

RAIN ATTENUATION PREDICTION BASED ON RAINDROP SIZE
DISTRIBUTION MEASUREMENT IN MALAYSIA

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To my beloved parents...

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ABSTRACT

Attenuation due to rain at frequencies above 10 GHz in temperate climates and above 7 GHz in tropical ones is a critical factor for both terrestrial and satellite link system designers. Knowledge of the rain drop size distribution (DSD) is essential for an accurate estimate of the attenuation experienced by electromagnetic waves traveling through the rain. Large uncertainties remain in the variability of DSDs and their dependence on rainfall types and climatological regimes. Such uncertainties are much more critical in the equatorial region, where there are only limited experimental results of DSD data. In this study, a two-year measurement of DSD, using a 2D video distrometer (2DVD) installed for the first time in UTM Johor Malaysia, has been used. The 2DVD is an advanced instrument that not only can measure large ranges of DSD but also can capture the raindrop shape, axial ratio, oscillation mode and drop fall velocity, so it can provide a higher accuracy of estimations than any other instrument. A millimeter wave (mmwave) link operating at 38 GHz and a meteorological station installed at the same location, as well as earlier DSD data from Kuala Lumpur, are used to validate the findings. Based on the statistical analysis of the measured data samples, DSD parameters are computed using T-Matrix calculations. Specific attenuation of mmwave signals is presented for vertical and horizontal polarisations. Satisfactory results are achieved in comparison with other prediction models. Further, the study separates stratiform and convective rain types using the characteristics of the main DSD parameters. Seasonal variations are studied to elucidate characteristics of DSD in the Asian monsoon region. It is found that DSDs are affected by diurnal convective cycles and seasonal variations in precipitation characteristics. The implications of the variations on specific attenuation are presented. The results of this study will be helpful for the proper design and allocation of the wireless communication system to achieve the expected quality of service (QoS) in Malaysia.

ABSTRAK

Pemerosotan isyarat oleh hujan pada frekuensi melebihi 10 GHz di iklim sederhana dan melebihi 7 GHz di tropika, merupakan faktor penting bagi pereka sistem pautan terrestrial dan satelit. Pengetahuan tentang taburan saiz titik hujan (DSD) adalah penting untuk peramalan yang tepat bagi pemerosotan yang dialami oleh gelombang elektromagnetik yang merambat dalam hujan. Ketidaktentuan yang besar wujud pada DSD dan kebergantungannya terhadap jenis-jenis hujan dan rejim klimatologi. Ketidaktentuan ini menjadi lebih kritikal di kawasan khatulistiwa yang mempunyai pengukuran DSD yang terhad. Dalam kajian ini, pengukuran DSD selama dua tahun menggunakan 2D *video distrometer* (2DVD) yang dipasang untuk kali pertama di UTM Johor Malaysia telah digunakan. *Distrometer* ini adalah peralatan termaju yang mampu bukan sahaja untuk mengukur julat DSD yang besar tetapi juga dapat merekod bentuk hujan, nisbah paksi, mod ayunan dan halaju titik hujan, dengan ketepatan yang lebih tinggi. Stesen meteorologi dan pautan gelombang milimeter (*mmwave*) yang beroperasi pada 38 GHz dipasang di lokasi yang sama serta data DSD terdahulu dari Kuala Lumpur digunakan untuk mengesahkan kajian. Berdasarkan analisis statistik sampel data yang diukur, parameter DSD dikira menggunakan pengiraan T-Matrix. Pemerosotan spesifik pada isyarat *mmwave* dibentangkan pada polarisasi menegak dan mendatar. Hasil yang memuaskan diperolehi berbanding dengan model ramalan yang lain. Kajian ini juga memisahkan jenis hujan *stratiform* dan jenis olakan menggunakan ciri-ciri parameter DSD. Variasi musim dikaji untuk menjelaskan ciri-ciri DSD di rantau monsun Asia. Adalah didapati bahawa DSD dipengaruhi oleh kitaran olakan diurnal dan variasi bermusim dalam ciri hujan. Implikasi variasi mengenai pemerosotan tertentu dilaporkan. Hasil kajian ini akan membantu dalam reka bentuk sistem komunikasi wayarles yang tepat untuk mencapai kualiti perkhidmatan yang diharapkan (QoS) di Malaysia.

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LIST OF ABBREVIATIONS

2DVD	-	2D Video Distrometer
DSD	-	Drop size Distribution
EHF	-	Extremely High Frequency
FSA	-	Forward Scattering Amplitude
HF	-	High Frequency
IUT	-	Indoor User Terminal
LF	-	Low Frequency
MJO	-	Maddan - Julian Oscillation
NE	-	Northeast
OU	-	Outdoor Unit
PSU	-	Power Supply Unit
QPE	-	Quantitative Precipitation Measurements
QPF	-	Quantitative Precipitation Forecast
ITU	-	International Telecommunication Union
UTM	-	University Teknologi Malaysia
ITCZ	-	Inter Tropical Convergence Zone
SW	-	Southwest
preNE	-	Pre-Northeast
preSW	-	Pre-Southwest
PDF	-	Probability Density Function
M-P	-	Marshall-Palmer
MoM	-	Method of Moments
MLE	-	Max likelihood estimation
T-C	-	Two component rain attenuation model

CCDF	-	Complimentary Cumulative Distribution Function
XPD	-	Cross-Polar Discrimination
SG	-	Singapore
STD	-	Standard Deviation
Sk	-	Skewness

LIST OF SYMBOLS

γ	-	Specific attenuation
σ	-	Standard Deviation
λ	-	Wave Length
R	-	Rain Rate
P	-	Power
A_R	-	effective aperture
$N(D)$	-	Raindrop size Distribution Function
D_m	-	Mass Weighted Diameter
D_m^{max}	-	Maximum Drop Size
D_i	-	Drop size in bin i
D_0	-	Median Diameter
d_a	-	Size Interval
N_0	-	Maximum Raindrop size Distribution
μ	-	Mean Shape Parameter
Λ	-	Slope Parameter
N_t	-	total Concentration
N_w	-	Generalized Intercept Parameter
f_h	-	Horizontal Scattering Amplitude
f_v	-	Vertical Scattering Amplitude

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The significant developments in the radar, earth-space and terrestrial communications, resulted in the development of the wireless transmission media, evolving over low frequency (LF), high frequency (HF), extremely high frequency (EHF) radio, to microwave and millimetre wave transmission, to free space optics, each having its distinct properties, advantages and disadvantages (Proakis *et al.*, 1994; Tomasi, 1987). The availability of wider bandwidths for carrying wireless signals at the millimetre wave spectrum is of major interest for the industry. Such bandwidths are useful for many applications, such as improved anti-jam performance for secure communications, video distribution, high speed data transmission and smaller component sizes (Marcus and Pattan, 2005).

These advantages can however be offset very easily due to increased propagation problems as the frequency of operation increases. Several propagation mechanisms affect these systems performances and constitute a major concern to system planners and designers. These mechanisms include ice depolarization, gaseous attenuation, sky noise, cloud and fog attenuation, rain attenuation and amplitude scintillation. However, attenuation due to rain is the most severe (Crane, 1980; Strangeways, 2006), especially at frequencies above 10 GHz, and particularly in tropical and equatorial regions like Malaysia (Lam *et al.*, 2015). In fact, precipitation causes attenuation due to scattering and absorption of the electromagnetic energy and leads to significant performance degradation.

To understand how this attenuation is influenced by rain parameters, a detailed understanding of the inherent raindrop size distributions (DSD) and the corresponding scattering mechanisms at these operating frequencies is essential (Townsend *et al.*, 2009). DSD is a fundamental microphysical property of precipitation. Understanding the variability of DSD is important for improving quantitative precipitation estimation (QPE) and microphysics parameterization in numerical weather prediction models for accurate quantitative precipitation forecast (QPF) (Milbrandt and Yau, 2005; Raupach and Berne, 2015; Zhang *et al.*, 2006).

The differences in DSD characteristics have been studied around the world using surface disdrometer measurements and are known to vary both spatially and temporally across different precipitation types, atmospheric conditions, geographical locations or climatic regimes, and orography (Thurai *et al.*, 2007; Tokay and Short, 1996; Ulbrich, 1983; Zhang *et al.*, 2006). DSDs are also affected by diurnal convective cycles and seasonal variations in precipitation characteristics. The probable duration of rain, the time of day when it is likely to occur, and how frequently it happens are all important aspects to consider in the design of the wireless communication systems (Allnutt, 1989). It's also found that the climate in the tropics is primarily organized by the intertropical convergence zone and the Madden-Julian oscillation (MJO), and is deeply influenced by monsoons (Zhang *et al.*, 2006).

To that aim, numerous propagation measurement campaigns have been actively carried out to characterise behavior of DSD variation and the resulted rain attenuation experienced by wireless links. However, most of the studies have been concentrated in temperate regions (García-Rubia *et al.*, 2013; Matricciani and Pawlina, 2000; Van de Kamp, 2003) that exhibit different DSD characteristics compared with tropical and equatorial regions. Therefore, characteristics of rain attenuation in temperate regions does not represent the characteristics of tropical and equatorial regions (ITU-R Study Group 3, 2012). Although several propagation studies have been carried in the past few decades at several locations in heavy rain regions such as Brazil, India, Indonesia (Castanet, 2011; Das *et al.*, 2010; Marzuki *et al.*, 2010) and Singapore and even Malaysia (Kumar, 2010; Lam, 2012). However, the features of precipitation in such areas are often dominated by local climatic peculiarities; furthermore, drop

size distribution measurement are usually expensive and time consuming and older disdrometer types underestimated the lower end of the distribution due its limitations (Thurai *et al.*, 2016). Additionally, identifying the dominant modes of tropical rain variability still need to be investigated, causing a major source of uncertainty in ground-based, ship-borne, and spaceborne radar rainfall estimation (Raupach and Berne, 2015).

Therefore, this study is carried to explore those crucial statistics in an equatorial site by exploiting the DSD measurements carried out at Universiti Teknologi Malaysia (UTM) in Johor Bahru, Malaysia. The work seeks to determine the regional raindrop size distribution as well as present the statistical variations, and investigate it's corresponding specific attenuation.

1.2 Problem Statement

As mentioned earlier, the differences in DSD characteristics play a major role in the design of wireless communications especially millimetre wave systems. Therefore, several problem statements to be addressed in this thesis work are summarized below:

The knowledge of DSD is essential to make an accurate estimation of the attenuation experienced by electromagnetic waves travelling through rain. Although there have been numerous studies to understand, parametrize and estimate DSD from various locations, however, large uncertainties remain in variability of DSD and their dependence on rainfall types and climatological regimes. (Thurai *et al.*, 2009). Such uncertainties are much more critical in equatorial region where there are only limited experimental results of DSD data. Therefore, it is worthwhile to further investigate and estimate the natural characteristics of DSD in Malaysia with respect to the experimental database available and several well-known DSD models from the established literature.

Besides the estimation of natural characteristics of DSD, attenuation of millimetre wave signal due to rain also can be estimated from the knowledge of rain

rates as recommended by ITU-R Recommendation (ITU, 2005). Such estimation provides specific attenuation values directly from the rainfall intensity without the needs of measured DSD data. However, employment of ITU-R recommendation P.838-3 might marked some discrepancies with respect to the calculated values derived from the measured DSD collected from different climatic region (Thurai *et al.*, 2007). Hence, in order to estimate reliable specific attenuation values, it is therefore of key importance to carefully assess the relationship between specific attenuation and rainfall rate from this climatic region directly inferred from the measured DSD.

It is also crucial to investigate the influence of critical seasonal and diurnal variation of the in Malaysia localized climate. on the estimations of the attenuation to help provide better mitigation technique and provide high quality of service.

1.3 Research Objectives

Due to the technology development and the problems mentioned in the previous section, the main goal of this study is to provide valuable information for the millimeter wave propagation channel during rain in Equatorial regions, specifically Malaysia, other main objective are as listed below:

- i To characterize the Raindrop Size Distribution (DSD), in Johor, Malaysia, and describe its seasonal variations and its dependency on precipitation types.
- ii To analyze specific attenuation, and provide its relationship coefficients with rainfall rate based on the measured DSD.
- iii To validate the performance of millimeter wave propagation, with respect to the characteristics of precipitation in Malaysia.

1.4 Scope of Work

The scope of this research consist of two parts, DSD investigation with detailed statistical analysis of it's variation providing all the detailed characteristics of rain physics, and measure the specific attenuation directly from the DSD measurment using advanced T-Matrix Technique, to achieve that the scope points are:

- i Analyze and characterize raindrop size distribution from the two-year 2D video disdrometer measurement, collected at Johor, Malaysia.
- ii Statistical analyses of raindrop size distribution parameters directly from the measured DSD database, and compare it to other equatorial locations.
- iii Inferred the specific attenuation due to precipitation for the millimeter wave frequencies and derived the coefficient of specific attenuation power law model.
- iv Analyze the local climatology characteristics (i.e. seasonal and diurnal variations) in equatorial Malaysia based on the one-minute rainfall rate data-set recorded for 2 years.

1.5 Research Contributions

The need for higher band width has urged the use of frequencies above 10 GHz which is in tropical and equatorial regions frequently suffer from severe propagation impairments mainly due to rain. In order to over come these issues, accurate propagation channel models based on accurate estimations are required. To this aim this work mainly focused on characterizing and providing all possible information on the DSD inferred directly form 2DVD data and their variations with detailed classifications and modeling. The following are the points identified to be the main contribution for the requirement of propagation channel modeling:

- i The first contribution concerned the statistical properties of raindrop size distribution parameters identified through the local measured raindrop size distribution in equatorial Malaysia. Such parameters are particular

importance for the calculation of specific rain attenuation through raindrop size distributions models for the prediction of rain attenuation.

- ii The second contribution is the determination of new power-law relationship coefficients between specific attenuation and rainfall rate, which are directly derived from the local disdrometer measurement in the heavy rain region. These new coefficients allowed inferring the values of specific rain attenuation in-both vertical and horizontal polarization.
- iii Third Contribution is to provide detailed data on the seasonal and diurnal variations of DSD parameters which can help not only propagation studies, but can be used for meteorological analysis to help better understand the climate in Equatorial regions.

1.6 Thesis Organization

This thesis is presented in five chapters. This chapter presents a brief research background of the investigated topic, identifying the motivations which have led to this research. The scientific objectives and the key contribution in this work are outlined and highlighted with a clear identification of the novel content in the research. The remaining chapters of the thesis are organized as follows.

Chapter 2 begins by discussing the electromagnetic propagation and the atmospheric effect. Detailed physical and microp-physical properties of rain drops are described, followed by a review of raindrop size distribution (DSD) together with its models and the characteristics of specific attenuation and the models used in it's prediction. Main features of climatology characteristic in tropical and equatorial regions, concentrating, in particular on equatorial Malaysia also discussed.

Chapter 3 investigates rain attenuation in an equatorial site by exploiting two years of rain Drop Size Distribution (DSD) measurements collected by a disdrometer in Johor, Malaysia. The methodology of the work is presented in this chapter, the instruments used and the detail maintenance and calibration process. The chapter

further introduce data processing steps, the calculation of the main parameters, and database validation.

Chapter 4 focuses on the main characteristic of rain and its microphysical properties in tropical and equatorial regions, concentrating in particular on Johor, Malaysia. Details on the classification of rain types and seasonal variations are given.

Chapter 5 provides an analytical approach to raindrop size distribution and its effect on specific rain attenuation. Similarly, the influence of the disdrometers on specific rain attenuation over millimeter links in Malaysia is also analyzed. On the basis of the different rainfall regimes.

Chapter 6 presents the conclusion and future works. The major works in this thesis are concluded and summarized, followed by some constructive recommendations on the further work given.

REFERENCES

- Abdullah, N., Shuhaimi, S., Toh, Y., Shafee, A. and Maznorizan, M. (2011). The Study of Seasonal Variation of PM10 Concentration in Peninsula, Sabah and Sarawak. *Malaysian Meteorological Department*. 9, 1–28.
- Abdulrahman, A. Y., Rahman, T. A., Rahim, S. K. A. and Islam, M. R. U. (2011). Empirically Derived Path Reduction Factor for Terrestrial Microwave Links Operating at 15 Ghz in Peninsula Malaysia. *Journal of Electromagnetic Waves and Applications*. 25(1), 23–37. doi:10.1163/156939311793898369.
- Ajayi, G. (1996). *Handbook on radiopropagation related to satellite communications in tropical and subtropical countries*. International Centre for Theoretical Physics.
- Ajayi, G. O. and Olsen, R. L. (1985). Modeling of a tropical raindrop size distribution for microwave and millimeter wave applications. *Radio Science*. 20(02), 193–202.
- Akuon, P. O. and Afullo, T. J. O. (2011). Rain Cell Size Mapping for Microwave Link Design Systems in South Africa. *Progress In Electromagnetics Research B*. 35, 263–285.
- Allnutt, J. E. (1989). Satellite-to-ground radiowave propagation-Theory, practice and system impact at frequencies above 1 GHz. *Stevenage Herts England Peter Peregrinus Ltd IEE Electromagnetic Waves Series*. 29.
- Atlas, D. (1974). The physical basis for attenuation-rainfall relationships and the measurement of rainfall parameters by combined attenuation and radar methods. *Jour. Res. Atmos.* 8, 275–298.
- Atlas, D., Ulbrich, C. W., Marks, F. D., Amitai, E. and Williams, C. R. (1999). Systematic variation of drop size and radar-rainfall relations. *Journal of Geophysical Research: Atmospheres*. 104(D6), 6155–6169.
- Barclay, L. (2003). *Propagation of radiowaves*. vol. 502. Iet.

- Battan, L. J. (1964). Some observations of vertical velocities and precipitation sizes in a thunderstorm. *Journal of Applied Meteorology*. 3(4), 415–420.
- Beard, K. V., Bringi, V. and Thurai, M. (2010). A new understanding of raindrop shape. *Atmospheric research*. 97(4), 396–415.
- Beard, K. V. and Chuang, C. (1987). A new model for the equilibrium shape of raindrops. *Journal of the Atmospheric sciences*. 44(11), 1509–1524.
- Bradley, S. and Stow, C. (1974). The measurement of charge and size of raindrops: Part II. Results and analysis at ground level. *Journal of Applied Meteorology*. 13(1), 131–147.
- Bringi, V. and Chandrasekar, V. (2001). *Polarimetric Doppler weather radar: principles and applications*. Cambridge university press.
- Bringi, V., Chandrasekar, V., Hubbert, J., Gorgucci, E., Randeu, W. and Schoenhuber, M. (2003). Raindrop size distribution in different climatic regimes from disdrometer and dual-polarized radar analysis. *Journal of the atmospheric sciences*. 60(2), 354–365.
- Bringi, V., Williams, C., Thurai, M. and May, P. (2009). Using dual-polarized radar and dual-frequency profiler for DSD characterization: A case study from Darwin, Australia. *Journal of Atmospheric and Oceanic Technology*. 26(10), 2107–2122.
- Caracciolo, C., Prodi, F., Battaglia, A. and Porcu, F. (2006). Analysis of the moments and parameters of a gamma DSD to infer precipitation properties: A convective stratiform discrimination algorithm. *Atmospheric research*. 80(2), 165–186.
- Carter, C. E., Greer, J., Braud, H. and Floyd, J. (1974). Raindrop characteristics in south central United States. *Transactions of the ASAE*. 17(6), 1033–1037.
- Castanet, L. (2011). Special issue on Channel modelling and propagation impairment simulation activities within the SatNEx project. *International Journal of satellite communications and networking*. 29(1), 1–6.
- Chen, B., Yang, J. and Pu, J. (2013). Statistical characteristics of raindrop size distribution in the Meiyu season observed in eastern China. *Journal of the Meteorological Society of Japan. Ser. II*. 91(2), 215–227.
- Cohen, A. C. and Whitten, B. J. (1980). Estimation in the three-parameter lognormal distribution. *Journal of the American Statistical Association*. 75(370), 399–404.

- Crane, R. (1980). Prediction of attenuation by rain. *IEEE Transactions on communications*. 28(9), 1717–1733.
- Crane, R. K. (1982). A two-component rain model for the prediction of attenuation statistics. *Radio Science*. 17(6), 1371–1387.
- Crane, R. K. (1996). *Electromagnetic wave propagation through rain*. Wiley-Interscience.
- Crane, R. K. (2003). *Propagation handbook for wireless communication system design*. CRC press.
- Crane, R. K. and Shieh, H.-C. (1989). A two-component rain model for the prediction of site diversity performance. *Radio Science*. 24(05), 641–665.
- Cruvinel, P. E., Minatel, E. R., Mucheroni, M. L., Vieira, S. R. and Crestana, S. (1996). An automatic method based on image processing for measurements of drop size distribution from agricultural sprinklers. *Anais Do Ix Sibigrapi*. 3, 39–46.
- da Silva Mello, L., Pontes, M., de Souza, R. and Prez Garca, N. (2007). Prediction of rain attenuation in terrestrial links using full rainfall rate distribution. *Electronics Letters*. 43(25), 1442. ISSN 00135194. doi:10.1049/el:20072410.
- Das, S., Maitra, A. and Shukla, A. K. (2010). Rain attenuation modeling in the 10-100 GHz frequency using drop size distributions for different climatic zones in tropical India. *Progress In Electromagnetics Research B*. 25, 211–224.
- Din, J. (1997). *Influence of Rainfall Drop Size Distribution on Attenuation at Microwave Frequencies in a Tropical Region*. Ph.D. Thesis. UTM.
- Edelson, B. I., Pelton, J. N., Bostian, C. W., Brandon, W. T., Chan, V. W., Hager, E. P., Helm, N. R., Jennings, R. D., Kwan, R. K. and Mahle, C. E. (1993). Satellite communications systems and technology. Volume 2: Site reports. In *Nasa technical reports*, vol. 2.
- Eigel, J. and Moore, I. (1983). A simplified technique for measuring raindrop size and distribution. *Transactions of the ASAE*. 26(4), 1079–1084.
- Evans, A. A. (2008). *Maximum Likelihood Estimation*. San Francisco State University.

- Fiser, O. (1993). A simple generator of forward scattering functions on spherical dielectrics. *Radioengineering*. 2(1), 21–22.
- Fuchs, N. and Petrjanoff, I. (1937). Microscopic examination of fog, cloud and rain droplets. *Nature*. 139, 111–112.
- García-Rubia, J. M., Riera, J. M., Garcia-del Pino, P. and Benarroch, A. (2013). Attenuation measurements and propagation modeling in the W-band. *IEEE Transactions on Antennas and Propagation*. 61(4), 1860–1867.
- Green, H. E. (2004a). Propagation impairment on Ka-band SATCOM links in tropical and equatorial regions. *IEEE Antennas and Propagation Magazine*. 46(2), 31–45.
- Green, H. E. (2004b). Propagation impairment on Ka-band SATCOM links in tropical and equatorial regions. *IEEE Antennas and Propagation Magazine*. 46(2), 31–45.
- Gunn, R. and Kinzer, G. D. (1949). The terminal velocity of fall for water droplets in stagnant air. *Journal of Meteorology*. 6(4), 243–248.
- Hall, M. (1970). Use of the stain method in determining the drop-size distributions of coarse liquid sprays. *Transactions of the ASAE*. 13(1), 33–0037.
- Hardy, K. (1963). The development of raindrop-size distributions and implications related to the physics of precipitation. *Journal of the Atmospheric Sciences*. 20(4), 299–312.
- Houze, R. A. (1989). Observed structure of mesoscale convective systems and implications for large-scale heating. *Quarterly Journal of the Royal Meteorological Society*. 115(487), 425–461.
- Houze Jr, R. A. (1997). Stratiform precipitation in regions of convection: A meteorological paradox? *Bulletin of the American Meteorological Society*. 78(10), 2179–2196.
- Ishimaru, A. (1978). *Wave propagation and scattering in random media*. vol. 2. Academic press New York.
- ITU (2005). *P. 838-3 Specific attenuation model for rain for use in prediction methods*.
- Ivanovs, G. and Serdega, D. (2006). Rain intensity influence on to microwave line payback terms. *Elektronika ir Elektrotechnika*. 70(6), 60–64.
- Jiang, H., Sano, M. and Sekine, M. (1997). Weibull raindrop-size distribution and

- its application to rain attenuation. *IEE Proceedings-Microwaves, Antennas and Propagation*. 144(3), 197–200.
- Joss, J., Thams, J. and Waldvogel, A. (1968). The variation of rain drop-size distributions at Locarno, paper presented at International Conference on Cloud Physics. *Am. Meteorol. Soc., Toronto, Ont., Canada*.
- Joss, J. and Waldvogel, A. (1969). Raindrop size distribution and sampling size errors. *Journal of the Atmospheric Sciences*. 26(3), 566–569.
- Joss, J., Waldvogel, A. and Collier, C. (1990). Precipitation measurement and hydrology. In *Radar in meteorology*. (pp. 577–606). Springer.
- Kanellopoulos, J. D., Koukoulas, S. G., Kolliopoulos, N. J., Capsalis, C. N. and Ventouras, S. G. (1990). Rain attenuation problems affecting the performance of microwave communication systems. *Annals of Telecommunications*. 45(7), 437–451.
- Khamis, N. H. H., Din, J. and Rahman, T. A. (2005). Analysis of rain cell size distribution from meteorological radar data for rain attenuation studies. In *Asia-Pacific Conference on Applied Electromagnetics, APACE*. IEEE.
- Kinnell, P. (1976). Some observations on the Joss-Waldvogel rainfall disdrometer. *Journal of Applied Meteorology*. 15(5), 499–502.
- Kohl, R. (1974). Drop size distribution from medium-sized agricultural sprinklers. *Transactions of the ASAE*. 17(4), 690–693.
- Kozu, T., Reddy, K. K., Mori, S., Thurai, M., Ong, J. T., Rao, D. N. and Shimomai, T. (2006). Seasonal and diurnal variations of raindrop size distribution in Asian monsoon region. *Journal of the Meteorological Society of Japan. Ser. II*. 84, 195–209.
- Kumar, L. S., Lee, Y. H. and Ong, J. T. (2010). Truncated gamma drop size distribution models for rain attenuation in Singapore. *IEEE transactions on antennas and propagation*. 58(4), 1325–1335.
- Lam, H. Y., Din, J. and Jong, S. L. (2015). Statistical and physical descriptions of raindrop size distributions in equatorial Malaysia from disdrometer observations. *Advances in Meteorology*. 2015, 1–14. ISSN 16879317. doi:10.1155/2015/253730.
- Lam, H. Y., Luini, L., Din, J., Capsoni, C. and Panagopoulos, A. D. (2012).

- Investigation of rain attenuation in equatorial Kuala Lumpur. *IEEE Antennas and Wireless Propagation Letters*. 11, 1002–1005.
- Laws, J. O. and Parsons, D. A. (1943). The relation of raindrop-size to intensity. *Eos, Transactions American Geophysical Union*. 24(2), 452–460.
- Lee, Y., Lakshmi, S. and Ong, J. (2007). Rain drop size distribution modelling in Singapore-critical diameters.
- Löffler-Mang, M. and Joss, J. (2000). An optical disdrometer for measuring size and velocity of hydrometeors. *Journal of Atmospheric and Oceanic Technology*. 17(2), 130–139.
- Marcus, M. and Pattan, B. (2005). Millimeter wave propagation: spectrum management implications. *IEEE Microwave Magazine*. 6(2), 54–62.
- Marshall, J. S. (1948). The distribution of raindrops with size. *J. Meteor.* 5, 165–166.
- Marzuki, Hashiguchi, H., Kozu, T., Shimomai, T., Shibagaki, Y. and Takahashi, Y. (2016). Precipitation microstructure in different Madden-Julian Oscillation phases over Sumatra. *Atmos. Res.* 168, 121–138. ISSN 01698095. doi:10.1016/j.atmosres.2015.08.022. Retrievable at <http://dx.doi.org/10.1016/j.atmosres.2015.08.022>.
- Marzuki, Randeu, W. L., Kozu, T., Shimomai, T., Hashiguchi, H. and Schounhuber, M. (2013). Raindrop axis ratios, fall velocities and size distribution over Sumatra from 2D-Video Disdrometer measurement. *Atmos. Res.* 119, 23–37. ISSN 01698095. doi:10.1016/j.atmosres.2011.08.006. Retrievable at <http://dx.doi.org/10.1016/j.atmosres.2011.08.006>.
- Marzuki, M., Randeu, W. L., Schönhuber, M., Bringi, V. N., Kozu, T. and Shimomai, T. (2010). Raindrop size distribution parameters of distrometer data with different bin sizes. *IEEE Trans. Geosci. Remote Sens.* 48(8), 3075–3080. ISSN 01962892. doi:10.1109/TGRS.2010.2043955.
- Matricciani, E. and Pawlina, A. (2000). Statistical Characterization of Rainfall Structure and Occurrence for Convective and Stratiform Rain Inferred from Long Term Point Rain Rate Data. In *AP2000 Millenium Conference on Antennas and Propagation*. 1–8.

- Matthews, P. A. (1965). *Radio wave propagation: VHF and above*. Chapman and Hall.
- May, K. (1945). The cascade impactor: an instrument for sampling coarse aerosols. *Journal of Scientific instruments*. 22(10), 187.
- Milbrandt, J. and Yau, M. (2005). A multimoment bulk microphysics parameterization. Part I: Analysis of the role of the spectral shape parameter. *Journal of the atmospheric sciences*. 62(9), 3051–3064.
- Mishchenko, M. I., Travis, L. D. and Lacis, A. A. (2002). *Scattering, absorption, and emission of light by small particles*. Cambridge university press.
- Oguchi, T. (1964). Attenuation of electromagnetic wave due to rain with distorted raindrops, 2. *Journal of the Radio Research Laboratory*. 10(53).
- Olsen, R., Rogers, D. V. and Hodge, D. (1978). The aR b relation in the calculation of rain attenuation. *IEEE Transactions on antennas and propagation*. 26(2), 318–329.
- Ong, J.-T. and Zhu, C.-N. (1997). Rain rate measurements by a rain gauge network in Singapore. *Electronics Letters*. 33(3), 240–242.
- P.530-17, I. (2017). *P.530-17: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems*.
- Paris, D. T. and Hurd, F. K. (1969). *Basic electromagnetic theory*. McGraw-Hill.
- Pearson, K. (1895). *Contributions to the Mathematical Theory of Evolution. II Skew Variation in Homogeneous Material Philosophical*, 186. W: K.
- Pontes, M., da Silva Mello, L., de Souza, R. and Miranda, E. (2005). Review of rain attenuation studies in tropical and equatorial regions in Brazil. In *Information, Communications and Signal Processing, 2005 Fifth International Conference on*. IEEE, 1097–1101.
- Proakis, J. G., Salehi, M., Zhou, N. and Li, X. (1994). *Communication systems engineering*. vol. 2. Prentice Hall New Jersey.
- Pruppacher, H. R. and Pitter, R. (1971). A semi-empirical determination of the shape of cloud and rain drops. *Journal of the atmospheric sciences*. 28(1), 86–94.
- Rappaport, T. S., Xing, Y., MacCartney, G. R., Molisch, A. F., Mellios, E. and Zhang, J. (2017). Overview of Millimeter Wave Communications for Fifth-Generation (5G)

- Wireless Networks-With a Focus on Propagation Models. *IEEE Transactions on Antennas and Propagation*. 65(12), 6213–6230. ISSN 0018926X. doi:10.1109/TAP.2017.2734243.
- Raupach, T. H. and Berne, A. (2015). *Correction of raindrop size distributions measured by Parsivel disdrometers, using a two-dimensional video disdrometer as a reference*. doi:10.5194/amt-8-343-2015. Retrievable at <http://www.atmos-meas-tech.net/8/343/2015/amt-8-343-2015.pdf>.
- Riva, C. (2004). Seasonal and diurnal variations of total attenuation measured with the ITALSAT satellite at Spino d'Adda at 18.7, 39.6 and 49.5 GHz. *International journal of satellite communications and networking*. 22(4), 449–476.
- Rosenfeld, D., Amitai, E. and Wolff, D. B. (1995). Classification of rain regimes by the three-dimensional properties of reflectivity fields. *Journal of Applied Meteorology*. 34(1), 198–211.
- Schönhuber, M., Lammer, G. and Randeu, W. (2007). One decade of imaging precipitation measurement by 2D-video-distrometer. *Advances in Geosciences*. 10, 85–90.
- Sekine, M. and Chii-Dong, C. (1985). Rain attenuation in terrestrial and satellite communications links. In *15th European Microwave Conference*. IEEE, 985–990.
- Sekine, M. and Lind, G. (1982). Rain Attenuation Of Centimeter, Millimeter and Submillimeter Radio Waves. In *12th European Microwave Conference*. IEEE, 584–589.
- Simpson, J., Adler, R. F. and North, G. R. (1988). A proposed tropical rainfall measuring mission (TRMM) satellite. *Bulletin of the American meteorological Society*. 69(3), 278–295.
- Strangeways, I. (2006). *Precipitation: theory, measurement and distribution*. Cambridge University Press.
- Thompson, E. J., Rutledge, S. A., Dolan, B. and Thurai, M. (2015). Drop size distributions and radar observations of convective and stratiform rain over the equatorial Indian and West Pacific Oceans. *J. Atmos. Sci.* 72(11), 4091–4125. ISSN 0022-4928. doi:10.1175/JAS-D-14-0206.1.

- Thurai, M. and Bringi, V. (2005). Drop axis ratios from a 2D video disdrometer. *Journal of Atmospheric and Oceanic Technology*. 22(7), 966–978.
- Thurai, M., Bringi, V. and Shimomai, T. (2007). 20 GHz Specific attenuation calculations using drop size distributions and drop shape measurements from 2D video disdrometer data in different rain climates. In *6th International Conference on Information, Communications and Signal Processing*. IEEE, 1–4.
- Thurai, M., Bringi, V., Szakáll, M., Mitra, S., Beard, K. and Borrmann, S. (2009). Drop shapes and axis ratio distributions: Comparison between 2D video disdrometer and wind-tunnel measurements. *Journal of Atmospheric and Oceanic Technology*. 26(7), 1427–1432.
- Thurai, M., Gatlin, P. N. and Bringi, V. N. (2016). Separating stratiform and convective rain types based on the drop size distribution characteristics using 2D video disdrometer data. *Atmos. Res.* 169, 416–423. ISSN 01698095. doi:10.1016/j.atmosres.2015.04.011. Retrievable at <http://www.sciencedirect.com/science/article/pii/S016980951500112X>.
- Thurai, M., Williams, C. and Bringi, V. (2014). Examining the correlations between drop size distribution parameters using data from two side-by-side 2D-video disdrometers. *Atmospheric research*. 144, 95–110.
- Timothy, K. I., Ong, J. T. and Choo, E. B. (2002). Raindrop size distribution using method of moments for terrestrial and satellite communication applications in Singapore. *IEEE Transactions on Antennas and Propagation*. 50(10), 1420–1424.
- Tokay, A., Petersen, W. A., Gatlin, P. and Wingo, M. (2013). Comparison of raindrop size distribution measurements by collocated disdrometers. *Journal of Atmospheric and Oceanic Technology*. 30(8), 1672–1690.
- Tokay, A. and Short, D. A. (1996). Evidence from tropical raindrop spectra of the origin of rain from stratiform versus convective clouds. *Journal of applied meteorology*. 35(3), 355–371.
- Tomasi, W. (1987). *Electronic communications systems: fundamentals through advanced*. Prentice Hall PTR.
- Townsend, A. J., Watson, R. J. and Hodges, D. D. (2009). Analysis of the variability in the raindrop size distribution and its effect on attenuation at 20-40 GHz. *IEEE*

- Antennas Wirel. Propag. Lett.* 8, 1210–1213. ISSN 15361225. doi:10.1109/LAWP.2009.2035724. Retrievable at <http://dx.doi.org/10.1109/LAWP.2009.2035724>.
- Ulbrich, C. W. (1983). Natural variations in the analytical form of the raindrop size distribution. *Journal of Climate and Applied Meteorology*. 22(10), 1764–1775.
- Ulbrich, C. W. and Atlas, D. (2007). Microphysics of raindrop size spectra: Tropical continental and maritime storms. *Journal of Applied Meteorology and Climatology*. 46(11), 1777–1791.
- Van de Kamp, M. M. (2003). Statistical analysis of rain fade slope. *IEEE Transactions on Antennas and Propagation*. 51(8), 1750–1759.
- Waldvogel, A. (1974). The N 0 jump of raindrop spectra. *Journal of the Atmospheric Sciences*. 31(4), 1067–1078.
- Wen, L., Zhao, K., Zhang, G., Xue, M., Zhou, B., Liu, S. and Chen, X. (2016). Statistical characteristics of raindrop size distributions observed in East China during the Asian summer monsoon season using 2-D video disdrometer and Micro Rain Radar data. *Journal of Geophysical Research: Atmospheres*. 121(5), 2265–2282. ISSN 21698996. doi:10.1002/2015JD024160. Retrievable at <http://dx.doi.org/10.1002/2015JD024160>.
- Westman, C. (1975). *Reference data for radio engineers*. Sams.
- Xie, Y.-n., Zhou, X.-l. *et al.* (2011). Error analysis of non-spherical raindrops on precipitation measurement. *Journal of Shanghai University (English Edition)*. 15(2), 92–95.
- Zhang, G., Sun, J. and Brandes, E. a. (2006). Improving Parameterization of Rain Microphysics with Disdrometer and Radar Observations. *J. Atmos. Sci.* 63(4), 1273–1290. ISSN 0022-4928. doi:10.1175/JAS3680.1.