical percentages of times in the simulated year.

Table 24. Diversity gain of the westward links at 11GHz

Percentage (%)	0.003	0.01	0.03	0.1
NTU - BT	7.95	9.30	9.45	7.91
NTU - SEN	17.46	11.94	11.16	8.82
NTU - SEL	20.46	15.61	13.83	10.12
NTU - TAM	19.75	16.26	14.98	10.65

Table 25. Diversity gain of the eastward links at 11GHz

Percentage (%)	0.003	0.01	0.03	0.1
NTU - BT	7.99	8.63	11.69	9.05
NTU - SEN	3.80	12.03	13.09	9.53
NTU - SEL	10.31	15.95	15.28	10.63
NTU - TAM	19.33	19.88	17.35	11.55

As illustrated in Figures 48 and 49, outstanding performances of site diversity technique are observed in both the NTU-Seletar (East-North Singapore) and NTU-Tampines (East-West Singapore) systems. Table 24 suggested that among the links pointing to the west (270° azimuth), the best performance is achieved in the NTU-Tampines system, in which for a reliability of 99.9% of time, the required fade margin is brought down to 1.6 dB from 12.2 dB. Similarly, this system also showed great capability in the eastwards (90° azimuth) links, which achieved an 11.55 dB diversity gain for a reliability of 99.9% of time. In this case, a fade margin of only 1.2 dB instead of 12.8 dB is required to sustain the satellite link.

The above results showed that the simple 2-site diversity systems work quite well in Singapore. In most of the situations, at least an 8 dB diversity gain is achievable for a 99.9% of reliability. The best scheme of site allocation is to place one site at the eastern Singapore, while the other at the western part of the territory. The fade margin can be safely reduced to below 2 dB with this scheme.

As a preliminary effort of future study, the similar simulations were carried out again with the working frequency of 18 GHz, which corresponds to the downlink frequency of Ka-band systems. The simulation results revealed the outstanding

capability of the site diversity technology in mitigating severe rain attenuation along the Ka-band links. The diversity gains at some typical percentage of time in the simulated period are listed in Tables 26 and 27. An ideal diversity gain of 18 dB is achievable in most of the cases. Moreover, the best performance of this technique occurs in the NTU-TAM system, which yields the 25.65 dB and 28.34 dB diversity gain, corresponding to the westward and eastward links, for a reliability of 99.9% of times.

Table 26. Diversity gain of the westward links at 18GHz

Percentage (%)	0.003	0.01	0.03	0.1
NTU - BT	16.66	20.58	21.44	18.60
NTU - SEN	38.04	27.10	25.91	20.89
NTU - SEL	44.39	35.47	32.34	24.25
NTU - TAM	43.05	37.29	35.28	25.65

Table 27. Diversity gain of the eastward links at 18GHz

Percentage (%)	0.003	0.01	0.03	0.1
NTU - BT	17.69	18.87	27.05	21.86
NTU - SEN	8.60	26.70	30.32	22.91
NTU - SEL	23.09	35.61	35.57	25.78
NTU - TAM	43.44	45.37	40.93	28.34

4.3 Summary

A 2-dimensional rainfall rate visualization model developed with the calibrated PPI RADAR rain database has been described in this chapter. The algorithms of the model are first introduced, followed by some typical applications of this model in the simulations on point rainfall rates and path rain attenuation with the local rain data.

The simulation results on the statistics of point rainfall rate at five satellite earth stations in Singapore showed that the rain climate zone P designated to Singapore by ITU-R tends to over estimate the intensity of rainfall in the local climate. Moreover, the seasonal pattern of rainfall suggested by MSS is affirmed by the simulation results on the monthly and diurnal variations of point rainfall rates.

The simulations results of several terrestrial wireless communication links around Singapore has shown that the ITU-R prediction model of the path rain attenuation

tends to under estimate the effect of rain on high frequency communication links in Singapore. It is also observed that the pattern of seasonal variation of rain attenuation agrees well with that of the point rainfall rates. Therefore, the high correlation between heavy rainfall and excessive rain attenuations is further affirmed.

The study of path reduction factor in Singapore suggested that the ITU-R prediction model does not fit the locally collected data very well. Therefore, two possible amendments have been suggested. It is observed that these two methods performed reasonably well in most of the cases. However, since the time span of the database utilized in the study is fairly short (12 months), further examination of the long term validation of the methods is recommended.

The performance of site diversity technique in Ku-band satellite communication systems has been simulated with the 2D rain model. The simulation results showed strong capability of this technique in mitigating excessive rain attenuation. The best allocations of diversity sites are also suggested based on the simulation results.

Chapter 5

The 3-Dimensional Rainfall Rate Model

The 2-Dimensional rainfall rate model described in the previous chapter is capable of implementing the simulations of rain attenuation along any terrestrial communication links. However, in the case of satellite communication systems, the simulation has to be carried out through slant paths, which is not feasible for the 2D model developed. Therefore, a 3-dimensional rainfall rate visualization model is of great importance for the studies of the performances of the satellite communication links. Hence, in this study, a 3D rainfall rate model is to be designed and developed. The experiences gained in the development of the 2D model and a lot of functional routines utilized will benefit the works with the 3D model. The model is based on the database of the raw reflectivity from the full-volume scans of the MDWR RADAR system of Singapore. However, since the negotiations with the MSS about purchasing this database are still ongoing by the completion of this thesis, we are still short of a full set of this 3D database except for a few samples of it. Hence, only some preliminary works are possible at this stage. In this chapter, a blueprint of this 3D model is to be plotted and the preliminary works done on it are to be described.

5.1 Database Specifications

The database to be utilized in the development of the 3D model is a set of raw reflectivity data stored in a collection of raw data files produced by the MDWR system of MSS. The operations of the RADAR system are controlled by the IRIS software package produced by SIGMET Inc [71]. According to MSS, the Doppler RADAR system is programmed to operate in two scanning models, namely, the Aerial Mode and the Airport Mode. The Aerial Mode traces the movement of the rain volumes in a large area around Singapore, while the Airport Mode mainly focuses on

the precise rain events over a small area ($40 \times 40 \text{ km}^2$) around the Changi Airport of Singapore. The normal operation of the RADAR system is in the Aerial Mode. The switching from Aerial to Airport Mode is triggered when showers above a certain intensity and size is detected within the $40 \times 40 \text{ km}^2$ region centered at the airport. The Airport Mode is maintained for at least 20 minutes, before switching back to Aerial Mode is applicable. In each scanning mode, the RADAR system implements full-volume scans in loops. The volume scans for both of the two scanning modes are composed of a sequence of tasks (A, B and C) that are carried out in the order specified. Each task contains sweeps of scan around the region at a few elevation angles. The same set of tasks is repeated in the successive scan when switching from mode to mode is not necessary. The actual compositions of elevations angles for each task are different with different scanning modes. The specifications of these tasks are listed in Table 28, while the schematic illustrations of the elevation angles in the full-volume scans in each mode are depicted in Figure 50. Note that in these figures, the number besides each beam represents the elevation angle in degrees.

Table 28. Specifications of scanning modes of MDWR system

Volume Scan Mode	Task Name	File Name Examples	Elevation Angles
<i>Aerial</i>	AERIAL_A	Si1050911171519.ARCT5M1	0.1
	AERIAL_B	Si1050911171519.ARCT5M2	1 1.5
	AERIAL_C	Si1050911171519.ARCT5M3	2 3 5 7.5 10 15 20
<i>Airport</i>	AIRPORT_A	Si1050730120111.ARC8BVM	1.7
	AIRPORT_B	Si1050730120111.ARC8BVN	1 15 1 30
	AIRPORT_C	Si1050730120111.ARC8BVP	1 20 1 40 1 1.5

(a) Aerial Model

(b) Airport Mode

Figure 50. Ranges of scanning of MDWR system

As illustrated in Figure 50, the maximum scanning range possible for the RADAR beams at most of the elevation angles is around 120 km. For the very low elevation scans, the maximum range is extended to as far as 480 km. Since precipitations only exists below certain altitudes, the RADAR reflectivity above the level are of no importance to the meteorology studies. This level is so called the melting layer, below which precipitation forms and falls on to the ground. According to Kozu et. al. [72], this layer exists in the heights ranging from 5 km to 9 km in Singapore. Therefore, the scanning range of RADAR beams with high elevation angles will be truncated. The truncation height is set to 30 km by MSS for the MDWR system. It should be noted that due to the truncation, the horizontal extend of these high elevation sweeps will be reduced to the values shown in the figures.

The sweep at each elevation angle consists of 360 azimuth angles with 1° separation. Therefore, a completed 360° view of the rain events around the RADAR can be provided by each sweep. The speed of the sweep is referred to as the Scan Rate. It is defined as the degrees of azimuth angle the RADAR can cover within one second. For a typical scan rate of 24 deg/sec, a 360° sweep can be completed in 15 seconds. At each azimuth angle, the RADAR sends out pulses of microwave signals and then measures the reflection from the targeted objects (rain, hail or snow for meteorological RADARs). The RADAR alternates between sending and receiving at Pulse Repetition Frequency (PRF), which is either 300 Hz or 1000 Hz for the MDWR system in Singapore. It should be noted that the full scanning range is divided into a number of sections, and the reflected signals are processed in each of these sections, which are normally referred to as bins. The size of these bins are called the bin widths (W). The reflectivity in each bin is digitized and stored in sequence in the data file. The distance from the antenna to the first available bin is called the start range (R). Therefore, the maximum scanning range (D) of the beam is determined as:

$$D = R + W \cdot N \quad (5.1)$$

where N refers to the number of bins in the beam. The range bin geometric is illustrated in Figure 51.

Figure 51. Range bin geometry of meteorological Doppler RADAR system

The specifications of the scanning schemes are summarized in Tables 29 and 30.

Table 29. Scanning scheme of aerial mode

Tasks	Aerial A	Aerial B	Aerial C
Elevation Angle(s)	0.1	1, 1.5	2, 3, 5, 7.5, 10, 15, 20
PRF (Hz)	300	1000	1000
Max Range (km)	480	120	120
Bin Spacing (m)	500	250	250
Scan Rate (deg/sec)	12	12	24
Output Bins	960	480	480
Start Range (km)	0.250	0.125	0.125

Table 30. Scanning scheme of airport mode

Tasks	Airport A	Airport B	Airport C
Elevation Angle(s)	1.7	1, 15, 1, 30	1, 20, 1, 40, 1, 1.5
PRF (Hz)	300	1000	1000
Max Range (km)	240	120	120
Bin Spacing (m)	250	250	250
Scan Rate (deg/sec)	12	24	24
Output Bins	960	480	480
Start Range (km)	0.250	0.125	0.125

The third column in Table 28 shows a few samples of the file names produced by a task of the RADAR. The naming convention of the product follows a fixed format: “Si1YYMMDDHHMM.ARCXXXX” where,

“Si1” – Site name specified by the RADAR operation center

“YY” – Year when the task was implemented

“MM” – Month when the task was implemented

“DD” – Date when the task was implemented

“HH” – Hour when the task was implemented

“MM” – Minute when the task was implemented

“XXXX” – Random letters

The reflectivity data is stored in these data files in a ‘sweep-by-sweep’ basis, meaning that one record in the data files contains the reflectivity collected from the scan at one and only one elevation angle. The detailed organizations of the raw data in the data files are explained in details in [71] from the SIGMAT Inc.

5.2 *A Blueprint of the 3D Rainfall Rate Visualization Model*

Similar to the 2D model described in Chapter 4, the main tasks of this 3D model can be expressed as:

- Extract the reflectivity data stored in the raw data files and convert it to rainfall rates
- Convert the rainfall rate data organized by polar coordination system into a volumetric dataset in 3D Cartesian coordination system.
- Implement the visualization of the 3D data and calculations for rain attenuation along satellite links.

For the ease of visualization and further calculation with the data, this 3D model can be subdivided into two subroutines, namely the *Preprocessing* and *Visualization and Simulation*. The main functionalities of these subroutines are to be explained in the following sections.

5.2.1 **Preprocessing**

This subroutine is in charge of the first two main tasks described above. Its main functionality can be illustrated by a simple chart depicted in Figure 52.

Figure 52. Functionality of preprocessing of the 3D model

As illustrated in the figure, this module starts by reading in the reflectivity data stream stored in the raw data files. The reflectivity data is stored in the data files in 1-byte DBZ data format. DBZ stands for decibel of the reflectivity (Z). Therefore, there are 256 possible values in this database, ranging from 0 to 255. The value of DBZ is interpreted from this unsigned data stream with the formula:

$$dBZ = \frac{N - 64}{2} \quad (5.2)$$

The reflectivity Z can then be calculated from DBZ value with:

$$Z = 10^{DBZ / 10} \quad (5.3)$$

The reflectivity data is then converted into actual rainfall rates by utilizing a proper reflectivity-to-rainfall model (Z - R model). The Z - R model suggested by MSS is:

$$Z = 200R^{1.6} \quad (5.4)$$

where R represents the rainfall rate in mm/hr. Therefore, the rainfall rate can be calculated from the reflectivity by

$$R = \left(\frac{Z}{200} \right)^{0.625} \quad (5.5)$$

As described in the previous section, the raw reflectivity data is stored in the raw data files in a sweep-by-sweep basis. Therefore the converted rain data is organized in a conical data system as illustrated in Figure 53.

Figure 53. Rainfall rate data organized in a conical manner

Each layer in Figure 53 depicts the grid of rain data sampled by the RADAR system at a certain elevation angle. Each elevation contains 360 rays of data corresponding to 360 azimuth angles. The spacing between two adjacent azimuth angels is 1° . Unfortunately, this conical data system is not compatible with most of the commonly used data visualization algorithms, which are more efficient to deal with databases organized in regularly spaced 3-dimensional Cartesian systems as illustrated in Figure 54. Therefore, for the ease of visualization and future usage of the data, conical rain database has to be converted to 3D volumetric system through a 3-dimensional interpolation. The interpolated 3D data matrix is then exported into data files with the same HDF data format described in the chapter of 2D model.

Figure 54. 3-dimensional Cartesian Coordinate system

5.2.2 Visualization and Simulation

This module mainly deals with the visualization of the 3D volumetric rainfall rate data produced in *Preprocessing* and the simulation of point rainfall rate and rain attenuation along slant path communication links. The program flow of this subroutine is illustrated schematically in the chart depicted in Figure 55.

Figure 55. Functionality of visualization and simulation of the 3D model

This subroutine firstly imports the volumetric rainfall rate data from the preprocessed data files, and then implements the visualization of the data in proper views. The visualization should be user friendly such that the perspective of view point and the resolution of the view can be easily adjusted. An example visualization of the volumetric data is presented in Figure 56.

Figure 56. Visualization of volumetric rainfall rate data

The second task of this subroutine is to carry out the simulations of the rain attenuation along the slant-path communication links specified. The functional modules developed for the 2D model can be easily modified and extend to implement these simulations in the 3D environment. Therefore, similar to the 2D model, the simulation results will be depicted in output windows and the selected results will be exported into proper output files.

5.3 *Some Preliminary Works for the 3D Model*

Due to the lack of the full-volume reflectivity data, only some preliminary study has been done on the 3D model by the completion of this thesis. These efforts are mainly devoted to the topics of 3-dimentional data interpolation and visualization. They are to be elaborated in detail in the following a few sections.

5.3.1 **Data Interpolation**

As stated in Section 2.5, the best performances of 3D data visualization are normally achieved when the volumetric data is organized in a regularly gridded 3-dimensional data matrix. Hence, it is an essential step to process the conically organized rainfall rate database to generate the corresponding volumetric data before it can be fed into the visualization routines. This can be done on the IDL platform through an off the shelf linear 3D interpolation routine. In order to verify the accuracy of the interpolation, it is examined with a sample set of full-volume RADAR rain data with sweeps at 7 different elevations, including 1°, 1.5°, 1.7°, 15°, 20°, 30° and 40°. The interpolation is carried out seven times, each with the data from 6 elevation angles, excluding one elevation at a time. Then the left-out sweep of rainfall rates are compared with the interpolated rainfall data at the corresponding coordinates so as to verify the interpolation accuracy. The comparison results are summarized in Table 31. The columns of “Elevation” and “Speed” in the table depict the elevation angles left out and the time (in seconds) consumed, respectively, in each interpolation. The total numbers of data points of the sweep at each elevation angle are listed in the last column. The comparison results between the measured and interpolated rainfall rate

data are presented in the columns under the label “ $\geq N$ ”, in which the numbers of erroneous data points with prediction error greater than the threshold value N (in mm/hr) are listed together with their percentages (denote as *perc*) within the total number of data points.

Table 31. Prediction error of 3D linear interpolation

Elevation	Speed (s)	≥ 200		≥ 100		≥ 50		≥ 10		Total no. of data
		error	Perc (%)	error	Perc (%)	error	Perc (%)	error	Perc (%)	
1	83	3	0.0047	91	0.144	1174	1.858	7384	11.686	63187
1.5	68	1	0.0016	71	0.112	710	1.117	6998	11.013	63545
1.7	58	2	0.0031	47	0.073	568	0.881	7088	10.999	64440
15	86	0	0	26	0.040	292	0.445	2655	4.043	65675
20	83	0	0	15	0.024	202	0.324	2031	3.260	62300
30	81	0	0	0	0	39	0.094	1053	2.528	41650
40	91	0	0	0	0	1	0.003	1095	3.335	32829
Average	79	0.86	0.0013	35.7	0.056	427	0.675	4043	6.695	56232

It is observed in Table 31 that the data points with the extremely high (≥ 200 mm/hr) prediction errors have a very rare occurrence. An average of less than 0.002% in the total data points have this problem. The moderate errors (≥ 50 mm/hr) also had a very low appearance (0.675% in average) in the database. Even in the case of a very low prediction error (≥ 10 mm/hr), the average occurrence is less than 7% within the total set of data. Therefore, it can be concluded that the 3D linear interpolation works quite well with the conversion of the rainfall rate database from conical coordination system to 3D Cartesian coordinates system. However, one problem associated with this technique is the processing speed. The averaged processing time of the experiments is around 80 seconds. Since the total number of full-volume scans implemented by the MDWR system is around 350 per day, it will take approximately 8 hours to process whole day’s rain data. To improve the efficiency of the 3D interpolation, the author has come up with the idea of carrying out the 3-dimensional interpolation “2-dimensionally”. This approach is inspired by the Magnetic Resonance Imaging (MRI) technology widely used in the applications such as the visualization inside living organisms and the detection of the composition of geological structures. This technique “see through” the object and “take pictures” at various layers by placing it under strong magnetic fields and non-ionizing radiations in the radio frequency range. Then the series of images are arranged in sequence and therefore, the volumetric dataset of the object can be interpolated through 2D

interpolations from the images. This approach can be applied in the case of RADAR data interpolation because, the RADAR beams with the same azimuth angles in different elevation sweeps are roughly aligned in the same vertical plane. Hence, the rainfall rates in these beams can be grouped together and utilized to generate a vertical “image” of rain volumes at each azimuth angle. Then a series of horizontal interpolations can be carried out with these 360 vertical slices and thus the 3D volumetric database can be produced. This concept is illustrated by Figure 57.

(a) ‘Vertical Cut’

(b) ‘Horizontal Cut’

Figure 57. 2-dimensional realization of 3D interpolation

As shown in Figure 57, the interpolation starts by performing a series of 2-dimensional interpolations at various azimuth angles. At each ‘vertical cut’, there are N available rays of rainfall rate data, where N is the number of elevation angles sampled in the full-volume scan of the MDWR system. A regular 2-dimensional data matrix is produced from this interpolation. After the ‘vertical cuts’ are successfully performed at each azimuth angle, another series of 2D interpolations are carried out at each height of interest. These ‘horizontal cuts’ utilize the data produced by the ‘vertical cuts’ at the corresponding heights. Therefore, in each ‘horizontal cut’, there are 360 available rays of data. The results from these 2D interpolations are then reorganized into a regularly gridded Cartesian coordinate system. This scheme breaks down the 3D interpolation into a series of 2D interpolations. The performance of this technique examined with the same set of sample data utilized previously is listed in Table 32.

Table 32. Prediction error of 2D realization of the 3D interpolation

Elevation	Speed (s)	≥ 200		≥ 100		≥ 50		≥ 10		Total no. of data
		error	Perc (%)	error	Perc (%)	error	Perc (%)	error	Perc (%)	
1	9.39	3	0.0047	93	0.147	1175	1.860	7337	11.611	63187
1.5	9.36	1	0.0016	72	0.113	694	1.092	7174	11.290	63545
1.7	9.25	0	0	31	0.048	531	0.824	7117	11.044	64440
15	9.28	0	0	26	0.040	283	0.431	2627	4.000	65675
20	9.38	0	0	17	0.027	184	0.295	1976	3.171	62300
30	9.5	0	0	0	0	38	0.091	1043	2.504	41650
40	9.44	0	0	0	0	5	0.015	106	0.323	32829
Average	9.37	0.571	0.0009	34.1	0.054	415.7	0.658	3911.4	6.278	56232

As illustrated in the table, this process can effectively reduce the computational power consumed and reduces processing time to only 12% of that of the direct 3D interpolation, while the prediction accuracy is not sacrificed.

Although the proposed scheme of 2D interpolation showed outstanding performance over the direct 3D interpolation, there was only one sample of data tested. Hence, more experiments ought to be carried out to further verify this technique when the full set of database is ready.

5.3.2 Data Visualization

For the users to be able to easily trace the trend of the movement of the rain volumes and to have a better idea of the characteristics of the rainfall rates around the region, a 3-dimensional data viewer is incorporated into the 3D model to be developed. This viewer should have full support to the normal visualization functions such as animation, rotation, translation and zooming, etc., as would be expected with a 3D data viewer. In IDL, there are a few convenient tools which can be used in the development of this viewer. Since some samples of the 3D volumetric data are already provided, a prototype of this viewer with some simplified features was developed. The usages of these useful IDL data visualization routines are familiarized. In this section, the functionality of this prototype viewer is to be explained.

When the program is first started, a dialog box will be shown as follows:

Figure 58. Volumetric data viewer

Loading Data

The volumetric data is to be loaded by clicking the 'Load' button at the top right corner. The user has to locate from the file-picking window the file containing the 3D data produced by preprocessing:

Figure 59. Locating data file

After the volumetric data is successfully loaded, it is visualized with the default perspective of view in the graph pane.

Figure 60. Default view

Changing the perspective

The view point can be changed by either using mouse control or by the precise control buttons beside the graph pane. The left mouse button controls the rotation of the view with respect to the center of the graph pane. The rotation can be realized by click and hold this button and drag the mouse within the graph pane. Same effect can be achieved by filling in the desired angles of rotation into the two text fields in the 'Rotation Control' areas. Then the rotation is realized by clicking the buttons around the fields which correspond to rotating towards either left/right or up/down.

The right mouse button is in charge of the translation of the view. When this button is held, the view of the data will be translated following the movement of the mouse.

The controls in the 'View Point Control' field provide the shortcuts to some most commonly used view points. Checking the 'Top View' or 'Side View' will directly force the view point to the top or the side of the view, while the 'Reset View' button provides a quite return to the default view.

Changing the Rendering Color

Sometimes the default color table cannot provide the best recognition of the details of the rain volumes. Therefore, some alternatives of predefined color tables are provided in the viewer. These color tables can be accessed by selecting the corresponding entry in the drop box under the tag 'Color Table':

Figure 61. Changing color table

When a new color table is successfully loaded, the rendering color of the data will be changed. The color gradient in the color bar will be changed simultaneously.

Figure 62. View with new color table

Zooming

The zooming of the view is controlled by the zooming slide bar. There are 4 levels of zooming provided by the viewer. Ranging from 0 (outmost, default) to 3 (most detailed). Moving the slide bar toward right has the effect of zooming in to the data, while moving to the left means zoom out. A portion of the data with the highest zooming power is as shown in Figure 63.

Figure 63. Zooming

5.4 Summary

In this chapter, the blueprint of a 3-dimensional rainfall rate visualization model has been described. The main structure of this model has been designed. Some preliminary effort has been devoted to the development of this model, including the proposal of a novel approach in 3-dimensional data interpolation and the development of the prototype of a volumetric data viewer. Plenty of experiences are gained from these efforts, and the knowledge will eventually benefit the successors of project in the development of the actual 3D visualization model. Therefore, there would be a much easier start for them when the full set of reflectivity data is ready.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

In this study, the feasibility of applying the rainfall rate database, which consists of a collection of Plan Position Indicator (PPI) images, in the prediction of rain attenuation, was firstly investigated. Due to the instantaneous and discrete nature of the RADAR data, it should not be directly employed in the commonly adopted attenuation prediction models. Therefore, a simple framework of calibrating the RADAR PPI rain database into its counterparts with one-minute integration time is developed. The calibrated RADAR rain statistics has shown good agreement to that of the desired one-minute database. Moreover, in order to further evaluate the performance of the calibration method, the correlation between the monthly rain amount and the hourly rainfall rate from the two systems were investigated. The finding in these studies shows high consistency between the calibrated rainfall rates and the one-minute rainfall rates. These observations have brought a certain level of confidence to the calibration framework, and therefore, it is proposed that this method be applied in future studies before using the PPI RADAR rain databases.

The PPI RADAR rain database calibrated with the above stated method is then used in the development of a 2-dimensional rainfall rate visualization model. This model has been employed in the simulations of the diurnal, monthly or yearly point rainfall rate and terrestrial path rain attenuation with the available PPI rain database. The simulation result has been analyzed and the observations can be summarized as:

- 1) Simulation conducted at five representative sites in Singapore shows that the yearly rain distributions of the local climate fall below that of the rain

climate zone P designated to Singapore in the ITU-R report, implying that the ITU-R recommendations tend to over estimate the rainfall rate for Singapore. Therefore, the locally collected rain statistics should be utilized in the future analysis. The monthly variations of rain statistics in Singapore agree well with the general descriptions stated by the Meteorological Service of Singapore (MSS), and moreover, the seasonal trend of the climate change in Singapore is affirmed by the observations. This trend has been further emphasized by the finding in the diurnal analysis of rainfall rates. Another promising observation from these analysis falls into the field of spatial variation of rain characteristics in Singapore. The rain distributions within the same period of time show great differences from site to site. This phenomenon suggests that site diversity technique would be feasible in the country.

- 2) Simulations on the terrestrial wireless communications links have been carried out at five sites in Singapore. It is observed that the ITU-R model underestimates the rain attenuation in Singapore. The monthly and diurnal analysis reveals that the variation of attenuation due to rain has a clear seasonal pattern, which agrees well with the observations in the investigations on point rainfall rate. Moreover, the study of spatial variation of diurnal, monthly and yearly statistics suggests the viability of site diversity to mitigate the excessive rain attenuation in Singapore.
- 3) As discrepancies between the prediction and simulation results are observed in the analysis of path rain attenuation, two possible modifications to the ITU-R rain attenuation prediction model are suggested to fit it to the local conditions. The direct approach (linear approach) modifies the model by applying a linear multiplier to the ITU-R prediction model for path reduction factor, while the indirect approach (exponential approach) applies an exponent to the path length to achieve the same goal. It is observed that, in most of the cases, the methods perform reasonably well, and the prediction errors are limited within the $\pm 3\%$ error bounds. Therefore, it can be concluded that both of the two approaches worked well in the Singapore climate, and hence, the methods can be applied in the future studies.

- 4) Performances of the site diversity technique in Ku-band satellite communication systems are studied at various sites in Singapore. Outstanding performances are observed in the simulation results of the simple 2-site diversity systems located at west-north and west-east parts of the country. The fade margins with 99.9% of reliability can be safely brought down to below 2 dB in both systems.

Some efforts have been devoted to the design and development of a 3-dimensional rainfall rate visualization model. The general outline of this 3D model has been proposed. At the completion of this thesis, due to the shortage of raw data from full-volume scans of the RADAR systems, only some preliminary studies are possible. These efforts have been focused on two topics: (1) the 3D data interpolation and (2) the volumetric data visualization. A novel approach of implementing the 3D interpolation with a series of 2D operations has been proposed and tested against the available data. Outstanding performance has been observed. A prototype of volumetric data viewer has also been developed in the IDL programming platform. Plenty of experiences are gained through these efforts, which will guarantee an easier start for the successors of this study.

6.2 Recommendations

Although much work had been done on the study of characteristics of rainfall rate and rain attenuation in Singapore, there are still great portions in this field left uncovered. Therefore, it is recommended that, in the future researches, the following topics to be studied:

- 1) Despite the good fit between the calibrated RADAR rain statistics and its counterparts from the one-minute system, the time span of the databases is too short to reveal the long-term validity of the calibration method proposed. Therefore, it is suggested that the method should be verified with databases that cover a longer period. The study on the monthly variations of calibration ratios is also of great importance that a seasonal protocol could be revealed. Furthermore, the issue of the alignment between the physical map and RADAR map in the PPI images ought to be investigated so as to

ensure a correct match between the actual point of interest and the corresponding pixel in the RADAR map.

- 2) Although the simulations on the point rainfall rate had shed some light on the characteristic of rain in the local climate, there are still plenty of possibilities for the further investigations in the field. One example is to study the applicability of various prediction models (e.g. the Moupfouma model [73]) of yearly rainfall rate distribution in Singapore. Moreover, the effect of integration times on the rainfall rate statistics is another promising topic to be investigated. This study might lead to the frameworks of conversion between the rainfall rates statistics with different integration times [74].
- 3) The proposed modifications to the ITU-R model of path reduction factor had shown good agreement with the simulation results in only the links with relatively long path length. Hence, future works on the topic should be directed to the development of a better estimate of path reduction factor at shorter ranges. The ITU-R model of predicting the attenuation statistics with percentage of times other than 0.01% (Equation 2.25 in Chapter 2) also needs to be examined against local data.
- 4) Due to the limitation of available full-volume RADAR database, the development of the 3D rainfall rate model was restricted to only some preliminary works. Hence, as a natural continuation, it is suggested that the work should be restarted as soon as the full set of data is ready. The simulations carried out with the 2D model can be similarly applied to the 3D space. With this model, the research on performance of various satellite links can be realized through simulations, which will give the researchers great convenience in the studies. Another promising topic related to the full-volume reflectivity database is in the establishment of a more accurate Z-R relationship for the local climate. This effort should be paralleled with the study of DSD characteristics of the country.

Author's Publications

1. **J. Cong**, J. T. Ong and Y. H. Lee, "Relationship between Doppler Radar Data and Point Rainfall Rate," *Proc. Int. Conf. ICICS*, Thailand, Dec. 2005.
2. **J. Cong**, J. T. Ong and Y. H. Lee, "Performance of Site Diversity in Ku- and Ka-band Satellite Communication Systems in Singapore." (In Preparation).

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Appendices

A. User Manual of the 2D Model with GUI

In order to make the program modules of the 2-dimensional rainfall rate visualization model more user friendly, Graphical User Interfaces (GUI) were built on the IDL platform. It is a collection of simple dialog box based user interfaces which integrates all the functions described in Chapter 4. This appendix provides a hands-on guide of using this program to implement the preprocessing of the PPI RADAR database and the simulations on the rainfall rate and rain attenuation statistics.

Preprocessing

As described in the Section 4.1.1, the subroutine of *Preprocessing* is designed to read in and extract the rain data from a series of PPI rainfall rate maps produced by the weather RADAR system, and export the data in data files in HDF format. The main window of this program is depicted in Figure A.1.

Figure A.1 Main Window of Preprocessing

Loading Data

The user is firstly prompt to specify the time span of the PPI rain database to be preprocessed by selecting from the drop box in the “Data Importing” module in the main window. The program is capable of processing one day’s, one month’s, or one year’s of data at a time.

Figure A.2 Period of processing

Then, the folder which contains the collection of PPI RADAR images is to be located through a folder selection dialog box by clicking the “Pick File” button.

Figure A.3 Locating folder of PPI data

Analysing Data

After the data folder is successfully loaded, user can analyze the available PPI data to be processed. The summaries of the main features of the database will be shown in a pop-up window. When one day's of data is selected, the PPI files in the folder will be populated in a table showing the file name and time stamp of each image. The overall availability of this day's database will also be calculated and shown at the head of the window.

Figure A.4 Summary window of one day's data

The user is prompt to either save or discard the summary by clicking “Save Summary” or “Exit” buttons. When the save option is selected, the information displayed will be exported to a summary file.

Figure A.5 Saving Summary file

Similarly, when one month's or one year's of data is chosen, the information of the database will be displayed in the summary windows with different bulletins.

Figure A.6 Summary window of one month's data

Figure A.7 Summary window of one year's data

Processing Data

If the user is ok with the specifications of the database, the preprocessing can be implemented by clicking the “Process” button in the summary window. As described in Chapter 4, the basic functional model of the program is capable of processing one day’s data at a time. Therefore, for the processing of one month’s and one year’s of data is implemented by applying the daily preprocessing successively on each day in the month or year. The progress of the preprocessing of the current day’s data is

indicated by the progress bar in the main window, while the date of the day under processing is shown in the “Date Indication” area.

Figure A.8 Preprocessing in progress

After the data is successfully processed, data files with the HDF format will be generated in the same folders of each day's PPI image files. The data files produced follow the common naming convention of:

YYYYMMDD.hdf

where YYYY, MM and DD indicates the year, month and date of the PPI RADAR data processed.

Simulation

This subroutine mainly deals with the simulations on the characteristics of either point rainfall rate or path rain attenuation in Singapore and the surrounding region. The main window of this program is as depicted in Figure A.9.

Figure A.9 Main Window of Simulation

Importing Data

The rain database to be utilized in the simulations is firstly imported into the program through the controls in the “Data Importing” area. The user is prompt to specify the time span of the analysis by selecting from the drop box.

Figure A.10 Period of simulation

The by clicking the “Pick file” button, either the data file of the day (processing one day’s data) or the folder contains the data files of the month/year (processing one month’s/year’s data) is to be located through file picking windows.

Figure A.11 Locating one day’s data

Figure A.12 Locating one month’s/year’s data

After the data is successfully imported, the date of the data will be indicated in the date fields.

Figure A.13 Date fields updated

Play Animated Rain Data

For the ease of the user to track the movement of rain cells in the territory, a feature of animating the rainfall rate data is provided by the program. This feature is available only for the analysis of one day's rain data. It is invoked by clicking the "Display" button in the main window. When this button is pressed, a pop-up window of data animation is produced.

Figure A. 14 Animation window of rain data

The animation can be started by clicking the “Play” button. When the animation is playing, this button will be converted to “Pause” automatically. When the animation is on-going, the time of each frame of rain data is displayed at the top right corner of the window. The display of the rain data can be precisely controlled by means of the “<Previous” and “Next>” buttons. A click of the “<Previous” button will display one frame before the current time, while the press on the “Next>” button will play one frame of rain data after the current one. The control on the playing speed is realized through the sliding bar. Ten levels of speed control is available with level 1 the slowest and level 10 the fastest.

Simulation

To implement the simulation on the point rainfall rate at a spot on the rain map, the user is prompted to check the check box of “Point Rainfall Rate” and then specify the latitude and longitude coordinates of the point of interest. This is done by either:

- (1) Clicking the “Coor” button and then left click at the pixel corresponds to the location on the RADAR map. The long and lat coordinates will be automatically updated when the mouse is moving on the map.
- (2) Typing the coordinates manually in the corresponding fields.

An example of updated coordinates is depicted in the Figure A.15.

☒ Point Rainfall Rate

Coor

X Coordinate

103

D

40

M

57

S (E)

Y Coordinate

1

D

21

M

42

S (N)

☐ Path Rain Attenuation

Starting Point

X Coordinate

0

D

0

M

0

S (E)

Y Coordinate

0

D

0

M

0

S (N)

Ending Point

X Coordinate

0

D

0

M

0

S (E)

Y Coordinate

0

D

0

M

0

S (N)

Plot

Figure A.15 Simulation on point rainfall rate

The simulation can then be started by clicking the “Plot” button.

Similarly, to simulate on the characteristics of rain attenuation along terrestrial links in Singapore, the check box of “Path Rain Attenuation” has to be checked. Then the long and lat coordinates of the starting and ending points of the wireless link have to be specified by either manually key in or by left clicking on the RADAR map. Note that before any selection from the RADAR map, the “Starting Point” or the “Ending Point” button has to be clicked. The updated coordinate fields are as shown in Figure A.16.

☐ Point Rainfall Rate

Coor

X Coordinate

0

D

0

M

0

 S (E)

Y Coordinate

0

D

0

M

0

 S (N)

☒ Path Rain Attenuation

Starting Point

X Coordinate

103

D

41

M

50

 S (E)

Y Coordinate

1

D

21

M

35

 S (N)

Ending Point

X Coordinate

103

D

44

M

38

 S (E)

Y Coordinate

1

D

19

M

56

 S (N)

Plot

Figure A.16 Simulation on path rain attenuation

The simulation results will be shown in the summary windows. As described in the Section 4.1.2, the analysis of instantaneous rainfall rate and rain attenuation is incorporated only in the simulations of one day’s data. Therefore, the models of the summary windows are different for the diurnal analysis and the monthly/yearly analysis. An example of the simulation results for a typical day is as shown in Figures A.17 and A.18.

Figure A.17 Plot of instantaneous results of one day's data

Figure A.18 Plot of cumulative results of one day's data

The user can switch between the views of the instantaneous characteristics and the cumulative statistics by clicking the corresponding buttons below the graph pane. The results can be saved through the “Save” button and exported into proper output files.

A similar summary window is produced for the monthly/yearly analysis which shows only the cumulative properties of the results.

Figure A.19 Output window of simulation results of one month's/year's data

B. Seasonal Variation of No. of Minutes with Heavy Rainfall in Each Hour

Bukit Timah

Seletar

Tampines

C. Seasonal Variation of Distributions of Rain Attenuation

Path 3 (South)

Path 4 (West)

Path 1 (North)

Path 2 (East)

Path 3 (South)

Path 4 (West)

Path 1 (North)

Path 2 (East)

Path 3 (South)

Path 4 (West)

Path 3 (South)

Path 4 (West)

D. No. of Minutes with Severe Rain
Attenuation in Each Hour

E. Seasonal Variation of No. of Minutes with Severe Rain Attenuation in Each Hour

NTU

Bukit Timah

Sentosa

Seletar

Tampines