

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

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

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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°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 $5^{\circ} \times 5^{\circ}$ 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 satuannya 0°C . *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 $5^{\circ} \times 5^{\circ}$ 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 monsoon. 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 di malam 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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LIST OF SYMBOLS

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)

ϵ_{mat}	-	Dielectric constants of the matrix phase	
ϵ_{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-Dimensional
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 received 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 an 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 for signal extinction in hydrometeors. Another problem is the paucity of Earth-Satellite rain attenuation databases 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 need 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 $0^{\circ}C$ isotherm heights.
2. Determination of the bright-band thickness (BB_{TH}).
3. Investigation into the effects of: -
 - i. Season variations on rain heights.
 - ii. Day/night variations on rain heights.
 - iii. 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. $2.02^{\circ}N$, long. $103.38^{\circ}E$) to Faculty of Electrical Engineering (FKE), Universiti Teknologi Malaysia (lat. $1.56^{\circ}N$, long. $103.64^{\circ}E$). The azimuth from Kluang to FKE was evaluated to be 169° . 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°C 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 $0^{\circ}C$ level and adding the attenuation excess of the melting layer. When the $0^{\circ}C$ 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 $5^{\circ} \times 5^{\circ}$ 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.

REFERENCES

- Abdulrahman, T. A. Rahman, M. R. Islam, B. J. Olufeagba, A. Yussuff, & N. H. Haji Khamis. (2013). An Improved Slant Path Attenuation Prediction Method in Tropical Climates. *Radioengineering*, 22(4), 1082-1090.
- Abdulrahman, A. Y. (2012). *Development of Terrestrial rain Attenuation Transformation Model for Slant-Path attenuation predictions in Tropical Regions*. (PhD), Universiti Teknologi Malaysia, Malaysia.
- Adetan, O., & Afullo, T. J. . (2014). Raindrop size distribution and rainfall attenuation modeling in equatorial and subtropical Africa: the critical diameters. *Annals of telecommunications-Annales des télécommunications*, 1-13.
- Adhikari, A., Bhattacharya, A., & Maitra, A. . (2012). Rain-induced scintillations and attenuation of Ku-band satellite signals at a tropical location *Geoscience and Remote Sensing Letters, IEEE*, 9(4), 700-704.
- Ajayi, G. O., & Odunewu, P. A. (1989). *Some Characteristics of the Rain Height in a Tropical Environment*. Paper presented at the Antennas and Propagation, 1989. ICAP 89, Sixth International Conference on (Conf. Publ. No. 301). IET, Coventry.
- Alberoni, P. P., Andersson, T., Mezzasalma, P., Michelson, D. B., & Nanni, S. (2001). Use of the vertical reflectivity profile for identification of anomalous propagation. *Meteor. Appl.*, 8, 257–266.
- Amisano, G., Capsoni, C., D'Amico, M., Bandinelli, M., Milani, F., de Vries, J., . . . Wasselin, J. P. (2012). *Cleopatra: A Novel Approach to Airborne radar Simulation*. Paper presented at the IET International Conference on Radar Systems (Radar 2012), Glasgow, UK.

- Anagnostou, E. N., Carlos A. Morales, and Tufa Dinku. (2001). The use of TRMM Precipitation Radar Observations in Determining Ground radar Calibration Biases. *Journal of Atmospheric and Oceanic Technology*, 18, 618.
- Arapoglou, P. D., Konstantinos Liolis, Massimo Bertinelli, Athanasios Panagopoulos, Panayotis Cottis, and Riccardo De Gaudenzi. (2011). MIMO over Satellite: - A review. *IEEE Communication Survey & Tutorial*, 13(1), 27.
- Atlas, D., & Plank, V. G. (1953). Drop-Size History during a Shower. *Journal of meteorology*, 10, 291-295.
- Austin, P. M., & Bemis, A. C. (1950). A Quantitative Study of the Bright Band in Radar Precipitation Echoes. . *Journal of Meteorology*, 7, 145-151.
- Awaka, J., Iguchi, T., Kumagai, H., & Okamoto, K. (1997). *Rain type classification algorithm for TRMM precipitation radar*. Paper presented at the IEEE 1997 Int. Geoscience and Remote Sensing Symp., Singapore.
- Awaka, J., T. Iguchi, & K. Okamoto. (1998). *Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar*. Paper presented at the Proc. 8th URSI Commission F Open Symp., Aveiro, Portugal.
- Azlan, M. A., Din, J., & Lam, H. Y. (2011). *Rain Height Information from TRMM Precipitation Radar for Satellite Communication in Malaysia*. Paper presented at the IEEE International Conference on Space Science and Communication (IconSpace), Penang, Malaysia.
- Bech, J., B. Codina, & J. Lorente. (2007). Forecasting weather radar propagation conditions. *Meteor. Atmos. Phys*, 96, 229–243.
- Bhattacharya, R., R. Das, R. Guha, S. Deb Barman, and A. B. Bhattacharya. (2007). Variability of Millimetre Wave Rain Attenuation and Rain Rate Prediction: - A Survey. *Indian Journal of Radio and Space Physics*, 36, 325-344.
- Bodtmann, W. F., & Ruthroff, C. L. (1974). Radio Attenuation on Short Radio Path, Theory, Experiment and Design. *Bell System Technical Journal*, 53(7), 1329-1349.
- Botta, G., K. Aydin, & Verlinde, J. (2010). Modeling of microwave scattering from cloud ice crystal aggregates and melting aggregates: A new approach. *IEEE Geosci. and Remote Sens. Lett.*, 7, 572–576.

- Brooks, I. M., A. K. Goroch, & D. P. Rogers. (1999). Observations of strong surface radar ducts over the Persian Gulf. *Journal Appl.Meteor.*, 38, 1293–1310.
- Brown, S. T., & Ruf, C. S. (2007). Validation and development of melting layer models using constraints by active/passive microwave observations of rain and the wind-roughened ocean surface *Journal of Atmospheric and Ocean Technology*, 24, 543–563.
- Bryant, G., Adimula, I., Riva, C., & Brussaard, G. (2001). Rain attenuation statistics from rain cell diameters and heights. *International journal of satellite communications*, 19(3), 263-283.
- Capsoni, Caboni, V., D'Amico, M., & Zanardi, M. (2003). *RADAR Estimate of Attenuation at K Band in Stratiform Rain Using a Physical Model of the Melting Layer*. Paper presented at the Geoscience and Remote Sensing Symposium, 2003. IGARSS '03. Proceedings. 2003 IEEE International
- Capsoni, L. Castanet, N. Jeannin, L. Luini, F.S. Marzano, M. Thurai, & V.N. Bringi. (2011). *Review of Radar Measurements of Precipitation for the Characterization of Propagation Effects on Terrestrial and Slant Path Radio Links*. Paper presented at the 6th European Conference on Antennas and Propagation (EUCAP), EUR Congressi in Rome, Italy, on 11-15 April 2011.
- Capsoni, Luini, L., Paraboni, A., Riva, C., & Martellucci, A. (2009). A new prediction model of rain attenuation that separately accounts for stratiform and convective rain. *Antennas and Propagation, IEEE Transactions on*, 57(1), 196-204.
- Chebil, J., & Rahman, T. A. (1999). Rain Rate Statistical Conversion for the Prediction of Rain Attenuation in Malaysia. *Electronics Letters*, 35, 1019-1021.
- Cheon-in oh, & al, e. (2006). Analysis of the Rain Fading Channel and the System Applying MIMO. *EEE Journal (ISCIT 2006I)*, 507.
- Chiu, L. S., Gerald R. North, David A. Short, & Alan McConnell. (1990). Rain estimation from satellites: Effect of finite field of view. *Journal of Geophysical Research: Atmos-pheres (1984–2012)*, 95(D3), 2177-2185.
- Crane, R. K. (1980). Prediction of Attenuation by Rain. *IEEE Transactions on Communications*, COM-28(9), 1717-1733.

- Crane, R. K. (2003). *Rain Attenuation Models: Attenuation by Clouds and Rain In Propagation Handbook for Wireless Communication System*. CRC Press, United States of America (pp. 225-280).
- Cunningham, R. M. (1947). A different explanation of the bright line. *Journal of Meteorology*, 4, 163.
- Das, S., & Maitra, A. (2011). *Some melting layer characteristics at two tropical locations in Indian region*. Paper presented at the General Assembly and Scientific Symposium, 2011 XXXth URSI. IEEE.
- DaSilva-Mello, L., & Pontes, M. S. (2012). Unified Method for the Prediction of Rain Attenuation in Satellite and Terrestrial Links. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, 11(1), 1-14.
- Dissanayake, A., Allnutt, J., & Haidara, F. (1997). A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths. *Antennas and Propagation, IEEE Transactions on*, 45(10), 1546-1558.
- Dissanayake, A. W., & McEwan, N. J. (1978). *Radar and attenuation properties of rain and bright band*. Paper presented at the Antenna and Propagation, London, U.K.
- Doviak, R. K., & Zrnich, D. S. (1984). *Doppler Radar and Weather Observations Orlando*: Published by New York Academic
- Du Toit, P. S. (1967). Doppler Radar Observations of Drop Size in Continuous Rain. *Journal of Applied Meteorology*, 6, 1082-1087.
- Ekpenyong, B. E., & Srivastava, R. C. (1970). *Radar characteristics of the melting layer – A theoretical study*. Preprints Paper presented at the 14th International Conference on Radar Meteorology, Tucson AZ.
- Fabry, Bellon, A., & Zawadzki, I. I. (1994). Long Term Observations of the Melting Layer Using Vertically Pointing Radars MW-101 *Cooperative Centre for Research in Mesometeorology (CCRM), Report (Vol. 65)*. Canada: McGill University.
- Fabry, F., & Szyrmer, W. (1999). Modeling of the Melting Layer. Part II: Electromagnetic. *American Meteorological Society*, 3593-3600.
- Funk, A., Schumacher, C., & Awaka, J. (2013). Analysis of Rain Classifications over the Tropics by Version 7 of the TRMM PR 2A23 Algorithm. *Journal of the Meteorological Society of Japan*, 91(3), 257-272.

- Galligani, V. S., C. Prigent, E. Defer, C. Jimenez, & Eriksson, P. (2013). The impact of the melting layer on the passive microwave cloud scattering signal observed from satellites: A study using TRMM microwave passive and active measurements. *Journal of Geophysical Research*, *118*, 5667–5678.
- Garcia-lopez, J. A., Hernando, J. M., & Selga, J. M. (1998). Simple rain attenuation prediction method for satellite radio links. *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, *36*(3), 444 – 448.
- García-Rubia, José Manuel Riera, Ana Benarroch, & García-del-Pino. (2011). Estimation of Rain Attenuation From Experimental Drop Size Distributions. *IEEE antennas and wireless propagation letters*, *10*, 839-842.
- Goddard Earth Sciences Data and Information Services Center. (2012). TRMM Satellite and Instruments. Retrieved 2012, from http://disc.sci.gsfc.nasa.gov/precipitation/additional/instruments/trmm_instr.shtml
- Goddard Earth Sciences Data and Information Services Center. (2013a). Algorithm 2A23 - PR Qualitative. Retrieved Dec. 15, 2013, from <http://trmm.gsfc.nasa.gov/2a23.html>
- Goddard Earth Sciences Data and Information Services Center. (2013b). Algorithm 3A25 - Space Time Statistics of Level 2 PR Products. Retrieved Dec. 15, 2013, from <http://trmm.gsfc.nasa.gov/3a25.html>
- Goddard Earth Sciences Data and Information Services Center. (2013c). TRMM Data Processing Overview V7. Retrieved Dec. 18, 2013, from http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_v7.shtml
- Goddard, J. W. F. (1991). *The Chibolton Rain Radar. IEE Colloquium on National Radio Propagation Programme, 8 January 1991.*
- Goldhirsh, J. (1979). A Review on the Application of Nonattenuating Frequency Radars for Estimating Rain Attenuation and Space-Diversity Performance. *IEEE Transactions on Geoscience Electronics*, *GE-17*(4), 218-239.
- Haddad, S. Z., & Park, K.-W. (2010). Vertical Profiling of Tropical Precipitation using Passive Microwave Observations and its Implications regarding the crash of AF447. *Journal of Geophysical Research*, *115*(D12), D12129.

- Hansson, L. (1990). New concept used to predict slant path rain attenuation statistics *Microwaves, Antennas and Propagation, IEE Proceedings H*, 137(2), 89-93.
- Hardaker, P. J., Holt, A. R., & Collier, C. G. (1991). *A theoretical study of the scattering effects of the melting layer*. Paper presented at the Preprints, 25th International Conference on Radar Meteorology, Paris, France.
- ITU-R. P.530-14. (2012). Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-Of-Sight Systems *Recommendation ITU-R. P Series*.
- ITU-R. P.839-3. (2001). Rain height model for prediction methods *Recommendation ITU-R P Series*.
- ITU-R. P. 618-11. (2013). Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunications Systems *Recommendation ITU-R P Series*.
- Japan Aerospace Exploration Agency (JAXA). (2013). TRMM Precipitation Radar- Algorithms. Retrieved Dec. 17, 2013, from http://www.eorc.jaxa.jp/TRMM/about/mechanism/pr/flow_e.htm
- Japan Meteorological Agency. (1979).
- JAXA Earth Observation Research Center. (2013a). JAXA Global Rainfall Watch. Retrieved Dec. 18, 2013, from <http://sharaku.eorc.jaxa.jp/GSMaP/index.htm>
- JAXA Earth Observation Research Center. (2013b). JAXA Global Rainfall Watch. Retrieved Dec. 17, 2013, from <http://sharaku.eorc.jaxa.jp/GSMaP/index.htm>
- JAXA Earth Observation Research Center. (2013c). TRMM Level 3 Selected Monthly Rainfall Data Set. Retrieved Dec. 18, 2013, from <http://www.eorc.jaxa.jp/cgi-bin/trmm/l3month.cgi?code=3A25G2&lang=e&ver=7>
- Keeler, R. J., & Passarelli, R. E. (1990). Signal processing for atmospheric radars. *Radar in Meteorology, .D. Atlas, Ed., Amer. Meteor. Soc.,* 199–229.
- Kessinger, C., Ellis, S., Van Andel, J., Yee, J., & Hubbert, J. (2004). *Current and future plans for the AP clutter mitigation scheme*. Paper presented at the Preprints, 20th Int. Conf. on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology Seattle, WA, USA.
- Khairayu Badron, Ahmad Fadzil Ismail, Jafri Din, & Tharek, A. R. (2010). Rain Induced Attenuation Studies for V-band Satellite Communication in Tropical Region. *Journal of Atmospheric and Solar-Terrestrial Physics*(73), 601-610.

- Khalid Mubara, Dawood, A., & Dosary, A. A. (2007). *Global Mapping of Height of Bright Band*. Paper presented at the Signal Processing and Its Applications, 2007. ISSPA 2007. 9th International Symposium. IEEE.
- Khamis N. H. H., Din J., & A., R. T. (2005). *Rainfall rate from meteorological radar data for microwave applications in Malaysia*. Paper presented at the 13th IEEE International Conference on Networks jointly held with the 2005 7th IEEE Malaysia International Conference on Communications, Malaysia.
- Khamis, N. H. H. (2005). *Path Reduction Factor for Microwave Terrestrial Links Derived from the Malaysian Meteorological Radar Data* (PhD), Universiti Teknologi Malaysia, Malaysia.
- Khamis, N. H. H., Omer, A. R. S., Hanzaz, Z., & Baharom, A. (2007). Determination of the Melting Layer from Meteorological Radar Data in Malaysia. *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, 1467-1470.
- Klaassen, W. (1988). Radar observations and simulation of the melting layer of precipitation. *Journal of the atmospheric sciences*, 45(24), 3741-3753.
- Klaassen, W. (1988). Radar observations and simulating of the melting layer of precipitation. *Journal of Atmosphere Society*, 45, 3741-3753.
- Kollias, P., & Albrecht, B. (2005). Why the melting layer radar reflectivity is not bright at 94 GHz. *Geophys. Res. Lett.*, 32(L248).
- Konstantinos Pipis, Melina Ioannidou, & Chrissoulidis, D. (2011). *Comparison of radar reflectivity calculations to satellite measurements across the melting layer of precipitation*. Paper presented at the General Assembly and Scientific Symposium, 2011 XXXth URSI IEEE.
- Kummerow, C., J. Simpson, O. Thiele, W. Barnes, A. T. C. Chang, E. Stocker, R. F. Adler et al. (2000). The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit *Journal of Applied Meteorology*, 39, 1965-1982.
- Lacomme, P., Hardange, J. P., Marchais, J. C., & Normant, E. (2001). *Air and Space borne Radar Systems: An Introduction*. United State of America (USA):: William Andrew publishing, LLC.
- Lahaie, P., Lecours, M., & Bellon, R. A. (1993). Use of Meteorological Radar Images to Build a Rain Attenuation Prediction Model for Terrestrial Microwave Radiocommunication. *Canadian Conference on Electrical and Computer Engineering*, 14-17 Sept. 1993, 1, 68 - 71.

- Laws, J. O., & Parsons, D. A. (1943). The Relationship of Raindrop Size to Intensity. *Transactions - America Geophysical Union*.24, 452–460.
- Leitao, M. J., & Watson, P. A. (1986). Method for prediction of attenuation on Earth-space links based on radar measurements of the physical structure of rainfall. *IEE Proceedings, 133 Pt. F*(4).
- Levis, C., Joel T. Johnson, and Fernando, L. Teixeira. (2010). *Radiowave Propagation: - Physics and Applications*.
- Lhermitte, R. M., & Atlas, D. (1963). *Doppler fall speed and particle growth in stratiform precipitation. Preprints*. Paper presented at the Tenth Radar Meteorology Conference, , Washington DC.
- Liu, G. (1998). A fast and accurate model for microwave radiance calculation. *Journal of Meteor. Soc. Japan*, 76, 335-343.
- Luini L., & Capsoni, C. (2013). *Performance Evaluation of Satellite Communication Systems Operating in the Q/V/W Bands*. Politecnico di Milano, Dipartimento di Elettronica e Informazione, Italy. (EOARD FA8655-12-1-2062)
- Maki, M., Tom D. Keenan, Yoshiaki Sasaki, and Kenji Nakamura. (2001). Characteristics of the Raindrop Size Distribution in Tropical Continental Squall Lines Observed in Darwin, Australia. *Journal of Applied Metrology*, 1393-1412.
- Malaysian Meteorological Department. (2013). What are the climate changes during an El Niño? Retrieved Dec. 31, 2013, from http://www.met.gov.my/index.php?option=com_content&task=view&id=73&Itemid=160&limit=1&limitstart=2&lang=english
- Mandal, B. K., Bhattacharyya, D., & Kang, S. . (2014). Attenuation of Signal at a Tropical Location with Radiosonde Data Due to Cloud. *International Journal of Smart Home*, 8(1), 15-22.
- Marshall, J. S., & Palmer, W. M. K. (1948). The distribution of raindrops with size. *Journal of meteorology*, 5(4), 165-166.
- Matricciani, E. (1996). Physical-Mathematical Model of The dynamics of Rain Attenuation Based on Rate Time Series and a Two-Layer Vertical Structure of Precipitation. *Radio science*, 31(2), 281–295.
- Matricciani, E. (2008). *Global formulation of the Synthetic Storm Technique to calculate rain attenuation only from rain rate probability distributions*. Paper

- presented at the IEEE International Symposium on Antennas and Propagation, San Diego.
- Matrosov, S. Y., A. J. Heymsfield, & Wang, Z. (2005). Dual-frequency radar ratio of nonspherical atmospheric hydrometeors *Geophys. Res. Lett.*, 32(L13816).
- Maxwell Garnett, J. C. (1904). Colors in metal glasses and in metallic films. *Phil. Trans. Roy. Soc. London*, A203, 385-420.
- Meneghini, R., & Liao, L. (1996). Dielectric Constants for Melting Hydrometeors as derived from a Numerical Method *Geoscience and Remote Sensing Symposium, 1996. IGARSS'96. 'Remote Sensing for a Sustainable Future.'*, 1, 16-18.
- Meneghini, R., & Liao, L. (2000). Effective dielectric constants of mixed-phase hydrometeors. *Journal of Atmospheric and Oceanic Technology*, 17, 628–664.
- Merhala Thurai , Eri Deguchi, Toshio Iguchi, & Okamoto, K. i. (2003). Freezing height distribution in the tropics. *International Journal of Satellite Communications and Networking*, 21, 533–545. doi: 10.1002/sat.768
- Moufouma, F. (1984). Improvement of a Rain Attenuation Prediction Method for Terrestrial Microwave Links. *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, AP-32(12), 1368-1372.
- Moufouma, F. (1987). More about Rainfall Rates and Their Prediction for Radio System Engineering. *Institution of Engineering & Technology, IEE Proceedings*, 34, Pt. H(6), 527-537.
- Moufouma, F. (2009). Electromagnetic Waves Attenuation Due to Rain: A Prediction Model for Terrestrial or L.O.S SHF and EHF Radio Communication. *Journal of Infrared Milli Terahz Waves*(30), 622–632.
- Nebuloni, R., & Capsoni, C. (2008). *Laser attenuation by falling snow*. Paper presented at the Communication Systems, Networks and Digital Signal Processing, CNSDSP 2008. 6th International Symposium.
- Nesbitt, S. W., & Zipser, E. J. (2003). The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements. *Journal of Climate*, 16, 1456-1475.
- Nishitsuji, A., M. Hoshiyama, J. Awaka, & Furuham, Y. (1983). An analysis of propagative character at 34.5 GHz and 11.5 GHz between ETS-II satellite and

- Kasima station - On the precipitation model from stratus. *IEICE Transactions, J66-B* 1163-1170.
- Ohtake, T. (1969). Observations of the size distribution of hydrometeors through the melting layer. *Journal of Atmosphere Society*, 26, 545-557.
- Ojo, & Omotosho. (2013). Comparison of 1-minute rain rate derived from TRMM satellite data and raingauge data for microwave applications in Nigeria. *Journal of Atmospheric and Solar-Terrestrial Physics*.
- Ojo, & Sarkar. (2008). Rainfall dynamics over two Indian tropical stations for radio communication. *International Journal of Infrared and Millimeter Waves*, 29(7), 649-656.
- Okamoto, K., Sasaki, H., Deguchi, E., & Thurai, M. (2004). *Bright-Band Height Statistics Observed by the TRMM Precipitation Radar*. Paper presented at the The 2nd TRMM International Science Conference, Nara, 9 September 2004.
- Olsen, R. L. (1982). A review of theories of coherent radio wave propagation through precipitation media of randomly oriented scatterers, and the role of multiple scattering. *Radio science*, 17(5), 913-928.
- Olsen, R. L., Rogers, D. V., & Hodge, D. B. (1978). The aR^b Relationship in the Calculation of Rain Attenuation. *IEEE Transactions on Antennas Propagation*, 26, 318-329.
- Olson, W. S., Peter Bauer, Nicolas F. Viltard, Daniel E. Johnson, Wei-Kuo Tao, Robert Meneghini, & Liao, L. (2001). A Melting-Layer Model for Passive/Active Microwave Remote Sensing Applications. Part I: Model Formulation and Comparison with Observations. *Journal of Applied Meteorology*, 40(7), 1145-1163.
- Omotosho, & Oluwafemi. (2009a). Impairment of radio wave signal by rainfall on fixed satellite service on earth–space path at 37 stations in Nigeria. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71(8), 830-840.
- Omotosho, & Oluwafemi. (2009b). One-Minute rain Distribution in Nigeria Derived from TRMM Satellite Data. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71(5), 625-633.
- Pan, & Bryant. (1994). Effective rain-cell diameters and rain-column heights in the tropics. *Electronics Letters*, 30(21), 1800-1802.
- Panagopoulos, A. D., Arapoglou P., Cottis D, M., & G., P. (2004). Satellite communications at Ku, Ka, and V bands: Propagation impairments and

- mitigation techniques. *Communications Surveys & Tutorials, IEEE*, 6(3), 2-14.
- Paraboni, A., A. Vernucci, L. Zuliani, E. Colzi, and A. Martellucci. (2007). A new Satellite Experiment in the Q/V Band for the Verification of Fade Countermeasures based on the Spatial Non-Uniformity of Attenuation. *The Second European Conference of Antenna and Propagation (EUCAP 2007)*, 6.
- Pavageau A., L. Castanet, C. Riva, & Baptista, J. P. V. P. (2001). *Test of rain attenuation and total attenuation prediction models for Earth-space paths* ITU-R 3J-3M meeting, Budapest, Hungary. Paper presented at the ITU-R 3J-3M meeting, Budapest, Hungary.
- Peter, Alan Seed, & Peter J. Steinle. (2013). Application of a Bayesian Classifier of Anomalous Propagation to Single-Polarization Radar Reflectivity Data. *Journal of Atmospheric and Oceanic Technology*, 30, 1985-2005. doi: 10.1175/JTECH-D-12-00082.1
- Pontes, M. S., L. A. R. da Silva Mello, & R. S. L. Souza. (1995). *Statistical behaviour of the effective rain height in the tropics*. Paper presented at the 9th International Conference on Antennas and Propagation.
- Pujol, Frédéric Mesnard, & Sauvageot, H. (2012). Effects of Melting Layer in Airborne Meteorological X-Band Radar Observations. *IEEE Transactions On Geoscience And Remote Sensing*, 50(6), 2318-2324.
- Rahim, S. K. A., Rahman, T. A., Tan, K. G., & Reza, A. W. . (2012). Microwave signal attenuation over terrestrial link at 26 GHz in Malaysia. *Wireless Personal Communications*, 67(3), 647-664.
- Ramachandran, V., & Kumar, V. (2007). Modified rain attenuation model for tropical regions for Ku-Band signals. *International Journal of Satellite Communications and Networking*, 25(1), 53-67.
- Raymond, L., et al (1999). *Improved Modelling of Propagation and Backscattering of Millimeter waves in the Melting Layer*. Paper presented at the IEEE National Conference on Antennae and Propagation.
- Rice, P. L., & Holmberg, N. R. (1973). Cumulative time Statistics of Surface-point Rainfall rates. *IEEE Transaction Com*(21), 1131–1136.
- Romo, J. A., M. Maruri, F. Perez Fontan, and I. Fernandez-Anitzine. (2012). Characterization of Maximum Radar Reflectivity Height During Stratiform

- Rain Events. *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*, 60(10), 4884-4891.
- Russchenberg, H. W. J., & Ligthart, L. P. (1993). *A doppler-polarimetric backscatter model of the melting layer*. Paper presented at the Eighth International Conference on Antennas and Propagation, Edinburgh.
- Ryde, J. W. (1946). The attenuation and radar echoes produced at centimeter wavelengths by various meteorological phenomena. . *Meteorological Factors in Radio Wave Propagation*. *Physics Society, London*, 169-188.
- Sassen, K. S., Matrosov, & Campbell, J. (2007). CloudSat spaceborne 94 GHz radar bright bands in the melting layer: An attenuation-driven upside-down lidar analog *Geophys. Res. Lett.*, 34(L16818).
- Schumacher, C., & Houze, R. A. (2000). Comparison of radar data from the TRMM satellite and Kwajalein oceanic validation site. *Journal of Appl. Meteor.*, 39, 2151–2164.
- Schumacher, C., & Houze, R. A. (2003). Stratiform Rain in the Tropics as Seen by the TRMM Precipitation Radar. *Journal of Climate*, 16, 1739-1756.
- Shin, D. B., & North, G. R. (2000). Errors incurred in sampling a cyclostationary field. *Journal of Atmospheric and Oceanic Technology*, 17(5), 656-664.
- Simpson, J., C. Kummerow, W-K. Tao, and Robert F. Adler. (1996). On the Tropical Rain Measuring Mission (TRMM). *Meteorological Atmospheric Physics*, 60, 19-36.
- Steiner, M., Houze Jr., R. A., & Yuter, S. E. (1995). Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *Journal of Applied Meteorology*, 34, 1978-2007.
- Steiner, M., & Houze, R. A. (1998). Sensitivity of monthly three-dimensional radar-echo characteristics to sampling frequency. *Journal of Meteor. Soc. Japan*, 76, 73–95.
- Steiner, M., & Smith, J. A. (2002). Use of three-dimensional reflectivity structure for automated detection and removal of nonprecipitating echoes in radar data. *Journal of Atmospheric and Oceanic Technology*, 19, 673–686.
- Stewart, R. E., Marwitz, J. D., Pace, J. C., & Carbone, R. E. (1984). Characteristics through the melting layer of stratiform clouds. *Journal of Atmosphere Society*, 41, 3227-3237.

- Stutzman, W., & Yon, K. (1986). A simple rain attenuation model for earth-space radio links operating at 10–35 GHz. *Radio science*, 21(1), 65-72.
- Takahashi, N., & Awaka, J. (2005). Introduction of a melting layer model to a rain retrieval algorithm for microwave radiometers. *Geoscience and Remote Sensing Symposium, IGARSS'05 Proceedings*, 5, 3404-3409.
- Tan, J., & Goddard, J. W. F. (1995). The use of dual-polarisation techniques for bright-band detection with PPI-based radars. *Radar Meteorology, IEE Colloquium, IET*, 11, 1-6.
- Thurai, M., Deguchi, E., Okamoto, K., & Salonen, E. (2005). Rain height variability in the Tropics. *IEE Proc.-Microwave Antennas Propagation*, 152(1), 17-23.
- Thurai, M., & Hanado, H. (2004). Melting layer model evaluation using fall velocity spectra at Ku-band,” *Microwaves. Antennas and Propagation, IEE Proceedings*, 151(5), 465-472.
- Thurai, M., Salonen, E., & Okamoto, K. (2005). Rain Height Variability in the Tropics and Implications for Rain Scatter Interference. *IEEE Transaction on Antennas and Propagation*, 997-1001. doi: 0-7803-9282-5/05
- Thurai, M., T. Iguchi, J. Goddard, Ong, J. T., & Awaka, J. (2003). *Melting Layer Model Evaluation in Singapore*. Paper presented at the Antennas and Propagation, (ICAP 2003), 12th International Conference on (Conf. Publ. No. 491).
- W. Klaassen. (1990). Attenuation and reflection of radio waves by a melting layer of precipitation. *IEE Proceedings*, 137, Pt. H(I), 39-44.
- Wei Zhang, & Moayeri, N. (1999). Power-Law Parameters of Rain Specific Attenuation *IEEE 802.16 Broadband Wireless Access Working Group* (pp. 1-8). IEEE: National Institute of Standards and Technology.
- Wexler, R., & Atlas, D. (1956). Factors influencing radar echo intensities in the melting layer. *Quarter Journal of Royal Meteorology Society*, 82, 349-351.
- Willis, P. T., & Heymsfield, A. J. (1989). Structure of the melting layer in mesoscale convective system stratiform precipitation. *Journal of Atmosphere Society*, 46, 2008-2025.
- Wilson, J. W. (1964). Evaluation of Precipitation Measurements with the WSR-57 Weather Radar. *Journal of Applied Meteorology*, 3, 164-174.

- Yokoyama, T., & Tanaka, H. (1984). Microphysical processes of melting snowflakes detected by two-wavelength radar. Part I. Principle of measurement based on medel calculation *Journal of Meteor. Soc. Japan*,, 650-667.
- Yokoyama, T., Tanaka, H., Nakamura, K., & Awaka, J. (1984). Microphysical processes of melting snowflakes detected by two-wavelength radar. Part II. Application of two-wavelength radar technique. *Journal of Meteorology Society, Japan*, 62, 668-678.
- Yussuff, A. I. O., & Khamis, N. H. H. (2013, December 09-11, 2013). *Comparison of Slant Path Rain Attenuation Models using Data from a Tropical Station*. Paper presented at the 2013 IEEE International RF and Microwave Conference (RFM2013), Penang, Malaysia.
- Yuter, S. E., & Houze, R. A. (1997). Measurements of raindrop size distribution over the Pacific warm pool and implications for Z–R relations. *Journal of Applied Meteorology*, 36, 847–867.
- Zhang, J., & Langston, C. (2008). Brightband Identification Based on Vertical Profiles of Reflectivity from the WSR-88D. *American Meteorological Society*, 25, 1859-1872. doi: 10.1175/2008JTECHA1039.1
- Zhang, J., & Qi, Y. (2010). A Real-Time Algorithm for the Correction of Brightband Effects in Radar-Derived QPE. *American Meteorological Society*, 11, 1157-1171. doi: 10.1175/2010JHM1201.1
- Zhang, W., & Moayeri, N. (2000). *Recommendation: Use of Various Raindrop Size Distributions for Different Geographical Locations in Calculating the Rain Specific Attenuation*. Paper presented at the Meeting. Richardson, TEXAS, Document Number IEEE 802.16cc-99/41. Presented at Session # 5 IEEE 802.16.2.