ESTIMATION OF RAIN HEIGHT AND ONE-MINUTE RAIN RATE BASED ON TROPICAL RAINFALL MEASURING MISSION PRODUCT

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To my beloved mother, Kamariah Abd Hamid, and father, Mohd Aris Othman,

and

To dearest wife, Alia Sofie Jemale and

My sons, Amirul Nafis and Aiman Nasri

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ABSTRACT

Rainfall is a major factor which affects radio communication systems operating at frequencies more than 10 GHz. Thus, measurements of rainfall are extensively carried out using either space-based or ground-based instruments. Now, Tropical Rainfall Measuring Mission (TRMM) satellite is considered one of space-based instruments that is able to provide reliable rainfall data. However, most studies involving TRMM are meant for hydrological and climatological purposes. Therefore, analyses are made to show the applicability of TRMM in radiowave propagation through the estimation of rain height and one-minute rain rate required in the step by step calculation of long term rain attenuation statistics by ITU-R recommendation P.618-10. First, bright-band height is estimated from TRMM Precipitation Radar observation available in 2A23 and 2A25 dataset. Then, the $0^{o}C$ isotherm height is calculated by assuming that it lies 500m above the bright-band. Comparison of the estimated bright-band and the $0^{o}C$ isotherm height with ground-based measurement data shows quite good agreement indicating the reliability of TRMM in estimating rain height. Next, a modified model for the prediction of one-minute integrated Complementary Cumulative Distribution Function (CCDF) of the rain rate ($P(R)_1$) valid for tropical and equatorial regions is proposed. The model inherits its analytical formulation from ITU-R recommendation P.837-6 Annex 1 and relies on TRMM PR 3A25 and TMPA 3B43 data for the extraction of probability of rain (P_0) and mean yearly accumulated rainfall (M_t) respectively in place of ERA40 database which suffers poor spatial resolution. Based on the testing, the prediction performance of the modified model with TRMM data shows better performance compared to the same procedure with ERA40 data. This study shows the applicability of TRMM to be employed in radiowave propagation, especially for the purpose of improving rain attenuation prediction model due to its reliability and higher spatial resolution database.

ABSTRAK

Hujan adalah faktor utama yang mempengaruhi sistem komunikasi radio yang beroperasi pada frekuensi lebih daripada 10 GHz. Justeru, ukuran hujan dijalankan secara meluas menggunakan instrumen angkasa atau daratan. Kini, satelit Misi Pengukuran Hujan Tropika (TRMM) dianggap sebagai salah satu instrumen angkasa yang mampu menyediakan data hujan secara tepat. Tetapi, kebanyakan kajian yang menggunakan TRMM adalah untuk tujuan hidrologi dan klimatologi. Maka, analisis dijalankan untuk menunjukkan kebolehpercayaan TRMM dalam kajian perambatan gelombang radio dengan menganggar ketinggian hujan dan kadar hujan satu minit yang diperlukan dalam langkah-langkah pengiraan statistik jangka panjang pelemahan hujan oleh ITU-R P.618 -10. Pertama, ketinggian *bright-band* dianggarkan daripada TRMM *Precipitation Radar* dan boleh didapati dalam dataset 2A23 dan 2A25. Kemudian, ketinggian 0^oC isoterma dikira dengan menganggap bahawa ia terletak 500m di atas *bright-band*. Perbandingan *bright-band* dan 0^oC isoterma dengan data dari pengukuran daratan menunjukkan persetujuan yang agak baik yang menunjukkan kebolehpercayaan TRMM dalam menganggarkan ketinggian hujan. Seterusnya, satu model diubahsuai bagi peramalan kadar hujan satu minit bersepadu Komplementari Pengagihan Fungsi Kumulatif (CCDF) ($P(R)_1$) untuk kawasan tropika dan khatulistiwa telah dicadangkan. Model mewarisi penggubalan analitis dari ITU-R P.837-6 Lampiran 1 dan menggunakan data TRMM PR 3A25 dan TMPA 3B43 untuk pengekstrakan kebarangkalian hujan (P_0) dan purata hujan terkumpul tahunan (M_t) bagi menggantikan ERA40 yang mengalami resolusi ruang yang rendah. Berdasarkan ujian, model diubahsuai menggunakan data TRMM menunjukkan prestasi yang lebih baik berbanding kaedah sama yang menggunakan data ERA40. Analisis menunjukkan keupayaan TRMM untuk digunakan dalam kajian perambatan gelombang radio terutama bagi tujuan menambahbaik model ramalan pelemahan hujan disebabkan oleh kebolehpercayaan dan pangkalan data resolusi ruang yang lebih tinggi.

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LIST OF ABBREVIATIONS

AMSR-E	-	Advance Microwave Scanning Radiometer-Earth Observing System
AMSU-B	-	Advanced Microwave Sounding Unit-B
CCDF	-	Complementary Cumulative Distribution Function
CDF	-	Cumulative Distribution Function
CERES	-	Clouds and Earth's Radiant Energy System
DBSG3	-	Database of ITU-R Study Group 3
DID	-	Department of Irrigation and Drainage
DSD	-	Drop Size Distribution
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ERA40	-	ECMWF Re-Analysis 40 Years
EXCELL	-	Exponential Cell
EXCELL RSC	-	Exponential Cell Rainfall Statistics Conversion
GEO	-	Geosynchronous Earth Orbit
GES-DISC	-	Goddard Earth Science Data and Information Services Center
GHCN	-	Global Historical Climatology Network
GMS	-	Geostationary Meteorological Satellite
GOES	-	Geostationary Operation Environmental Satellites
GPCC	-	Global Precipitation Climatology Centre
GPCP	-	Global Precipitation Climatology Project
GPM	-	Global Precipitation Mission
GR	-	Ground-based Radar
GUI	-	Graphical User Interface
HDF	-	Hierarchical Data Format
HYCELL	-	Hybrid Cell
IFOV	-	Instantaneous Field of View

ITU-R	-	International Telecommunication Union, Radiocommunication sector
JAXA	-	Japan Aerospace Exploration Agency
LIS	-	Lightning Imaging Sensor
MEASAT 3	-	Malaysia East Asia Satellite 3
MMD	-	Malaysia Meteorological Department
NASA	-	National Aeronautics and Space Administration
NCEP2	-	National Centers for Environmental Prediction project II Reanalysis
NUBF	-	Non-Uniform Beam Filling
PIA	-	Path Integrated Attenuation
PPS	-	Precipitation Processing System
PR	-	Precipitation Radar
RMS	-	Root Mean Square
RT	-	Real Time
SRT	-	Surface Reference Technique
SSM/I	-	Special Sensor Microwave/Imager
THOR	-	Tools for High-resolution Observation Review
TMI	-	TRMM Microwave Imager
TMPA	-	TRMM Multi-satellite Precipitation Analysis
TOVAS	-	TRMM Online Visualization and Analysis System
TRMM	-	Tropical Rainfall Measuring Mission
VIRS	-	Visible and Infrared Scanner
WD	-	Water District

LIST OF SYMBOLS

D_0	-	Median volume diameter of the DSD
D_{th}	-	Average annual number of thunderstorm days
E	-	Average of error figure
$\varepsilon(P)$	-	error figure at probability P%
f	-	Frequency
h_0	-	0^oC isotherm height
h_{BB}	-	Bright-band height
h_R	-	Rain height
h_s	-	Earth station altitude
$k(s)$	-	Specific attenuation
L_G	-	Horizontal projection of L_S
L_s	-	Slant-path length
M_c	-	Mean yearly convective rainfall accumulation
M_m	-	Highest monthly precipitation observed over 30 years
M_t	-	Mean yearly rainfall accumulation
N_R	-	Number of rainy pixel
N_T	-	Number of total pixel
N_w	-	Intercept parameter
ϕ	-	Earth station latitude
$P(R)_1$	-	1-minute rain rate CCDF
$P(R)_T$	-	T-minute rain rate CCDF
P_0	-	Probability of rain in an average year
P_{r6h}	-	Probability to have rain in 6-hour period
$P_S(R)$	-	Spatial rain rate statistics
R	-	rain rate
$R_{0.01}$	-	rainfall rate exceeded for 0.01% of the yearly time
$R_1(P)$	-	1-minute rain rate at probability P%

R_e	-	Earth radius
$R_e(P)$	-	Estimated rain rate at probability P%
$R_m(P)$	-	Measured rain rate at probability P%
$R_T(P)$	-	T-minute rain rate at probability P%
Z_e	-	Effective radar reflectivity factor
Z_m	-	Measured radar reflectivity factor
β	-	Convectivity or thunderstorm ratio
$\Delta\sigma^o$	-	Reduction of apparent surface cross section
ζ	-	Polarization angle
σ	-	Standard deviation
$\sigma^o{}_{no\ rain}$	-	Surface cross section during clear sky
$\sigma^o{}_{rain}$	-	Surface cross section during rain
Ψ	-	Elevation angle

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Rainfall studies are of great interest in several fields due to its high spatial and temporal variability. Hydrologist and meteorologist for example, require knowledge on rainfall to understand and predict the global climate change as well as weather anomalies. With regards to its importance, measurement of rainfall using spaceborne instruments is required in addition to the ground-based instrument such as rain gauge and weather radar to provide reliable observation data especially over the vast ocean. According to Kozu (1991), measuring global rainfall through space-based (i.e. satellite remote sensing) observation is one of the best alternative in addition to the ground-based measurement due to its wider coverage. To date, one of the most powerful space-based instruments is Tropical Rainfall Measuring Mission (TRMM) satellite. At present, TRMM satellite has been continuously observing the tropical climatic since its launch in November 1997. Main purpose of the TRMM observation is to understand the tropical rainfall distribution and its effects to the global climate.

For engineers' community in the radiowave propagation field, major interest towards rainfall study is the transmission impairment due to rain. Rainfall cause absorption, scattering and depolarization to the microwave signal, in which all of them contribute to the rain attenuation. Moreover, the effects of rain could be quite severe in tropical and equatorial regions due to significantly higher rainfall rate compared to the temperate region especially for systems operating at frequencies more than 10 GHz (Dissanayake *et al*., 1997). Rapid developments for radio system to fulfil both terrestrial and satellite services require the use of higher frequency bands such as Ka (20 GHz to 30 GHz), and Q/V (40 GHz to 50 GHz) because of congestion that the Ku band is experiencing. As the operating frequency increase, the magnitude of fades also increases thus the system design have become more challenging. Therefore, the knowledge of rain attenuation especially to overcome rain fades is strongly required when designing a radio communication system.

Information of rain attenuation could be obtained by measuring the received signal strength of satellite beacon during rain as shown by previous researchers. One of the examples is from Ismail and Watson (2000). However, the measurement setup requires a number of outdoor and indoor equipments which are expensive. Therefore it can only be carried out at limited location and period. To overcome such limitation in getting rain attenuation information, model for rain attenuation prediction had been developed extensively since decades ago. One of the most accepted and well established models is as recommended by International Telecommunication Union for Radiocommunication (ITU-R).

The ITU-R recommendation P.618-10 predicts various propagation parameters needed in planning Earth-space systems. It provides step by step calculation of long-term rain attenuation which requires a number of meteorological parameters. Some parameters are provided by other ITU-R recommendations, for example rain height (h_{R}) and one-minute rain rate at 0.01% of the time ($R_{0.01}$). The former could be obtained from ITU-R recommendation P.839-3 while the latter is available from the prediction model in ITU-R recommendation P.837-6. To adequately estimate the rain attenuation, accurate information of rain height and one-minute rainfall cumulative distribution function ($P(R)_1$) is fundamental as recommended by ITU.

In ITU-R method for attenuation prediction, it uses a fixed value of rain height which currently estimated in relation to the 0°C isotherm level inferred from ITU-R P.839-3. Although the fixed value is represented by average of long-term data, it should be noted that each regions in the world experience strong variation of rain height. One of the examples is as shown by Mandeep (2008) through radiosonde observation in Malaysia that, even though not as strong as in temperate regions, the 0°C isotherm height displays seasonal type dependency. Thurai *et al.* (2005) stated that a significant error may occur due to the utilization of constant rain height in the attenuation calculation. Thus, it is crucial to have accurate information on rain height statistics in order to produce a better estimation on rain attenuation.

Beside the rain height, one-minute rain rate is considered another crucial parameter that is required in the prediction of rain attenuation, especially in the model that has been recommended by ITU-R. Ito and Hosoya (2006) stated that one-minute rainfall rate (mm/h) is the depth of rain for one-minute integration time which is equivalent to the accumulation of one minute rainfall (mm) multiplied by 60. This integration time is the most suitable time interval to be used to measure rain rate in order to properly capture the temporal dynamics of the rainfall process (Emiliani *et al.*, 2009). In fact, the use of integration time longer than one minute would result in an averaging effect which underestimates the high rain rate value as stated by Emiliani and Luini (2010).

However, main obstacle faced by the radiowave propagation engineer community is the lack of local one-minute integrated rain rate data. Rainfall data with longer integration times are commonly available compared to short interval integration time. In Malaysia, rainfall is commonly measured with one-hour integration time or longer either by rain gauge or meteorological radars. As stated by Chebil and Rahman (1999), most of these works are usually carried out for meteorological, hydrological and agricultural purposes.

To overcome such limitation, there is a need to develop the conversion models for rain rate from longer integration time into one-minute integration time. Conversion methods have become the subject of analysis since 1980's. To date, many different methods and approach already been proposed and developed to fulfil the needs for one-minute rainfall rate cumulative distribution that can be divided into two type based on their different principle which are conversion method and meteorology-based method.

The conversion method which could be considered better in term of prediction accuracy requires the knowledge of *T*-minute rain rate statistics, $P(R)_T$, where T is typically from 5 minutes up to 60 minutes. Prediction models in this category usually apply the power law equation and/or conversion factor to relate the T-integration time with one-minute integration time. Some model even goes to the extent of modeling the physical process of rainfall formation such as performed by EXCELL RSC model (Capsoni and Luini, 2009). However these kind of models, as mentioned above, requires availability of $P(R)_T$ information.

The other method is a prediction based on local meteorology inputs which requires no T-minute rain rate statistics. These kinds of model needs long-term input parameter to represent their local climatic environment such as mean yearly rainfall accumulation (M_t) and convectivity ratio (β). The most acknowledged within this type are Rice-Holmberg (Rice and Holmberg, 1973), Dutton-Dougherty (Dutton *et al*., 1974) and ITU-R model. Among the models available, the best established and applicable worldwide is as recommended by ITU-R.

ITU-R P.837-6 provides a method to predict one-minute rainfall rate from the knowledge of the local meteorological parameter. The parameters are currently derived from ERA40 (ECMWF (European Centre for Medium-range Weather Forecast) re-analysis of 40 years) database (Uppala *et al*., 2005). However, the database suffers from low spatial resolution (currently at 1.125^ox1.125^o grid on the ground). Since the TRMM database provides a fine spatial resolution of data (0.25^ox0.25^o and 0.5^ox0.5^o for TMPA and TRMM PR respectively) as compared to the ERA40, the utilization of TRMM database might improve the prediction of one-minute minute rain rate at least in tropical/equatorial regions.

1.2 Problem Statements

In addition to the research background, the statements of the problems are summarized in this subchapter. Main concern currently is the reliability of TRMM in the radiowave propagation studies such as prediction of rain attenuation. In this research, estimation of rain height and one-minute rain rate are classified as rain attenuation studies due to their significance in the global rain attenuation prediction model by ITU-R recommendation. Since the launch date in 1997, few efforts have been carried out to take advantage of the capability of TRMM in the radiowave propagation field due to availability of other reliable database such as ERA40 and GPCC that could provide longer-term of data. Most of the studies involving TRMM are meant for observation for hydrological extreme, weather forecasting and atmospheric science studies. Therefore, this research could provide significant contribution for assessing the applicability of TRMM in the radiowave propagation studies.

Validation of the rain height retrieved from TRMM with the other instrument is of important task. Common testing activity to assess the validity and reliability of measurement from an instrument is by comparing the results with other instruments data. In the aspect of rain height variation, TRMM could provide wider data coverage in comparison with, for example, radiosonde and ground radar. Furthermore, TRMM also provides finer spatial resolution data compared to the ITU-R recommendation. The significance of rain height could be displayed through the estimated rain attenuation based on various rain height values.

Regarding the poor resolution of ERA40 database which is currently being relied on by ITU-R model to predict one-minute rain rate, it is worth mentioning that TRMM provides an opportunity in improving the current prediction through the finer resolution of database. Since the work in improving current prediction model is a continuous effort, an availability of such high spatial resolution database as TRMM is expected to provide more accurate estimation or prediction, specifically in this case, prediction of one-minute rain rate statistics. To validate this hypothesis, a proposed method using TRMM database to provide input meteorological parameter should be tested against current global prediction model. As a result, the research carried out in this thesis could also been viewed as promoting the TRMM capability towards rain attenuation studies especially for tropical/equatorial regions.

1.3 Objectives

With regards to the problems mentioned above, the main aim of this study is to analyze the applicability of TRMM in estimating local meteorological parameter for radiowave propagation studies. Such aim is expected to be achieved through the objectives that have been listed as below:

1. To estimate rain height from TRMM database.
2. To propose a one-minute rain rate prediction model based on TRMM database applicable for tropical and equatorial regions with expected improved accuracy.

1.4 Scope of Work

The key contribution in this research is the usage of TRMM database in the radiowave propagation studies, which in fact provides better spatial resolution data compared to the current database that has been relied on by ITU-R in several recommendations; namely ERA40 database. The analyses includes the estimation of rain height and one-minute rain rate to show the advantages of TRMM over ERA40 database. In order to achieve the objective of this research while considering for the limitation and time constraint, few scopes have been outlined.

First is the use of TRMM database as resource to provide required data. The TRMM database consists of many datasets which are the products of its sensors observation algorithms. In this research, the data products originated from TRMM Precipitation Radar and TRMM Multi-satellite Precipitation Analysis are used as main resources for estimating the required parameters. Since TRMM developed their own algorithm for their respective products, therefore all results are subject to the accuracy of the algorithms.

Secondly, rain height and one-minute rain rate are the two parameters which commonly involve in the radiowave propagation studies to be estimated employing

TRMM database. Studies on rain height are focused to the variation and its effect to the rain attenuation prediction model. It is estimated based on the knowledge of bright-band height which is provided by TRMM PR 2A23 and 2A25 datasets. Comparison with ground measurement data which are taken from other researchers is carried out to highlight the validity of TRMM database.

This research emphasizes on the one-minute rain rate considering its significance to the radiowave propagation studies. A modified prediction model of one-minute rain rate that originated from analytical formulation of ITU-R P.837-5 is proposed which uses TRMM database as its source to extract the required meteorological inputs. The capability of the TRMM database to estimate useful parameters meant for radiowave propagation studies is shown through several testing activities that involve selected areas or locations within tropical and equatorial regions. Most data for the comparison purpose are extracted from ITU-R DBSG3 databank (will be elaborated in methodology chapter). Last but not least, ITU-R recommendations are used as main reference as well as other data from appropriate literatures for comparison purposes.

1.5 Research Methodology Summary

The aim of this research is to analyze the capability of TRMM in providing parameters required in radiowave propagation study. Therefore, a proper method has been planned in order to achieve the research objective. The methodology are divided into two sections for estimating the two intended rainfall parameters; rain height and one-minute rain rate.

The first section is for estimating rain height. Two parameters included in this section is bright-band height and 0^oC isotherm height. The bright-band height which is able to be extracted from TRMM PR 2A23 product is used as reference to estimate the 0^oC isotherm height. Then, two comparisons are made where the bright-band height extracted from TRMM PR 2A23 is compared with bright-band height data made extracted from Thurai and Iguchi (2000), while the 0^oC isotherm height estimated from TRMM-extracted bright-band height is compared with radiosonde data made available by Mandeep (2008).

The second section presents the one-minute rain rate prediction model based on parameters extracted from TRMM 3A25 (to estimate the probability of rain, P_0) and TMPA 3B43 (to estimate the mean yearly rainfall accumulations, M_t) product. The model originated from ITU-R P.837-6 Annex 1 model is applied with minor modification to suit the input from TRMM products. Testing activity is carried out to compare the modified model's output with current ITU-R model's output and also data extracted from ITU-R DBSG3 databank (considered as measured data contributed by other researchers to the ITU-R Study Group 3). Details on the methodology will be described in Chapter 3.

1.6 Thesis Outline

The first chapter of this thesis presents overview of the research. A brief justification on the significance of this work is stated in the background and problem statement subchapter. Then, objectives and scopes of work are highlighted.

Literature reviews are presented in Chapter two which reviews the Tropical Rainfall Measuring Mission (TRMM) and the two rainfall parameters; rain height and one-minute rain rate. This chapter provides explanation on the TRMM mission and its reliability. It is useful to mention here that Precipitation Radar on board of TRMM satellite is the main focus in this chapter. Lastly, the chapter also presents the TRMM Multi-satellite Precipitation Analysis (TMPA) product data. Next is the review on the rainfall parameters. It is divided into two subsections which are rain height and one-minute rain rate. Rain height studies provide understanding on several rain height terms. Reviews on other works regarding this topic are included. Next, one-minute rain rate studies provide classification of available prediction model. Explanations on ITU-R global prediction model is described in details.

Chapter three describes methodologies in this research work. The chapter is divided into two parts which cover for the rain height and one-minute rain rate. Description on data selection, data processing and testing activity are also explained in this chapter.

Chapter four shows the results from rain height and one-minute rain rate analyses. All results on validation process and testing activity are thoroughly discussed.

The last chapter, Chapter 5 concludes the finding of the research. Significant contributions are highlighted based on the results obtained. Recommendations for future works are also included in this chapter.

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