Cloud detection and attenuation modelling in tropical region

Yuan, Feng

2018

Yuan, F. (2018). Cloud detection and attenuation modelling in tropical region. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/74836>

<https://doi.org/10.32657/10356/74836>

Cloud Detection and Attenuation Modelling in Tropical Region

YUAN FENG

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University

in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

Acknowledgement

First I would like to express my utmost appreciation and thanks to my supervisor, Professor Lee Yee Hui, she is a tremendous mentor for me. I would like to thank her for encouraging my research and her patient guidance throughout my PhD journey. I also want to thank my co-supervisor Dr. Yu Song Meng for his invaluable suggestions and editing the papers for me.

I also would like to thank all my wonderful team members Prof. Ong Jin Teong, Dr. Stefan Winkler, Dr. Lakshmi Sutha, Dr. Yeo Jun Xiang, Florian Savoy, Dr. Soumyabrata Dev and Shilpa Manandhar who have helped me and given a lot of brilliant advices throughout the project.

A special thanks to all my friends who give me a lot of supports during my PhD journey. Thanks to Li Juekun, Zhang Qiao, Gao Dongfang, Meng Fanzeng, Mi Siya, Dr. Yang Zaifeng, and Dr. Wang Jiang. I also want to thank all my lab technicians and final year project students for their support and contribution toward the whole project.

I also want to acknowledge DSTA (Defence Science and Technology Agency) Singapore for supporting this research project.

Last but by no means least, I would like to thank my parents Yuan Zhongde and Jiang Fengyi for raising me with all their love and supporting me in all my pursuits. Their encouragement helped me pass through the hardest time during my PhD journey. I express my sincere gratitude towards them.

Contents

Acknowledgement	i
Table of Contents	vii
Summary	viii
List of Figures	xvi
List of Tables	xviii
List of Abbreviations	xix
List of Notations	xxi
1 Introduction	1
1.1 Motivation and Objective	1

CONTENTS

1.2	Thesis Outline and Main Contributions	3
2	Literature Review	6
2.1	Overview	6
2.2	Atmospheric Impairments	7
2.3	Gaseous Attenuation	7
2.4	The Melting Layer Effect	12
2.5	Progress in Cloud Detection Studies	14
2.5.1	Decker Model	17
2.5.2	Wang and Rossow Model	17
2.5.3	Pierdicca, Pulvirenti, and Marzano Algorithm	18
2.5.4	Salonen and Uppala Cloud Detection Model	19
2.6	Progress in Cloud Attenuation Studies	20
2.6.1	Altshuler and Marr Model	21
2.6.2	Dintelmann and Ortgies Model	22
2.6.3	Salonen and Uppala Model	23
2.6.4	DAH Model	25
2.6.5	ITU-R P.840-6 Model	26

CONTENTS

2.7	Summary	29
3	Instrument and Dataset Processing	30
3.1	Introduction	30
3.2	Radiosonde	30
3.3	Ceilometer	36
3.4	Surface Observation Data	38
3.5	Weather Station	42
3.6	S-Band Dual-polarization Weather Radar	43
3.7	Beacon Receiver	44
3.8	IGS PWV Database	48
3.9	Summary	49
4	Cloud Vertical Structure Analyses and Modelling	51
4.1	Introduction	51
4.2	Cloud Detection Model Comparison	52
4.3	Methodology for Water Vapor Pressure Cloud Detection	56
4.4	Cloud Vertical Structure	59

CONTENTS

4.5	Cloud Occurrence in Different Levels	62
4.6	Cloud Base Height	67
4.7	Summary	73
5	Melting Layer Detection for Stratiform and Convective Rain Clouds in Tropical Region	74
5.1	Introduction	74
5.2	Identification of Melting Layer for Different Rain Cases	75
5.3	Differentiation between Stratiform and Convective Rain	78
5.4	Proposed Threshold for Convective Rain Melting Layer Detection	84
5.5	Performance Evaluation of Proposed Threshold	87
5.6	Special Case for Convective Rain	89
5.7	Summary	90
6	Statistical Study of Cloud Attenuation on Ka-band Satellite Signal	93
6.1	Introduction	93
6.2	Gaseous Absorption on Ka-band Satellite Signal	95
6.3	Differentiate Cloud from Rain Events for Beacon Signal	99

CONTENTS

6.4	Comparison between Beacon Measured Cloud Attenuation and ITU-R Model	103
6.5	Summary	105
7	Cloud Attenuation Analyses and Modelling	106
7.1	Introduction	106
7.2	0 °C and -20 °C Isotherm Height Distribution	107
7.3	Cloud Liquid Water Content Comparison	109
7.4	Proposed Cloud Attenuation Prediction Model for Tropical Region . .	111
7.5	Comparison between the Proposed Cloud Attenuation Model and ITU-R Model	117
7.6	Summary	121
8	Conclusion and Future Work	122
8.1	Conclusion	122
8.2	Future Work	124
	Publication List	127
	Bibliography	144

Summary

Cloud plays a significant role in both the ground-to-space radio communication system and climate system of Earth. In a tropical country like Singapore, more than 80% of observed clouds are thick cumulus/cumulonimbus clouds that are heavy with high liquid water content, and consequently accounts for a significant amount of attenuation on satellite signals. In this thesis, various types of data are collected from different kinds of instruments including radiosonde, ceilometer, dual-polarization weather radar, Ka-band beacon receiver, weather station and whole sky imager. By processing and analyzing these data, we study the various aspects of cloud including cloud vertical structure, melting layer of rain cloud, and the impact of cloud on the satellite communication for tropical region.

To detect cloud vertical structure, four year radiosonde data from 9 tropical stations are processed and analyzed. A new method using water vapor pressure (WVP) is then proposed for cloud detection in the tropical region. The proposed model detects the presence of clouds based on the following criterion: the measured water vapor pressure is larger than the derived critical water vapor pressure at the same level. The estimated cloud vertical structure using the proposed method is compared with the Salonen and Uppala (SU) model, the ceilometer data and two kinds of meteorologi-

CONTENTS

cal observation data, namely, SYNOP (surface SYNOptic observations) and METAR (MEteorological Terminal Aviation Routine weather report) . Our proposed model shows a higher accuracy of prediction of the cloud vertical structure as compared to the existing SU model.

After studying the cloud vertical structure, the melting layers for the stratiform and convective rain clouds are investigated by using data from the dual-polarization radar. In the tropical region, convective rain dominates the rain events, however, knowledge of the melting layer from convective rain is very limited. Therefore, we processed and analyzed the dual-polarization radar data to identify both stratiform and convective rain melting layer in the tropical region of Singapore. By studying and differentiating these two types of rain events, it is found that amongst the three radar measurements of reflectivity (Z), differential reflectivity (Z_{DR}), and cross-correlation coefficient (ρ_{HV}), the best indicator for the melting layer of convective rain events is the cross-correlation coefficient. After comparing the convective rain melting layer top heights with the corresponding 0 °C isotherm heights, it is found that for convective rain events, the threshold to detect melting layer should be modified to $\rho_{HV} = 0.95$ for tropical region.

In order to detect clouds, several cloud detection methods are applied in order to achieve accurate cloud attenuation estimation. Two year statistical beacon data are collected and processed. Experimental results from the beacon receiver is also analyzed for the calculation of cloud attenuation. These results are then compared to the existing ITU-R model for same frequency and elevation angle. The complementary cumulative distribution function (CCDF) of the 2-year cloud attenuation derived from the beacon receiver shows that the Ka-band cloud attenuation can be up to 4 dB at

CONTENTS

the time exceedance of 0.01%. The ITU-R model is found to underestimate the cloud caused attenuation in the tropical region.

After analyzing the cloud attenuation along the satellite slant path link, a new model is proposed to improve the ITU-R cloud attenuation model. The improved model incorporates precipitable water vapor (PWV) value to estimate integrated liquid water content (ILWC), and then determine the cloud attenuation for the tropical region. From the analysis of 2 year radiosonde data from 8 sites in the tropical region, the results show that the ILWC along the path can be approximated by a power function relationship with the PWV. The estimated cloud attenuation using the improved model is then compared with the values calculated using the existing ITU-R model and the cloud attenuation derived from a Ka-band beacon data. Results calculated from the proposed model has shown good agreements with the ITU-R model at high percentage of time exceedance which also matches well with the cloud attenuation suffered by the beacon signal at low percentage of time exceedance. It is noted that with the introduction of the use of PWV data from GPS (Global Positioning System), higher temporal resolution of cloud attenuation can be achieved comparing to the existing ITU-R cloud attenuation model.

In this thesis, we have proposed a model to detect cloud vertical structure, studied and detect the melting layer for rain cloud, done statistical analysis of cloud attenuation on Ka-band satellite link and also proposed a method for cloud attenuation calculation in tropical region. The algorithms and techniques developed in this thesis will assist in remote sensing applications and satellite communication applications.

List of Figures

2.1	Illustration of various fading impairments on a satellite path link. . . .	8
2.2	Gaseous attenuation due to water vapor and dry air along the slant path ($\theta=44.5^\circ$, $p=995$ hPa, $t=25^\circ\text{C}$, $\rho_s=23$ g/m ³).	11
3.1	Radiosonde image archived from radiosonde museum of North America	31
3.2	Locations of radiosonde stations	32
3.3	Height of cloud base calculated using SU model for two database in Singapore WSSS station in February 2013.	34
3.4	0°C isotherm height derived using two database in Singapore WSSS station in February 2013.	35
3.5	Cloud attenuation in Singapore WSSS station in February 2013. . . .	36
3.6	Ceilometer from Vaisala ceilometer CL31 datasheets.	37
3.7	Histogram of cloud coverage in Singapore WSSS station in 2013. . . .	39

LIST OF FIGURES

3.8	Histogram of cloud base heights in Singapore WSSS station in 2013. . .	41
3.9	Davis weather station at NTU S2.1 building rooftop	42
3.10	Ka-band (WINDS) outdoor system at NTU S2 building rooftop . . .	45
3.11	The Ka-band beacon signal for WINDS slant path with derived signal reference level and corresponding radar reflectivity on 27th January 2014.	47
4.1	The measured relative humidity profile versus the cloud detection thresh- olds.	53
4.2	Comparison of cloud base height determined using different methods with the ceilometer (CL31) in Singapore in February 2013.	54
4.3	Histograms of the difference between the CBHs detected by the ceilome- ter and the heights estimated using the SU and De90 models in Singa- pore in February 2013.	55
4.4	Water vapor pressure at different altitude levels (a) one data set, (b) 36 years of radiosonde data collected from 9 locations in tropical region with curve fitting.	58
4.5	Cloud vertical structure detection and comparison by (a) WVP model (b) De90 model, SU model, and WVP model in Singapore WSSS sta- tion at 10:00 UTC on 22nd Oct 2013.	61

LIST OF FIGURES

4.6	Cloud image taken by whole sky imager at NTU at 10:00 UTC on 22nd Oct 2013.	62
4.7	Site difference between NEA upper air observatory and Changi airport.	63
4.8	Percentage of the matched cloud occurrence cases of SU/WVP model comparing with SYNOP/METAR in Singapore in 2013.	67
4.9	Histogram of CBHs from SU model, WVP model, ceilometer and human observation in Singapore in 2013.	69
4.10	Scatter plot of CBH measured by CL31 with (a) CBH estimated by SU model (b) CBH estimated by WVP model in Singapore in 2013. . .	70
4.11	Histograms of difference between the CBHs detected by the ceilometer and the heights estimated using the SU and WVP models in Singapore in 2013.	72
5.1	Dual-polarized radar PPI images of Z for (a) stratiform rain only, (b) convective rain only, and (c) stratiform rain together with convective rain.	77
5.2	Dual-polarized radar PPI images of (a) ρ_{HV} , and (b) Z_{DR} in Singapore at 05:45 UTC on 21st April 2014 with an elevation angle of 5°	79
5.3	Radar reflectivity PPI for two separated rain events in Singapore at 05:45 UTC on 21st April 2014	81

LIST OF FIGURES

5.4	Averaged vertical profiles of (a) ρ_{HV} , (b) Z and (c) Z_{DR} at the same height for convective rain cell and stratiform rain cell in Singapore at 05:45 UTC on 21st April 2014.	83
5.5	Scatter plot between the 0 °C isotherm height and the corresponding ρ_{HV} value for convective rain melting layer in Singapore.	86
5.6	Scatter plot between 0°C isotherm height and convective rain melting layer top height detected using two different thresholds in Singapore.	88
5.7	Histogram of convective rain cell melting layer thickness using two different thresholds.	89
5.8	Radar reflectivity measured in Singapore at 14:55 UTC on 14th June 2014 (a) PPI image (b) mapped on the height-azimuth plane	91
6.1	The triangulation structure among WINDS satellite, beacon receiver, weather station, whole sky imager, radiosonde and weather Radar.	94
6.2	The zenith gaseous attenuation due to the water vapor and dry air using ITU-R Recommendation P.676-11 and weather station data in Singapore in 2012.	96
6.3	Four-year (2012-2015) total gaseous attenuation with the slow trends in Singapore.	97
6.4	Cumulative distribution function of gaseous attenuation in Singapore for the year of 2012 to 2015.	98

LIST OF FIGURES

6.5	The processed Ka-band beacon signal for WINDS slant path with Radar reflectivity and rainfall rate on 12th April 2015.	100
6.6	The Radar reflectivity PPI map between NTU and Changi airport with WINDS slant path link at 14:50 pm on 12th April 2015.	101
6.7	Cloud image taken by Whole Sky Imager at NTU at 13:14 pm on 12th April 2015.	102
6.8	Complementary cumulative distribution function of cloud attenuation estimated from WINDS satellite beacon signal for the year of 2014 and 2015.	104
7.1	Histogram of altitudes (a) at temperature of 0 °C (b) at temperature of -20 °C in Singapore in 2012.	108
7.2	Cloud liquid water density calculated by SU model and WVP model in Singapore WSSS station on (a) 15th January 2012 (b) 22nd January 2012.	110
7.3	Zenith ILWC processed from 8 radiosonde station for the years 2013 and 2014 versus zenith PWV from the respectively collocated IGS station. (a) scatter plot, (b) density color image.	114
7.4	CCDF of cloud integrated liquid water content calculated from radiosonde data and proposed model for the year of 2013 and 2014. . .	116

LIST OF FIGURES

7.5	CCDF of cloud attenuation derived from WINDS satellite beacon signal, estimated from the proposed model and ITU-R model in year of (a) 2014 and (b) 2015.	119
7.6	Idea of zenith PWV determination.	120

List of Tables

2.1	Average cloud properties in DAH model	26
3.1	N_h - amount of low level or middle level cloud coverage	39
3.2	h - the lowest cloud base height above the surface.	41
3.3	Radar reflection and rainfall rate	44
3.4	Measurement site and satellites characteristics	46
3.5	Data availability and resolution of different database	50
4.1	9 Radiosonde stations selected in the tropical region	57
4.2	Comparison of cloud occurrence between METAR report and SYNOP report in Singapore in 2013*	64
4.3	Comparsion of cloud occurrence from models (SU and WVP) and ob- servation reports (SYNOP and METAR) in Singapore in 2013*	65

LIST OF TABLES

4.4	Correct detection rate of CBH from comparing SU and WVP models with ceilometer/METAR data	72
5.1	Convective rain melting layer events with closest radiosonde data	85
7.1	Radiosonde stations with collocated IGS stations for tropical regions .	113
7.2	ILWC value calculated by using proposed model with typical PWV value in tropical region	115

List of Abbreviations

CBH	Cloud Base Height
CCDF	Complementary Cumulative Distribution Function
ECMWF	European Center for Medium-Range Weather Forecasts
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GIPSY-OASIS	GPS Inferred Positioning SYstem-Orbit Analysis and Simulation Software
ILWC	Integrated Liquid Water Content
IGS	International GNSS Service
ITU-R	International Telecommunication Union - Radio
KDP	specific differential propagation phase
LNB	Low-Noise-Block
LDR	Linear Depolarization Ratio
METAR	MEteorological Terminal Aviation Routine weather report
NEA	National Enviroment Agency
NTU	Nanyang Technological University
NOAA	National Oceanic and Atmospheric Administration

NWP	Numerical Weather Prediction
PWV	Precipitable Water Vapor
RH	Relative Humidity
SU	Salonen and Uppala
SYNOP	surface SYNOptic observations
USAT	Ultra Small Aperture Terminal
VSAT	Very Small Aperture Terminal
WMO	World Meteorological Organization
WVP	Water Vapor Pressure
WINDS	Wideband InterNetworking engineering test and Demonstration Satellite
WSR	Weather Surveillance Radar
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Total Delay
ZWD	Zenith Wet Delay

List of Notations

A	path attenuation
A_c	cloud attenuation
A_m	mixed cloud attenuation
A_o	dry air attenuation
A_w	water vapor attenuation
Alt	altitude
a_e	effective earth radius
C_H	high level cloud type
C_L	low level cloud type
C_M	middle level cloud type
c	speed of light
D	distance through the attenuating layer
δt	interval time
e_c	critical water vapor pressure function
$erfc$	complementary error function
ε	dielectric permittivity of water
ε'	real part of the permittivity of water

ε''	imaginary part of the permittivity of water
f	frequency
f_p	principal relaxation frequency
f_s	secondary relaxation frequency
g	acceleration due to gravity
γ_c	the specific cloud attenuation
γ_o	the specific dry air attenuation
γ_w	the specific water vapor attenuation
H_c	cloud vertical extent
h	cloud base height
h_c	height from the cloud base
h_e	effective height of the attenuating layer
h_o	equivalent height for dry air
h_w	equivalent height for water vapor
K_l	specific attenuation coefficient
κ	specific heat ratio
L_c	cloud horizontal extent
L_{red}	reduced liquid water content
λ	wavelength
N_h	cloud coverage
N_w''	imaginary part of complex refractivity
P	Probability
PI	dimensionless conversion factor
p	pressure
p_{tot}	total air pressure

p_w	cloud liquid water fraction
ρ_{HV}	cross-correlation coefficient
ρ_s	surface water vapor density
ρ_w	water density
R	fundamental gas constant
r_0	path length
σ	ratio of the measured level pressure and surface level pressure
σ_c	standard deviation of cloud attenuation
T	temperature in Kelvin
T_s	surface temperature
t	temperature in °C
θ	elevation angle
U_c	critical humidity function
w	liquid water density
Z	reflectivity
Z_{DR}	differential reflectivity
z	spatial range

Chapter 1

Introduction

1.1 Motivation and Objective

Cloud plays a significant role in both the Earth's climate system [1] [2] [3] and ground-to-space radio communication system [4] [5]. The study of clouds in the atmosphere is becoming popular amongst the remote sensing and satellite communication community for various applications. By influencing the hydrological cycle and the radiation balance [6] [7], it can cause a wide variation in the weather conditions.

Cloud can also cause severe impairment to satellite communications [8] [9]. As the frequency spectrum becomes crowded and the high data transmission rates demand increases, the high operating frequency bands such as Ka-band and Q/V bands are becoming increasingly interesting for satellite service operators. Several fading impairments [10], such as precipitation attenuation [11] [12] [13], cloud attenuation [14] [15], gaseous absorption [16], melting layer attenuation [17], and tropospheric scintilla-

1.1. MOTIVATION AND OBJECTIVE

tion [18], affect the Earth-to-Space and Space-to-Earth systems. With the increase in operating frequency, both rain attenuation and cloud attenuation become important for the satellite system design and operation. This is especially so for low margin systems such as VSAT (Very Small Aperture Terminal) and USAT (Ultra Small Aperture Terminal) [19] operating in the Ka-band (20/30 GHz) or above.

For optical satellite communications, cloud liquid water droplet is one of the dominant fading factors [20] since the optical link can easily be blocked by the presence of clouds. Therefore, it is very important to study and understand the probability of the cloud occurrence, cloud coverage, and cloud optical thickness. This information must be taken into consideration for design of optical satellite communication systems.

For the tropical region, the effects tends to be more severe than the temperate regions due to the high probability for occurrence of convective clouds. Unlike clouds found in other subtropical and temperate regions, these convective clouds are cumulus and cumulonimbus [21] that extends over high vertical altitudes, and are high in liquid water content. Therefore, these kinds of cloud can degrade the performance of satellite systems in the tropical region significantly.

Our objective is to use data collected from various instruments to provide an analysis of the impact of clouds on the satellite communication links in tropical region like Singapore. In order to analyze the cloud attenuation, beacon signal data from a Ka-band satellite is used. By analyzing signal strengths from satellite signals, data from radiosonde vertical profile, data from dual-polarization weather radar and data from surface weather stations are obtained.

Major contributions:

1.2. THESIS OUTLINE AND MAIN CONTRIBUTIONS

- A model to detect the cloud vertical structure for the tropical region is proposed.
- Technique used to identify the melting layer for stratiform and convective rain clouds is recommended.
- Steps required to detect the clouds along the satellite slant path link are given.
- High temporal resolution model for the calculation of cloud attenuation in the tropical region is proposed.

1.2 Thesis Outline and Main Contributions

Chapter 1: The motivation and objectives and outline of the thesis in this chapter are discussed. Briefly highlight the main contributions which were offered throughout this thesis.

Chapter 2: This chapter introduces the literature review and background of the related research work. The literature review includes the impairments from atmosphere on the satellite propagation link; the algorithms to detect cloud vertical structure and cloud occurrence; and the models to calculate cloud attenuation along the slant path.

Chapter 3: The instruments and datasets used in the work are presented in this chapter, these are the radiosonde, ceilometer, surface observation data, weather station, beacon receiver, S-band dual-polarization radar and IGS PWV database. The processing and availability of the datasets are also detailed.

Chapter 4: A new model applying radiosonde vertical profile is proposed to

1.2. THESIS OUTLINE AND MAIN CONTRIBUTIONS

determine the cloud vertical structure for the tropical region. This includes not only the cloud base height (CBH) but also the cloud occurrences at different levels in the atmosphere. In order to validate the performance of this model, the results from the proposed cloud detection model are compared with those from the Salonen and Uppala (SU) model, Decker model, ceilometer measurements and meteorological surface observations.

Chapter 5: In this chapter, the dual-polarization radar data are processed to identify the melting layer of both stratiform and convective rain clouds in the tropical region of Singapore. These two types of rain events are studied using three measurements (reflectivity, differential reflectivity and cross-correlation coefficient) from the radar data that are processed and analyzed. The capability and performance of the three measurements for convective rain melting layer detection are also discussed. In addition, the updraft phenomena is also investigated for the convective rain event.

Chapter 6: Total attenuation suffered by the Ka-band satellite is derived from measurements after removing the scintillation and anomalies. The gaseous absorption are also investigated on this Ka-band satellite signal. After subtracting the gaseous attenuation, rain and cloud attenuation are derived. In order to separate these two attenuation, several methods are presented and combined to differentiate cloud and rain events. By applying this assembled differentiation method, the attenuation are divided into rain attenuation and cloud attenuation. The two year statistical results of cloud induced attenuation are analyzed and compared with the results calculated using the ITU-R model.

Chapter 7: In the previous chapter, the ITU-R cloud attenuation model is found to underestimate the cloud attenuation for tropical region. Therefore in this chap-

1.2. THESIS OUTLINE AND MAIN CONTRIBUTIONS

ter, a new cloud attenuation model with high temporal resolution is proposed. The cloud attenuation is strongly correlated to liquid content within the cloud layers, and temperature influence the water and ice phase of clouds; the 0°C and -20°C isothermal heights distribution are investigated. The method to calculate cloud liquid water content in SU model is also presented. A new model incorporates precipitable water vapor (PWV) value to estimate liquid water content and derived cloud attenuation. To validate the performance of this model, the result is compared with the existing ITU-R P.840-6 model and cloud attenuation derived from Ka-band satellite signal presented in chapter 6.

Chapter 8: A summary of the results presented in the thesis is provided and the promising future works are also recommended.

Chapter 2

Literature Review

2.1 Overview

Literature review on the various aspects of cloud are presented in this chapter. As mentioned from the previous chapter, this thesis focuses on the remote sensing of cloud vertical structure, detection of melting layer for stratiform and convective rain clouds, investigation of cloud attenuation on Ka-band satellite link, and the estimation of cloud attenuation in the tropical region. To understand the impact of cloud attenuation along the satellite path, the different types of atmospheric impairments are introduced including rain attenuation, gaseous attenuation, and melting layer effect. Then the existing models and results about cloud vertical structure detection and cloud attenuation in this particular field will be described. Finally the advantages and disadvantages of existing models will be discussed and a few research gaps will be identified.

2.2 Atmospheric Impairments

The effect of atmosphere on radio wave propagation for earth-to-space communication is one of the important concern for satellite communication systems design. For these satellite communication systems, when the signal transmits through the atmosphere, it suffers from several fading impairments. They are primarily rain attenuation, cloud attenuation, gaseous absorption, and melting layer attenuation as shown in Fig. 2.1. The frequency of the radio wave is the most important factor in determining whether these impairments are dominant on the communication links.

Rain attenuation is the most severe effect for earth-to-space communication operating at frequencies of 10 GHz and above. Due to the energy absorption and scattering effect of the raindrops on the radio wave [22], the rain precipitation degrades the performance and reliability of the satellite link. Rain attenuation mainly depends on the frequency of transmitting signal, the rainfall rate, the rain droplet shape and the rain drop size distribution. The rain attenuation along the slant path propagation link has been extensively investigated and studied in the tropical region [12] [22] [23] [24]. Therefore in the following section, only the gaseous attenuation, melting layer effect and cloud attenuation will be introduced in detail since most of the work done in this thesis is on these impairments.

2.3 Gaseous Attenuation

The gaseous absorption [16] [25] [26] consists of dry air attenuation (oxygen, pressure-induced nitrogen and non-resonant Debye attenuation) and water vapor attenuation.

Figure 2.1: Illustration of various fading impairments on a satellite path link.

For a tropical region like Singapore, the total gaseous attenuation especially the water vapor attenuation is relatively large since the temperature and relative humidity is quite high throughout the year relative to subtropical and temperate regions.

Although the gaseous attenuation is relatively small compared to the other effect such as precipitation and cloud [4], for systems operating in Ka band (around 22 GHz) and V/W frequency bands or for the cases where the elevation angles are low, the gaseous attenuation has to be taken into consideration. In the following, the

2.3. GASEOUS ATTENUATION

algorithms for approximate estimation of gaseous attenuation proposed by ITU-R P.676-11 [25] is introduced.

By applying the following simplified algorithm, the specific attenuation due to dry air and water vapor can be calculated. The specific attenuation for dry air, r_0 (dB/km), and the specific attenuation for moist air, r_w (dB/km), are given by the following equations:

$$r_0 = 0.1820f \left(\sum_{i(Oxygen)} S_i F_i + N_D''(f) \right) \quad (2.1)$$

$$r_w = 0.1820f \sum_{i(WaterVapor)} S_i F_i \quad (2.2)$$

where S_i , F_i , $N_D''(f)$ are defined in the equations which can be found in P.676-11 [25].

For a horizontal path or some slightly inclined paths, the total gaseous attenuation, A , is given as:

$$A = \gamma \cdot r_0 = (\gamma_0 + \gamma_w)r_0 \quad (2.3)$$

where r_0 is the path length (km).

For calculating the gaseous absorption on the slant path links passing through atmosphere, the equivalent heights need to be calculated, which are mainly dependent on pressure.

The dry air equivalent height can be calculated by:

$$h_o = \frac{6.1}{1 + 0.17r_p^{-1.1}} (1 + t_1 + t_2 + t_3) \quad (2.4)$$

2.3. GASEOUS ATTENUATION

where

$$t_1 = \frac{4.64}{1 + 0.066r_p^{-2.3}} \exp\left[-\left(\frac{f - 59.7}{2.87 + 12.4\exp(-7.9r_p)}\right)^2\right] \quad (2.5)$$

$$t_2 = \frac{0.14\exp(2.12r_p)}{(f - 118.75)^2 + 0.031\exp(2.2r_p)} \quad (2.6)$$

$$t_3 = \frac{0.0114}{1 + 0.14r_p^{-2.6}} f \frac{-0.0247 + 0.0001f + 1.61 \times 10^{-6}f^2}{1 - 0.0169f + 4.1 \times 10^{-5}f^2 + 3.2 \times 10^{-7}f^3} \quad (2.7)$$

with the constraint that:

$$h_o \leq 10.7r_p^{0.3} \quad (2.8)$$

For the water vapor equivalent height, it can be calculated as

$$h_w = 1.66\left(1 + \frac{1.39\sigma_w}{(f - 22.235)^2 + 2.56\sigma_w} + \frac{3.37\sigma_w}{(f - 183.31)^2 + 4.69\sigma_w} + \frac{1.58\sigma_w}{(f - 325.1)^2 + 2.89\sigma_w}\right) \quad (2.9)$$

$$\sigma_w = \frac{1.013}{1 + \exp[-8.6(r_p - 0.57)]} \quad (2.10)$$

For the slant path attenuation with an elevation angle within 5° and 90°, the total gaseous attenuation can be calculated as

$$A = \frac{A_o + A_w}{\sin\theta} \quad (2.11)$$

where $A_o = h_o\gamma_o$ and $A_w = h_w\gamma_w$

Fig. 2.2 shows the trends of gaseous attenuation versus signal frequencies. This result is calculated at elevation angle of 44.5° and based on the weather station data that surface pressure p is around 995 hPa, temperature t is 25 °C and water vapor density ρ_s is around 23 g/m³. As the frequency increases up to 54 GHz, the dry air at-

2.3. GASEOUS ATTENUATION

tenuation keeps increasing with the frequency. Notice that the water vapor has much more contribution up to a frequency of 48 GHz, after that the dry air, mostly from oxygen attenuation, becomes dominant, and the gaseous absorption becomes only due to dry air attenuation. For the WINDS (Wideband InterNetworking engineering test and Demonstration Satellite) system, the operating frequency of the beacon signal is 18.9 GHz with the elevation angle around 44.5° , the total calculated gaseous attenuation is around 0.7 dB, which should be also considered when deriving the cloud attenuation from the beacon signal. Chapter 6 will introduce the further details on gaseous attenuation analysis on the WINDS geostationary satellite communication link for tropical region.

Figure 2.2: Gaseous attenuation due to water vapor and dry air along the slant path ($\theta=44.5^\circ$, $p=995$ hPa, $t=25^\circ\text{C}$, $\rho_s=23$ g/m³).

2.4 The Melting Layer Effect

The melting layer is the region where the ice crystals melt and transit into precipitating raindrops. Therefore, the altitude of the melting layer is defined as the effective rain height. At this melting region, the reflectivity increases and causes a bright band effect in the radar measurements. The study of the characteristics of melting layer is very important for the accurate estimation of rainfall and microphysical characterization of the cloud [27].

For satellite-to-earth communications and radar remote sensing applications, the melting layer can cause both attenuation [28] [29] [30] [31] and scattering [32] [33] [34] to the propagating signal at microwave frequencies. It has been reported that the melting layer contributes significantly to the overall path attenuation during the periods of stratiform rain for slant paths with low elevation angles [4].

Previously, reflectivity (Z) measurements from conventional radar have been used for calculating the rainfall rate and detecting the melting layer bright band. However, the transition between ice crystals and water droplets in melting layer cannot be well identified with only the reflectivity, Z , measurements especially for convective rain events. Dual-polarized radar measurements do not only include the reflectivity, Z , measurement, but also the differential reflectivity, Z_{DR} , the linear depolarization ratio, LDR, the specific differential propagation phase, K_{DP} , and the correlation coefficient between copolar returns (cross correlation coefficient), ρ_{HV} [35]. Some of these parameters from the dual-polarized radar measurement can provide a better way to identify the melting layer. In a recent study of the melting layer detection using dual-polarized radar measurements, Giangrande et al. [27] proposed the use

2.4. THE MELTING LAYER EFFECT

of three of these parameters for the detection of stratiform rain melting layer. It suggested that the value of ρ_{HV} should fall between 0.90 and 0.97, the maximum value of Z_{DR} should be within the interval of 0.8 to 2.5 dB and the maximum value of Z should fall between 30 and 47 dBZ. All these three criteria should be fulfilled in the same window of 500 m for a melting layer to be identified.

However, most of the existing studies on melting layer are for stratiform rain events, very limited research work is performed for convective rain events. This might be because most of the studies are carried out in the temperate region, where there are very few convective rain events. Another reason for the lack of research work on convective rain events is because there is typically no bright band effect in Z for convective rain events and therefore, it is very difficult to identify the convective rain melting layer by using a single parameter from conventional radar reflectivity measurements [36] [37].

Recently, Teshiba et al. [38] reported polarimetric melting signatures in a convective rainfall area in central Oklahoma. They found that in one convective downdraft event, larger Z was observed at lower altitude of below 3 km, and the downdraft resulted in a depression of melting layer height as indicated by the vertical profiles of Z_{DR} and ρ_{HV} . In [39] [40], Shusse et al. presented the convective rain melting layer characteristics in East China Sea region by using C-band polarimetric radar data. After applying the classification method to separate the convective rain and stratiform rain on a 3-hour event, they found that the melting layer in the convective region showed a marked decrease in ρ_{HV} together with an increase in Z_{DR} around the 0°C isotherm height. They also concluded that the average height of the melting layer signature maximum (defined by the level of the ρ_{HV} minimum in the melting

2.5. PROGRESS IN CLOUD DETECTION STUDIES

level) in the convective region is 0.46 km higher than that in the stratiform region.

In the tropical country of Singapore, there are frequent convective precipitations relative to the temperate region. Therefore, it is ideal to study the convective rain melting layer in a tropical country like Singapore. With the recent implementation of S-band dual-polarized radar in Singapore, both the stratiform and convective melting layers will be investigated in details in this paper, with a focus on the convective melting layer. By analyzing the recorded convective rain events, a method to detect the convective rain melting layer will be proposed in chapter 5.

2.5 Progress in Cloud Detection Studies

Cloud is very important for both climatology and satellite communication systems. It can cause a wide variation in the weather conditions by influencing the hydrological cycle and irradiance. Cloud can also cause attenuation to satellite communication links, especially for low-margin systems such as VSAT and USAT operating in Ka-band (20/30 GHz) or above. Moreover, absorption from clouds can affect several kinds of sensors [41]. Due to the high probability of occurrence of convective clouds, these effects are even more severe for tropical regions. Unlike clouds found in other subtropical and temperate regions, these convective clouds are cumulus, extending over high vertical altitudes, and are heavy in liquid water content [21]. Therefore, cloud detection becomes a very important for the remote-sensing applications.

The radio-sounding observation is performed using various sensors to measure several important parameters such as temperature, relative humidity, pressure, dew point, wind speed and wind direction along a vertical path. Therefore, it has been

2.5. PROGRESS IN CLOUD DETECTION STUDIES

widely applied to model the cloud vertical structure [42] [43] [44] [45]. To determine the cloud base height (CBH), ceilometer is sometimes used [46] [47] [48] [49] [50]; while the meteorological surface observations are also effective for CBH and cloud coverage determination [51] [52].

Decker et al. [42] in 1978, proposed to use certain relative humidity as a constant threshold to detect the CBH and cloud thickness. CBHs were determined to be at the level where the relative humidity first exceeded 95% and the cloud thickness was determined to be where the relative humidity drops below 95% along the same cloud layer. While in 1995, after comparing the ceilometer measurements of CBH with radiosonde humidity profiles, Han and Westwater revised this constant relative humidity threshold to be 90% [43] to have better agreements between the ceilometer measurements and radiosonde measurements. Later in 1995, Wang and Rossow [44] proposed a method with three relative humidity criteria to identify the cloud vertical structure, these criteria are the maximum value of relative humidity in a cloud should be larger than 87%, the minimum value of relative humidity in a cloud should be larger than 84%, and for the top and bottom of clouds, the relative humidity should jump more than 3%.

Another typical approach for cloud detection applied by Salonen and Uppala [45] in 1991 uses a pressure-dependent critical humidity function to detect the presence of cloud. It is noted that all these existing cloud detection models mentioned above are based on a single weather related parameter, the relative humidity.

Water vapor plays an important role for the hydrologic cycle in the Earth [53]. It evaporates from river, lake or sea surface, and then condenses to form clouds. Blown by winds, clouds change their shape and move to other places. Finally they

2.5. PROGRESS IN CLOUD DETECTION STUDIES

will precipitate in the form of rain and/or snow thus falling back onto the Earth's surface. The amount of water vapor suspended in the air and the temperatures are two key factors for the clouds formation. Relying on these two key factors, water vapor pressure (WVP) should have positive correlation with the cloud. In chapter 4, a new model is presented using the water vapor pressure to detect cloud vertical structure.

The cloud vertical structure includes cloud base height, cloud layer thickness and cloud top height, it is an essential factor for the calculation of cloud attenuation. Generally, cloud can be divided into three categories depending on the cloud base height [54]:

- Low level clouds: the cloud base heights are below 2,000 m. They generally contain large amount of liquid water droplets. Examples include Cumulus, Cumulonimbus, Stratus, and Stratocumulus.
- Middle level clouds: the cloud base heights are ranging from 2,000 ~ to 5,000 m. They generally contain water droplets and ice crystals. Examples include Altocumulus, Altostratus, and Nimbostratus.
- High level clouds: the cloud base height is from 5,000 ~ 14,000 m. They usually only contain ice crystals. Examples include Cirrostratus, and Cirrocumulus.

For the research of cloud attenuation, the focus will be on the low level and middle level clouds, which are with heavy cloud liquid water content. That is because clouds that are forming at other higher altitudes would consist mostly of ice particles and therefore the attenuation would be negligible at frequencies lower than 100 GHz

2.5. PROGRESS IN CLOUD DETECTION STUDIES

[45]. In the following section, a review of cloud vertical structure detection model is provided.

2.5.1 Decker Model

The Decker algorithm [42] identifies clouds from atmospheric profiles by applying a specific relative humidity (RH) as a fixed threshold as shown in eq. (2.12)

$$RH > 95\% \quad (2.12)$$

The height of the cloud base is determined as the first level at which the RH value is larger than 95%, and the cloud top height is the last level fulfill this criteria within the same cloud layer. This threshold (named as “De95”) is set at a relative high value, and could make misdetection of the cloud using radiosonde data. Han and Westwater [43] then suggested a new specific value (named as “De90”) as

$$RH > 90\% \quad (2.13)$$

2.5.2 Wang and Rossow Model

Cloud layer top and base are identified in [44] [55] [56] by jumping of relative humidity more than 3%. The following steps are need to be performed to detect the cloud vertical structure:

- Step 1: The base height of the lowest cloud layer can be detected when the level satisfied any of the following three conditions: (a) RH is more than 87% (b) RH

2.5. PROGRESS IN CLOUD DETECTION STUDIES

on this non-surface level should be more than 84% and less than 87%, and RH should increase by more than 3% from the previous level (c) RH on the surface level is more than 84%.

- Step 2: The following levels are still considered inside the same cloud layer if RH is more than 84% until the RH is below 84% on certain level or the cloud top criteria is satisfied.
- Step 3: The levels within the cloud layer should be checked again from the highest cloud top level down to the cloud base, and the cloud top layer is detected if the corresponding level satisfy any of the following three conditions:
(a) RH is more than 87% (b) If this level is not the top of the profile, RH should be more 84% but less than 87%, and there should be at least a 3% RH increase from the previous level (c) RH is more than 84% if this level is the top of the profile.
- Step 4: If there is no such a top found in step 3, the layer is not considered to be a cloud layer. If a top is found, the maximum RH in the layer is found. The detected moist layer is finally judged to be a cloud layer only if the maximum RH is above 87%. Here 87% and 84% are called the maximum and minimum RH thresholds in a cloud, respectively.

2.5.3 Pierdicca, Pulvirenti, and Marzano Algorithm

In order to determine the critical relative humidity function, the Pierdicca, Pulvirenti, and Marzano model [57] derives the histogram of RH for each layer of the profiles with presence of clouds. The critical relative humidity function U_c was defined as the

value with 95% of the histogram.

$$U_c = \begin{cases} 3.04394 - 9.97858\sigma + 13.7378\sigma^2 - 5.86410\sigma^3, & 0.344 \leq \sigma \leq 1 \\ 1, & \sigma < 0.344 \end{cases} \quad (2.14)$$

where σ is the ratio between the measured level pressure and the surface level pressure.

2.5.4 Salonen and Uppala Cloud Detection Model

Salonen Uppala (SU) proposed to use a critical humidity function to detect cloud. The critical humidity function [45] used to detect clouds at each measured level is

$$U_c = 1 - \alpha\sigma(1 - \sigma)[1 + \beta(\sigma - 0.5)] \quad (2.15)$$

where the independent parameters $\alpha=1.0$ and $\beta=\sqrt{3}$, σ is the ratio between the measure level pressure and the surface level pressure.

If the measure relative humidity is more than the calculated critical humidity function U_c at the same level, this level is considered to be in a cloud layer. By using this function, the different layers of clouds can be detected and the base and top of cloud can be determined by using linear interpolation.

After processing radiosonde data by using these cloud detection models, it is found that SU model and De90 model has better estimation of cloud base height [21].

2.6 Progress in Cloud Attenuation Studies

For space-to-earth communication system, although the most severe effect is from rain precipitation, for some low margin systems such as VSAT and USAT operating in Ka-band (20/30 GHz) and above, the cloud attenuation should be taken into consideration. In addition, cloud attenuation accounts for a relative large percentage of time for signal attenuation since clouds present more frequently than rain. For a tropical region like Singapore, the situation is even worse due to the high probability of occurrence of convective clouds characterized by a large liquid water content inside the thick layers.

From literature, rain attenuation in the tropical region has been extensively studied [12] [22] [23] [24]. However, the cloud caused attenuation in the tropical region is less investigated. There are several cloud attenuation prediction models reported [19] [45] [58] [59] [60] [61] [62] [63]. However, these models are mainly developed and evaluated using data collected in temperate countries. In their works, Altshuler et al. [58] and Dintelmann et al. [59] attempted to apply regression technique on surface meteorological parameter (i.e., surface humidity) to estimate cloud attenuation. Later in 1991, Salonen and Uppala [45] proposed to use the radiosonde vertical profile to detect the cloud vertical structure and then integrate the cloud liquid water content within the cloud layers to estimate the cloud attenuation. Owing to the microphysical concepts of SU model, it was adopted by ITU-R Recommendation P.840-6 [60]. In 1997, a new approach to estimate cloud attenuation was proposed by Dissanayake et al. [19] [61]. They categorized the clouds into four different types (cumulonimbus, cumulus, nimbostratus, and stratus) using the average cloud properties like vertical/horizontal extension, the liquid water content and their cover. The respective

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

cloud attenuations can then be calculated using the cloud water content where a best-fit log-normal relationship for cloud attenuation distribution was used.

Recently, Luini and Capsoni [62] [64] processed the liquid water content observed by cloud profiling radar onboard the CloudSat Earth Observation satellite, and proposed to scale the statistical cloud attenuation model with the elevation of communication link, especially for low elevation links. In 2017, Lyraset al. [63] proposed a stochastic dynamic model for calculating the integrated liquid water content (ILWC) fields. After applying Mie scattering theory and categorizing the types of cloud, they proposed a cloud attenuation model for frequencies above Ka-band up to the optical range.

It is well-known that water vapor plays an important role for the hydrologic cycle in the Earth [53]. When the amount of water vapor is saturated at a certain temperature, it will condense to form clouds. Therefore, in chapter 7, we will discuss about the correlation between the amount of ILWC and that of precipitable water vapor, and then propose an improved approach for determining the cloud attenuation in the tropical region. In the following, a review of some cloud attenuation models are provided, and different approaches to estimate the liquid water content and cloud attenuation are discussed.

2.6.1 Altshuler and Marr Model

Altshuler and Marr [58] proposed a cloud attenuation model by applying surface meteorological variable in two conditions, i.e., complete cloud cover and partial cloud cover. For complete cloud cover, the attenuation A_c is given by

$$A_c = (-0.0242 + 0.00075\lambda + \frac{0.403}{\lambda^{1.15}})(11.3 + \rho_s)D(\theta) \quad (2.16)$$

where λ is the wavelength in mm, ρ_s is the surface water vapor density in g/m^3 , and $D(\theta)$ is the distance in km through the attenuating layer as shown below,

$$D(\theta) = \begin{cases} \csc \theta, & \theta > 8^\circ \\ [(a_e + h_e)^2 - a_e^2 \csc^2 \theta]^{1/2} - a_e \sin \theta & \theta \leq 8^\circ \end{cases} \quad (2.17)$$

where θ is the elevation angle, $a_e = 8497(km)$ is the effective radius of earth, and $h_e = 6.35 - 0.302\rho_s$ (km) is the effective height of the attenuating layer.

For partial cloud cover, the mixed cloud attenuation A_m is estimated to be

$$A_m = 0.85A_c \quad (2.18)$$

2.6.2 Dintelmann and Ortgies Model

The basic idea in Dintelmann and Ortgies model [59] is that the formation of clouds is due to the condensation of water vapor above the ground level. The cloud attenuation on a communication link with elevation angle θ can be calculated as

$$A_c = \frac{90.88M}{\lambda^2} \Delta / \sin \theta \quad (2.19)$$

where

$$\Delta = 0.15 - 0.023 \times M + 0.0055 \times M^2 \quad (2.20)$$

$$M = \rho_s \frac{T_s}{270} \left\{ 1 - \frac{\kappa - 1}{\kappa} \frac{gH}{RT_s} \right\}^{\kappa/(\kappa-1)} - 3.82 \quad (2.21)$$

$$H = 0.89 + 0.165(T_s - 273) \quad (2.22)$$

λ is wavelength in millimeter, ρ_s is the water vapor density at ground level in g/m^3 , T_s is the surface temperature in K, κ is the specific heat ratio which is equal to 4/3, g is the gravity acceleration and R is the fundamental gas constant.

2.6.3 Salonen and Uppala Model

Salonen and Uppala [45] proposed another method to estimate the cloud attenuation by using radiosonde profile, with consideration of vertical water profile and cloud extent. They firstly developed a critical humidity function to detect different cloud layers, as shown in eq. (2.15).

Then the cloud liquid water content in g/m^3 is calculated by applying the following expression:

$$w = \begin{cases} w_0(1 + ct)\left(\frac{h_c}{h_r}\right)p_w(t), & t \geq 0^\circ C \\ w_0e^{ct}\left(\frac{h_c}{h_r}\right)p_w(t) & t < 0^\circ C \end{cases} \quad (2.23)$$

where t is the temperature in $^\circ C$, h_c is the height of the cloud base in meter, $w_0 = 0.17$ (g/m^3), $c = 0.04$ ($1/^\circ C$) and $h_r = 1500$ (m). The cloud liquid water fraction can be estimated by using the following function:

$$p_w(t) = \begin{cases} 1, & t > 0^\circ C \\ 1 + \frac{t}{20}, & -20^\circ C < t \leq 0^\circ C \\ 0, & t \leq -20^\circ C \end{cases} \quad (2.24)$$

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

The above two expressions are developed by using the cloud properties with different cloud thickness and temperatures. The liquid water droplets are the main components in the clouds. Generally the temperature of cloud with liquid water droplets is higher than 0 °C and the temperature of cloud with ice crystals is lower than around -20 °C. In the middle range of temperature, the cloud is a mixture of ice crystals and water droplets. For the microwave range, the ice cloud is not considered to cause attenuation because the ice dielectric permittivity is nearly real. For the cloud attenuation model, the specific cloud attenuation γ_c (dB/km) can be calculated as

$$\gamma_c = 0.182fN_w''(f) \quad (2.25)$$

where f is frequency in GHz and N_w'' is the imaginary part of water complex refractivity. N_w'' is given as

$$N_w'' = \frac{9}{2} \frac{w}{\varepsilon''(1 + \eta^2)} \quad (2.26)$$

where w is the cloud liquid water density (g/m³) and

$$\eta = \frac{2 + \varepsilon'}{\varepsilon''} \quad (2.27)$$

where ε' and ε'' are the real and imaginary parts of water permittivity. The dielectric spectra for water can be calculated using [65]:

$$\varepsilon'(f) = \varepsilon_2 + \frac{\varepsilon_0 - \varepsilon_1}{1 + (\frac{f}{f_p})^2} + \frac{\varepsilon_1 - \varepsilon_2}{1 + (\frac{f}{f_s})^2} \quad (2.28)$$

$$\varepsilon''(f) = \frac{f(\varepsilon_0 - \varepsilon_1)}{f_p[1 + (\frac{f}{f_p})^2]} + \frac{f(\varepsilon_1 - \varepsilon_2)}{f_s[1 + (\frac{f}{f_s})^2]} \quad (2.29)$$

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

where

$$\varepsilon_0 = 77.66 + 103.3\left(\frac{300}{T} - 1\right) \quad (2.30)$$

$$\varepsilon_1 = 5.48 \quad (2.31)$$

$$\varepsilon_2 = 3.51 \quad (2.32)$$

The principal and secondary relaxation frequencies (GHz) are

$$f_p = 20.09 - 142\left(\frac{300}{T} - 1\right) + 294\left(\frac{300}{T} - 1\right)^2 \quad (2.33)$$

$$f_s = 590 - 1500\left(\frac{300}{T} - 1\right) \quad (2.34)$$

where T is in Kelvin.

2.6.4 DAH Model

Later in 1997, by taking into consideration the different cloud types, DAH Model [19] was developed based on the cloud properties such as the vertical and horizontal extent of clouds and the cloud liquid water density. Taking the properties of the four types of cloud listed in Table 2.1 and assuming the statistical distribution of cloud attenuation follows a log-normal probability law, the specific attenuation γ_{ci} for each cloud type i can be calculated as follows

$$\gamma_{ci} = 0.4343\left(\frac{3\pi w}{32000\lambda\rho_w}\right)Im\left(\frac{1 - \varepsilon}{2 + \varepsilon}\right) \quad (2.35)$$

where w is the cloud liquid water density in g/m^3 , ρ_w is water density = 1 (g/m^3), and $\varepsilon = \varepsilon' - j\varepsilon''$.

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

Table 2.1: Average cloud properties in DAH model

Cloud Type	Vertical Extent	Horizontal Extent	Water Density
Cumulonimbus	3 km	4 km	1 g/m ³
Cumulus	2 km	3 km	0.6 g/m ³
Nimbostratus	0.8 km	10 km	1 g/m ³
Stratus	0.6 km	10 km	0.4 g/m ³

The zenith cloud attenuation A_{ci} can be calculated by the multiplication of the vertical extent with the specific attenuation

$$A_{ci} = \gamma_{ci} H_{ci} \quad (2.36)$$

where H_c is the cloud vertical extent in kilometers.

The four cloud types when arranged in rank order of attenuation provide four points on the conditional cloud attenuation distribution curve A_c , which has the following form:

$$P(A > A_c) = \frac{P_0}{2} \operatorname{erfc}\left(\frac{\ln A - \ln \bar{A}_c}{\sqrt{2}\sigma_c}\right) \quad (2.37)$$

where $P(A > A_c)$ is the probability of A_c not exceeding A , P_0 is the probability when cloud attenuation presents, and σ_c is the standard deviation of A_c . The total cloud cover provides the conditional probability for the cloud attenuation distribution. With the five points selected above, the best fit log-normal relationship for the cloud attenuation distribution is obtained using linear regression analysis.

2.6.5 ITU-R P.840-6 Model

In more recent years, 2013, ITU-R P.840-6 [60] recommendation applied the SU method [45] to EMCWF (European Center for Medium-Range Weather Forecasts)

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

derived vertical profiles to achieve the liquid water content and cloud attenuation in the frequency range below 200 GHz. The ITU-R model provides a global yearly average map of liquid water content statistics.

In ITU-R model, since the clouds only consists of small droplets, the Rayleigh approximation is applied and the specific cloud attenuation can then be calculated as

$$\gamma_c = K_l w \quad (2.38)$$

where γ_c is the specific attenuation (dB/km) within the cloud, K_l is the specific attenuation coefficient ((dB/km)/(g/m³), w is liquid water density in the cloud or fog (g/m³).

By using Rayleigh scattering model, K_l based on dielectric permittivity of water, can be calculated as:

$$K_l = \frac{0.819f}{\varepsilon''(1 + \eta^2)} \quad (2.39)$$

where f is the frequency (GHz). Actually eq. (2.39) is the combination of eq. (2.25) and eq. (2.26) without liquid water content w . All the other variables can be calculated by using eq. (2.27)-(2.30) in Salonen and Uppala model, except for the updated parameters ε_1 , ε_2 , f_p and f_s .

$$\varepsilon_1 = 0.0671\varepsilon_0 \quad (2.40)$$

$$\varepsilon_2 = 3.52 \quad (2.41)$$

$$f_p = 20.20 - 146\left(\frac{300}{T} - 1\right) + 316\left(\frac{300}{T} - 1\right)^2 \quad (2.42)$$

$$f_s = 39.8f_p \quad (2.43)$$

2.6. PROGRESS IN CLOUD ATTENUATION STUDIES

In order to calculate the cloud attenuation along the slant path for a certain probability, the statistics of the integrated cloud liquid water content reduced to a temperature of 0 °C, L_{red} (kg/m^2), can be derived from the digital map provided by ITU-R model, the slant path cloud attenuation can be calculated by

$$A_c = \frac{L_{red}K_l}{\sin\theta} \quad (2.44)$$

where θ is the elevation angle.

To summarize the cloud attenuation models discussed above, it is found that Altshuler and Marr model requires complete/partial cloud coverage information that is commonly difficult to obtain. The SU model applies radiosonde vertical profiles which can have a better vertical resolution, however, due to the low temporal and spatial resolution (typically 2 times per day from meteorological service), it is difficult to determine the cloud attenuation at none-weather- balloon-launching times and sites. However, owing to its strong microphysical theory, the SU model was applied in ITU-R recommendation with a slightly better temporal resolution (4 times per day) provided by EMCWF. The DAH model utilized the properties (water content, horizontal/vertical extent, cloud cover) of four types of cloud. However, they assumed that the distribution of cloud attenuation follows a log-normal probability law and that different cloud types do not occur at the same time. This makes the DAH model also inaccurate.

In addition, all these models were developed and evaluated using data collected in the temperate countries and therefore has limited application to the tropical region [66]. Of these models, the ITU-R model is the most promising as reported by Mandeep et. al. [67]; in fact, the ITU-R model has a good agreement with their Ku-band

measurements in tropical region. However, since this model lacks temporal resolution, it is of great interest to propose a high temporal resolution cloud attenuation model for the tropical region as it is introduced in chapter 7.

2.7 Summary

In this chapter, the background and literature review with related works are introduced. This includes the atmospheric impairments along the satellite propagation link including rain attenuation, gaseous absorption, melting layer effect. The algorithms to detect cloud vertical structure and cloud occurrence are also introduced for comparison in chapter 4; and the different approaches and limitation of existing cloud attenuation models are also pointed out.

Chapter 3

Instrument and Dataset Processing

3.1 Introduction

In order to investigate the different characteristics of clouds and evaluate the accuracy of different models, several instruments and datasets are used in this work and introduced in this chapter. The instruments and database include radiosonde, ceilometer, surface observation data, weather station, S-band dual-polarization radar, beacon receiver and GPS data.

3.2 Radiosonde

A radiosonde is a balloon-borne device, like the one shown in Fig. 3.1, equipped with a radio transmitter and several sensors. It measures the vertical profile of meteorological parameters and send them back to a land-based or sea-based station. During the one

3.2. RADIOSONDE

or two hours ascent of the radiosonde, the sensors measure pressure, temperature, relative humidity, wind speed and wind direction [68] at various altitudes from ground to tens of km.

Figure 3.1: Radiosonde image archived from radiosonde museum of North America

More than 1000 operational radiosonde stations [69] all over the world shown in Fig. 3.2 have joined the World Meteorological Organization's (WMO) World Weather Watch program and share freely their data. In order to prevent signal interference, the meteorological community assigns two radio frequency bands (400-406 MHz and 1675-1700 MHz) for transmitting radiosonde data.

There are two main important applications of radiosondes, one is to analyse current weather condition, and the other is to provide inputs for short and medium range weather forecast models. By processing the worldwide radiosonde data and correlating the data with each other, an instantaneous picture of weather conditions

Figure 3.2: Locations of radiosonde stations

throughout the world can be created. For our project, radiosonde data is mainly used to model the cloud vertical structure and cloud attenuation in the tropical region.

The radio-sounding profiles used for analyzing the cloud attenuation can be obtained from two data sources, both collected by the National Environment Agency (NEA) at Singapore Upper Air Observatory (1.34 °N, 103.89 °E), Station Number 48698 in the WMO network. The radiosonde observation is performed twice a day at time of approximately 00:00 UTC and 10:00 UTC. The relative humidity (0% to 100%), temperature (-60 °C to 30 °C), altitude (0 m to 12000 m) and pressure (180 hPa to 1010 hPa) measured by radiosonde are used to detect the cloud layers and calculate cloud attenuation.

NEA collects the accurate data recorded at 1 second interval. NEA converts the fine resolution data into a coarse resolution version and then puts this into the online

3.2. RADIOSONDE

database [70]. The main difference is the time resolution and the accessibility of the database. In order to find out the feasibility of using the data from online radiosonde database for this research work, a comparison between these two radiosonde data base have been done by calculating the CBH, 0°C isotherm height, and cloud attenuation.

The SU critical humidity function of eq. (2.15) is used to detect the cloud base height. Fig. 3.3 shows the estimated cloud base height for the month of February 2013. From Fig. 3.3, it is observed that the estimated CBH varies from 260 m to 2300 m, where most of heights falls in the range of [350 m, 1000 m]. These values are compatible with seasonal variations of low cloud base height [350 m, 850 m] as reported for a tropical rain forest region [71].

It is also observed in Fig. 3.3 that the plot based on the online data is slightly higher than that from the NEA data. This is because, the online data has a low vertical resolution, and therefore the CBH estimation is less accurate and clouds might be undetected.

For cloud attenuation prediction, 0°C isotherm height is important since it indicates the freezing level. Far beyond this level, the liquid water droplets of a cloud turn to ice crystals, which can be neglected in the cloud attenuation estimation. Fig. 3.4 shows the estimated 0°C isotherm height for the month of February 2013 using the two data sets. From Fig. 3.4, it is found that most of the 0°C isotherm height falls in [4800 m, 5100 m], and good agreement is found between the two plots. As comparing to the height of cloud base, there is a better match for the 0°C isotherm height due to the interpolation applied.

Cloud attenuation as plotted in Fig. 3.5 is calculated for a satellite application

Figure 3.3: Height of cloud base calculated using SU model for two database in Singapore WSSS station in February 2013.

with operating frequency of 30 GHz using the cloud water density and the cloud layer thickness from SU model in eq. (2.23)-(2.25). The attenuation is expected to be higher if a slant path attenuation model is used for satellite to ground propagation link. From Fig. 3.5, the cloud attenuation is observed to vary between 0 dB to 2.1 dB, which agrees well with the cumulative distributions of Ka-band (30 GHz) cloud attenuation as reported in [71]. Slightly high attenuations are observed for the NEA data from Fig. 3.5. This is because its high resolution can detect some thin clouds which could be missed out by the free online data.

Figure 3.4: 0°C isotherm height derived using two database in Singapore WSSS station in February 2013.

Comparison of radio-sounding profiles with different resolutions for cloud attenuation prediction was performed using the SU model [45]. The results show that there is slight difference in the cloud attenuation prediction using the high resolution NEA data and the low resolution online data. The estimated height of cloud base and cloud attenuation are compared with those existing results reported in the literature review and reasonable agreements are observed. Hence, the online radiosonde data will be used to study the cloud attenuation in the tropical region. However, it is noted that there might be an underestimation of the cloud attenuation if there are thin clouds which could be easily missed out due to its low resolution.

Figure 3.5: Cloud attenuation in Singapore WSSS station in February 2013.

In order to derive a cloud detection model suitable for the tropical region, the radiosonde data from 9 tropical stations, each station for Year 2010 to 2013, a total of 36 years, are acquired from the online database.

3.3 Ceilometer

A ceilometer is an instrument to detect the CBH using laser technique. A common ceilometer are made of a laser transmitter and a receiver vertically pointed. When the pulse of laser is sent to the atmosphere, some fraction of the light is scattered

3.3. CEILOMETER

back to the receiver. Then the spatial range z can be calculated by using the time interval δt :

$$z = \frac{c \cdot \delta t}{2} \quad (3.1)$$

where c is the speed of light. Fig. 3.6 shows the Vaisala ceilometer CL31, which is the model used by NEA. It is vertical pointing and is placed at Changi airport (1.37 °N, 103.98 °E) of Singapore.

Figure 3.6: Ceilometer from Vaisala ceilometer CL31 datasheets.

In chapter 4, the ceilometer data for the year 2013 is used to validate the CBH determined by different models. The ceilometer continuously records data at a time interval of 1 minute with a vertical resolution of 5 m. Although the ceilometer claims that it can provide CBH information for up to three layers, the available information of the upper two layers is very limited. Therefore, only the CBHs (0 to 2000 m) of the first layer is used.

3.4 Surface Observation Data

Two types of surface observation data are introduced in this section, one is hourly surface reports (METAR report in this study), and the other is Surface Synoptic Observations (SYNOP report in this study). METAR report can also be obtained from the surface database provided by the University of Wyoming [70]. The raw data are collected at the Changi Airport office of NEA (same as ceilometer). Raw data includes cloud coverage and cloud height information at different levels with an interval of half an hour for Singapore. The cloud data are also processed to allow the comparison of cloud occurrence at low, middle and high levels in chapter 4.

SYNOP is a code used by WMO for reporting and recording the meteorological observations measured by weather stations. The SYNOP reports are recorded twice per day, as for the radiosonde data. The cloud information is represented as N_h, h, C_L, C_M, C_H in cloud group section.

N_h represents the coverage of the low level cloud or the middle level cloud, which plays a critical role in the solar radiation system. Table 3.1 shows the codes that identify different amount of cloud coverage. SYNOP data collected in 2013 are processed to investigate the cloud coverage in Singapore. Since two observations are regularly made per day, there are in total around 700 data points for one year observation. It can be observed that on most days, there is only 1 or 2 oktas of clouds as shown in Fig. 3.7. The readings from SYNOP data is based on the human observation. The human observer looks in all directions around the sky. Therefore, it is difficult to have 7 or 8 oktas cloud coverage since it might be overcast in one direction but clear sky in the other side.

3.4. SURFACE OBSERVATION DATA

Table 3.1: N_h - amount of low level or middle level cloud coverage

Code figure	Amount of cloud
0	0
1	1 okta or less, but not zero
2	2 oktas
3	3 oktas
4	4 oktas
5	5 oktas
6	6 oktas
7	7 oktas or more, but not 8 oktas
8	8 oktas
9	Sky obscured by fog or other meteorological phenomena
/	Observation is not made

Figure 3.7: Histogram of cloud coverage in Singapore WSSS station in 2013.

3.4. SURFACE OBSERVATION DATA

h represents the base height of the lowest cloud above ground surface. Since it is detected by the human observer, the estimation lacks in accuracy and therefore is recorded in terms of ranges rather than actual height as shown in Table 3.2. Data for the year 2013 is shown in Fig. 3.8. Most of cloud base height are observed in range of 300 to 600m. In the next chapter, these CBH estimated by human observer are used to compare with the results estimated by different observations and models.

The WMO general classification consists of 10 categories. Those can be sorted out into three basic groups based on their levels: low level clouds (C_L), middle level clouds (C_M), high level clouds (C_H). According to the shape and structure, C_L can be divided into four types of clouds, which are cumulus, cumulonimbus, stratus, and stratocumulus; C_M represents three types of clouds, which are altostratus, altocumulus, nimbostratus; C_H represents three types of clouds, which are cirrus, cirrostratus, and cirrocumulus.

From [19], six types of clouds are considered to have relatively large liquid water content and large vertical extent. Among these six types of clouds, four types are the low level clouds, they are cumulus, cumulonimbus, stratus and stratocumulus; two types are the middle level clouds, they are altostratus and nimbostratus. However, nimbostratus is extremely rare in Singapore. By processing data for year 2013, the percentage of low level cloud types could be calculated. Cumulonimbus occurs about 22% of the time and it has the largest average water content of 2.5 g/m^3 and largest average vertical height of 2 km. Cumulus occurs about 77% of the time and it has relatively large average water content of 1 g/m^3 and large average vertical height of up to 2 km. Stratocumulus, which occur 0.73% of the time, and stratus, which occurs 0.29% of the time, seldom appear in Singapore. Since they have less water content

3.4. SURFACE OBSERVATION DATA

and small vertical extent, they cause negligible attenuation.

Table 3.2: h - the lowest cloud base height above the surface.

Code figure	Cloud base height
0	0 to 50 m
1	50 to 100 m
2	100 to 200 m
3	200 to 300 m
4	300 to 600 m
5	600 to 1000 m
6	1000 to 1500 m
7	1500 to 2000 m
8	2000 to 2500 m
9	2500 m or more, or no cloud
/	Base height of cloud not known

Figure 3.8: Histogram of cloud base heights in Singapore WSSS station in 2013.

3.5 Weather Station

Davis 7440 [72] weather station is located at the roof top of Nanyang Technological University (NTU). It is equipped with rain gauges, solar radiation sensor and anemometer as shown in Fig. 3.9. Meteorological data are recorded by the weather station every 1 minute, it measures several surface parameters such as pressure, relative humidity, temperature, dew point, rainfall rate, wind speed and direction, and solar radiation. In chapter 6, weather station rainfall rate data (0 mm/hr to 200 mm/hr) for the year of 2014 and 2015 is used to study the occurrence of rainfall near the WINDS satellite beacon receiver.

Figure 3.9: Davis weather station at NTU S2.1 building rooftop

3.6 S-Band Dual-polarization Weather Radar

A dual-polarization weather radar is mainly used to measure rainfall rate, and estimate the type of the precipitation such as rain, snow, hail. It can transmit and receive both horizontally and vertically polarization signals, and provide more detailed information than conventional radar. In addition to traditional reflectivity (Z) and Doppler measurements, linear polarimetric observations [73] include differential reflectivity (Z_{DR}), linear depolarization ratio (LDR), specific differential propagation phase (KDP), and correlation coefficient (ρ_{HV}).

Reflectivity (Z) [73] is related to the power of a horizontally polarized backscattered electric field from a radar resolution volume for a horizontally polarized transmitted wave. It can be used to calculate the rainfall rate. Differential reflectivity (Z_{DR}) is the ratio of the horizontal copolar return to the vertical copolar return. It can be used to discriminate between the oblate rain (high Z_{DR}) and more spherical hail (low Z_{DR}). Linear depolarization ratio is the ratio between vertically polarized power backscattered for a horizontally polarized transmitted wave and copolar backscattered power. Tumbling, wet nonspherical particles such as hail and melting aggregates are identified with large LDR values whereas light rain, cloud droplets, and dry ice particles are associated with low LDR values. Specific differential propagation phase (KDP) is the difference in phase per kilometer of the received horizontal and vertical polarized waves. KDP can be used to identify nonspherical particles, such as ice crystals and raindrops. The correlation coefficient between copolar returns is denoted as correlation coefficient (ρ_{HV}). If values of ρ_{HV} are close to unity, then it indicates rain and pure ice crystals. In the case of melting and mixed phase (rain and hail) conditions, ρ_{HV} is smaller than unity because of the variability in scattering

3.7. BEACON RECEIVER

characteristics of precipitation particles for a given size.

Table 3.3: Radar reflection and rainfall rate

Z	Rainfall Rate (mm/hr)
65	406.4+
60	203.2
55	101.6
52	63.5
47	31.8
41	12.7
36	6.35
30	2.54
20	Trace
<20	No rain

In our study, dual-polarization radar data for the years 2014 and 2015 are processed. Radar reflectivity (-20 dBZ to 65 dBZ), differential reflectivity (-8 dB to 8 dB) and cross-correlation coefficient (0 to 1) are processed to detect the melting layer for stratiform and convective rain cloud in chapter 5. Radar reflectivity is also used to differentiate rain events and non-rain events. The correlation between radar reflectivity and rainfall rate is shown in Table 3.3 provided by NOAA (National Oceanic and Atmospheric Administration) website; it can be concluded that if the radar reflectivity is less than 20 dBZ [74], there is no rain. By applying this criterion, it can be easily deduced if the slant path beacon signal is suffering from rain attenuation. Details on this method are introduced in chapter 6 when deriving cloud attenuation.

3.7 Beacon Receiver

The WINDS geostationary satellite beacon receiver is set up at roof top of NTU, the satellite beacon signal strength (-80 dBm to -40 dBm) is continuously recorded.

3.7. BEACON RECEIVER

Fig. 3.10 shows the WINDS beacon receiver outdoor unit. Table 3.4 lists some of the key parameters of the WINDS beacon signal. Since the beacon signal strength are continuously monitored from the satellite at an average sampling rate of 516 samples per minute, these measured signal strength can be processed and analyzed to derive the rain and cloud attenuation. For the beacon signal processing, after a spectral study, the rapid fluctuation due to tropospheric scintillation is removed using a 6th-order Butterworth filter at a cutoff frequency of 20 mHz [24] [75] [76] [77] [78].

Figure 3.10: Ka-band (WINDS) outdoor system at NTU S2 building rooftop

In order to calculate the cloud attenuation suffered by the beacon signal, the reference signal level should be derived. Since the amplifier gain of the Low-Noise-Block (LNB) down converter varies with temperature, a sliding window technique

3.7. BEACON RECEIVER

Table 3.4: Measurement site and satellites characteristics

	WINDS
Satellite Location ($^{\circ}$ E)	143
Downlink Beacon Frequency (GHz)	18.9 (Ka)
Polarization	RHCP
Antenna Diameter (m)	1.8
Antenna Elevation Angle ($^{\circ}$)	44.5
Antenna Azimuth Angle ($^{\circ}$)	91.64 (E)

is applied to reduce this effect. It should be noticed that the temperature variation can be a result of several factors, such as rain, cloud and daily variation in solar irradiance. In order to find the reference signal level for the beacon signal, the radar reflectivity and weather station rainfall data are used to differentiate the rain and non-rain events. The rain events are isolated and the sliding window technique is applied to the non-rain period of time to derive the non-rain day signal reference level. For the rain events, the sliding window technique is applied to the period of time just before the rain occurred to derive the signal reference level.

Fig. 3.11 shows the Ka-band beacon signal after removing scintillation effect and the derived signal reference level. The radar reflectivity from the top plot shows that there is no rain event on that day. In the middle plot, the red line is obtained after applying the sliding window technique on the beacon signal that is represented by the blue line. After investigating two years of beacon signal data, a window size of 3 hours is chosen since it can detect most of the thick clouds along the slant path of the Ka-band beacon receiver to WINDS satellite. After calculating the difference between the smoothed beacon signal (red line) and the actual beacon signal (blue line), a cloud is considered to be along the slant satellite path when there is a difference in value between the two lines. However, this technique tends to underestimate the cloud attenuation as shown at the 4th to 5th hour in the middle plot, where the beginning

3.7. BEACON RECEIVER

and end of the cloud passing the slant path is missed out. Therefore, a technique to search the local maximum of the beacon signal is applied to find the beginning and ending of the cloud pass. The final signal reference level is derived from beacon signal as shown in the bottom plot by the red line. The same cloud pass between the 4th to 5th hour in the middle plot can be actually over a longer period of time as shown in the bottom plot. After calculating the difference (dB) between the beacon signal (dBm) and the signal reference level (dBm), the cloud attenuation (dB) can be derived.

Figure 3.11: The Ka-band beacon signal for WINDS slant path with derived signal reference level and corresponding radar reflectivity on 27th January 2014.

By applying this technique, most of the cloud passes especially the thick layer of clouds can be detected. However, it also has its limitations as there are still a lot of thin layer of clouds that cannot be detected and taken as clear sky condition (0 dB). Thin clouds are easily missed out for several reasons, signal reference level,

3.8. IGS PWV DATABASE

Ka band cloud attenuation for thin clouds is too small, and scintillation removal. This will affect the probability of cloud occurrence and the statistical results of cloud attenuation for thin layer of clouds in chapter 6 and 7.

After using S-band weather radar to differentiate between the rain and cloud events and applying this sliding window technique to find beacon signal floor, the results can be used to study the cloud attenuation in the tropical region. In chapter 6, two consecutive years (2014 and 2015) WINDS beacon signal data are processed to determine the statistical cloud caused attenuation. This complementary cumulative distribution function (CCDF) of cloud attenuation is used to analyze the results from the proposed cloud attenuation model in chapter 7.

3.8 IGS PWV Database

The International GNSS (Global Navigation Satellite System) Service (IGS), formerly the International GPS Service, is a voluntary collaboration of more than 200 organizations in more than 80 countries. They provide dataset for formulating precise products such as satellite ephemerides and clock solutions [79].

Precipitable water vapor (PWV) is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area between any two specified levels. The PWV values can be determined based on the time delay of the signal traveling from the GPS satellite to the ground receiver. The total delay along the zenith path is called as Zenith Total Delay (ZTD). The ZTD can be partitioned into two parts: Zenith Hydrostatic Delay (ZHD), and Zenith Wet Delay (ZWD). ZHD mainly depends on the surface pressure [80], and the ZWD is a function of the atmospheric

3.9. SUMMARY

water vapor profile. In this thesis, GPS Inferred Positioning SYstem-Orbit Analysis and Simulation Software (GIPSY-OASIS) [81] has been used for the computation of the ZWD.

After ZWD is computed, PWV values [80] are calculated using 3.2.

$$PWV = \frac{PI \cdot ZWD}{\rho_w} \quad (3.2)$$

Here, PI is the dimensionless conversion factor, ρ_w is the density of liquid water. For the tropical region, it has been studied that the PI values are almost constant and equal to 0.163 [82]. Using this procedure, two-year (2013 and 2014) PWV data are calculated for the 8 collocated tropical IGS stations. The resolution of GPS PWV data is 5 minutes. These PWV data will be applied to model the cloud liquid content and cloud attenuation in chapter 7.

3.9 Summary

In this chapter, various instruments and database are introduced for different applications in this thesis. In a summary, the data availability and resolution for each database is listed in Table 3.5.

Radiosonde vertical profile are used to provide inputs for cloud vertical structure and cloud attenuation modelling. Ceilometer and surface observation data are processed for comparison with the cloud vertical structure detection models and evaluate performance of the different models (such as Decker model, SU cloud vertical structure detection model) in chapter 4. S-band dual-polarization radar data are analyzed

3.9. SUMMARY

Table 3.5: Data availability and resolution of different database

Database	Availability	Data Resolution
Radiosonde data	2010-2015	two profiles per day
Ceilometer data	2013	1 minute
Surface observation SYNOP data	2013	two times per day
Surface observation METAR data	2013	30 minutes
Weather station data	2010-2015	1 minute
WINDS beacon data	2014-2015	516 samples per minute
S-band dual-polarization radar data	2014-2015	5 minutes
GPS PWV data	2013-2015	5 minutes

to detect the stratiform and convective rain cloud melting layer. These radar data together with the weather station data are also used to differentiate the cloud attenuation from the rain attenuation. The signal strength collected from WINDS beacon receiver are used to derive the cloud attenuation at Ka band, to be compared with the cloud attenuation models. For IGS PWV database, the PWV values are compared with the cloud liquid water content and the cloud attenuation for the tropical region is calculated.

Chapter 4

Cloud Vertical Structure Analyses and Modelling

4.1 Introduction

Cloud plays a significant role in both the ground-to-space radio communication system and climate system. By influencing the hydrological cycle and the radiation balance, it can cause a wide variation in the weather conditions. Cloud can also cause severe impairment to satellite communications, especially for low-margin systems operating in the Ka-band (20/30 GHz) or above. Moreover, absorption from clouds constituents can affect some sensors. These effects are even more severe for tropical region (e.g., Singapore) due to the high probability of occurrence of convective clouds. Unlike clouds found in other subtropical and temperate regions, these convective clouds are cumulus, extending over high vertical altitudes, and are heavy in liquid water content.

Therefore, cloud detection becomes a very important for remote-sensing applications.

4.2 Cloud Detection Model Comparison

In this section, two major cloud detection methods to detect the cloud and its vertical structure are described; the first one is to adopt a constant threshold of relative humidity, Decker model [42] [43]; the second type is to define a mathematical relationship to calculate a varied threshold for critical humidity (e.g, SU model [45]).

Fig. 4.1 shows the measured relative humidity radiosonde profile and the three critical humidity thresholds. It is observed that for the SU model, its threshold is mostly like a U-bend curve. The Decker model (De95 and De90) uses a constant threshold, not varying with the altitude.

Another observation in Fig. 4.1 is that, in the range less than 7000 m where low and medium clouds (containing high amount of water droplets) exist and contribute significantly in the cloud attenuation, the criteria of SU cloud detection is easy to meet. However for the De95 and De90 models, the criteria (higher critical humidity thresholds in general) is difficult to meet, and this might lead to some misdetection.

Fig. 4.2 shows the results of the CBHs estimated using the models SU, De95 and De90 and the CBHs detected by a ceilometer (CL31) which is used here as reference [49]. From Fig. 4.2, it is found that less accurate cloud detections are observed for De95 model. This is due to its high threshold as discussed. The SU and De90 models present more consistent results with reference to the ceilometer data.

Statistically, with one-month (February 2013) ceilometer data as a reference, the

4.2. CLOUD DETECTION MODEL COMPARISON

Figure 4.1: The measured relative humidity profile versus the cloud detection thresholds.

performance of different models are compared. If the difference in CBH between the ceilometer data and the models are within ± 250 m, the results are assumed to be a correct detection. Therefore, the SU model has a 98% correct CBH detection; the De90 model has an 82% correct CBH detection; while De95 only has a 42% correct CBH detection. It could be concluded that the De95 model with a relatively high threshold has poor performance for cloud detection in the tropical region.

From Fig. 4.2, it is clearly observed that there are some differences between the CBHs detected by the ceilometer and estimated using the SU and De90 models based on the radiosonde data, although both the models have good cloud detection abilities.

4.2. CLOUD DETECTION MODEL COMPARISON

Figure 4.2: Comparison of cloud base height determined using different methods with the ceilometer (CL31) in Singapore in February 2013.

Fig. 4.3 shows the histograms of the difference between the cloud heights detected by the ceilometer and the heights estimated using the SU and De90 models. In the Fig. 4.3, one bin size is taken as 500 m. It can be seen that the SU has more accurate detection in the range of -250 m to 250 m, whereas the De90 model intends to have a larger variation. Another possible reason for such a deviation may be due to the low resolution of the online radiosonde data used.

In this section, comparison and analysis of different cloud models are performed for the detection of clouds and its CBH in the tropical region. To evaluate the cloud detection ability of the three models (SU, De95 and De90), the critical humidity

4.2. CLOUD DETECTION MODEL COMPARISON

Figure 4.3: Histograms of the difference between the CBHs detected by the ceilometer and the heights estimated using the SU and De90 models in Singapore in February 2013.

threshold and the CBH with the ceilometer data as reference are presented. The results indicate that for the De95 model, the threshold for cloud detection is too high and therefore difficult to reach, while the SU and De90 models are found to be better in the tropical region, especially the SU model. However, it is noted that all these cloud detection models mentioned above are based on a single weather related parameter: the relative humidity. These models are also developed using the meteorological data collected in temperate region. Therefore in the following section, a new model is developed to detect cloud vertical structure in the tropical region and the results are compared with the SU model.

4.3 Methodology for Water Vapor Pressure Cloud Detection

Water vapor is very important for the hydrologic cycle in the Earth. It can be continuously produced by evaporation from the river or sea and it can turn to be clouds by condensation. Finally the clouds will precipitate in the form of rain and/or snow and fall back onto the Earth's surface. The amount of water vapor suspended in the atmosphere and the temperatures of water vapor are the two key factors contributing to the formation of clouds. Water vapor pressure (WVP) relying on these key factors should have some positive correlation with the cloud.

Since the condensation of water vapor is a source of cloud formation, correlation of the WVP (affecting the condensation and evaporation of water vapor) with the cloud vertical structure should be very obvious. Thereby WVP can be a good parameter for cloud detection.

In order to calculate the WVP at different atmospheric levels, RH and temperature data from radiosonde vertical profiles are used [83, 84]

$$WVP = RH \times \exp(-37.2465 + 0.213166T - 2.56908 \times 10^{-4}T^2) \quad (4.1)$$

where RH is the relative humidity in percentage, T is the absolute temperature in degrees Kelvin, and WVP stands for the water vapor pressure in hPa.

An example of the water vapor pressure at different levels is shown in Fig. 4.4(a), It can be easily observed that the water vapor pressure has a negative exponential relationship with the altitude. In order to properly and accurately estimate the expo-

4.3. METHODOLOGY FOR WATER VAPOR PRESSURE CLOUD DETECTION

Table 4.1: 9 Radiosonde stations selected in the tropical region

Station ID	Location	Lat.	Lon.
WAAA	Hasanuddin Ujung AB, Indonesia	5.06 °S	119.5 °E
WSSS	NEA Upper Air Observatory, Singapore	1.34 °N	103.89 °E
WIMM	Medan Polonia MIL, Indonesia	3.57 °N	98.68 °E
DIAP	Abidjan, Cote d'Ivoire	5.25 °N	3.93 °W
VOMM	Madras Minambak, India	13.00 °N	80.18 °E
MMAA	Acapulco G. Alvarez, Mexico	16.77 °N	99.75 °W
MKJP	Norman Manley Kings, Jamaica	17.93 °N	76.78 °W
MDSD	Caucedo De Las Amer, Dominican Republic	18.43 °N	69.67 °W
MWCR	Owen Roberts Intl., Cayman Islands	19.28 °N	81.35 °W

nential relationship, 36 years of radiosonde data (totally 891,710 data points) collected at 9 different locations (shown in Table 4.1) in the tropical region have been processed using regression techniques.

Fig.4.4(b) presents the variation of water vapor pressure versus altitude. It can be observed that below around 12000 m, the water vapor pressures have large variations. This variation is due to the change of relative humidity and temperature on different days which could indicate the appearance of cloud.

A critical water vapor pressure function (Red solid line in Fig.4.4(b)) for cloud detection is determined by applying the exponential curve-fitting technique on the dependent variable (water vapor pressure) and the independent variable (altitude) in the form

$$WVP_c = a \times \exp(b \times Alt) \quad (4.2)$$

where Alt is the altitude in meters, and WVP_c is the critical water vapor pressure threshold in hPa. Through least square regression technique, empirical values for the two parameters a and b are derived to be 28.81 and -0.0004363. The applicable ranges for cloud vertical structure is from 0 to 12000 m.

4.3. METHODOLOGY FOR WATER VAPOR PRESSURE CLOUD DETECTION

(a)

(b)

Figure 4.4: Water vapor pressure at different altitude levels (a) one data set, (b) 36 years of radiosonde data collected from 9 locations in tropical region with curve fitting.

4.4. CLOUD VERTICAL STRUCTURE

The criterion of cloud detection proposed in this study is: if the measured water vapor pressure is larger than the critical water vapor pressure threshold given in eq. (4.2) at the same level, this level is assumed to be in cloud.

Wang and Rossow [44] have reported that if the detected cloud base is lower than 500 m above the ground level, the cloud layer shall be discarded. However for the tropical region, the seasonal low-level CBHs are found to vary from 356 to 820 m as reported in [71]. Therefore the baseline of 500 m reported in [44] may not be applicable for the tropical region. For this study, the baseline will be adjusted to about 300 m for our cloud detection model. Furthermore, since most of water vapor pressure variations are below around 12000 m, an upper applicable range of 12000 m is assumed.

In the next section, our proposed cloud detection model (WVP model) given in eq. (4.2) will be compared and verified with existing models and meteorological data sets.

In order to evaluate the performance of WVP model, comparisons with the SU model, De90 model, human observations, ceilometer measurements, and hourly surface report are carried out.

4.4 Cloud Vertical Structure

The cloud vertical structure detected by the SU model, De90 model, and WVP model are compared using the simultaneous radiosonde data. Fig. 4.5 shows an example of cloud detection at 10:00 UTC on 22nd October 2013. As shown in Fig. 4.5(a)), if the

4.4. CLOUD VERTICAL STRUCTURE

measured WVP is above the WVP threshold given by eq. (4.2), it indicates that a cloud is present. The red squares represent the cloud detected by the WVP model. One thick layer of cloud can be observed in Fig. 4.5(a), and the cloud is from around 500 m to 8000 m. Fig. 4.5(b) shows the cloud detected by the SU model and the De90 model in comparison with the cloud detected by the WVP model (red squares). The De90 model could only detect one thin layer of cloud at around 5500 m. As stated in last section, the De90 model is found to be inaccurate for the detection of clouds and is seldom used for the tropical region. Cloud detected by the SU model is shown by the green dots in Fig. 4.5(b): low level clouds from 1000 m to 1900 m and middle level clouds from 2000 m to 7500 m. Comparing both the WVP model and the SU model, both models indicates an existence of thick clouds stretching from a low level up to high level. However, the SU model has split the thick clouds into two layers whereas the WVP model has detected one thick layer. In addition, the cloud base heights and cloud top heights are slightly different.

To further compare the performance of the three cloud detection models, cloud images taken by a Whole Sky Imager [85] at NTU is shown in Fig. 4.6. It is observed that the sky is overcast with dark thick low level cloud around the same time of the cloud detection in Fig. 4.5. Although there is a site difference between the radiosonde observation site and the NTU whole sky imager site, due to the small size of the tropical country of Singapore, this heavy low level cloud is covering the whole island. Therefore, the image can be used to show the existence of a thick low level cloud as estimated by the empirical models of the SU model and our WVP models.

4.4. CLOUD VERTICAL STRUCTURE

(a)

(b)

Figure 4.5: Cloud vertical structure detection and comparison by (a) WVP model (b) De90 model, SU model, and WVP model in Singapore WSSS station at 10:00 UTC on 22nd Oct 2013.

Figure 4.6: Cloud image taken by whole sky imager at NTU at 10:00 UTC on 22nd Oct 2013.

4.5 Cloud Occurrence in Different Levels

Cloud occurrence is classified into 3 categories according to the CBH above ground level. They are typically low level cloud with CBH from 0 to 2000 m, middle level cloud with CBH from 2000 m to 5000 m, and high level cloud with CBH above 5000 m (referred to the METAR report). The occurrences of cloud determined by the SU and WVP models are classified into the 3 corresponding levels as stated above for comparison purposes. For the SYNOP and METAR reports, the cloud data have

4.5. CLOUD OCCURRENCE IN DIFFERENT LEVELS

already been categorized into the 3 different levels.

Table 4.2 shows the comparison of the percentage of cloud occurrence detected by the SYNOP and METAR reports. It should be noted that the SYNOP data is collected at NEA upper air observatory site whereas METAR data is collected at a different location at Changi Airport site, 12 km apart shown in Fig. 4.7. It can be observed that for low level clouds, the detection is consistent, with more than 97% of the time with clouds detected by both the SYNOP and METAR reports. This is due to the large coverage area of low level clouds. However, for middle level and high level clouds, around 40% and 39% of the time respectively, both reports detected clouds. This is due to the different geographical locations of the two observation sites. METAR reports being collected at the east coast of Singapore, tends to experience less cloud and rain events as reported in [86].

Figure 4.7: Site difference between NEA upper air observatory and Changi airport.

To analyze the performance of our proposed WVP model, a comparison with the

4.5. CLOUD OCCURRENCE IN DIFFERENT LEVELS

Table 4.2: Comparison of cloud occurrence between METAR report and SYNOP report in Singapore in 2013*

Low Level		SYNOP	
		clear sky	cloudy
METAR	clear sky	0	0.86
	cloudy	1.86	97.28
Middle level		SYNOP	
		clear sky	cloudy
METAR	clear sky	3.15	55.87
	cloudy	0.86	40.11
High level		SYNOP	
		clear sky	cloudy
METAR	clear sky	1.29	57.74
	cloudy	1.58	39.40

* All the numbers shown in Table 4.2 are in the unit of %.

SU model is done. Table 4.3 summarizes the percentages of matched and unmatched cloud occurrence from the two models and from the SYNOP and METAR data for the year 2013 in Singapore. The total number of observations is 698 instead of 730 due to some missing radiosonde data. As shown in Table 4.3,

- M1 represents the percentage of the cases in which neither the models nor the SYNOP/METAR report data indicate the cloud occurrence simultaneously. For example, for 0.43% of the time, both the SU model and SYNOP data did not detect any low level clouds, while for 0.29% of the time, both the SU model and the METAR data did not detect any low level clouds. Similarly, both the proposed WVP model and the SYNOP data did not detect any low level clouds for 0.43% of the time, while both the WVP model and METAR data did not detect any low level clouds for 0.14% of the time.
- S is the percentage of the cases in which the model doesn't detect any cloud while the SYNOP/METAR report data indicate a cloud,

4.5. CLOUD OCCURRENCE IN DIFFERENT LEVELS

- R is the percentage of the cases in which the models detects a cloud while the SYNOP/METAR report data indicate no cloud, and
- M2 represents the percentage of the cases in which both the model and the SYNOP/METAR report data indicate the cloud occurrence.

For the total matched cases, the percentage is the summation of M1 and M2; while for the unmatched cases, the percentage is the summation of S and R.

Table 4.3: Comparison of cloud occurrence from models (SU and WVP) and observation reports (SYNOP and METAR) in Singapore in 2013*

Low level	SYNOP/METAR report			
Model	M1	S	R	M2
SU	0.43/0.29	19.63/19.77	1.43/0.57	78.51/79.37
WVP	0.43/0.14	2.15/2.44	1.43/0.72	95.99/96.70
Middle level	SYNOP/METAR report			
Model	M1	S	R	M2
SU	0.86/6.30	6.88/1.43	3.15/52.72	89.11/39.54
WVP	0.43/2.58	2.44/0.29	3.58/56.45	93.55/40.69
Low level	SYNOP/METAR report			
Model	M1	S	R	M2
SU	0.43/21.06	23.07/2.44	2.44/37.97	74.07/38.54
WVP	0.29/3.01	3.15/0.43	2.58/56.02	93.98/40.54

* All the numbers shown in Table 4.3 are in the unit of %.

As observed from Table 4.3, for low level cloud occurrence, the WVP model has more than 90% correct detection. To illustrate, the correct detection of the WVP model compared to the SYNOP data is $95.99\% + 0.43\% = 96.42\%$ and the correct detection of WVP model compared with the METAR data is $96.70\% + 0.14\% = 96.84\%$. It can also be seen that the correct detection of the SU model for low level cloud occurrence, compared with the two report data is only around 80%. This is 16% less accurate than our proposed WVP model, although both models are relatively accurate for low level cloud detection. For middle level cloud occurrence, the two

4.5. CLOUD OCCURRENCE IN DIFFERENT LEVELS

models match the SYNOP report data well, and both have more than 90% matched cases. For high level cloud occurrence, the two models match the SYNOP report data at about 75% for the SU model and 94% for the WVP model. The proposed WVP model has a higher accuracy for cloud detection at high level. However, there are fewer cases of matching between both models and METAR data as compared to the SYNOP data as shown in Fig. 4.8. This is due to the difference in location between the two measurement sites (Fig. 4.7). The radiosonde data used in the SU and WVP models and the SYNOP report data both are collected at the same NEA upper air observatory site, while the METAR data is collected at the Changi Airport site (12 km away).

The conclusion can be summarized in Fig. 4.8. As shown, the proposed WVP model almost always compares better with the SYNOP data. This shows a higher accuracy for cloud structure determination as compared to the existing SU model. Another conclusion is that the SYNOP data always compares better with the two models as compared to the METAR data. This is due to the geographical location of the measurement sites, which can be also observed from Table 4.3. Note that the low level cloud detection by both the SU model and the WVP model compared to both SYNOP and METAR data are relatively better as compared to middle and high level cloud detections. This might be due to the likelihood of a low level cloud having a larger horizontal extension as compared to middle level and high level clouds.

Figure 4.8: Percentage of the matched cloud occurrence cases of SU/WVP model comparing with SYNOP/METAR in Singapore in 2013.

4.6 Cloud Base Height

CBHs are taken as the lowest heights estimated by the two models (the SU and WVP models), by human observations and by the first layer CBH from ceilometer measurements. The CBHs obtained from these four methods are compared at the same time.

4.6. CLOUD BASE HEIGHT

Fig. 4.9 shows one year (2013) comparison of ceilometer measurements and human observation data, with the results estimated by the SU and WVP models in Singapore. The number 0 to 9 (same as Table 3.2) represents different ranges according to the SYNOP human observation criteria. It is obvious that for bin 4 (300 m to 600 m), the detected CBHs by the SU model deviates quite a lot from the CBHs detected/observed by the WVP model, ceilometer and SYNOP report data. The later three methods have very similar performance as shown in Fig. 4.9 . Furthermore, it can be observed that our proposed WVP model have a very good agreement with the ceilometer and SYNOP report data in the range 4 and 5 where most of the low-level CBHs exist in this region.

Since the ceilometer data have been widely used to verify the CBH [46] [47] [48] [49] [50], we compare the CBHs estimated by the SU model and WVP model with ceilometer determined CBH. Fig. 4.10 shows the scatter plots of CL31 data versus the estimated CBHs for the year of 2013. The upper limit of CBH is set to 2000 m since most of CBHs (99.14% for Singapore for 2013) falls into this range. As indicated in [49], if the difference in CBH between the ceilometer data and the models are within ± 200 m, the empirical models are assumed to have a correct detection.

Two red slant lines representing the accurate detection are plotted in Fig. 4.10 for a clear illustration. If the CBH data falls within the range of the two lines, it can be assumed that the model has a correct detection. Fig. 4.10(a) shows the correlation between results of the SU model and the CL31. It can be observed that around 25% of the total data is within the lines and can be regarded as correct detection. It is also observed that, the SU model tends to overestimate the CBH. This is shown by the large portion of data below the lower limit slant line. For our proposed WVP model

Figure 4.9: Histogram of CBHs from SU model, WVP model, ceilometer and human observation in Singapore in 2013.

in Fig. 4.10(b), it is obvious that around 60% of the CBH data are concentrated in the range of ± 200 m, within the two lines. Although there are still some falling beyond the limits, the proposed WVP model clearly has higher detection accuracy as compared to the SU model for the tropical region.

The outliers in the detection results may be due to the slight time difference of the ceilometer data and the radiosonde data. The balloon of the radiosonde needs some rising time to hit the cloud base, and this period is relatively uncertain depending on the rising velocity of the balloon, the wind speed and wind direction. Furthermore,

4.6. CLOUD BASE HEIGHT

(a)

(b)

Figure 4.10: Scatter plot of CBH measured by CL31 with (a) CBH estimated by SU model (b) CBH estimated by WVP model in Singapore in 2013.

4.6. CLOUD BASE HEIGHT

the exact releasing time for the radiosonde is not fixed, which also leads to additional error.

Another reason might be due to the site difference (less than 12 km) between radiosonde observation site and ceilometer detection site as shown in Fig. 4.7. If the cloud does not extend widely in the horizontal direction, detection errors will exist.

Fig. 4.11 shows the histograms of actual difference between the ceilometer data and the results estimated using the two models. The bin size is set as 400 m so that the bin at zero represents a correct detection where the difference is within ± 200 m. It can be observed that, in 2013, the SU model has around 25% correct detection as compared to the WVP model which is more than 60%.

To further verify our proposed WVP model, radiosonde data from other tropical regions are processed using the same procedures. Two locations in Central America, Mexico (MMAA) and Dominican Republic (MDSD) are used in this study. For these two sites, the CBHs estimated using the SU model and the WVP model are also compared with the METAR CBH data for low level clouds.

The statistical information for correct detection of CBH (within ± 200 m) by the two models is summarized in Table 4.4. From Table 4.4, it is found that, the WVP model has more than 60% correct CBH detection, while the SU model has less than 30% correct CBH detection. Therefore, it can be concluded that the proposed WVP model has a better detection capability than the traditional SU model and is more suitable for CBH detection within the tropical region.

4.6. CLOUD BASE HEIGHT

Figure 4.11: Histograms of difference between the CBHs detected by the ceilometer and the heights estimated using the SU and WVP models in Singapore in 2013.

Table 4.4: Correct detection rate of CBH from comparing SU and WVP models with ceilometer/METAR data

Station ID	Correct Detection Rate	
	SU	WVP
WSSS	22.54%	62.75%
MMAA	16.56%	62.03%
MDSD	28.02%	62.70%

4.7 Summary

A new method for the detection of cloud vertical structure is proposed in this chapter. The method is based on a critical water vapor pressure model estimated from 36 sets of vertical radiosonde profiles collected in 9 different locations in tropical regions over a period of 4 years. This model is used as a detection threshold. It uses the water vapor pressure, a function of both the temperature and relative humidity, instead of only the relative humidity as is traditionally done.

The estimated results of cloud vertical structure using our proposed WVP model is compared with the results from the SU model and ceilometer data. Furthermore, the results from two types of observation data, the SYNOP and the METAR data are also compared and verified. Analysis shows that the proposed WVP model is able to detect the cloud vertical structure better than the existing SU model. Through a comparison of the WVP model and the SU model on CBH estimation for other tropical countries, it is concluded that the proposed WVP model is significantly better suited for the detection of CBHs for the tropical region. This is because instead of using only the relative humidity for cloud vertical structure determination, both the temperature and relative humidity are used in the cloud vertical structure detection. In addition, since the WVP model is derived using tropical region data, it is suitable for the tropical region.

Chapter 5

Melting Layer Detection for Stratiform and Convective Rain Clouds in Tropical Region

5.1 Introduction

The melting layer is related to the effective rain height, where the snow precipitation are turned into rain precipitation. At this height, melting layers often causes the increase in radar reflectivity, which is known as the radar bright band. The study of the characteristics of melting layer is very important for accurate estimation of rainfall and microphysical characterization of the clouds.

For radar remote sensing applications and satellite-to-earth communications, the melting layer can cause both attenuation and scattering at microwave frequencies. In

5.2. IDENTIFICATION OF MELTING LAYER FOR DIFFERENT RAIN CASES

tropical region, convective rain dominates the number of rain events, however, the knowledge of melting layer for convective rain is very limited. In this chapter, the dual-polarization radar data are processed to identify both stratiform and convective rain melting layer in the tropical region of Singapore.

5.2 Identification of Melting Layer for Different Rain Cases

To investigate and identify the characteristics of melting layers in the tropical region, the dual-polarized radar data from three different categories of rains are processed and analyzed. The three different rain categories include stratiform rain only, convective rain only, and stratiform rain together with convective rain. The radar PPI (Plan Position Indicator) image of the reflectivity measurement (Z) for each rain case is plotted in Fig. 5.1 over a 200 km square area.

As shown in Fig. 5.1, the center is Changi airport where the dual-polarized radar is located. Since the height information is very important for melting layer detection, the contour lines indicating the heights of the pixels are included in the figures. The contour lines at 2 km intervals are specified as shown in Fig. 5.1. For the 5° elevation angle, the maximum height is 10 km for the range of 200 km.

In Fig. 5.1(a), high reflectivity is observed at a height of around 4 km, which are due to the bright band effect of stratiform rain melting layer. Similar effect can be also observed in Fig. 5.1(c) in the south western part at a similar height of around 4 km. For convective rain event shown in Fig. 5.1(b), no bright band effect can be observed since the large reflectivity spreads over the height ranging from ground level to around 5 km. In this rain region, the maximum reflectivity is recorded to be

5.2. IDENTIFICATION OF MELTING LAYER FOR DIFFERENT RAIN CASES

(a)

(b)

5.2. IDENTIFICATION OF MELTING LAYER FOR DIFFERENT RAIN CASES

Figure 5.1: Dual-polarized radar PPI images of Z for (a) stratiform rain only, (b) convective rain only, and (c) stratiform rain together with convective rain.

56 dBZ, which is equivalent to a rainfall rate of 115 mm/hr based on the Marshall-Palmer formula [87]. This high rainfall rate clearly is categorized as convective rain as reported in [88]. Similar convective rain cell can also be observed in Fig. 5.1(c) in the northern part. The maximum reflectivity in the northern part of Fig. 5.1(c) is at 57.5 dBZ (i.e., rainfall rate of 143 mm/hr) which clearly indicates a convective rain event. Therefore it is clear from Fig. 5.1(a) and (c) that for the stratiform rain, large reflectivity is concentrated in the melting layer area with similar altitude, the bright band, while for the convective rain the high reflectivity spreads across a vertical range from ground level to 5 km and therefore, the melting layer cannot be easily identified.

To detect the melting layer accurately, as reported in the Giangrande model [27],

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

three measurements (Z , Z_{DR} , ρ_{HV}) from the dual-polarized radar should be processed and analyzed. Taking the stratiform rain together with convective rain case in Fig. 5.1(c) as an example, radar PPI images of ρ_{HV} and Z_{DR} at the same moment are plotted in Fig. 5.2. In Fig. 5.2(a), a light circle ring with ρ_{HV} around 0.95 can be observed at the height around 4 km indicating the melting layer. The height of convective rain melting layer in the northern part is found to be slightly higher between 4 km to 5 km as compared to the stratiform rain melting layer in the south western part. In Fig. 5.2(b) for stratiform rain region, the maximum value of differential reflectivity Z_{DR} can be found around the melting layer area region, however for the convective rain region, it is scattered. Similar patterns are also observed for all other rain events processed. Therefore, among these three measurements (Z , Z_{DR} , ρ_{HV}), it can be concluded that ρ_{HV} is the best indicator for melting layer detection, since it has the ability to detect both the stratiform and convective rain melting layers. In the next section, the differentiation of the two types of stratiform and convective rain melting layers will be carried out. By processing the three parameters (Z , Z_{DR} , ρ_{HV}) of radar measurements along the slant path from each type of rain events, the characteristics of stratiform and convective rain melting layers will be analyzed and discussed.

5.3 Differentiation between Stratiform and Convective Rain

In order to better understand the characteristics of stratiform rain and convective rain cells, a method to differentiate these two types of rain is proposed in this section. By considering the top height of the melting layer to be at the 0 °C isotherm height and the thickness is around 500 m [27] [89] [90], it is noted that in the tropical region,

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

(a)

(b)

Figure 5.2: Dual-polarized radar PPI images of (a) ρ_{HV} , and (b) Z_{DR} in Singapore at 05:45 UTC on 21st April 2014 with an elevation angle of 5°

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

the height of stratiform rain melting layer is typically within 3 km to 5 km [37] [91].

The proposed method for the classification of the stratiform rain cell and convective rain cell in this study is given as such:

(i) a reflectivity of 30 dBZ [27] is taken as the threshold for melting layer detection, if the maximum reflectivity is above or equal to the threshold within the height range of 3 km to 5 km, then this ray is considered to be passing through the stratiform rain cell.

(ii) with the same threshold of 30 dBZ, if the maximum reflectivity is above or equal to the threshold within the height range of 1 km to 3 km, then this ray is considered to be passing through the convective rain cell.

After classifying all the slant rays, a clear separation of the stratiform rain cell and the convective rain cell from Fig. 5.1(c) is plotted in Fig. 5.3. It can be observed that the bright band area from stratiform rain melting layer is clear in the south western region of the plot. Although the convective rain cell can be identified in the northern region of the plot, there is no clear indication of the melting layer for the convective rain cell.

Therefore, in order to identify the convective melting layer and better understand the stratiform melting layer, the vertical profiles of ρ_{HV} , Z and Z_{DR} for the two categories of rain cells are combined and averaged across the same height along each slant ray. The averaged vertical profile of the radar 3 parameters for the convective rain cell and the stratiform rain cell is presented in Fig. 5.4. The vertical red line in Fig. 5.4(a) is a reference line representing $\rho_{HV}=0.97$ [27]. The lower and upper boundary of the melting layer can be identified from the interception point between the

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

Figure 5.3: Radar reflectivity PPI for two separated rain events in Singapore at 05:45 UTC on 21st April 2014

measured ρ_{HV} and the red line. The horizontal black line in Fig. 5.4(a) indicates the minimum point of the measured ρ_{HV} within the melting layer. From Fig. 5.4, it can easily be seen that for the stratiform rain event, as indicated by the Giangrande model, the maximum value of Z and Z_{DR} in Fig. 5.4(b) and (c) respectively corresponds well to the minimum value of ρ_{HV} in Fig. 5.4(a) by the black line in all plots. This occurs roughly around the same height of 4 km.

However, for the convective rain event, there is no obvious maximum in the Z and Z_{DR} values in Fig. 5.4(b) and Fig. 5.4(c) respectively. Two local maximums can be observed around the height of 2.5 km. However, this is not the melting layer height

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

5.3. DIFFERENTIATION BETWEEN STRATIFORM AND CONVECTIVE RAIN

Figure 5.4: Averaged vertical profiles of (a) ρ_{HV} , (b) Z and (c) Z_{DR} at the same height for convective rain cell and stratiform rain cell in Singapore at 05:45 UTC on 21st April 2014.

for a convective rain cell in the tropical region. In [91], the 0 °C isotherm heights for tropical region are reported to be typically within the range of [4.2 km, 5.5 km]. It is reported in [27] [92] [93] that the 0 °C isotherm height is generally taken as the top boundary of melting layers. Examining the value of ρ_{HV} along the slant path of the convective rain cell in Fig. 5.4(a), by using a threshold of $\rho_{HV} < 0.97$, the melting layer height of the convective rain cell can be detected. In addition, it can be observed that the ρ_{HV} minimum level of melting layer in the convective rain region is around 0.5 km higher than that of the stratiform rain region, which is also discussed in [40].

In summary, the results show that the cross-correlation coefficient ρ_{HV} can indicate the melting layer height not only for stratiform rain cells but also for convective

5.4. PROPOSED THRESHOLD FOR CONVECTIVE RAIN MELTING LAYER DETECTION

rain cells. The variation and the maximum value of Z and Z_{DR} are not so useful for convective rain cell melting layer detection.

5.4 Proposed Threshold for Convective Rain Melting Layer Detection

After processing two-year dual-polarized radar data by using the same differentiation and categorization methods as discussed in previous section, 13 convective rain events with corresponding melting layers found via the radiosonde temperature profiles in the years 2014 and 2015. These events are listed in Table 5.1 with their corresponding date and time information. Since the top boundary of the melting layer is typically located where the 0 °C isotherm height is [27] [92] [93], the vertical profiles of temperature data measured by the radiosonde are processed in order to retrieve the 0 °C isotherm height. In Table 5.1, the convective rain with melting layers detected are found to have the corresponding radiosonde measurements (at 00:00 UTC and 10:00 UTC) of 0 °C isotherm height within 6 hours. The time difference for these events can be as small as 1 hour to as large as 5 hours and 40 minutes. Due to the limitation in radiosonde data resolution, linear interpolation technique is applied to the temperature and height data. From Table 5.1, it can be observed that for these recorded events, the range of 0 °C isotherm height is from around 4500 m to 5100 m with very small variations throughout the whole year. This is because Singapore is in the equatorial region where seasonal temperature fluctuation is very small compared to the subtropical and temperate regions.

In order to determine the threshold value of ρ_{HV} for the detection of the top

5.4. PROPOSED THRESHOLD FOR CONVECTIVE RAIN MELTING LAYER DETECTION

Table 5.1: Convective rain melting layer events with closest radiosonde data

Event	Time (UTC)	Time Difference	0°C Isothermal Height (m)
04 Jan 2014	18:40	5hr 20min	4775
05 Jan 2014	20:25	3hr 35min	4663
21 Apr 2014	05:45	4hr 15min	5102
05 Jun 2014	06:15	3hr 45min	4898
14 Jun 2014	05:50	4hr 10min	5090
30 Nov 2014	23:00	1hr	4820
04 Dec 2014	01:25	1hr 25min	4741
12 Aug 2015	02:20	2hr 20min	4764
01 Oct 2015	21:40	2hr 20min	4578
27 Oct 2015	21:00	3hr	4727
08 Dec 2015	18:20	5hr 40min	5041
12 Dec 2015	14:10	4hr 10min	4999
13 Dec 2015	07:45	2hr 15min	4955

boundary of the convective rain cell melting layer and ensure that this detected top boundary corresponds to the 0 °C isotherm height obtained from the radiosonde data, the 0 °C isotherm height with its corresponding ρ_{HV} for each convective rain cell is plotted in Fig. 5.5. Among the recorded events, the time difference between the recorded dual-polarized radar data and the closest radiosonde data are divided into 3 categories: 2 convective rain cells are detected within 2 hours of the radiosonde, 6 convective rain cells are detected within 3 hours and all the events are within 6 hours as listed in Table 5.1.

From Fig. 5.5, the ρ_{HV} values at 0 °C isotherm heights for all the 13 events fall into the range of 0.94 to 0.965, which are all less than the threshold of 0.97 proposed in the Giangrande model [27]. Therefore, for the convective rain cell melting layer detection, the threshold of 0.97 is too high and can cause overestimation. From the analysis of results shown in Fig. 5.5, data with less time difference is found to be more concentrated together due to the relatively small drifting effect. In order to propose

5.4. PROPOSED THRESHOLD FOR CONVECTIVE RAIN MELTING LAYER DETECTION

Figure 5.5: Scatter plot between the 0 °C isotherm height and the corresponding ρ_{HV} value for convective rain melting layer in Singapore.

an appropriate ρ_{HV} value for convective rain cell melting layer detection, we focus on the data with 0 °C isotherm height that is less than 3 hours apart. It can be observed that most of ρ_{HV} values are around 0.95 in Fig. 5.5.

Therefore, the proposed criterion for convective rain cell melting layer detection in this study is given as:

Convective rain cell: if the measured cross correlation coefficient ρ_{HV} is smaller than 0.95, this level is assumed to be in the melting layer.

5.5 Performance Evaluation of Proposed Threshold

In order to evaluate the performance of the proposed threshold for detecting the top boundary of the convective rain melting layer, a scatter plot between the 0°C isotherm height and the top boundary of the melting layer detected by the new proposed threshold and by the Giangrande model [27] are both plotted in Fig. 5.6. The black line is $y = x$, which represents when the height of the melting layer top boundary is equal to the 0°C isotherm height. From Fig. 5.6, it can clearly be observed that the top boundary of the melting layer detected by using the new proposed threshold ($\rho_{HV} = 0.95$) are much closer to the 0° C isotherm heights, and the threshold ($\rho_{HV} = 0.97$) from the Giangrande model tends to overestimate the convective melting layer top heights.

By applying the new proposed threshold ($\rho_{HV} = 0.95$), the melting layer top and bottom heights are estimated for each convective rain cell. By taking the difference between the melting layer top height and bottom height, the thickness of the convective rain cell melting layer can be determined. The histograms of convective rain melting layer thickness by using the two different thresholds (proposed threshold of 0.95 and Giangrande threshold of 0.97) are plotted in Fig. 5.7 with the bin size of 250 m. It can be observed that for the convective rain melting layer thickness detected by the proposed threshold ($\rho_{HV} = 0.95$), the minimum thickness is around 500 m, and the maximum is around 1500 m with most of the thickness around 1000m. While for the convective rain melting layer thickness detected by using the Giangrande threshold ($\rho_{HV} = 0.97$), the minimum thickness is around 1250 m, and maximum is around 2500 m with most of the thickness around 1750 m. As discussed in the previous section, the threshold from the Giangrande model tends to overestimate the convective

Figure 5.6: Scatter plot between 0°C isotherm height and convective rain melting layer top height detected using two different thresholds in Singapore.

melting layer top heights, therefore it also overestimate the thickness of the convective rain melting layer.

As reported in [40], the convective rain melting layer thickness is about 1.5 to 2 times that of the stratiform rain melting layer. The stratiform rain melting layer thickness is found to be around 500 m [27] [89] [90]. Therefore, the convective rain cell melting layer is around 1000 m. Using the Giangrande model, the thickness of convective rain melting layer is around 3 to 4 times that of the stratiform rain melting layer height as shown in Fig. 5.7. Clearly, the model overestimates the thickness of the convective rain melting layer. From our proposed model, the convective rain melting

Figure 5.7: Histogram of convective rain cell melting layer thickness using two different thresholds.

layer is found to be approximately 2 times that of the stratiform rain melting layer (Fig. 5.7), this is consistent with those reported in [40]. Therefore, the new proposed threshold is more accurate for detecting the convective rain melting layer thickness.

5.6 Special Case for Convective Rain

One special case with convective rain updraft effect recorded at 14:55 UTC on the 14th June 2014 as shown in Fig. 5.8 was identified while processing the dual-polarized radar data. Fig. 5.8 (a) shows many simultaneous small-scale convective rain cells

5.7. SUMMARY

scattered over the eastern part. To study the vertical structure of these small-scale convective rain cells, the radar reflectivity mapped on the height-azimuth plane for Fig. 5.8 (a) is plotted in Fig. 5.8 (b). The maximum reflectivity of this convective rain event is recorded at an azimuth angle of 150° with a maximum reflectivity of 52.5 dBZ (i.e., rainfall rate of 70 mm/hr). This represents a heavy convective rain event and the rain cell height extends up to above 6 km. This height is around 1 km higher than the average 0°C isotherm heights which is reported in [91] to be within [4.2 km, 5.5 km] (processed from one-year radiosonde temperature vertical profiles in Singapore [91]). In [27] [92] [93], it was reported that the 0°C isotherm height is close to the top boundary of the melting layer and the rain height. Therefore, the raindrops around 6 km in this convective rain event is most probably due to the lifting effect from an updraft phenomenon. For this type of convective rain events, the melting layer cannot clearly be identified due to the mixing of raindrops with the melting layer region.

5.7 Summary

In this chapter, the dual-polarized radar data are used for the analysis of the melting layer structure for both convective and stratiform rains in the tropical region, especially convective rain. Among the three radar measurements, the cross-correlation coefficient ρ_{HV} is found to be the best indicator for the identification of the melting layer particularly for convective rain cells.

By applying the proposed method to differentiate and categorize different rain cells, 13 convective rain cells melting layers with associated radiosonde temperature

5.7. SUMMARY

(a)

(b)

Figure 5.8: Radar reflectivity measured in Singapore at 14:55 UTC on 14th June 2014
(a) PPI image (b) mapped on the height-azimuth plane

5.7. SUMMARY

profiles are found in the year of 2014 and 2015. Taking 0°C isotherm height from radiosonde profile as the top boundary for the melting layer, it is found that for convective rain events in the tropical region, the proposed threshold for melting layer detection is $\rho_{HV} = 0.95$. In addition, by applying this newly proposed threshold, the thickness of convective rain melting layer is found to be more accurate. The detected melting layer thickness for convective rain is around 2 times that of the melting layer thickness of the stratiform rain.

Chapter 6

Statistical Study of Cloud Attenuation on Ka-band Satellite Signal

6.1 Introduction

With the rapid growth in satellite communication services, high frequency bands such as Ka and Q/V bands are becoming more attractive to satellite system operators. The atmosphere such as rainfall, cloud and various gases has strong impact on the Space-to-Earth satellite communication links. Among these phenomena, precipitation is commonly known to cause the most severe impairment. As the operating frequency increases (Ka-band and above), cloud attenuation becomes significant and can no longer be neglected. This situation is much worse for the tropical region (e.g.,

6.1. INTRODUCTION

Singapore) due to the higher occurrence of cumulus and cumulonimbus clouds, which occupy large columnar volume with heavy liquid water content.

In this chapter, the algorithm to differentiate cloud from rain events is proposed based on various instruments. The triangulation structure between the WINDS satellite, beacon receiver, weather station, whole sky imager, radiosonde and weather Radar is shown in Fig. 6.1.

Figure 6.1: The triangulation structure among WINDS satellite, beacon receiver, weather station, whole sky imager, radiosonde and weather Radar.

After applying the differentiation algorithm, cloud attenuation on the Ka-band WINDS propagation link is analyzed and discussed in this chapter. Two-year statis-

tical results of cloud attenuation derived from the beacon signal will be presented, together with the ITU-R model for reference.

6.2 Gaseous Absorption on Ka-band Satellite Signal

The total slant path attenuation on the beacon signal can be estimated after the removal of scintillation [94] and temperature effects. This total attenuation may consist of rain attenuation, cloud attenuation and gaseous absorption. Typically, the attenuation by atmospheric gases does not vary much over a day. Surface relative humidity, temperature and pressure recorded (per minute) by the weather station is used in the ITU-R P. 676-10 model [25] to remove the effect of both dry air attenuation and water vapor attenuation.

In this section, gaseous attenuation along a Ka-band slant path link is investigated and analyzed for the tropical country of Singapore. The signal is chosen at a frequency of 18.9 GHz with an elevation angle 44.5° . To estimate the gaseous attenuation along this path, the ITU-R P.676-10 model recommendation is applied. Four-year gaseous attenuation is processed and analyzed.

Fig. 6.2 shows an example of calculated zenith dry air attenuation and water vapor attenuation at 18.9 GHz in the year of 2012. From Fig. 6.2, it can be observed that the zenith dry air attenuation is around 0.05 dB with small variations with a maximum variation of 0.007 dB. The zenith water vapor attenuation fluctuates from 0.25 dB to 0.5 dB with large variations.

It can also be observed that, for Ka-band signal, the water vapor causes much

6.2. GASEOUS ABSORPTION ON KA-BAND SATELLITE SIGNAL

larger attenuation compared to the dry air attenuation and the seasonal variation of total gaseous attenuation is mainly due to the amount of water vapor in the air. It is noted that similar results are also observed for other years.

Figure 6.2: The zenith gaseous attenuation due to the water vapor and dry air using ITU-R Recommendation P.676-11 and weather station data in Singapore in 2012.

Fig. 6.3 shows the four-year slant path total gaseous attenuation calculated for 18.9 GHz with an elevation angle of 44.5° . In order to study the trends of seasonal variation of total gaseous attenuation, a moving average technique with sliding window of 30-day is applied. The maximum total gaseous attenuation is around 0.84 dB and the minimum is around 0.42 dB.

Figure 6.3: Four-year (2012-2015) total gaseous attenuation with the slow trends in Singapore.

It can be observed that the seasonal variation of gaseous attenuation has similar trend from 2012 to 2015. This is because for the tropical country of Singapore, there are two monsoon seasons, namely the Northeast Monsoon (around December to March) and the Southwest Monsoon (around June to October). In between the monsoon seasons are the two inter-monsoon seasons. This kind of variation is mainly due to the seasonal alteration of the dry/wet and hot/cool phases. The maximum gaseous attenuation is observed to be around the wet and hot phase of month May and the minimum gaseous attenuation is observed to be around the dry and cold

6.2. GASEOUS ABSORPTION ON KA-BAND SATELLITE SIGNAL

phase of month February.

Figure 6.4: Cumulative distribution function of gaseous attenuation in Singapore for the year of 2012 to 2015.

Fig. 6.4 shows the four-year (2012-2015) cumulative distribution function of slant path gaseous attenuation at 18.9 GHz. It can be observed that at 0.01% of time, the gaseous attenuation can be up to 0.78 dB. In addition, the gaseous attenuation keeps increasing from 2012 to 2015. The difference between 2012 and 2015 is about 0.05 dB for Ka-band signal. Therefore, for systems operating at higher frequencies such as the V/W band, the gaseous attenuation is relatively large [95], and should be taken into consideration during the system design phase.

6.3. DIFFERENTIATE CLOUD FROM RAIN EVENTS FOR BEACON SIGNAL

In this section, four-year gaseous attenuation on a Ka-band slant path link was studied. ITU-R P.676-10 model and surface meteorological data are applied to calculate the gaseous attenuation.

The results indicate that for Ka-band signal, the water vapor attenuation is much larger than the dry air attenuation. The variation of gaseous attenuation is mainly due to the alternation of seasonal dry/wet and hot/cool phases. The maximum gaseous attenuation happens during the wet and hot phase. It is also noted that the gaseous attenuation keeps increasing from 2012 to 2015.

6.3 Differentiate Cloud from Rain Events for Beacon Signal

After removing the gaseous attenuation, the total slant path attenuation will be mainly due to rain attenuation and cloud attenuation. To differentiate the cloud events from the rain events, the weather station and the whole sky imager at NTU site can be used as a reference. Since the WINDS satellite link is a slant path with an elevation angle of 44.5° , weather Radar reflectivity data can also be used to provide information along the slant path as illustrated in Fig. 6.1. In order to detect and differentiate the clouds from the rain events, the technique reported in [74] is used. The dual-polarized weather Radar performs a full volumetric scan with 8 elevation angles, and therefore the 8 non-uniforming distributed intersection points provide rainfall information along the slant satellite link. As concluded in [74], if the reflectivity is less than 20 dBZ, the event will be considered as cloud instead of rain.

In order to illustrate the cloud and rain differentiating technique from [74], an

6.3. DIFFERENTIATE CLOUD FROM RAIN EVENTS FOR BEACON SIGNAL

example with both cloud and rain events are shown in Fig. 6.5. The top plot shows the maximum weather radar reflectivity along the satellite slant path link over a day. The middle plot is the point rainfall rate obtained from the weather station at NTU. The bottom plot is the attenuation (cloud and/or rain attenuation) suffered by the WINDS satellite beacon signal.

Figure 6.5: The processed Ka-band beacon signal for WINDS slant path with Radar reflectivity and rainfall rate on 12th April 2015.

From Fig. 6.5, it can be observed that a rain event was recorded by the weather

6.3. DIFFERENTIATE CLOUD FROM RAIN EVENTS FOR BEACON SIGNAL

Figure 6.6: The Radar reflectivity PPI map between NTU and Changi airport with WINDS slant path link at 14:50 pm on 12th April 2015.

station at 15:12 pm at the NTU site, the maximum rainfall rate was 36 mm/hr based on the weather station. At that instance, the Radar reflectivity along the path reached a maximum of 40 dBZ and the corresponding rain attenuation was 8 dB. However, before this rain event, the radar reflectivity was larger than 20 dBZ at around 14:50 pm; this is due to the rainfall happening along the satellite-to-ground station slant path, which can be observed using the radar PPI as shown in Fig. 6.6. The solid black line represents the direction of the geostationary WINDS satellite link from

6.3. DIFFERENTIATE CLOUD FROM RAIN EVENTS FOR BEACON SIGNAL

NTU site. At this moment the path suffers from rainfall at around -30 to -10 km in zonal distance. Therefore, by using the radar reflectivity, rain events along the slant path can easily be detected. This allows for the differentiation between a rain event and a cloud event.

Figure 6.7: Cloud image taken by Whole Sky Imager at NTU at 13:14 pm on 12th April 2015.

Next, a cloud attenuation event is analyzed based on observations from Fig. 6.5. Before the rain event, starting at around 12:30 pm, there is no rainfall recorded by the weather station nor the weather radar. Therefore, it can be deduced that the

6.4. COMPARISON BETWEEN BEACON MEASURED CLOUD ATTENUATION AND ITU-R MODEL

attenuation is mainly caused by multiple layers of clouds along the satellite slant path. A maximum cloud attenuation of 3.5 dB can be seen at 13:13 pm in Fig. 6.5. The existence of corresponding cloud image taken by the whole sky imager at NTU site also shows the dark thick clouds with heavy liquid water content at 13:14 pm as shown in Fig. 6.7.

All the above information and techniques described will be used to accurately determine attenuation caused by cloud from the received beacon signal strength for the years 2014 and 2015.

6.4 Comparison between Beacon Measured Cloud Attenuation and ITU-R Model

By applying the above mentioned cloud differentiation methods and the algorithm for beacon signal processing in section 3.7, the cloud attenuation suffered by the WINDS beacon signal can be estimated. The yearly (Year 2014 and Year 2015) complementary cumulative distribution function for cloud induced attenuation is presented in Fig. 6.8 with the cloud attenuation calculated by using the ITU-R model [60] at the same frequency of 18.9 GHz with the same elevation angle of 44.5°. It is noted that the statistics derived from beacon data include only the contribution of clouds in non-rainy conditions. The reduced liquid water content maps of ITU-R P.840-6 recommendation [60] were derived by applying the Salonen Uppala (SU) method [45] to ECMWF-derived vertical profiles, both the ITU-R model and the SU model are introduced in chapter 2 section 6.

From radiosonde data, by using the SU model and the proposed WVP cloud detec-

6.4. COMPARISON BETWEEN BEACON MEASURED CLOUD ATTENUATION AND ITU-R MODEL

Figure 6.8: Complementary cumulative distribution function of cloud attenuation estimated from WINDS satellite beacon signal for the year of 2014 and 2015.

tion model, the cloud events could be detected twice per day as discussed in chapter 4. For SU model, the percentage of time with cloud is 94.89% for 2014 and 92.97% for 2015; while for WVP cloud detection model, the percentage of time with cloud is 98.97% for 2014 and 99.68% for 2015. Since the cloud detection algorithm from the SU model was developed by using meteorological data collected from temperate region instead of tropical region, it is well-known that it underestimates the cloud attenuation in the tropical region.

As shown in Fig. 6.8, the yearly complementary cumulative distribution function of cloud attenuation estimated from WINDS beacon signal is compared with the

6.5. SUMMARY

ITU-R model and SU model. The majority of clouds in Singapore are either cumulus (76%) or cumulonimbus (22%). These cloud types result in larger cloud attenuation as compared to the cloud types observed in the temperate region. It should be noted that the ITU-R is a global model and might not serve well for specific regions. It is reported in [96] that severe weather conditions in the tropical region can result in a much higher cloud attenuation at lower percentages of time exceedance (less than 0.1% of time). For higher percentage of time exceedance (greater than 1% of time), the beacon derived cloud attenuation appears to be less than that estimated by the ITU-R model. The main reason is that, larger percentage of time exceedance includes a significant amount of cloud attenuation caused by thin layer of cloud. Since the thin cloud attenuation is very small for Ka-band satellite signal, it is difficult to extract it from the beacon signal [67] as discussed in section 3.7.

6.5 Summary

In this chapter, two-year statistical results of cloud attenuation on a Ka-band satellite link have been reported, with correlation analysis of cloud existence using different techniques. The yearly CCDF results indicate that at time exceedance of 0.01%, the cloud attenuation can reach up to 4.2 dB in the tropical region. It is also shown that the ITU-R model underestimate the cloud attenuation in the tropical region. Further study will be carried out to evaluate and model the cloud attenuation in the tropical region.

Chapter 7

Cloud Attenuation Analyses and Modelling

7.1 Introduction

As the frequency spectrum becomes crowded and the demand for high data transmission rates increases, high frequency bands such as Ka-band and Q/V-bands has drawn more attention to satellite service operators. With the increase in operating frequency, not only rain attenuation but also cloud attenuation becomes important for the satellite system design and operation. This is especially so for some low margin systems such as VSAT and USAT.

For the tropical region, the situation is severe due to the high-probability of occurrence of cumulus and cumulonimbus clouds with heavy liquid water content over a large vertical extent. Therefore, cumulus and cumulonimbus cloud degrade the per-

7.2. 0 °C AND -20 °C ISOTHERM HEIGHT DISTRIBUTION

formance of satellite systems in the tropical region significantly. Since the cloud liquid water content is the main cause for cloud attenuation, the results of cloud liquid water content is introduced in this chapter.

It is well-known that water vapor plays an important role for the hydrologic cycle in the Earth. When the amount of water vapor is saturated at a certain temperature, it will condense to form clouds. Therefore, in this chapter, the correlation between the amount of integrated liquid water content and that of precipitable water vapor is studied, and then an improved approach for determining the cloud attenuation is proposed in the tropical region.

7.2 0 °C and -20 °C Isotherm Height Distribution

For cloud liquid water content calculation, 0 °C and -20 °C isotherm heights are quite important since they are the boundaries to differentiate cloud liquid droplets and cloud ice crystal. 0 °C isotherm height indicates the level where cloud liquid droplets start to freeze, while -20 °C isotherm height indicates the level above which clouds only exist as ice crystals. In between these two levels, clouds are in a mixture of both liquid droplets and ice crystals.

Fig. 7.1(a) shows the distribution of 0 °C isotherm heights for the year of 2012 derived from the radiosonde vertical profile. It can be observed that the 0 °C isotherm height falls within the range of [4200 m, 5600 m], which is within the middle level cloud height range (typically 2000 m to 5000 m [54]). This indicates that for the tropical region, the middle level clouds consist of large portion of liquid water droplets; therefore they contribute to the cloud attenuation.

7.2. 0 °C AND -20 °C ISOTHERM HEIGHT DISTRIBUTION

(a)

(b)

Figure 7.1: Histogram of altitudes (a) at temperature of 0 °C (b) at temperature of -20 °C in Singapore in 2012.

7.3. CLOUD LIQUID WATER CONTENT COMPARISON

The distribution of $-20\text{ }^{\circ}\text{C}$ isotherm height for the same year of 2012 is shown in Fig. 7.1(b). It falls in the region of $[7600\text{ m}, 9000\text{ m}]$, which is in the high level cloud height range above 5000 m [54]. This indicates that the high level clouds above 9000 m has negligible cloud attenuation in the microwave range [45] since they are constituted mainly by ice crystals. However, the high level clouds should be taken into account for the signal depolarization [45]. In addition, the variation of $0\text{ }^{\circ}\text{C}$ and $-20\text{ }^{\circ}\text{C}$ isotherm heights are both around 1400 m , which is relatively small compared to the temperate region. Take Beijing as an example, the variation of $0\text{ }^{\circ}\text{C}$ and $-20\text{ }^{\circ}\text{C}$ deduced from radiosonde data is more than 6000 m . This kind of large variation is due to seasonal changes which does not exist in the tropical region.

7.3 Cloud Liquid Water Content Comparison

From eq. (2.23) and eq. (2.24), it is observed that cloud liquid water content is dependent on temperature, and on height above the cloud base within the same cloud layer.

Fig. 7.2 shows some examples of cloud liquid water density along the radiosonde vertical path on the 15th and the 22nd of January 2012 by using the SU model and the WVP model. Two horizontal reference lines indicate the $0\text{ }^{\circ}\text{C}$ isotherm height and $-20\text{ }^{\circ}\text{C}$ isotherm height. The vertical profile can be divided by two reference lines into three regions as shown in Fig. 7.2. The clouds at low level (below 0°C isotherm height) are full of liquid water droplets, the clouds in the middle level are in the mixed phase with water droplets and ice crystals, while the high level clouds only contain ice crystals. Therefore, the liquid water density at high level is always zero.

7.3. CLOUD LIQUID WATER CONTENT COMPARISON

(a)

(b)

Figure 7.2: Cloud liquid water density calculated by SU model and WVP model in Singapore WSSS station on (a) 15th January 2012 (b) 22nd January 2012.

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

In Fig. 7.2(a), comparing the clouds in liquid water phase region (below 0 °C isotherm height), the cloud base/top height detected by WVP cloud detection model proposed in chapter 4 is relatively lower/higher than that detected by SU model. Same observation can be seen in Fig. 7.2(b) for the clouds in the mixed phase region. This is because the WVP model has a better performance for cloud detection compared to the SU model as discussed in chapter 4, verified using the results from the human observation and ceilometer measurements. As a result, cloud thickness and cloud water content derived from WVP model are much larger than those from SU model. In addition, it is found from Fig. 7.2(b) that, SU model detects four different layers of thin clouds, while WVP model detects two layers of thick clouds. The first three cloud layers (starting from low altitude) detected by SU model are actually a continuous cloud with very small separation as shown by the WVP model.

Moreover, it should be noted that the two constants α and β from the SU model eq. (2.15) are empirical parameters derived by using temperate meteorological data. Therefore, the SU model intends to underestimate the cloud thickness and cloud liquid water content in the tropical region.

7.4 Proposed Cloud Attenuation Prediction Model for Tropical Region

In order to form clouds, the condensation of water vapor is a necessary process, and therefore the relationship between the amount of water vapor suspended in the air and the liquid water content in cloud is highly correlated. For the ITU-R model which is found to be the best for tropical regions [67] among existing models, there is still

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

unsatisfactory temporal resolution (4 times per day) and spatial resolution (limited to sites where radiosonde data are available). In the tropical region, there is also a decrease in accuracy at low percentage of time exceedance where cumulonimbus clouds with higher cloud attenuation is present as discussed in chapter 6. The ground-based GPS meteorology with high temporal resolution (1 data per 5 minutes) is a promising alternative solution, since its derived PWV values along the propagation path is a good indicator for high resolution remote sensing of ILWC.

For calculating the zenith ILWC, we need to detect the cloud layers and calculate the liquid water content within that specific cloud layer, and then integrate them along the path. For cloud detection in the tropical region, a new model for detecting cloud vertical structure, i.e. water vapor pressure model, has been presented in chapter 4. The model is shown to be more accurate than the SU cloud detection model in eq. (2.15) for the tropical region.

To calculate the zenith ILWC, eq. (2.23) and eq. (2.24) provided by the SU model are applied to the cloud layers detected by the WVP model. The ILWC can be calculated twice per day at a point location due to the low radiosonde launching resolution. The PWV data from GPS signal are recorded every 5 minutes. For comparison purposes, in order to match the temporal and spatial resolution, only the PWV data at radiosonde launching time are processed for the regression fitting analysis.

The scatter plot of PWV versus ILWC for two-year (2013-2014) data from 8 different tropical stations listed in Table 7.2 is shown in Fig. 7.3(a). It can be observed that the range of PWV data measured from GPS is from around 20 mm to 70 mm in the tropical region; while the ILWC calculated from radiosonde is from 0

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

Table 7.1: Radiosonde stations with collocated IGS stations for tropical regions

Radiosonde Station ID	Lat.	Lon.	IGS Station ID	Distance*
MDSD	18.43 °N	69.88 °W	RDSD	4.79 km
TFFR	16.26 °N	61.51 °W	ABMF	1.88 km
SOCA	4.83 °N	52.36 °W	KOUG	43.02 km
WSSS	1.34 °N	103.89 °E	NTUS	23.37 km
WIII	6.11 °S	106.65 °E	BAKO	47.69 km
NFFN	17.75 °S	177.45 °E	LAUT	15.73 km
YBTL	19.25 °S	146.76 °E	TOW2	31.10 km
NWWN	22.26 °S	166.45 °E	NRMD	5.04 km

*Distance is between IGS station and radiosonde station.

mm to 4 mm. It is also observed that the ILWC along the same propagation path has an approximate power function relationship with the PWV in the tropical region.

However, there are also some outliers observed in Fig. 7.3(a), which might be due to the physical location separation between the IGS stations and the radiosonde stations. In order to achieve a relatively large database for the tropical region in this study, the collocated IGS and radiosonde stations are selected if their physical location separation distance is less than 50 km as listed in Table 7.2. Another reason might be due to the position drifting of radiosonde. It is found that position of a radiosonde can drift according to the wind direction and might go towards or backwards to IGS stations. In addition, the zenith PWV values determined from GPS signal is an average from GPS data along different slant paths, which is different from the zenith ILWC from radiosonde since the zenith PWV from GPS are not along the same vertical path.

In order to find the data concentration in Fig. 7.3(a), the density color image of ILWC versus PWV data is plotted in Fig. 7.3(b). It can be observed that most of ILWC values are within the range of [0 0.5] mm. For the tropical region, the frequently

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

(a)

(b)

Figure 7.3: Zenith ILWC processed from 8 radiosonde station for the years 2013 and 2014 versus zenith PWV from the respectively collocated IGS station. (a) scatter plot, (b) density color image.

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

observed cloud type is the convective rain cloud (i.e., cumulus or cumulonimbus). Cumulonimbus clouds that occurs 22% of the time, are characterized as having a large vertical extent and heavy liquid water content greater than 2.5 mm. From the density color image in Fig. 7.3(b), the correlation between ILWC and PWV can be seen.

The regression fitting formula that relates ILWC and PWV is then determined by applying a power function curve-fitting technique and can be expressed in the form,

$$ILWC = a \times PWV^b \quad (7.1)$$

where PWV is the precipitable liquid water in millimeter, and ILWC is the integrated liquid water content in millimeter or kg/m^2 . This ILWC is calculated by using WVP cloud detection model and SU cloud liquid water density model, which might not be accurate in the tropical region. Through regression technique, empirical values for the two parameters a and b are derived to be 1.123×10^{-17} and 9.794.

Table 7.2: ILWC value calculated by using proposed model with typical PWV value in tropical region

ILWC (kg/m^2)	PWV (mm)
0.003	30
0.055	40
0.490	50
2.921	60

By applying the WVP cloud detection method on all the available radiosonde profiles from 8 different stations, it is found that the cloud occurrence is around $10106/11686 = 86.48\%$. Fig. 7.4 shows the complementary cumulative distribution function of cloud integrated liquid water content calculated from radiosonde data and

7.4. PROPOSED CLOUD ATTENUATION PREDICTION MODEL FOR TROPICAL REGION

proposed model for the year of 2013 and 2014. As shown in Fig. 7.4, around 90% of time, the two CCDF curves are in agreement with each other. However, for the remaining 10% of time, the two curves diverge from each other, the ILWC calculated from radiosonde is going to be saturated at around 3.84 kg/m^2 (1.76 dB for 18.9 GHz satellite beacon signal with an elevation of 44.8°), while for the ILWC calculated from the proposed model, it is going up to around 8.54 kg/m^2 (3.91 dB for 18.9 GHz satellite beacon signal with an elevation of 44.8°). The attenuation calculated based on the radiosonde data is saturated at 1.76 dB which is very small comparing to the cloud attenuation measured by our beacon signal and the reported cloud attenuation in [67]. This should be due to the cloud liquid water density function from SU model is derived using radiosonde data collected in temperate region, which underestimates the cloud liquid water content in tropical region.

Figure 7.4: CCDF of cloud integrated liquid water content calculated from radiosonde data and proposed model for the year of 2013 and 2014.

7.5 Comparison between the Proposed Cloud Attenuation Model and ITU-R Model

The ITU-R model has been reported to be a relative reasonable model for estimating cloud caused attenuation in the tropical region. To improve its temporal resolution (4 times per day limited by EMCWF), the relationship between PWV and ILWC in eq. (7.1) can be utilized. A high resolution ITU-R model for cloud attenuation A_c estimation is therefore proposed in this study as,

$$A_c = \frac{0.92 \times 10^{-17} \cdot f \cdot PWV^{9.794}}{\varepsilon'' \cdot (1 + \eta^2) \cdot \sin\theta} \quad (7.2)$$

where f is the frequency in GHz and θ is the elevation angle of the slant path. The respective updated equations of ε' and ε'' can be found in ITU-R P.840-6. This model is expected to have a much higher temporal resolution of 5 minutes and high spatial resolution, limited only by the time resolution and space density of GPS receivers, respectively.

To evaluate the performance of the proposed high resolution ITU-R model given in eq. (7.2), comparisons with the existing ITU-R P.840-6 model and cloud attenuation derived from WINDS beacon signal at 18.9 GHz are carried out for a satellite to ground communication link with an elevation angle of 44.5°.

For comparison purposes, the WINDS beacon signal from the year of 2014 and 2015 are processed using the method in chapter 6. The respective CCDFs are plotted in Fig. 7.5 (a) and (b). After processing the GPS PWV data with interval of 5 minutes for the years 2014 and 2015, the cloud attenuation can be calculated using

7.5. COMPARISON BETWEEN THE PROPOSED CLOUD ATTENUATION MODEL AND ITU-R MODEL

eq. (7.2) directly. For ITU-R P.840-6 model, after using the latitude and longitude of the respective location to find the distribution of reduced liquid water content, the CCDF of cloud attenuation can be presented. It should be noticed that after using the WVP cloud detection model to detect the cloud events, it is found that the percentage of time with cloud is 98.97% for 2014 and 99.68% for 2015 for Singapore.

In Fig. 7.5, the CCDFs of cloud attenuation for the year 2014 and 2015 are plotted. It can be observed that for the higher percentage of time exceedance (greater than 1%), the proposed method has similar cloud attenuation to the ITU-R method. The reason is because, PWV averaged over several GPS line of sight satellite links as shown in Fig. 7.6. Therefore, it will have a higher probability of detecting cloud layers than one single propagation path given by the radiosonde. For the cloud attenuation derived from WINDS beacon signal, at higher percentage of time exceedance (greater than 1%) where attenuation is due to the thin layer of clouds, cumulative cloud attenuation is low. This is due to the fact that thin cloud attenuation is almost always missed since it is almost impossible to process thin cloud attenuation out from beacon signal discussed in section 3.7.

Another interesting observation is that, at the lower percentage of time exceedance of less than 0.1%, the cloud attenuation estimated by the proposed model matches better with that derived from beacon signal, compared to ITU-R model. The cloud attenuations reach around 4 dB in 2014 and 3.5 dB in 2015 at 0.01% of time. However, for the ITU-R model, the maximum cloud attenuation is only around 1.86 dB. It should be noted that the ITU-R is a global model and it applies the SU model derived from temperate region, which might not serve well for the tropical region. In addition, it is also discussed in [96] that severe weather conditions in the tropical region

7.5. COMPARISON BETWEEN THE PROPOSED CLOUD ATTENUATION MODEL AND ITU-R MODEL

(a)

(b)

Figure 7.5: CCDF of cloud attenuation derived from WINDS satellite beacon signal, estimated from the proposed model and ITU-R model in year of (a) 2014 and (b) 2015.

7.5. COMPARISON BETWEEN THE PROPOSED CLOUD ATTENUATION MODEL AND ITU-R MODEL

Figure 7.6: Idea of zenith PWV determination.

can result in much larger cloud attenuation at lower percentages of time exceedance especially for less than 0.1% of time.

Furthermore, it is found that there is less cloud attenuation determined by the proposed model for 2015 at the lower percentage of time exceedance. The main reason is that in the year of 2015, the El Nino climate dominates in Singapore, and the weather was warm and dry (less PWV) giving rise to less clouds.

7.6 Summary

In this chapter, an improved approach to estimate the cloud attenuation along the propagation path is proposed. The model is based on the correlation relationship between PWV and ILWC, which was determined from 2-year GPS-PWV and radiosonde data collected from 8 tropical stations.

The estimated results of cloud attenuation using our proposed model are compared with those results from ITU-R model and beacon signal. The results show that the proposed model has a better performance for estimating cloud attenuation in tropical region at lower percentage of time exceedance. For the higher percentage of time exceedance, it slightly overestimates the cloud appearance percentage comparing with ITU-R model.

In general, investigation in this study shows that the proposed modified ITU-R model can be used for cloud attenuation estimation in tropical region with much better temporal resolution and improved accuracy.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

In this thesis, various types of data are collected from different kinds of instruments including radiosonde, ceilometer, dual-polarization weather radar, Ka-band beacon receiver, weather stations and whole sky imagers. By processing and analyzing the data collected from these instruments, the study of various aspects of the cloud including cloud vertical structure, melting layer of rain clouds, and the impact of cloud on the satellite communication link for the tropical region is performed.

A new method for the detection of cloud vertical structure and cloud occurrence for the tropical region is proposed. This proposed model is based on the fact that the measured water vapor pressure is larger than the derived critical water vapor pressure at the same level, which indicates the presence of clouds. The estimated cloud vertical structure using the proposed method is compared with the Salonen and

8.1. CONCLUSION

Uppala model, the ceilometer data and two kinds of meteorological observation. The proposed model shows a higher accuracy of prediction of the cloud vertical structure as compared to the existing SU model for the tropical region.

A method for the detection of the melting layers for the stratiform and convective rain clouds using dual-polarization radar data is proposed. By studying the difference between these two types of rain events, it is found out that among the three radar measurements; reflectivity; differential reflectivity; and cross-correlation coefficient; the cross-correlation coefficient is the best indicator for convective rain melting layer detection in the tropical region, whereas the reflectivity is sufficient for the detection of stratiform rain melting layer. In addition, it has been observed that due to the nature of convective rain events, their raindrops can move upwards to above 6 km as recorded by the radar data. This height is even higher than the top boundary of the melting layer.

For satellite communication applications, it is important to be able to differentiate cloud events from rain events along the link. Several cloud detection methods are applied in order to accurately detect the clouds for cloud attenuation estimation . In this research, beacon data are collected and processed to differentiate clouds from rain and then to study cloud attenuation in the tropical region. The cloud attenuation results are compared to the ITU-R model for Ka band frequency. It was concluded that at Ka band, the maximum cloud attenuation is about 4 dB. This shows that the ITU-R model is derived for temperate regions and tends to underestimate the cloud attenuation in the tropical region.

Therefore, in this research work, a new cloud attenuation model is proposed for the tropical region. This model incorporates precipitable water vapor value to esti-

8.2. FUTURE WORK

mate integrated liquid water content, and then determine the cloud attenuation. The estimated cloud attenuation using this new model is compared with the ITU-R model and the cloud attenuation derived from Ka-band beacon data. One of the main advantages of using PWV data from GPS for cloud attenuation modelling is its increase in temporal resolution as compared to the use of radiosonde data.

In this thesis, we have proposed a model to detect cloud vertical structure for tropical region, studied the melting layer for both stratiform and convective rain clouds, done statistical analysis of cloud attenuation on a Ka-band satellite link and also proposed a high temporal resolution method for cloud attenuation calculation in tropical region. We believe that the algorithms and techniques developed in this thesis will assist the remote sensing and satellite communication community with a better understanding of clouds.

8.2 Future Work

This thesis explored various aspects of cloud using different kinds of instruments and database. It solved most of the fundamental problems for cloud detection and cloud attenuation in tropical region, and also helped us to generate future research proposal. In this section, some intended works will be briefly mentioned.

The cloud detection model in chapter 4 can detect the cloud vertical structure and cloud occurrence accurately in tropical region. However, the feasibility and performance of the method applying in temperate region haven't been investigated. Therefore, one of the future work can be done is to use regression method to get the value of a and b in critical water vapor pressure function for temperate and subtropical

8.2. FUTURE WORK

region. The a and b might be varied dependent on the seasons changing of temperate and subtropical region.

Furthermore, latitude and longitude might be also helpful for this cloud detection modelling. For the validation of cloud detection, the cloud base height can be compared with the results from ceilometer, CloudSat and CALIPSO satellite since these two satellites can provide the cloud liquid water content and cloud vertical structure in a vertical profile. If this method can be developed then it might also be adopted in tropical region and become a global cloud detection model.

Since cloud can block the optical satellite communication link easily, it is very important to study and predict the cloud occurrence and cloud optical thickness for optical satellite communication systems. The vertical structure of cloud results from chapter 4 can be used to find the occurrence and thickness of the cloud in low level, middle level and high level. These results can be compared with the cloud optical thickness measured by MODIS (Moderate-Resolution Imaging Spectroradiometer) satellite, which could be useful for the optical satellite communication.

Cloud attenuation is differentiated from the rain attenuation using mainly dual-polarization weather radar with other instruments in chapter 6. The reflectivity of 20 dBZ is applied to differentiate cloud events. Some other parameters should be also investigate for cloud detection and differentiation such as differential reflectivity, specific differential phase and cross-correlation coefficient. A more accurate differentiation method is expected with the implementation of these data. More years of cloud attenuation from beacon signal can be derived by applying the differentiation method.

8.2. FUTURE WORK

For cloud attenuation modelling, the most important factor is to estimate the cloud liquid water content accurately. In this thesis, the cloud liquid water content is calculated using the radiosonde vertical profiles. There are some other instruments and database can be used to acquire the cloud liquid water content such as radiometer and satellites (MODIS, CloudSat, CALIPSO). Although these instruments measures cloud liquid water content from different approaches, some are from the bottom of cloud and some are from the top of clouds. It might be helpful to process all these cloud liquid water content data and correlate with the precipitable water vapor to generate a more accurate cloud attenuation model.

In addition, the correlation between the precipitable water vapor and cloud liquid water content in temperate and subtropical region should be also investigated. This might be also helpful for cloud attenuation calculation in the temperate and subtropical region.

Publication List

Journal Publications

1. F. Yuan, Y. H. Lee, Y. S. Meng, J. X. Yeo, and J. T. Ong, 'Statistical Study of Cloud Attenuation on Ka-band Satellite Signal in Tropical Region,' IEEE Antennas and Wireless Propagation Letters, Vol. 16, pp. 2018 - 2021, April 2017.
2. F. Yuan, Y. H. Lee, Y. S. Meng and J. T. Ong, 'Water Vapor Pressure Model for Cloud Vertical Structure Detection in Tropical Region,' IEEE Transactions on Geoscience and Remote Sensing, Vol. 54, pp. 5875 - 5883, October 2016.
3. S. Manandhar, Y. H. Lee, Y. S. Meng, F. Yuan and J. T. Ong, 'GPS Derived PWV for Rainfall Nowcasting in Tropical Region,' submitted in IEEE Transactions on Geoscience and Remote Sensing. (accepted)
4. F. Yuan, Y. H. Lee, Y. S. Meng and J. T. Ong, 'Characterization of Dual-polarization Radar Data for Convective Rain Melting Layer Detection in Tropical Region,' submit in IEEE Transactions on Geoscience and Remote Sensing.
5. F. Yuan, Y. H. Lee, Y. S. Meng and J. T. Ong, 'High resolution ITU-R Cloud

8.2. FUTURE WORK

Attenuation Model for Satellite Communications in Tropical Region,' submit in IEEE Transactions on Antenna and Propagation.

Conference Publications

1. F. Yuan, Y. H. Lee, S. Manandhar, Y. S. Meng, 'Investigation of Melting Layer for Convective Rain in Tropical Region', accepted in IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Boston, USA, Jul. 2018.
2. S. Manandhar, Y. H. Lee, Y. S. Meng, F. Yuan, S. Dev, 'A Potential Low Cost Remote Sensing Using GPS Derived PWV', accepted in IEEE International Geoscience and Remote Sensing Symposium (IGRSS), Valencia, Spain, Jul. 2018.
3. F. Yuan, Y. H. Lee, Y. S. Meng, 'Melting Layer Detection in Tropical Region', Progress in Electromagnetics Research Symposium (PIERS), Singapore, Nov. 2017.
4. F. Yuan, S. Manandhar, Y. H. Lee, Y. S. Meng, 'Investigation of Gaseous Attenuation on a Ka-Band Propagation Link in Tropical Region', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, San Diego, USA, Jul. 2017.
5. S. Dev, S. Manandhar, F. Yuan, Y. H. Lee, S. Winkler, 'Cloud Radiative Effect Study Using Sky Camera', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, San Diego, USA, Jul. 2017.

8.2. FUTURE WORK

6. S. Manandhar, F. Yuan, S. Dev, Y. H. Lee, Y. S. Meng, 'A Constant Conversion Factor for Retrieval of PWV from GPS Signals in Tropical Region', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, San Diego, USA, Jul. 2017.
7. F. Yuan, S. Manandhar, Y. H. Lee, Y. S. Meng, 'Model Comparison for Estimating Cloud Liquid Water Content and Attenuation in Tropical Region', IEEE Region 10 Conference (TENCON), Singapore, Nov. 2016.
8. S. Manandhar, F. Yuan, S. Dev, Y. H. Lee, Y. S. Meng, 'Weather Radar to Detect Cloud Occurrence Level', IEEE Region 10 Conference (TENCON), Singapore, Nov. 2016.
9. F. Yuan, Y. W. Lek, Y. H. Lee, Y. S. Meng, 'Correlation between cloud optical thickness and solar radiation', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Puerto Rico, USA, Jul. 2016.
10. F. Yuan, Y. H. Lee, Y. S. Meng, 'Investigation of cloud attenuation on Ka-band beacon signal in tropical region', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Puerto Rico, USA, Jul. 2016.
11. S. Manandhar, F. Yuan, Y. H. Lee, Y. S. Meng, 'Weather radar to detect and differentiate clouds from rain events', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Puerto Rico, USA, Jul. 2016.
12. F. Yuan, Y.H. Lee, Y.S. Meng, J.T. Ong, 'Detection of cloud vertical structure

8.2. FUTURE WORK

- using water vapor pressure in tropical region', IEEE International Geoscience and Remote Sensing Symposium (IGRSS), Milan, Italy, July 2015.
13. F Yuan, Y. H. Lee, Y. S. Meng, and S. Winkler, 'Impact of Cloud Effective Temperature on Cloud Attenuation in Tropical Region', IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP 2015), Bali, July 2015.
 14. F. Yuan, Y. H. Lee and Y. S. Meng, 'Comparison of Cloud Models for Propagation Studies in Ka-band Satellite Applications', International Symposium on Antennas and Propagation (ISAP), KaohSiong, Taiwan, December 2014.
 15. L. S. Kumar, F. Yuan, Y. H. Lee, 'Comparison of precipitable water vapor derived from GPS and radiosonde data for Singapore', International Symposium on Antennas and Propagation (ISAP), KaohSiong, Taiwan, December 2014.
 16. F. Yuan, Y. H. Lee and Y. S. Meng, 'Comparison of Radio-Sounding Profiles for Cloud Attenuation Analysis in the Tropical Region', IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Memphis, Tennessee, USA, July 2014.

Bibliography

- [1] W. B. Rossow and R. A. Schiffer, “Advances in understanding clouds from IS-CCP,” *Bull. Amer. Meteorol. Soc.*, vol. 80, no. 11, p. 2261–2287, Nov. 1999.
- [2] G. Hong, P. Yang, H. L. Huang, B. A. Baum, Y. Hu, and S. Platnick, “The sensitivity of ice cloud optical and microphysical passive satellite retrievals to cloud geometrical thickness,” *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 5, p. 1315–1323, May 2007.
- [3] P. M. et al., “CERES edition-2 cloud property retrievals using TRMM VIRS and Terra and Aqua MODIS data—part I: Algorithms,” *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 11, pp. 4374–4400, Nov. 2011.
- [4] A. D. Panagopoulos, P. M. Arapoglou, and P. G. Cottis, “Satellite communications at Ku, Ka, and V bands: propagation impairments and mitigation techniques,” *IEEE Commun. Surv. Tutor.*, vol. 6, no. 3, pp. 2–14, Oct. 2004.
- [5] L. Luini and C. Capsoni, “Scaling cloud attenuation statistics with link elevation in earth-space applications,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 1089–1095, March 2016.

BIBLIOGRAPHY

- [6] P. M. et al., “CERES Edition-2 cloud property retrievals using TRMM VIRS and Terra and Aqua MODIS data—Part II: Examples of average results and comparisons with other data,” *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 11, pp. 4401–4430, Nov. 2011.
- [7] T. Maestri and R. E. Holz, “Retrieval of cloud optical properties from multiple infrared hyperspectral measurements: A methodology based on a line-by-line multiple-scattering code,” *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 8, p. 2413–2426, Aug. 2009.
- [8] L. Luini, C. Riva, C. Capsoni, and A. Martellucci, “Attenuation in nonrainy conditions at millimeter wavelengths: Assessment of a procedure,” *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 7, pp. 2150–2157, Jul. 2007.
- [9] L. Luini, C. Riva, and C. Capsoni, “Reduced liquid water content for cloud attenuation prediction: the impact of temperature,” *Electronics Letters*, vol. 49, no. 20, pp. 1259–1261, Sep. 2013.
- [10] G. A. Siles, J. Riera, and P. G. del Pino, “Atmospheric attenuation in wireless communication systems at millimeter and THz frequencies,” *IEEE Antennas Propag. Mag.*, vol. 5, no. 1, pp. 48–61, Feb. 2015.
- [11] A. D. Panagopoulos and J. D. Kanellopoulos, “Statistics of differential rain attenuation on converging terrestrial propagation paths,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 9, pp. 2514–2517, Sep. 2003.
- [12] L. S. Kumar, Y. H. Lee, and J. T. Ong, “Truncated Gamma drop size distribution models for rain attenuation in singapore,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1325–1335, Apr. 2010.

BIBLIOGRAPHY

- [13] S. A. Kanellopoulos, A. D. Panagopoulos, C. I. Kourogiorgas, and J. D. Kanellopoulos, "Satellite and terrestrial links rain attenuation time series generator for heavy rain climatic regions," *IEEE Trans. Antennas Propag.*, vol. 61, no. 6, pp. 3396–3399, Jun. 2013.
- [14] P. G. Davies, "Attenuation by cloud and rain on earth-sun paths at 12 to 71 GHz," *Electronics Letters*, vol. 11, no. 22, pp. 547–548, Oct. 1975.
- [15] K. Al-Ansafi, P. Garcia, J. M. Riera, and A. Benarroch, "One-year cloud attenuation results at 50 GHz," *Electronics Letters*, vol. 39, no. 1, pp. 136–137, Jan. 2003.
- [16] P. Bouchard, "Approximate method for estimating gaseous loss at very low angles along paths of finite length and earth-space paths," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 687–699, Feb. 2016.
- [17] A. Bellon, I. Zawadzki, and F. Fabry, "Measurements of melting layer attenuation at X-band frequencies," *Radio Science*, vol. 32, no. 3, pp. 943–955, May. 1997.
- [18] H. Vasseur, "Prediction of tropospheric scintillation on satellite links from radiosonde data," *IEEE Trans. Antennas Propag.*, vol. 47, no. 2, pp. 293–301, Feb. 1999.
- [19] A. Dissanayake, J. Allnutt, and F. Haidara, "A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths," *IEEE Trans. Antennas Propag.*, vol. 45, no. 10, pp. 1546–1558, Oct. 1997.
- [20] N. K. Lyras, C. I. Kourogiorgas, and A. D. Panagopoulos, "Cloud free line of sight prediction modeling for optical satellite communication networks," *IEEE Communications Letters*, vol. 21, no. 7, pp. 1546–1558, Jul. 2017.

BIBLIOGRAPHY

- [21] F. Yuan, Y. H. Lee, and Y. S. Meng, "Comparison of cloud models for propagation studies in Ka-band satellite applications," *Proc. 19th Int. Symp. Antennas Propag.*, pp. 383–384, Dec. 2014.
- [22] J. X. Yeo, Y. H. Lee, and J. T. Ong, "Rain attenuation prediction model for satellite communications in tropical regions," *IEEE Trans. Antennas Propag.*, vol. 62, no. 11, pp. 5775–5781, Nov. 2014.
- [23] L. S. Kumar, Y. H. Lee, and J. T. Ong, "Two-parameter Gamma drop size distribution models for Singapore," *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 9, pp. 3371–3380, Sept. 2011.
- [24] J. X. Yeo, Y. H. Lee, L. S. Kumar, and J. T. Ong, "Comparison of S-band radar attenuation prediction with beacon measurements," *IEEE Trans. Antennas Propag.*, vol. 60, no. 10, pp. 4892–4900, Oct. 2012.
- [25] "Attenuation by atmospheric gases," Rec. ITU-R P.676-10, 2013.
- [26] O. T. Davies and A. D. Papatsoris, "Monthly mean gaseous attenuation maps at 93 GHz for united kingdom and ireland," *Electronics Letters*, vol. 34, no. 12, pp. 1208–1210, Jun. 1998.
- [27] S. E. G. adn J. M. Krause and A. V. Ryzhkov, "Automatic designation of the melting layer with a polarimetric prototype of the wsr-88d radar," *J. Appl. Meteor.*, vol. 47, pp. 1354–1364, Jul. 2007.
- [28] W. Zhang, S. I. Karhu, and E. T. Salonen, "Predictions of radiowave attenuations due to a melting layer of precipitation," *IEEE Trans. Antennas Propag.*, vol. 42, no. 4, pp. 492–500, Apr. 1994.

BIBLIOGRAPHY

- [29] J. A. Romo, M. Maruri, F. Pérez-Fontán, and I. Fernández, “Characterization of maximum radar reflectivity height during stratiform rain events,” *IEEE Trans. Antennas Propag.*, vol. 69, no. 10, pp. 4884–4891, Oct. 2012.
- [30] A. von Lerber, D. Moiseev, J. Leinonen, J. Koistinen, and M. T. Hallikainen, “Modeling radar attenuation by a low melting layer with optimized model parameters at C-band,” *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 2, pp. 724–737, Feb. 2015.
- [31] O. Pujol, F. Mesnard, and H. Sauvageot, “Effects of melting layer in airborne meteorological X-band radar observations,” *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 6, pp. 2318–2324, June 2012.
- [32] H. W. J. Russchenberg and L. P. Ligthart, “Backscattering by and propagation through the melting layer of precipitation: a new polarimetric model,” *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 1, pp. 3–14, Jan 1996.
- [33] L. Raynaud, I. Chenerie, and J. Lemorton, “Modeling of radiowave scattering in the melting layer of precipitation,” *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 4, pp. 1574–1584, Jul 2000.
- [34] F. S. Marzano and P. Bauer, “Sensitivity analysis of airborne microwave retrieval of stratiform precipitation to the melting layer parameterization,” *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 1, pp. 75–91, Jan 2001.
- [35] J. Vivekanandan, D. S. Zrnic, S. M. Ellis, R. Oye, A. V. Ryzhkov, and J. Straka, “Cloud microphysics retrieval using s-band dual-polarization radar measurements,” *Bull. Amer. Meteorol. Soc.*, vol. 80, no. 3, pp. 381–388, Mar 1999.

BIBLIOGRAPHY

- [36] C. L. Wilson, J. Tan, J. W. F. Goddard, and J. T. Ong, “Radar vertical profiles and melting layer studies from an s-band doppler polarization-diversity radar campaign in singapore,” *30th International Conference on Radar Meteorology - American Meteorological Society*, pp. 423–425, Munich, Germany, 2017.
- [37] C. L. Wilson and J. Tan, “Melting layer studies in singapore: experimental results from an S-band doppler polarisation-diversity radar,” *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, vol. 23, no. 10, pp. 1129–1132, Oct. 2000.
- [38] M. S. Teshiba, P. B. Chilson, A. V. Ryzhkov, T. J. Schuur, and R. D. Palmer, “A combined wind profiler and polarimetric weather radar method for the investigation of precipitation and vertical velocities,” *J. Atmos. Oceanic Technol.*, vol. 26, pp. 1940–1955, Nov. 2008.
- [39] Y. Shusse, K. Nakagawa, N. Takahashi, S. Satoh, and T. Iguchi, “Characteristics of polarimetric radar variables in three types of rainfalls in baiu front event over the east china sea,” *J. Meteor. Soc. Japan*, vol. 87, pp. 865–875, Jun. 2009.
- [40] Y. Shusse, N. Takahashi, K. Nakagawa, S. Satoh, and T. Iguchi, “Polarimetric radar observation of the melting layer in a convective rainfall system during the rainy season over the east china sea,” *J. Appl. Meteor. Climatol.*, vol. 50, pp. 354–367, Sep. 2011.
- [41] L. Gómez-Chova, G. Camps-Valls, J. Calpe-Maravilla, L. Guanter, and J. Moreno, “Cloud-screening algorithm for ENVISAT/MERIS multispectral images,” *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 12, p. 4105–4118, Dec. 2007.

BIBLIOGRAPHY

- [42] M. T. Decker, E. R. Westwater, and F. O. Guiraud, “Experimental evaluation of ground-based microwave radiometric sensing of atmospheric temperature and water vapor profiles,” *J. Appl. Meteor.*, vol. 17, no. 12, p. 1788–1795, Dec. 1978.
- [43] Y. Han and E. R. Westwater, “Remote sensing of tropospheric water vapor and cloud liquid water by integrated ground-based sensors,” *J. Atmos. Oceanic Technol.*, vol. 12, p. 1050–1059, Oct. 1995.
- [44] J. H. Wang and W. B. Rossow, “Determination of cloud vertical structure from upper-air observations,” *J. Appl. Meteor.*, vol. 34, no. 10, p. 2243–2258, Oct. 1995.
- [45] E. Salonen and S. Uppala, “New prediction method of cloud attenuation,” *Electron. Lett.*, vol. 27, no. 12, p. 1106–1108, Jun. 1991.
- [46] M. Costa-Surós, J. Calbó, J. González, and J. Martin-Vide, “Behavior of cloud base height from ceilometer measurements,” *Atmos. Res.*, vol. 127, pp. 64–76.
- [47] T. Berendes, D. Berendes, R. Welch, E. Dutton, T. Uttal, and E. Clothiaux, “Cloud cover comparisons of the modis daytime cloud mask with surface instruments at the north slope of Alaska ARM site,” *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 11, pp. 2584–2593, Nov. 2004.
- [48] M. Costa-Surós, J. Calbó, J. A. González, and C. N. Long, “Comparing the cloud vertical structure derived from several methods based on measured atmospheric profiles and active surface measurements,” *Atmos. Chem. Phys. Discuss.*, vol. 13, no. 6, pp. 14 405–14 445, Jun. 2013.

BIBLIOGRAPHY

- [49] V. Mattioli, P. Basili, S. Bonafoni, P. Ciotti, and E. R. Westwater, “Analysis and improvements of cloud models for propagation studies,” *Radio Sci.*, vol. 44, no. RS2005, Apr. 2009.
- [50] J. Zhang, H. Chen, Z. Li, X. Fan, L. Peng, Y. Yu, and M. Cribb, “Analysis of cloud layer structure in shouxian, china using RS92 radiosonde aided by 95 GHz cloud radar,” *J. Geophys. Res.*, vol. 115, no. D7, Apr. 2010.
- [51] W. B. Rossow, Y. C. Zhang, and J. H. Wang, “A statistical model of cloud vertical structure based on reconciling cloud layer amounts inferred from satellites and radiosonde humidity profiles,” *J. Climate*, vol. 18, no. 17, pp. 3587–3605, Sep. 2005.
- [52] W. Josefsson and T. Landelius, “Effect of clouds on UV irradiance: As estimated from cloud amount, cloud type, precipitation, global radiation and sunshine duration,” *J. Geophys. Res-Atmos.*, vol. 105, no. 4, pp. 4927–4935, Feb. 2000.
- [53] D. Ji and J. Shi, “Water vapor retrieval over cloud cover area on land using AMSR-E and MODIS,” *IEEE J. Sel. Topics Appl. Earth Observ.*, vol. 7, no. 7, pp. 3105–3116, Jul. 2014.
- [54] T. A. Alawadi, “Investigation of the effects of cloud attenuation on satellite communication systems,” Ph.D. Thesis, Department of Engineering Physics, School of Engineering, Cranfield University, UK, 2012.
- [55] K. D. Poore, J. H. Wang, and W. B. Rossow, “Cloud layer thicknesses from a combination of surface and upper-air observations,” *J. Climate*, vol. 8, p. 550–568, 1995.

BIBLIOGRAPHY

- [56] J. H. Wang, W. B. Rossow, and Y. Zhang, “Cloud vertical structure and its variations from a 20-yr global rawinsonde dataset,” *J. Climate*, vol. 13, p. 3041–3056, 2000.
- [57] N. Pierdicca, L. Pulvirenti, and F. S. Marzano, “A model to predict cloud density from mid-latitude atmospheric soundings for microwave radiative transfer applications,” *Raido Sci.*, vol. 41, 2006.
- [58] E. Altshuler and R. Marr, “Cloud attenuation at millimeter wavelengths,” *IEEE Trans. Antennas Propag.*, vol. 37, no. 11, pp. 1473–1479, Nov. 1989.
- [59] F. Dintelmann and G. Ortgies, “Semiempirical model for cloud attenuation prediction,” *Electron. Lett.*, vol. 25, no. 22, pp. 1487–1488, 1989.
- [60] “Attenuation due to clouds and fog,” Rec. ITU-R P.840-6, 2013.
- [61] A. Dissanayake, J. Allnutt, and F. Haidara, “Cloud attenuation modelling for SHF and EHF applications,” *Int. J. Satell. Commun.*, vol. 19, no. 3, pp. 335–345, May 2001.
- [62] L. Luini and C. Capsoni, “Modeling high-resolution 3-D cloud fields for earth-space communication systems,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, p. 5190–5199, Oct. 2014.
- [63] N. K. Lyras, C. I. Kourogorgas, and A. D. Panagopoulos, “Cloud attenuation statistics prediction from Ka-band to optical frequencies: integrated liquid water content field synthesizer,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 1, pp. 319–328, Jan. 2017.

BIBLIOGRAPHY

- [64] L. Luini and C. Capsoni, “Scaling cloud attenuation statistics with link elevation in earth-space applications,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 1089–1095, Mar. 2016.
- [65] T. Manabe, H. Liebe, and G. Hufford, “Complex permittivity of water between 0 and 30 THz,” *Conf. Dig., Twelfth Int. Conf. on Infrared and Millimeter Waves*, pp. 229–230, 1987.
- [66] F. Yuan, Y. H. Lee, Y. S. Meng, J. X. Yeo, and J. T. Ong, “Statistical study of cloud attenuation on Ka-band satellite signal in tropical region,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2018–2021, 2017.
- [67] J. Mandeep, J. Ojo, and L. Emiliani, “Statistics of annual and diurnal cloud attenuation over equatorial climate,” *IET Communications*, vol. 3, pp. 630–635, 2009.
- [68] J. Wang, W. Rossow, and Y. Zhang, “Cloud vertical structure and its variations from a 20-yr global rawinsonde dataset,” *J. Climate*, vol. 13, p. 3041–3056, 2000.
- [69] I. Durre, R. S. Vose, and D. B. Wuertz, “Overview of the integrated global radiosonde archive,” *J. Climate*, vol. 19, pp. 53–68, 2006.
- [70] Department of Atmospheric Science University of Wyoming. [Online]. Available: <http://weather.uwyo.edu/upperair/sounding.html>
- [71] T. V. Omotosho, J. S. Mandeep, and M. Abdullah, “Cloud-cover statistics and cloud attenuation at Ka- and V-bands for satellite systems design in tropical wet climate,” *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1194–1196, 2011.
- [72] “Rain collector II owner’s manual,” Davis Instruments, 1993.

BIBLIOGRAPHY

- [73] J. Vivekanandan, S. Ellis, R. Oye, D. Zrnic, A. Ryzhkov, and J. Straka, “Cloud microphysics retrieval using S-band dual-polarization radar measurements,” *Bull. Amer. Meteor. Soc.*, vol. 80, p. 381–388, 1999.
- [74] S. Manandhar, F. Yuan, Y. H. Lee, and Y. S. Meng, “Weather radar to detect and differentiate clouds from rain events,” in *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, 2016, Puerto Rico, USA.
- [75] R. Ott and M. Thompson, “Atmospheric amplitude spectra in an absorption region,” *1976 Antennas and Propagation Society International Symposium*, pp. 594–597, Amherst, MA, USA, 1976.
- [76] T. Mouldsley and E. Vilar, “Experimental and theoretical statistics of microwave amplitude scintillations on satellite down-links,” *IEEE Transactions on Antennas and Propagation*, vol. 30, no. 6, pp. 1099–1106, Nov. 1982.
- [77] Y. Karasawa and T. Matsudo, “Characteristics of fading on low-elevation angle earthspace paths with concurrent rain attenuation and scintillation,” *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 5, pp. 657–661, May 1991.
- [78] F. S. Marzano and C. Riva, “Cloud-induced effects on monthly averaged scintillation amplitude along millimeter-wave slant paths,” *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 4, pp. 880–887, Apr. 2003.
- [79] C. E. Noll, “The crustal dynamics data information system: A resource to support scientific analysis using space geodesy,” *Advances in Space Research*, vol. 45, no. 12, pp. 1421–1440, Jun. 2010.

BIBLIOGRAPHY

- [80] G. Elgered, J. L. Davis, T. A. Herring, and I. I. Shapiro, “Geodesy by radio interferometry: water vapor radiometry for estimation of the wet delay,” *J. Geophys. Res.*, vol. 96, no. B4, p. 6541–6555, Apr. 1991.
- [81] S. Desai and W. Bertiger, “GIPSY/OASIS (GIPSY) overview and under the hood,” JPL, Mar. 2014.
- [82] S. Manandhar, F. Yuan, Y. H. Lee, and Y. S. Meng, “A constant conversion factor for retrieval of pwv from gps signals in tropical region,” *to appear in Proc. 2017 USNC-URSI Radio Sci. Meeting*, 2017, San Diego, USA.
- [83] Y. Liu and Y. Chen, “Precision of precipitable water vapour from radiosonde data for GPS solutions,” *Geomatica*, vol. 54, no. 2, pp. 171–175, 2000.
- [84] Y. Liu, “Remote sensing of atmospheric water vapor using gps data in the Hong Kong region,” PhD thesis, The Hong Kong Polytechnic University, 2000.
- [85] S. Dev, F. Savoy, Y. H. Lee, and S. Winkler, “Wahrsis: A low-cost, high-resolution whole sky imager with near-infrared capabilities,” *Proc. IST/SPIE Infrared Imaging Systems: Design, Analysis, Modeling, and Testing*, vol. 9071, May 2014.
- [86] J. X. Yeo, Y. H. Lee, and J. T. Ong, “Site diversity gain at the equator: radar-derived results and modeling in Singapore,” *Int. J. Satell. Commun. Network*, vol. 33, no. 2, pp. 107–118, Mar. 2015.
- [87] J. S. Marshall and W. M. Palmer, “The distribution of raindrops with size,” *Journal of Atmos. Sci.*, vol. 5, p. 165–166, 1948.
- [88] C. Capsoni, L. Luini, A. Paraboni, C. Riva, and A. Martelluci, “A new prediction model of rain attenuation that separately accounts for stratiform and convective rain,” *IEEE Trans. Antennas Propag.*, vol. 57, no. 1, pp. 196–203, Jan. 2009.

BIBLIOGRAPHY

- [89] F. Fabry and I. Zawadzki, “Long-term radar observations of the melting layer of precipitation and their interpretation,” *J. Atmos. Sci.*, vol. 52, pp. 838–851, Apr. 1995.
- [90] W. Hall, M. A. Rico-Ramirez, and S. Kramer, “Classification and correction of the bright band using an operational C-band polarimetric radar,” *Journal of Hydrology*, vol. 531, pp. 248–258, Dec. 2015.
- [91] F. Yuan, S. Manandhar, Y. H. Lee, and Y. S. Meng, “Model comparison for estimating cloud liquid water content and attenuation in tropical region,” *2016 IEEE Region 10 Conference (TENCON)*, pp. 1317–1320, 2016, Singapore.
- [92] D. Wolfensberger, D. Scipion, and A. Berne, “Detection and characterization of the melting layer based on polarimetric radar scans,” *Q. J. R. Meteorol. Soc.*, vol. 142, pp. 108–124, Nov. 2015.
- [93] “Rain height model for prediction methods,” ITU-R: Recommendation P.839-3, Geneva, Switzerland, 2001.
- [94] F. Yuan, Y. H. Lee, and Y. S. Meng, “Investigation of cloud attenuation on ka-band satellite beacon signal in tropical region,” in *Proc. IEEE Antennas Propagat. Soc. Int. Symp.*, 2016, Puerto Rico, USA.
- [95] T. V. Omotosho, M. L. Akinyemi, J. S. Mandeep, and M. Abdullah, “Total atmospheric absorption of fixed satellite communication signal due to oxygen and water vapor in Nigeria,” *IEEE Antennas and Propagation Magazine*, vol. 56, no. 2, pp. 108–121, Apr. 2014.

BIBLIOGRAPHY

- [96] “Fascicle concerning the statistical distribution of integrated water vapour and liquid water contents given in recommendations ITU-R P.836-4 and ITU-R P.840-4,” ITU-R, 2013.