DETERMINATION OF THE MELTING LAYER FROM METEOROLOGICAL RADAR DATA

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To

my Beloved Mother, Father, Brothers and Faience.

and to

the Souls of Mohammed Abdel Aziz and Mustafa Hashim

who devoted their lives towards defending Islam and our country.

ACKNOWLEDGMENT

In the name of Allah, Most Gracious, and Most Merciful

Praise be to Almighty Allah (Subhanahu Wa Ta'ala) who gave me the courage and patience to carry out this work. Pease and blessing of Allah be upon his last prophet Mohammed (Sallulaho-Alaihe Wassalam) and all his companions (Sahaba), (Razi-Allaho-Anhum) who devoted their lives towards the prosperity and spread of Islam.

My deep appreciation and heartfelt gratitude goes to my supervisor, Dr. Nor Hisham Bin Hj Khamis for his kindness, constant endeavor, guidance and the numerous moments of attention he devoted through out this work.

I extend my deepest gratitude to my close friend, Eng. Ayman A.A. Alwarfalli for his encouragement and motivation. A special thanks and deepest gratitude to my friends, Eng. Abdel razig Saeed Mohammed, Eng. Elmueiz El tayeb Sulaiman, and Eng. Naji Abdel Gadir Ahmed for providing their workstations to complete my work.

Acknowledgement is due to my senior colleague and friend Eng. Illiasaak Ahmad, and my classmate Eng. Sahazati bt. Md. Rozali for translating the abstract to Bahasa Malaysia. Also, a heartfelt acknowledgement is due to Dr. Abdelwahab Mohammed Ali, who revised the thesis, for his valuable comments about the thesis format and the language.

A heartfelt gratitude and acknowledgement are due to the Sudanese community in UTM, Skudai for their kindness, care, valuable advices and cooperation, which generates a similar environment as what I left.

Sincere friendship is the flavor and spice of life, I owe thanks to my close friends in Sudan, who offered different kinds of support. Sincere thanks are extended to my classmates and colleagues in the international student building (KTC-S46 and S47) at UTM, Skudai.

I would like to extend the acknowledgement to the Industrial Research and Consultancy Centre (IRCC), Sudan, and all my colleagues there for their continuous courage and support. Special heartfelt thanks to the Engineering Industries Department and the Economical Studies Department in IRCC for their cooperation, patience and unlimited support.

Family support plays a vital role in the success of any individual. I would like to convey a heartfelt thanks to my parents, brothers, and other family members including all my uncles, ants and their families; their prayers and encouragement always helped me take the right step in life. Also special thanks to all neighbors in Block 11, Alsafiah, Sudan, for their spiritual support and heartiest prayers.

ABSTRACT

The bright band is the enhanced radar echo (reflectivity) associated with the melting of hydrometeors in stratiform rain. However; incorrect determination of the bright-band may lead to significant overestimation of precipitation such as rainfall rate reaching the ground, sometimes by as much as a factor of five, as in the example for rainfall rate. Radar has the potential to distinguish between different hydrometeors through the vertical profile of reflectivity by its statistical moments. The vertical profile can be used to determine the bright band. The main objective of this project is to determine the boundaries of the melting layer (bright band) based on the meteorological radar measurements. This determination includes the evaluation of the rain height and zero degree isotherms height. To achieve this description fully, the raw radar measurements have been sorted out, filtered, and decoded, plotted and analyzed. Radar observables have been plotted against the corresponding heights, and their boundaries have been determined according to the enhancement and transition of radar parameters. The results give an acceptable correlation with the international telecommunication union- radio communication sector (ITU-R) recommendations and a good one with the results that are obtained from the precipitation radar on-board the tropical rainfall measuring mission (TRMM) satellite and the characteristics of the melting layer in Singapore, which obtained using S-band polarization-diversity Doppler radar.

ABSTRAK

Jalur terang ialah pantulan radar yang ditingkatkan nilainya dan berkait rapat dengan pencairan pemendakan hujan *stratiform*. Namun begitu, kesilapan dalam penentuan kadar gema bagi jalur terang mengakibatkan kesan yang ketara semasa menentukan kadar pemendakan. Kesilapan anggaran kadang-kala boleh mencecah sehingga 5 skala-faktor akibat daripada kesilapan penganggaran kadar turun hujan, contohnya. Radar mempunyai potensi untuk mengklasifikasikan jenis pemendakan melalui data *statistical moments* pantulan profil menegak. Oleh yang demikian, objektif utama dalam projek ini adalah untuk menentukan sempadan-sempadan lapisan pencairan bagi jalur terang berdasarkan data yang diperolehi daripada radar meteorologi. Selain daripada itu, penilaian keatas *rain height* dan *zero degree isotherms height* juga dilakukan. Data mentah yang diperolehi dari radar telah disusun, disaring, dinyahkod, dan seterusnya dianalisa bagi mendapatkan maklumat yang sebaik mungkin. Data yang telah diproses tadi kemudiannya diplotkan berlawanan dengan nilai tinggi. Sempadan bagi data-data tersebut ditentukan mengikut peningkatan dan had transisi radar. Keputusan yang diperolehi adalah memberangsangkan kerana ianya selari dengan cadangan yang diberikan oleh ITU-R. Keputusan yang diperolehi juga sama baiknya dengan keputusan yang didapati melalui radar satelit pemendakan TRMM (Tropical Rainfall Measuring Mission). Ianya juga bersamaan dengan ciri-ciri pencairan lapisan di Singapura yang diperolehi melalui radar *S-band polarization-diversity Doppler*.

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A	Area (m^2)
A	Total Attenuation (in dB)
A_g	Geometric area
A_{eff}	Effective area (m^2)
AS_{in}	Inner average slope
AS_{out}	Outer average slope
BB_H	Radar bright-band height (km)
BB_{th}	Bright band thickness (km)
C_R	Radar calibration constant
c	Velocity of propagation (m/sec)
D	Diameter (m), size of particles
D_o	Outer diameter (m)
D_i	Inner diameter (m)
dBZ	dB Z= 10 $\log_{10}$ Z
e	Relative dielectric constant
e_m	Dielectric constant of the medium
e_{in}	Dielectric constant of the inclusions or embedded particles
FH	Freezing height (km)
f	Fraction of the total particle volume
f	Frequency (Hz)
$G_t(r)$	Gain of the transmitted antenna in direction **r**
$G_r(r)$	Gain of the received antenna in direction **r**
H (t-τ)	Impulse response of the radar receiver
h	Length of square-wave pulse in Radar
*h*B	Bottom border of bright band
h_{bot}	Bright band region bottom height (km)

h_{peak}	Height of peak of bright band reflectivity
h_R	Rain height (km)
$h\mathrm{T}$	Top border of bright band
h_{top}	Bright band region top height (km)
h_0	0°C isotherm height, peak of reflectivity
L	Losses of microwave measurement element
L_{DR}.	Linear depolarization ratio
N	Concentration of particles in certain size
N (D)	The drop size distribution (DSD)
n	Complex index of refraction
$P_1(r)$	Power transmitted in direction **r** (W)
$P_2(r)$	Power transmitted by omni-directional antenna in direction **r** (W)
P_t	Transmitted power (W)
P_r	Received power (W)
R, r	Range, distance or radius (m)
Tx	Transmitter
V	Resolution volume (m^3)
W	Power density (W/m^2)
Z	Effective reflectivity factor (mm^6/m^3)
Z_{DR}	Differential reflectivity
Z_H	Reflectivity measured at horizontal polarization
Z_V	Reflectivity measured at vertical polarization
Z_e	Effective radar reflectivity factor (mm^6/m^3)
Z_{peak}	Peak of bright band reflectivity
Z_{rain}	Reflectivity of rain
Z_{snow}	Reflectivity of snow
Ω	Antenna solid angle
Φ_{DP}	Differential phase shift
η	Radar reflectivity (m^2 m^{-3})
λ	Wavelength (m)
τ	Pulse duration (second)
σ	Effective area of the radar target (m^2)
σ_H	Backscatter cross section for horizontal polarization

σ_V	Backscatter cross section for vertical polarization
γ_g	Specific attenuation for atmospheric gases (dB/km)
γ_c	Specific attenuation for clouds (dB/km)
γ_p	Specific attenuation for precipitation (dB/km)
φ	Latitude of the earth-station location
ρ_{co}	Co-polar correlation
δco	Scattering differential phase

LIST OF ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
AZ	Azimuth angle (degree)
BB	Bright Band
CW	Continuous wave
DSD	Drop Size Distributions
EA	Elevation angle
EM	Electromagnetic
ISO	International Standard Organization
ITU-R	International telecommunication union – Radio communication sector
JDN	Julian Day Number
LOS	Line-of-site
PPI	Plan position indicator
PE	Permanent Echo
RADAR	Radio Detection And Ranging
RCS	Radar Cross Section
RHI	Range Height Indicator
RIU	Radar Interface Unit
RR	Resolution Range
SNR	Signal to Nose ratio
TRMM-PR	Tropical Rainfall Measuring Mission-Precipitations Radar
UK	United Kingdom
UTM	Universiti Teknologi Malaysia
VPR	Vertical profile of radar reflectivity
VRP	Vertical reflectivity profiles

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Satellite communications systems become an important segment of the global telecommunication infrastructure. This includes an integration of number of applications and services, which use satellites to relay radio transmissions between earth terminals. These services had traditionally been available via terrestrial networks and radio broadcastings.

With the rapid growth of the information technology there is an increasing demand for broadband satellite services, which will provide reliable transmission of information. Multi-media applications including data and video require large bandwidth and low error rates for satisfactory performance. This demand will exceed the present services existence today. Furthermore, there will be increasing problems of finding the required frequency spectrum to provide the bandwidth for broadband services, which has brought saturation to the conventional frequency bands allocated for satellite services, namely L (1/2 GHz), S (2/4 GHz), and C (4/6 GHz).

New and demanding satellite applications evolved has led to utilize and exploit higher frequencies bands such as Ka-band (20/30 GHz) and above. Spectrum at Ka-band (20/30 GHz) or higher frequencies band has great importance for broadband services. This is because of its relatively unused spectrum with no congestion problem, which offers much greater bandwidths, frequency reuse capability than the current spectrum at Ku-band (11/12 GHz), and smaller component sizes.

1.2 Project Background and Problem Statement

The use of higher and higher frequencies in telecommunication systems requires the investigation of the effects of troposphere on electromagnetic wave propagation, and particular attention must be paid to the attenuation induced by raindrops and other hydrometeors along the radio path (Capsoni *et al*, 2003).

Rain affects the design of any communication or remote sensing system that relies on the propagation of electromagnetic waves thorough the lowest 10 km of Earth's atmosphere at frequencies above 1GHz. Communication systems may experience loss of signal due to the attenuation caused by rain on a radio link and might be temporarily unavailable for use. The problem for system designers is the prediction or forecast the effects of rain on communication system located anywhere on or above the surface of Earth (Crane, 1996).

The direct measurements approach to investigate the rain effect and its parameters is, in most cases, not feasible or convenient because of the cost and time to collect statistically meaningful data and the difficulty to extrapolate the results to other sites. Therefore, nowadays, the indirect measurement technique has become widely used. In this respect, there is a growing interest on radar data; the main reason is the ability of this instrument to detect with great spatial detail precipitation over a large area, in real time, and with a single installation. Radar data can be used, in principle, to evaluate through simulations, propagation impairments due to hydrometeors for any length of ground or satellite radio paths, any kind and complexity of the radio system and for any frequency. The drawback is that radar reflectivity (Z), which is the basic measure of the meteorological target, cannot be directly used; its conversion to rain intensity (or attenuation) is not unique, depending mostly on Drop Size Distributions (DSD). Hence, the need of a "calibration" that multi-parameter radar can carry out, in some way, using the set of independent measurements on the state of precipitation they perform, while single parameter radar cannot (Capsoni *et al*, 2003).

The enhancement in radar reflectivity caused by melting snowflakes below the 0°C isotherm is known as the "bright-band". It is due to changes in size, fall speed and phase during the melting process. If unrecognized, the bright-band can lead to significant overestimation of precipitation reaching the ground, sometimes by as much as a factor of 5 (Tan and Goddard, 1995).

Although the qualitative explanation of the reflectivity enhancement causing the bright band has been made by Ryde (1946), still there is no consensus after more than 60 years on a quantitative assessment because the bright band is usually more intense than predicted. Earlier quantitative estimates by Austin and Bemis (1950); Wexler (1955); Wexler and Atlas (1956); and Lhermitte and Atlas (1963) as well as the models of Ekpenyong and Srivastava (1970) either confirmed this observation or attempted to explain the differences either through shape effects (non-sphericity of snowflakes and melting snowflakes, Atlas *et al.*(1953) or by growth of precipitation through condensation and aggregation at the top of the melting layer followed by breakup below. This aggregation-breakup combination appeared essential in all cases to explain the bright band intensity and several in-situ or aircraft measurements were attempted to verify this claim. However, there is still debate as to whether this effect is important (Stewart *et al*. 1984; Yokoyama *et al.*, 1985; Willis and Heymsfield, 1989) or negligible (Du Toit 1967; Ohtake 1969). Recent models of Dissanayake and McEwan (1978), Klaassen (1988), and Hardaker *et al*. (1991) either obtain correct reflectivity enhancement or overestimate the bright band intensity by considering the bright band enhancement to be caused by the melting of low-density snowflakes alone.

The lack of agreement between model results and observations is also exacerbated by the fact that there are no extensive measurement records of the bright band. Most comparisons of models and observations are too often based on one or few events or even simply on the first published bright band measurement made with a Doppler radar (Lhermitte and Atlas, 1963). Given the large number of factors that may influence the bright band shape such as snowflake sizes and shapes, temperature profile, and vertical air velocity, it is not surprising to have so many, often contradictory, explanations of the bright band phenomenon (Fabry *at el.*, 1994).

The lack of knowledge on the detailed physics of the melting layer has some practical consequences in hydrology and microwave communication. In microwave communication, the enhanced reflectivity of the bright band results in enhanced scattering and greater signal extinction. Scattering causes interference between microwave links while extinction disrupts communications. As current microwave frequencies are becoming crowded, new bands will have to be used and a good quantification of bright band effects becomes necessary to estimate the reliability of these new frequencies. Knowledge of attenuation by the melting layer will also be crucial in order to properly estimate rainfall using short wavelength space-borne radars (Fabry *at el.*, 1994).

The estimated rain rate from $Z_{H,V}$ is undoubtedly overestimated. It is necessary to correct for the effect of the bright-band on radar measurements when attempting to interpret estimates of rain rate from radar data. The critical step is to detect the height where the melting process happens, which means the height of bright-band (Tan and Goddard, 1995).

Finally, the bright band phenomenon is a challenge to the knowledge of precipitation physics and scattering theory. The inability to explain it quantitatively is a proof that our understanding of these topics is incomplete and additional efforts must be invested to quantify the mechanisms causing the bright band.

Long term measurements of the bright band will allow us to derive the dependence of bright band characteristics on precipitation type and intensity that should help to quantify the contribution of the various causes to the bright band signature. Averages over long records are insensitive to the peculiarities of a given event, such as contamination by horizontal advection, and emphasize the characteristics that are persistent and related to the physics of snow melting. Although no upper air microphysical observations can be made over such a long period, several hypotheses can be tested using the average reflectivity signature in and around the melting layer.

Data collected in the first half of 1998 using meteorological S-band radar located in Kluang (Malaysia) are used to compute average profiles of radar reflectivity in and surrounding the melting layer in an attempt to determine its boundaries.

From the above discussion, it is clear any obtained data about the rainfall rate cannot be directly interpreted. It is rather important to predetermine the boundaries of the melting layer in order to conduct a valid as well as accurate estimation of the rain rate.

1.3 Project Objective

The main objective of this project is to determine the boundaries of the melting layer (bright band) based on the meteorological radar measurements. This determination includes the evaluation of the rain height (h_R), zero degree Celsius isotherm height (h_0), melting layer or bright band height (BB_H) and its thickness (BB_{th}).

1.4 Scope of the Project

The scope of this project includes:

- Instrument and Location: Meteorological S-band radar belongs to the Meteorological Department of Malaysia, which is located in Kluang (Latitude=2.02°, Longitude=103.320° and height=88.1 m above MSL).

- Duration: The used data covers 116 days collected over the period from 2nd January to 18th June 1998 for 285,231 scans (1.26 GB on disk) with 15 elevation angles of 0.5°, 1.2° 1.9°, 2.7°, 3.5°, 4.6°, 6.0°, 7.5°, 9.2°, 11.0°, 13.0°, 16.0°, 20.0°, 25.0°, and 32.0°

- Resolution Range: Two types of radar resolution ranges of 500m and 1000m were used interchangeably and simultaneously.

- Development of programs to sort out, filter, decode the radar data and plot the vertical profile of radar reflectivity from the decoded data over the radar ranges using MATLAB platform (version 7.04 release14).

- Determination the melting layer boundaries according to the plotted profile. These boundaries include the rain height (h_R), zero degree Celsius isotherm height (h_0), melting layer or bright band height (BB_H) and its thickness (BB_{th}).

1.5 Project Methodology

To carry out this project, the following methodology is designed:

- Build up of the vertical reflectivity profile (VRP) based on radar data, which includes the following tasks:
  - Preprocessing tasks, which include sorting out and filtering the meteorological radar data.
  - Decoding the radar data, and calculation of its reflectivity intensity in decibel (dBZ) for the full range of Azimuth for all the 15elevation angles.
  - Plot the reflectivity versus height curves.

- Determination of the boundaries of bright band according to:

  - Curvature of reflectivity versus height curve.
  - Increasing and Decreasing of reflectivity.
  - Maximum reflectivity.

- Comparison the results with ITU-R model and other models in tropical regions for validation

1.6 Thesis Out line

Chapter one concerns with the introduction of the study in hand, which starts with brief introduction, and continues stating the problem, the objective, the scope of the study and finally methods employed to achieve the goals set forth. Chapter two, which is the first chapter of the literature review, presents the RADAR principles and characteristics, by focusing on meteorological radar, which its data is used in this project. Chapter three shows the concept of the melting layer and its properties. In this chapter, different procedures of detecting and determining the boundaries of the melting layer are explored. Chapter four explains the execution of the project by driven its wheel and handle the analysis of the meteorological data. Chapter five presents and discuses the findings of the analytical procedures employed. The results were interpreted and compared with the ITU-R recommendations and other findings in the tropical region to measure the validity of the obtained results. Chapter six summarizes and emphasizes the obtained results and the contribution of the study. This chapter also proposes the future work that can be done for more accurate determination of the boundaries of the bright band as well as better understanding of the melting process and its characteristics.