CHARACTERIZATION OF BRIGHT-BAND IN A TROPICAL STATION FOR SATELLITE COMMUNICATION

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DEDICATION

To

Omobolanle,
Olamide,
Opeyemi,
Opemipo,
and
Opeoluwa

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ABSTRACT

Tropical regions experience signal degradations due to hydrometeors in addition to paucity of database for slant path rain propagation estimations. The melting layer is the region where rain starts to occur; lying just below the $0^{o}C$ isotherm height. Frozen hydrometeors exhibit peculiar characteristics in the form of increased radar reflectivity as they fall from the sky, morphing from solid to liquid; and manifesting itself as the popular bright-band signature. Knowledge of the formation and recognition of the bright-band is necessary to characterize the melting layer. Adequate information on diurnal, seasonal and annual variation effects on rain height can give valuable information for satellite equipment design and planning. Rain height is highly correlated with signal attenuation and co-channel interference resulting from scattering. This work involves the characterization of bright-band data for UTM Johor Bahru campus, Malaysia. Thirteen months (1 November, 2006 to 30 November, 2007) 3D RAPIC ground radar data at 500 m range bins resolution were sourced from MMS. Additionally, twenty-two months (January 2011 to May 2013) TMPA-RT radar data at 5^{0} x 5^{0} latitude-longitude horizontal resolution were obtained to complement the ground radar data. The reflectivity from these data was analysed to characterize the melting layer. Malaysia experiences two monsoon events yearly: The North-East monsoon and the South-West monsoon. Results from this work suggest that freezing and rain heights are highest in the months of November 2006, March and September 2007; which coincides with the end of the two monsoons. Equally, these parameters are observed to be lowest in February, April, July and October; thus suggesting seasonal and annual variability. The bright-band is thicker in the day, while freezing and rain heights are higher at night than in the day time, suggesting diurnal dependence. However, data for a longer period of time is needed to consolidate these findings. The results show good degree of agreement when compared with similar previous findings from Malaysia. But, ITU-R.P. 618 model largely underestimated the total measured attenuation. Thus, there is a need to include the melting layer effect in satellite communication attenuation prediction in the tropics for improved Quality of Service.

ABSTRAK

Kawasan tropika mengalami rosotan isyarat yang disebabkan oleh *hydrometeors* dan kurangnya pengkalan data untuk meramal perambatan hujan laluan sendeng. Lapisan pencairan adalah di mana hujan mula berlaku; terletak di bawah ketinggian satuanhaba 0^oC. *Hydrometeor* terbeku mempamerkan ciri-ciri khas iaitu peningkatan reflektiviti radar semasa jatuh daripada langit, bertukar daripada pepejal kepada cecair, dan menyerlah sebagai jalur terang yang amat dikenali. Pengetahuan tentang pembentukan dan mengenalpasti jalur terang ini adalah perlu untuk menentukan sifat lapisan pencairan ini. Maklumat yang mencukupi tentang perubahan yang disebabkan oleh keadaan siang-malam, pertukaran musim dan tahunan ke atas ketinggian lapisan hujan akan memberi maklumat berguna untuk perancangan dan reka bentuk peralatan dan rangkaian satelit. Ketinggian lapisan hujan adalah berkait rapat dengan rosotan isyarat dan gangguan saluran bersebelahan yang disebabkan oleh penyerakan. Kajian ini melibatkan pencirian data jalur terang untuk kampus UTM Johor Bahru, Malaysia. Data radar bumi 3D RAPIC selama 13 bulan (Januari 2012 hingga Mei 2013) pada resolusi jarak kotak 500 m adalah diperolehi dari MMS. Disamping itu, data radar TMPA-RT pada resolusi mendatar 5^o x 5^o latitud-longitud diperolehi untuk komplemen data radar bumi. Reflektiviti daripada data-data ini dianalisa untuk menentukan ciri-ciri lapisan pencairan. Setiap tahun, Malaysia mengalami dua jenis monsoon: iaitu Monsun Timur-laut dan Monsun Barat-daya. Hasil dari kajian ini menunjukkan bahawa ketinggian pembekuan dan hujan adalah tertinggi pada bulan November, 2006, Mac dan September 2007; yang bertepatan dengan penghujung kedua-dua monsun. Parameter-parameter ini adalah terendah pada bulan Februari, April, Julai dan Oktober; yang menunjukkan perubahan mengikut musim dan tahunan. Jalur-terang adalah lebih tebal pada siang hari, manakala pembekuan dan ketinggian hujan adalah lebih tinggi dimalam hari berbanding pada siang hari, yang menunjukkan kebergantungan kepada pertukaran siang-malam. Walau bagaimanapun, data untuk tempoh yang lebih lama adalah diperlukan untuk mengukuhkan penemuan-penemuan ini. Keputusan ini menunjukkan persetujuan yang tinggi dengan hasil kajian yang serupa di Malaysia sebelum ini. Tetapi, jangkaan yang diberikan model ITU-R.P.618 adalah sering lebih rendah dari jumlah keseluruhan rosotan yang diukur. Ini membuatkan perlunya kesan lapisan pencairan diambilkira bagi penentuan rosotan perhubungan satelit di kawasan tropika untuk penambahbaikan kualiti perkhidmatan.

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H_S	-	Altitude of earth station	(km)
H_0	-	Average height of freezing level	(km)
L_{eff}	-	Effective slant path	(km)
α	-	Exponent factor of the ($kR^{\alpha}{}_{\%p}$) relation	
f	-	Frequency	(GHz)
D_m	-	Melting layer thickness	(mm)
k	-	Multiplicative factor of the ($kR^{\alpha}{}_{\%p}$) relation	
L_m	-	Path length through the melting layer	(km)
$\%p$	-	Probability level	
$A_{\%p}$	-	Rain attenuation at $\%p$	(dB)
$A_{0.01}$	-	Rain attenuation at 0.01%	(dB)
H_R	-	Rain height above freezing level	(km)
$R_{0.01}$	-	Rainfall rate exceeded at 0.01% of the time	(mm/h)
R_p	-	Rainfall rate exceeded at $\%p$ of the time	(mm/h)
γ	-	Specific attenuation	(dB/km)
θ	-	Elevation angle	(degrees)
l_s	-	Slant path	(km)
L_T	-	Terrestrial path length	(km)
L_{eff}	-	Effective slant path	(km)
$r_{d0.01}$	-	Path reduction factor at 0.01% of the time	
A_m	-	Melting layer attenuation	(dB)
α_m	-	Melting layer specific attenuation	(dB/km)

$\in_{mat}$	-	Dielectric constants of the matrix phase	
$\in_{inc}$	-	Dielectric constants of the inclusion phase	
ρ_m	-	Uniform density of melting ice	(g/m^3)
f_m	-	Melted fraction of ice	
ρ_s	-	Density of dry snow	(g/m^3)
ρ_w	-	Density of water	(g/m^3)
P_{AB}	-	Breakpoint attenuation probability level	(%)
P_{RB}	-	Breakpoint rain rate probability level	(%)
A_B	-	Breakpoint attenuation	(dB)
R_B	-	Breakpoint rain rate	(mm/h)
$C_{\%p}$	-	Terrestrial-to-slant path conversion factor at $\%p$	
$A_{s\%p}$	-	Slant path attenuation at $\%p$	(dB)
$A_{T\%p}$	-	Terrestrial attenuation at $\%p$	(dB)

LIST OF ABBREVIATIONS

3D	-	3-Dimentional
ASCII	-	American Standard Code for Information Interchange
CERES	-	Cloud and Earth's Radiant Energy System
CNES	-	Centre National d'Études Spatiales
COST	-	European Cooperative Program
CRL	-	Communication Research Laboratory
CS	-	Convective-Stratiform
DMSP	-	Defence meteorological satellite program
DSD	-	Drop Size Distribution
DVR	-	Digital Video Recorder
EA	-	Elevation Angle
ECM	-	Electronic Counter Measure
EOC	-	Earth Observation Centre
EOSDIS	-	Earth Observing System Data and Information System
EUMETSAT	-	European Organization for the Exploitation of Meteorological Satellites
FKE	-	Faculty of Electrical Engineering
GDAAC	-	Goddard Earth Science Distributed Active Archive Centre
GESDISC	-	Goddard Earth Sciences Data and Information Services Centre
GMT	-	Greenwich Mean Time
GPM	-	Global Precipitation Measurement
GPS	-	Global Positioning System
GR	-	Ground Radar
GSFC	-	Goddard Space Flight Centre
HDF	-	Hierarchical Data Format
ID	-	Identity

IEEE	-	Institution of Electrical and Electronic Engineers
ISO	-	International Standard Organization
ISRO	-	Indian Space Research Organization
ITU-R	-	International Telecommunications Union on Radio Propagation
JAXA	-	Japan Aerospace Exploration Agency
JDN	-	Julian Day Number
Lat	-	Latitude
LIS	-	Lighting Imaging Sensor
Long	-	Longitude
LOS	-	Line Of Sight
L-P	-	Laws and Parsons
MEASAT 3	-	Malaysian East Asia Satellite 3
MMS	-	Malaysian Meteorological Services
M-P	-	Marshall and Palmer
NASA	-	National Aeronautics and Space Administration
NASDA	-	National Space Development Agency of Japan
NEXRAD	-	National Weather Service Next Generation Doppler Weather Radar
NOAA	-	National Oceanic and Atmospheric Administration
PPI	-	Plan Position Indicator
PPS	-	Precipitation Processing System
PR	-	Precipitation Radar
PRF	-	Pulse Repetition Frequency
PSD	-	Particle Size Distribution
QoS	-	Quality of Service
R	-	Rainfall rate
RAPIC	-	Radar Picture
RCS	-	Radar Cross-Section
RHI	-	Range Height Indicator
RNGRES	-	Range Resolution
Rx	-	Receiver
SAM	-	Simple Attenuation Model
SSM/I	-	special sensor microwave/imager

SST	-	Synthetic Storm Technique
STARTRNG	-	Start Range
STC	-	Sensitivity Time Control
TMI	-	TRMM Microwave Imager
TMPA-RT	-	Tropical Rain Measurement Mission Multi-Satellite Precipitation Analysis
TRMM	-	Tropical Rain Measurement Mission
Tx	-	Transmitter
US	-	United States
UTC	-	Universal Time Coordinated
UTM	-	Universiti Teknologi Malaysia
VIDRES	-	Video Resolution
VIRS	-	Visible and Infrared Scanner
VRP	-	Vertical Reflectivity Profile
Z	-	Reflectivity factor
Z-R	-	Reflectivity-Rain Rate Relationship

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CHAPTER 1

Introduction

1.1 Background

The restrained use of the higher frequency bands, particularly above X-band, mostly due to commercial operations, along the slant-path has elicited interest for migration from the Ku frequency band (14/12 GHz). Research activities are now directed towards the full utilization of the Ka-band (30/20 GHz), while the V-band (50/40 GHz) and W-band (50-90 GHz) is being considered for applications in the near future (Luini L. & Capsoni, 2013; Panagopoulos *et al.*, 2004) . However, the attenuation of electromagnetic waves by rain is a major impediment for telecommunications engineers and researchers. Signal attenuations in tropical regions are often due to degradations by hydrometeors such as rain, hail, cloud, and melting layer. These can cause several problems, such as signal fading, depolarization and co-channel polarization due to scattering along the satellite link.

Rain attenuation analyses due to the melting layers are crucial for the study of the rain fade characteristics. This would serve as a useful piece of information in the link budget estimation for predicting the expected outage as a result of rain attenuation on a microwave link (Luini L. & Capsoni, 2013). Additionally, the inadequate availability of database along the slant-path in the tropical regions for use in rain propagation studies at microwave frequencies requires more studies to be carried out (Adetan, 2014; Mandal, 2014).

Bright-band is the observed enhancement in radar measurements due to the echoes from hydrometeors within the melting layer. The enhancement is particularly visible as a result of the difference in the dielectric constant of ice and water, as the melting ice continues to fall on the impact of gravity. The detection of the bright-band signifies the presence of the melting layer, and its boundaries also define the boundaries of the melting layer.

1.2 Problem Statement

The complex nature of the rainfall structure along the Earth-Satellite link has been identified as a major source of attenuation prediction errors along this path. The melting layer is therefore a key critical factor responsible for majority of the problems encountered in microwave signal propagation characterization and modelling. Also, the uncertainty in the estimation of attenuation due to melting layer has steered the general perception that attenuation within the melting layer to be considered insignificant and consequently neglected (ITU-R. P. 618-11, 2013; Thurai *et al.*, 2005) .

However, recent researches has shown that the effect of melting layer on signal attenuation is not after all negligible (Nebuloni & Capsoni, 2008; Pujol, Frédéric Mesnard, & Sauvageot, 2012), especially for weak rain rates (Takahashi & Awaka, 2005) and in the Q/V/W frequency bands (Luini L. & Capsoni, 2013).

Attenuation due to the melting layer (containing melting hydrometeors) has receives less interest over the years when compared to rain and dry snow attenuations. This is because the melting layer is more difficult to compute than the other parameters. X-band radar observations have shown that bright-band attenuation is three to five times the specific attenuation computed for rain (without considering melting layer) (Pujol et al., 2012). Therefore, there is urgent need to include attenuation due to the melting layer in satellite attenuation prediction models, especially the ITU-R. P. 618 (2013), for better link budget analysis for satellite communication equipment.

Scattering (above and within the melting layer) and absorption (within and below the melting layer) are key factors responsible to signal extinction in hydrometeors. Another problem is the paucity of Earth-Satellite rain attenuation database for use in rain propagation studies in the tropical regions of the world (A. Y. Abdulrahman, 2012; Adetan, 2014; Adhikari, 2012; Ajayi & Odunewu, 1989; Mandal, 2014; Rahim, 2012).

Most countries in tropical regions have reasonably sufficient terrestrial rain attenuation data. On the contrary, there is very little data available for Earth-to-Satellite links for purposes of design and budget analysis. For these reasons, amongst others, urgent and concerted efforts needed to be geared towards the characterization of the bright-band to facilitate a more accurate determination of rain height. If the bright-band was not recognized, it can result in serious under-estimation of total link budget analysis for satellite communication (Luini L. & Capsoni, 2013; Pujol et al., 2012), especially in the tropical regions of the world.

1.3 Research Objectives

The objectives of this research are as follows: -

1. Determination of the 0^0C isotherm heights.
2. Determination of the bright-band thickness ($BB_{TH)}$.
3. Investigation into the effects of: -
   1. Season variations on rain heights.
   2. Day/night variations on rain heights.
   3. Yearly variations on rain heights.
4. Investigate the impact of melting layer on satellite communication propagation predictions.

1.4 Scope of the Research

This research involves the characterization of bright-band using two sources of radar data. One is that obtained from the Kluang Radar Station of Johor, Malaysia. This meteorological radar data was sourced from the Meteorological Department of Malaysia. The analysis undertaken is for a 62 km range at a resolution of 500 meters from Kluang radar station (lat. 2.02^{o}N, long. 103.38^{o}E) to Faculty of Electrical Engineering (FKE), Universiti Teknologi Malaysia (lat. 1.56^{o}N, long. 103.64^{o}E). The azimuth from Kluang to FKE was evaluated to be 169^o. The data duration spans thirteen months (November 2006 to November 2007). Kluang radar does a composite PPI scan every 10 minutes and a volumetric scan every 30 minutes. With one PPI scan per minute (rotation of the antenna is 3 r.p.m.) and azimuthal volumetric scan duration of five minutes (for the 15 volumetric elevation angles). The selected data has 48324 rain events. The amount data capture in a year of radar measurement is quite significant in addition to its wider coverage and ability to record images of spatial and temporal variations of the phenomenon being monitored. This is a major advantage over measurements using a network of rain gauges.

The second source of radar data are the monthly TRMM-PR 3A25 (January 2011 to May 2013) and daily 2A23 (May 2013) precipitations which are obtained from the near-real-time. The selected 3A25 and 2A23 data contains 72,382 and 61,369 rain scans respectively. Tropical Rain Measuring Mission Multi-Satellite Precipitation Analysis (TMPA-RT) processed from the TRMM Satellite on-board precipitation radar (PR). The data is sourced on-line at the US National Aeronautics and Space Administration (NASA) Goddard Earth Sciences Data and Information Services Centre (GES DISC).

The 0^0C isotherm height and bright-band thickness is determined separately from each of these sources of data after appropriate processing is undertaken. Additionally, diurnal, seasonal and annual variations' effects on rain heights were studied and discussed.

1.5 Significance of the Research

This research characterises the bright-band for Johor state of Malaysia, a tropical region of the globe, using meteorological data from both ground-based and space-borne precipitation radars and its impact on satellite communication. The results should provide useful information for satellite link quality predictions in order to provide an acceptable and adequate quality of service (QoS) to users.

The lack of direct knowledge of the microphysical and associated radiative properties of certain precipitation particles like melting hydrometeors, which have an important radiative impact in stratiform regions, have led to subjective assumptions in the retrieval algorithms; neglecting the effect of the melting layer in the retrieval has been shown to lead to an overestimation of the precipitation for light stratiform rain (Brown & Ruf, 2007). The total path attenuation is found by assuming rain up to the $0^0 C$ level and adding the attenuation excess of the melting layer. When the $0^0 C$ level is higher, the relative influence of the melting layer decreases and vice versa (Klaassen, 1988; W. Klaassen, 1990).

Furthermore, failure to account for attenuation due to the melting layer will result in poor attenuation predictions and link budget analysis for satellite communications, particularly in the tropical regions. Therefore, attenuation due to the melting layer should be included in the ITU-Rec. P.618 to adequately account for attenuation loss due to the melting layer. As shown in the results of this work, the ITU-Rec. P.618 model which is presently the most popular and widely adopted attenuation prediction method for satellite communication largely under-estimated the attenuation loss along the slant-path because of its failure to include melting layer attenuation in its formulation.

1.6 Thesis Layout

Chapter one presents the introductory part of the research. It deliberates on the background of the study, problem statement and research objectives. The scope and significance of the study were also expounded in this chapter.

Chapter two briefly reviews the background of specific rain attenuation and rain attenuation prediction models. Brief survey of some of the existing models for predicting rainfall rate cumulative distributions (CDs) is undertaken. Some propagation impairments mitigating against rain attenuation prediction models both along terrestrial and slant path were briefly discussed. Finally, a brief review of the melting layer characteristics, attenuation and models were presented.

Chapter three discusses the methodology for the ground-based meteorological data. The set-up and characteristics of the Kluang radar station is presented. Procedures for data collection, extraction, sorting, filtering, processing and decoding of the data obtained from the Malaysian Meteorological Department is presented. Procedures for plotting the vertical profile of radar reflectivity from the already processed and decoded data are discussed.

Chapter four is the methodology for the Tropical Rain Measurement Mission precipitation radar. The TRMM PR 3A25 and 2A23 algorithms, as well as some of the deficiencies of measurements taken from this space-borne radar are elucidated. Procedures for the extraction, filtering and plotting of the rain vertical reflectivity profiles from the monthly 3A25 of the Planetary Grid 1 Structure representing the low horizontal resolution of 5^0 x 5^0 latitude-longitude structure and the daily 2A23 data are presented.

Chapter five presents the results obtained from both ground-based and satellite-borne (TRMM) radar data. The monthly and yearly analyses of these data and the variations of the characterised bright-band parameters within these periods were presented. Furthermore, daily extracted data for a month from each of the ground and TRMM were classified into day- and night-time and the diurnal impacts on the bright-band parameters were analysed and discussed.

In chapter six, conclusion inferred from the results obtained is presented. Recommendations for future works are subsequently volunteered.

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