TROPOSPHERIC SCINTILLATION FOR KU-BAND SATELLITE COMMUNICATION LINK IN EQUATORIAL MALAYSIA

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To my beloved parents, my husband Ali Elgayar, my daughter Fawzia Elgayar and my son Ibrahim Elgayar for their encouragement and support”

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ABSTRACT

Tropospheric scintillation is a rapid fluctuation of the amplitude of received signal causes propagation impairments that affect satellite communication systems operating above 10 GHz. This work concentrates on those aspects in equatorial Johor Bahru, Malaysia, based on a two-year K_u-band propagation measurement campaign, utilizing the equipment of Direct Broadcast Receiver (DBR) and Automatic Weather Station (AWS). The study is divided into two parts. First, the investigation of clear sky scintillation through classification and analysis of a time-series satellite broadcasting signals, followed by comparison of the statistical results with existing scintillation prediction models. A new processing method is proposed to enhance the estimation of dry scintillation, specifically for the diurnal behavior of scintillation variance. Second, this study focuses to investigate the relationship between wet scintillation and rain attenuation using experimental measurement, and concentrate on the probability density function (PDF) of different scintillation parameters. From the results, it is concluded that wet scintillation intensity increases with rain attenuation. Thus, the relationship can be phrased by linear equations or power-law. The PDFs of wet scintillation intensity, adapted to a given rain attenuation level, are found lognormally distributed, leading to selection of method for determining the relation between conditional PDFs and rain attenuation. Finally, seasonal and diurnal variations of wet scintillation are also investigated. It is found that wet scintillation fade is likely to occur in the afternoon from 3 pm to 6 pm. Meanwhile, wet scintillation intensity of the inter-monsoon shows a relatively higher rate of change of attenuation. The results can provide system operators and radio communication engineers with critical information on the fluctuations of tropospheric scintillation variance of the satellite signal during a typical day, taking into the account of local meteorological peculiarities.

ABSTRAK

Kelipan troposfera merupakan perubahan mendadak bagi amplitud isyarat penerima yang boleh menyebabkan rosotan perambatan yang mempengaruhi sistem komunikasi satelit pada frekuensi melebihi 10 GHz. Kajian ini menumpukan kepada aspek-aspek tersebut di Johor Bahru, Malaysia, yang berada pada jalur Khatulistiwa berdasarkan dua tahun kempen pengukuran perambatan jalur- K_u yang merangkumi peralatan Penerima Langsung Penyiaran (DBR) dan Stesen Cuaca Automatik (AWS). Kajian ini terbahagi kepada dua bahagian. Pertama, kajian terhadap kelipan langit cerah melalui klasifikasi dan analisis dari isyarat siri masa penyiaran satelit dan seterusnya dibandingkan dengan keputusan model statistik kelipan sedia ada. Satu kaedah pemprosesan baru telah dicadangkan bagi menambahbaik penganggaran kelipan kering, khususnya tingkahlaku diurnal bagi varians kelipan. Kedua, kajian ini menumpukan kepada kajian terhadap hubungan antara kelipan basah dan gangguan hujan menggunakan pengukuran, dan tumpuan kepada fungsi ketumpatan kebarangkalian (PDF) bagi parameter kelipan berbeza. Ianya menunjukkan bahawa intensiti kelipan basah meningkat dengan kadar pengecilan hujan. Maka, hubungan antara keduanya boleh difrasakan kepada linear atau hukum kuasi. PDF bagi keamatan kelipan basah, disesuaikan dengan tahap gangguan hujan taburan lognormal yang membawa kepada kaedah pemilihan bagi menentukan hubungan antara PDF bersyarat dan pengecilan hujan. Akhir sekali, variasi bermusim dan diurnal bagi kelipan basah juga dikaji. Didapati bahawa pemudaran kelipan basah adalah kerap berlaku pada petang dari jam 3 hingga 6 petang. Manakala, intensiti kelipan basah bagi peralihan musim menunjukkan kadar perubahan gangguan hujan yang tinggi. Keputusan kajian memberikan operator dan jurutera komunikasi radio maklumat kritikal mengenai ayunan varians kelipan troposfera bagi isyarat satelit pada selang masa sepanjang hari biasa dengan mengambil kira ciri-ciri meteorologi tempatan.

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LIST OF SYMBOLS

A	-	Attenuation
D_a	-	Antenna diameter
D_{eff}	-	Effective antenna diameter
e_S	-	Saturated water vapor pressure
f	-	Frequency
G	-	Antenna aperture averaging factor
H	-	Relative humidity
h	-	Height of the turbulent layer
L	-	Effective path length
N_{wet}	-	Wet reflectivity
p	-	Time percentage
$p(x)$	-	Probability density function
R	-	Effective radius of circular antenna
T	-	Surface temperature
x	-	Scintillation amplitude
σ_x	-	Scintillation intensity
θ	-	Elevation angle
η	-	Antenna efficiency
σ_{ref}	-	Refractivity-dependent term
η_f	-	Frequency dependent term
η_θ	-	Elevation angle dependent term
η_D	-	Antenna aperture term
λ	-	Wavelength
η_A	-	Fade percentage factors
η_E	-	Enhancement percentage factors
σ_x^2	-	Scintillation variance
$\Gamma(\,)$	-	Gamma function

LIST OF ABBREVIATIONS

Astro	-	All-Asian Satellite Television and Radio Operator
AWS	-	Automatic Weather Station
BPF	-	Band Pass Filter
CCDF	-	Complementary Cumulative Distribution Function
DBR	-	Direct Broadcast Receiver
ECMWF	-	European Centre for Medium-Range Weather Forecasts
EIRP	-	Effective Isotropically Radiated Power
HPF	-	High Pass Filter
IF	-	Intermediate Frequency
ITALSAT	-	Italian Satellite
ITU-R	-	International Telecommunication Union, Radio communication sector
LNB	-	Low Noise Block down Converter
LPF	-	Low Pass Filter
MEASAT	-	Malaysia East Asia Satellite
NE	-	Northeast
PDF	-	Probability Density Function
QoS	-	Quality of Service
RMSE	-	Root Mean Square Error
SatCom	-	Satellite Communication
SW	-	Southwest
Syracuse	-	Satellite-based radio communication system
UTHM	-	Universiti Tun Hussein Onn Malaysia
UTM	-	Universiti Teknologi Malaysia

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Satellite communication systems operating at low fade margins with a frequency above 10 GHz are generally exposed to the turbulent fluctuations of the refractive index, which cause random fading and enhancement of the received signal. This propagation mechanism, which affects the received signal level, is known as (tropospheric scintillation). The rapid fluctuation of the received signal amplitude can range up to several decibels. The intensity of the fluctuations in the refractive index can produce significant impairments, as the margin of the communications systems decreases. This is common in places having frequencies above 10 GHz, particularly in tropical and equatorial regions like Malaysia, which has uniform temperature, high humidity and heavy rainfall. It is therefore of key importance to investigate the characteristics of this phenomenon for the optimization of channel capacity (Garcia-del-Pino, Riera et al. 2012).

Generally, the fluctuation of the electromagnetic wave signal passing through the atmospheric medium is primarily due to turbulent irregularities in temperature, humidity and pressure (Van de Kamp, Riva et al. 1999). The impact of the behaviour or a feature of those parameters on scintillation is of key importance, particularly in the equatorial region that is often dominated by local climatic peculiarities (Rahim, Islam et al. 2013).

Nevertheless, numerous propagation measurement campaigns have been actively carried out to characterise the behaviour of clear sky scintillation experienced by satellite radio links. Unfortunately, most of the concentrated studies are only based on the measurement database in temperate regions (Karasawa, Yamada et al. 1988, Ortgies 1993, Otung 1996, Marzano and D'Auria 1998, ITU-R 2015) which have different climate compared with tropical and equatorial regions. The findings or model proposed for the temperate region certainly do not reflect the scintillation structure in equatorial and tropical areas. Furthermore, there is very limited number of investigations clear sky scintillation carried out regarding equatorial and tropical region (Akhondi and Ghorbani 2005, Mandeep, Yee et al. 2011, Abdul Rahim, Islam et al. 2012, Rahim, Islam et al. 2013, Yee, Mandeep et al. 2013, Chen and Singh 2014). In relation to that, only a few propagation studies of wet scintillation have been carried in the past few decades regarding equatorial and tropical region (Suryana, Utoro et al. 2005, Maitra and Adhikari 2010, Adhikari and Maitra 2011).

As a consequence, the statistics of clear-sky scintillation in the equatorial zone remains an interesting topic for investigation. Therefore, this study intends to explore those statistics in an equatorial site by exploiting the propagation measurements carried out at Universiti Teknologi Malaysia (UTM) in Johor Bahru, Malaysia. This work will be a helping hand in providing knowledge for characterising wet scintillation, by investigating the relationship between wet scintillation and rain attenuation.

1.2 Problem Statement

As briefly mentioned above, characteristics of the scintillation effect play an important role in the optimization of the channel capacity for satellite communication system. In this respect, several problem statements that need to be addressed and resolved in this thesis work are summarized as below:

The improvement of clear sky scintillation model specifically for heavy rain region is necessary. This is due to the typically lower prediction accuracy of the models currently available (with respect to temperate region). Several studies have been concentrated to predict clear-sky tropospheric scintillation, in particular using diurnal behaviour related to the hour of the day. Unfortunately, most of the models developed are only based on the measurement database in temperate regions (Karasawa, Yamada et al. 1988, Ortgies 1993, Otung 1996, Marzano and D'Auria 1998, ITU-R 2015). Similar studies that focus on this aspect in heavy rain regions are still very rare, with the exception of studies by (Mandeep, Yee et al. 2011, Abdul Rahim, Islam et al. 2012, Chen and Singh 2014). Therefore, it is worthwhile to further investigate the diurnal variations of scintillation in this heavy rain region, as well as their relationship with meteorological parameters, such as temperature, humidity and atmospheric refractive index.

In addition to the specific diurnal scintillation model on clear sky condition, the estimation of the amount of signal drop due to the concurrent occurrence of the rain attenuation and wet scintillations is significant (Filip and Vilar 1990). This is prominent, especially in tropical and equatorial regions where convective rain is most frequent, although there have been some studies to understand and estimate the relationship between wet scintillation and rain attenuation in the temperate region (Matricciani, Mauri et al. 1996, Matricciani, Mauri et al. 1997, Matricciani and Riva 2008, Garcia-del-Pino, Riera et al. 2012). However, there are only limited experimental results of wet scintillation in equatorial and tropical regions (De, Chakraborty et al. , Suryana, Utoro et al. 2005, Maitra and Adhikari 2010, Adhikari and Maitra 2011). Therefore, it is worthwhile to further investigate and estimate the natural characteristics of wet scintillation in Malaysia with respect to the experimental database available and relationships between wet scintillation and rain attenuation models from the established literature.

Besides the estimation of wet scintillation characteristics, seasonal and diurnal variations of wet scintillation also provide good insight in the design and implementation of fade margin. However, only a few researchers have performed analyses on seasonal and diurnal variation of wet scintillation in tropical and equatorial regions (Dao, Md Rafiqul et al. 2013, Mandeep and Islam 2014).

Therefore, the aim of this study is to investigate and provide detailed analysis of seasonal and diurnal variations of wet scintillation in an equatorial site.

In addition, scintillation distribution is one of the important parameters in analysing scintillation effects. Most studies show that normal and lognormal distributions of clear sky scintillation are suitable in accordance to scintillation amplitude and scintillation intensity, respectively (Moulsley and Vilar 1982, Ortgies 1985). although, their physical mechanisms are slightly different between clear sky scintillation and wet scintillation. Nevertheless, the statistical properties of wet scintillation can be derived from similar distributions used for clear sky scintillation, only differ by considering explicitly the rain attenuation level (Mertens and Vanhoenacker-Janvier 2001, Garcia-del-Pino, Riera et al. 2012). Based on this consideration, it is required to further investigate to derive probability density functions (PDFs) of wet scintillation using an integration of conditional PDFs and rain attenuation in equatorial regions.

1.3 Research Objectives

The objectives of this research are:

i. To propose an improved diurnal clear sky scintillation model for satellite communication application in equatorial Malaysia.
ii. To obtain the relationship between wet scintillation and rain attenuation, as well as statistically characterize the probability density function (PDF) of wet scintillation in equatorial Johor Bahru.
iii. To analyse diurnal and seasonal characteristics of wet scintillation for the K_u-band earth-space propagation link in equatorial Malaysia.

1.4 Scope of Work

The scope of this research work consists of two parts, scintillation analysis under clear-sky conditions and the analysis of the effect of rain attenuation on scintillation.

Firstly, the studies in this thesis work focus on several frequencies in Ku, Ka-band, such as 11.075 GHz (MEASAT-1 satellite), 12.2 GHz (MEASAT-3 satellite) and 20.245 GHz (Syracuse-3A satellite using beacon receiver). The locations of the analyses in this work are restricted only to the two locations in southern Peninsula Malaysia namely Skudai (UTM) (for MEASAT satellite and satellite beacon receiver) and Batu Pahat (UTHM) (for satellite beacon receiver only).

The research begins with analyzing the clear sky scintillation characteristics based on one year of measurements data collected throughout the year 2001 in UTM, followed by a comparison of clear sky scintillation using the current existing prediction models. Then, seasonal and diurnal variations of clear sky scintillation have been investigated based on one year of measurements data collected throughout the year 2001 in UTM. Consequently, current diurnal clear sky scintillation models for the satellite communication has been improved, with considerations of effects of temperature, humidity, and wet refractivity in this hot and humid region.

The second part of this work is to evaluate the relationship between rain attenuation and wet scintillation characteristics based on one year of measurements data collected throughout the year 2013 in this heavy rain region. Thus, seasonal and diurnal variations of wet scintillation and rain attenuation in equatorial Malaysia have been analyzed based on one year of attenuation data recorded throughout the year 2013. Consequently, the probability density functions (PDFs) of wet scintillation intensity as a function of rain attenuation have been investigated. Whereas, a new method using an integration of distribution input parameters and rain attenuation has been provided in equatorial regions.

In additional, the characteristic of clear sky scintillation and wet scintillation have been analyzed for one-month measurement data, collected from satellite beacon receiver in 2015 at UTM and UTHM locations.

1.5 Research Contributions

Current and future satellite communication systems are operating at any frequency above 10 GHz in tropical and equatorial regions, and frequently suffer from Quality of Service (QoS) due to tropospheric scintillation. In order to establish reliable Earth-space communication services in these equatorial regions, accurate propagation channel models with respect to the local characteristic of tropospheric scintillation are required. Thus, the present work focuses mainly on the characterization of local tropospheric scintillation, specifically devoted to clear sky scintillation and wet scintillation behavior. The main contributions are as follows:

i. The first contribution is proposal of two enhance diurnal scintillation prediction models, named as Temperature and Humidity ($T \& H$) and Temperature and Wet refractivity ($T \& N_{wet}$). These models are capable of predicting the clear sky scintillation variance on an hourly basis from the input of link parameters (i.e. frequency, elevation angle and antenna diameter), and meteorological data (i.e. temperature, relative humidity).

ii. The second contribution focuses on the statistical analysis of wet scintillation characteristics, particularly on the relationships between rain attenuation and scintillation intensity, which are directly derived from the local measurement data in the heavy rain region.

iii. The third contribution concerns the statistical of probability density functions (PDFs) of wet scintillation intensity as a function of local measured rain attenuation in equatorial Malaysia. New relationships are to be made between conditional PDFs and rain attenuation.

iv. The fourth contribution focuses on the analysis of seasonal and diurnal variations of wet scintillation and rain attenuation in equatorial Johor Bahru.

These characteristics will help to provide essential information to the design and implementation of fade margin.

1.6 Thesis Outline

This thesis contains six chapters. Chapter 1 provides an overview of the research background on the topic of interest and identifies the problem statements that need to be resolved. This section outlines the research objectives, scope of work and highlights the contributions of this work.

Chapter 2 begins by providing the climatology characteristics of the equatorial region, particularly equatorial Malaysia. These characteristics include seasonal and diurnal variations of tropospheric scintillation in this heavy rain region. Next, prediction models for estimating clear sky scintillation from meteorological parameters are reviewed. Review is continued with explanation on the specifications of filters to separate wet scintillation and rain attenuation, followed by the characteristics of wet scintillation and the relationship between wet scintillation and rain attenuation. A review on scintillation amplitude distribution and scintillation intensity distribution is also included. Finally is brief introduction to MEASAT and Syracuse satellites communication system.

Chapter 3 focuses on the methodology and concept used in this work. It begins by providing an overview of the methodology of this work; flow chart is included for ease of understanding. Three sets of equipment, Direct Broadcast Receiver (DBR), satellite beacon receiver and Automatic Weather Station (AWS) are described. Discussion continues by description on scintillation signals fluctuation processing, followed by a detailed rain attenuation data processing description. In addition, necessary input parameters for the diurnal behaviour of scintillation variance model are provided, and some key concepts of $(T\&H)$ and $(T\&N_{wet})$ models are briefly discussed. Finally, specific information is provided for the relationship between wet scintillation and rain attenuation.

Chapter 4, which provides the results of scintillation analysis in a K_u and K_a band under clear-sky conditions, is divided into three parts. Firstly is discussion on the evaluation of the statistical distribution of scintillation parameters collected in Universiti Teknologi Malaysia (UTM) Johor, Malaysia. Secondly is discussion on the statistical analysis of diurnal variations of scintillation for K_u band in a heavy rainfall region. This is followed by analyses on the performances of surface temperature and humidity ($T\&H$), and proposal of the use of surface temperature and wet refractivity ($T\&N_{wet}$) prediction models to estimate hourly scintillation variance in an equatorial region. Lastly is discussion on the analysis of clear sky scintillation for K_a-band using low elevation angle, obtained from the measurement campaign carried out at Universiti Teknologi Malaysia (UTM), Johor Bahru, and Universiti Tun Hussein Onn Malaysia (UTHM), BatuPahat, Malaysia.

Chapter 5 presents the analysis on the effect of rain attenuation on scintillation. In relation to this, statistical analysis of rainfall rate database from Automatic Weather Station (AWS) located in UniversitiTeknologi Malaysia (UTM) is presented. In addition, the effects of rain attenuation on the wet scintillation analysis, with seasonal and diurnal variations for both phenomena, are discussed. Finally, the statistical analyses of wet scintillation using K_a-band beacon satellite are presented.

Chapter 6 summarises the conclusions obtained from the results, followed by some recommendations for future work.

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