ATTENUATION MODEL FOR FREE SPACE OPTICS USING LATENCY MEASUREMENTS

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DEDICATIONS

To the memory of my father,

To my mother,

To my wife; Rahmah

To my children; Faisal, Arwa, Asad, Mohammad and Zainab

To my family

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Thanks to Allah for every thing I have achieved and thanks to Allah for every thing I have tried but could not achieve.

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ABSTRACT

This study proposes a prediction model for the calculation of rain attenuation for optical wavelengths. Based on latency measurements via 850 nm free space optics transceiver, exponential drop size distribution is derived by method of inference from knowledge of attenuation at the highest rain rate. As an alternative to the inferred exponential distribution, a lognormal drop size distribution that suits the observed measurements is derived from published distribution models. Both distributions are found to be consistent with measured data. Furthermore, a formula relating latency to rain rate is derived by nonlinear regression analysis. The derived formula gives a very good correlation of 0.971 with the measured data. Regression analysis is also performed to attenuation data obtained by graphically converting measured latency data to attenuation. The results are compared to the proposed attenuation model and found to be identical. The attenuation model, using both drop size distributions, is then compared to well established models in the literature and is found to be mathematically consistent and in good agreement with these models and their measured data. While the established models are for rain rates of up to 100 mm/hr, the proposed model with a simpler derived power law is for rain rates up to 250 mm/hr. The power law, $\gamma(R) = 1.118R^{0.614}$, is derived for economy of calculation and ease of use.

ABSTRAK

Kajian ini bertujuan untuk mendapatkan model anggaran bagi hujan pada perambatan gelombang optik. Berdasarkan pengukuran masa lengah, satu pemancar-penerima optik yang menggunakan panjang gelombang 850 nm digunakan. Hasil daripada data yang diperolehi, agihan saiz titisan diterbitkan secara eksponen menggunakan kaedah taabiran berpandukan kombinasi data yang diperolehi pada kadar hujan tertinggi. Sebagai alternatif lain untuk mendapatkan keputusan yang sama, agihan saiz titisan lognormal dipadankan dengan rujukan model yang telah diterbitkan. Kedua-dua agihan ini digunakan untuk memantapkan hujah bagi membuktikan data yang diperolehi adalah benar. Tambahan pula, dengan menggunakan penganalisaan regrasi tak lelurus, satu persamaan yang menghubungkan kadar hujan lengah bingkisan dihasilkan. Analisis regrasi kemudiannya digunakan pada data perambatan yang diperolehi daripada graf pengukuran masa lengah yang ditukarkan kepada graf perambatan. Keputusan ini kemudiannya dibandingkan dengan model yang diperkenalkan, dan hasilnya didapati sama. Model perambatan yang diperkenalkan kemudiannya dibanding dengan model perambatan yang telah diterima pakai dan didapati ia bersesuaian secara matematik dan aritmatik. Model yang diterima pakai hanya sesuai pada kadar 100 mm/hr menggunakan formula biasa manakala model yang diperkenalkan boleh mencapai kadar sehingga 250 mm/hr dengan penggunaan formula yang lebih mudah. Dengan hanya menggunakan formula $\gamma(R) = 1.118R^{0.614}$, anggaran perambatan boleh dikira dengan mudah dan ekonomik.

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LIST OF SYMBOLS

Symbol	Description	Chapter
A	Wave amplitude	3
a	Radius	5, 7
$B(\mathbf{r})$	Covariance function	2-4
C	Structure constant	2-4
$C_{a,s}$	Cross section	5, 7
c	Speed of light	2-4
D	Aperture diameter	4-7
D_n	Structure function	2-4
D	Diameter of drops	5, 7
E	Electric field	2-4
F	2D Spectral density	2-4
f	Frequency	2-4
G	Green function	3, 4
H	Magnetic field	3
I	Irradiance/Intensity	All
J	Bessel function	All
k	Free space wave number	All
L	Length/Distance	All
l_0	Inner scale of turbulence	2-4
L_0	Outer scale of turbulence	2-4

m	Refractive index	5, 7
N	Drop size distribution	5, 7
$N_{0,T}$	DSD parameter	5,7
n	Refractive index	All
P	Power	6, 7
p	Pressure	1-4
Q_{ext}	Extinction efficiency factor	5, 7
R	Rain rates	5, 7
$\mathbf{r}$	3D vector (x, y, z)	1-4
S	Phase of the wave	2-4
T	Temperature K	2-4
$T(\ )$	Transmittance	5
u	Velocity	1, 2
U	Complex amplitude	2-4
V	Visibility	5
v	Viscosity	2
v	Velocity	5, 7
W	Beam spot size	3, 4
α	$\left[\left(2/kW_0^2\right)+j/F_0\right]$	3, 4
α	$=(2\pi a/\lambda)$	5, 7
Γ	Correlation function	2-4
Γ	Gamma function	5
δ	Dirac delta function	3, 4
ε	Permittivity	2-4
H_n	Hankel function	5
Θ	Gaussian beam parameter	2-4

θ	Divergence angle	7
κ	Spatial wavenumber	2-4
λ	Wavelength	All
Λ	Gaussian beam parameter	2-4
Λ	DSD parameter	5, 7
μ	Mean	5,7
ρ	Density	1
ρ	Transverse displacement	2-4
σ	Standard deviation	5, 7
σ_χ^2	Log-amplitude variance	3, 4
σ_I^2	Variance of intensity	3, 4
γ	Extinction coefficient	5, 7
Φ	Power spectral density	2-4
χ	Log-amplitude	3, 4
ψ	$= \chi + jS$	3, 4
ω	Angular frequency	2-4
μ	Coefficient of viscosity	1 pg 4
τ	Time difference	2 pg 21

Trying to follow the universal notations used in the literature, led to some symbols being repeated due to the two division of theories treating waves in turbulent and turbid media. However, to avoid confusion, this list indicates the chapter number where each symbol is used.

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CHAPTER 1

INTRODUCTION

It is hard to imagine a subject more complex, and yet more useful, than the study of the propagation of light in the atmosphere [1]. Atmospheric optics is one of the most interesting, literature rich, and mathematical rigorous subject. Yet, its progress, hindered by atmospheric effects, troubles the most devoted scientists and engineers of the field. The subject's history starts with astronomy and is a matter for a wide variety of fields such as optical communications and remote sensing among others. The interest has accelerated with the invention of the laser in 1960 to a prevalent level only to be overwhelmed by the optical fiber dominance in the 1970s. Nevertheless, development in space technology applications, the need for a fiber-like mobile capacity, and the recognition of a potential in free space optics have brought the pace of interest even higher.

Some of the advantages of free space optics include low cost fiber-like quality, reliability, capacity, mobility, and fast installation [2]. Furthermore, the majority of R&D effort today surrounds the use of point-to-point free space optical communications links [3].

1.1 Atmospheric Turbulence

The small temperature variations, on the order of $0.1-1C°$, that are related to the sun's heating of the atmosphere and turbulent motion of the air cause perturbations in the refractive index of the atmosphere, on the order 10^{-6}, and hence changes in the velocity of optical waves passing through it. Although the variations of the refractive index from its mean is very small, the cumulative effect on a light-wave propagating through a large refractive index inhomogeneities can be very significant. Thus the intervening medium affects the properties of the received signal by distorting the intensity (scintillations), phase, angle-of-arrival, and displacing the light beam.

The aforementioned effects on light waves are caused by an intervening medium that is turbulent. A second category of effects are those caused by a turbid medium that is composed of large numbers of discrete scatters or aerosol particles (e.g., rain, fog, or dust), which give rise to strong scattering effects. In such a medium refractive index variations are large, on the order of unity, and sharp due to the discrete particles. Consequently, the scattering is strong and in all directions (including backscattering) and the average beam intensity is strongly attenuated.

The random fluctuations experienced by the amplitude and phase of the electric field of an optical wave traversing the atmosphere have been described by several mathematically rigorous theories based upon solving the wave equation for the electric field of the wave or for various moments of the field. Unfortunately, these mathematically rigorous approaches in most cases have led to tractable analytic results supported by experimental data only in certain asymptotic regimes [4].

One of the early attempts to solve the wave equation was based on the geometric optics approximation, which ignores diffraction effects. Thus it is a simple method, but is generally limited to propagation paths, in which $L \ll l_0^2/\lambda$, where l_0 is the inner scale of turbulence. This is then followed by solutions based on perturbation theories widely known as the Born approximation and Rytov approximation that takes into account diffraction effects, important in the analysis of irradiance fluctuations sensitive to small scale sizes on the order of the Fresnel zone $\sqrt{\lambda L}$.

The latter of the aforementioned methods also called the method of smooth perturbations treats the perturbation terms as multiplicative to the unperturbed field and the Born approximation or method of small perturbation assumes additive perturbations. Both of these perturbation theories are restricted to weak fluctuation conditions that normally limit the propagation path length to a few hundred meters [5, 6, 7].

Furthermore, the method of small perturbations leads to an expression for the probability density function of the irradiance as a modified Rice-Nakagami distribution [8]. This is considered not a suitable model when compared with experimental data except, possibly, under extremely weak fluctuations [9]. On the other hand the Rytov approximation method leads to a lognormal distribution that works fine in the weak fluctuation regimes but experimentally found to be inappropriate in strong fluctuations regimes [4, 10].

The Rytov method came into existence due to the inadequacy of the Born approximation and its predecessor geometrical optics. It turned out however that the Rytov method is also inadequate except for path lengths of few hundred meters or so. This is considered logic from the view point that since a perturbation approach is used; the results are to be valid only if the perturbations are small. Nonetheless, the Rytov method is the standard method used today under weak fluctuations conditions [4].

1.1.1 History

The problem of homogeneous turbulence was pioneered by G. I. Taylor (1935) introducing the correlation between the velocities at two points as one of the quantities needed to describe turbulence [11]. After Taylor has furnished the literature with his theory of turbulence by introducing the assumptions of statistically homogeneous and isotropic turbulence among others, various workers have contributed to the development of the theory of turbulence using Taylor's concept like Von Kármán and other workers and the use of the Navier-Stokes equation – the equation governing the variation of the spatial distribution of the velocity with time given by

$$\frac{\partial}{\partial t}\mathbf{u}(\mathbf{r},t) = -\mathbf{u}\cdot\nabla\mathbf{u} - \frac{1}{\rho}\nabla p + v\nabla^2\mathbf{u} \tag{1.2}$$

Where p represents pressure, $\mathbf{u}$ is the vector velocity of the turbulent motion at a position in the field specified by the vector coordinate $\mathbf{r}$, ρ is the density, and $v = \mu/\rho$ is the kinematics viscosity.

Kolmogorov (1941) then formulated his theory which is now the starting-point for many researchers. The hypothesis of small-scale components of the turbulence are approximately statistically equilibrium was also brought about independently at the same time by A. Obukhoff (1941), by L. Onsager (1945), and by C. F. von Weizsäcker (1948), [11].

Active research in the effects of the atmosphere on light waves are traced to 1950s, where a number of papers appeared about twinkling (scintillation) and quivering (irregular displacements of the image of a star in random directions) of stellar images in telescopes, [12].

Effects of atmospheric turbulence on sound waves started as early as 1941, [1]. Studies first used geometrical optics method, but the limitation on this technique of restricting the path length quite severely initiated the transition to the wave optics or diffraction theory techniques.

A revolution came with the invention of the laser in 1960 by Theodore Maiman and the Hughes Aircraft Co. [13]. This allowed the use of coherent light, bringing the possibilities of wave optics, introduced through Huygens' ideas and Fresnel mathematical models, to their full potential. However the optimism about its use as an optical communication tool was struck by the limitation and system degrades encountered due to the atmospheric effects.

Therefore, physicists and engineers alike carried on their shoulders the heavy task of first revealing the magnitude of the difficulties with analytical models and then try to search for a solution to get the focus back on optics again. This task was greatly achieved by the monographs of Russian scientists Tatarski [5] and Chernov [6] analyzing the effects of atmospheric turbulence on optical frequencies by suggesting the Rytov approximation as a best model.

Before 1967 almost all of the theory was centered on plane-wave propagation for mathematical simplicity. The first comprehensive paper on beam-wave propagation was published in 1967 [8].

Experimental results for long distance wave propagation in the early 1960s by Russian scientists revealed that the intensity fluctuations predicted by use of Rytov's method does not agree with experimental result. It was found that the fluctuations reach a peak after which it saturates and no more increase is observed. Thus, an extensive effort was devoted in the development of new theories that better model optical wave propagation in the atmosphere.

This resulted in the categorization of two regimes, namely the weak fluctuation regime where Rytov's approximation is valid and the strong fluctuation regime over which new models were sought. This resulted in few models such as the Extended Fresnel-Huygens method and the Markov approximation among others.

Although the new models contributed to a better understanding of the atmospheric effects and its characterizations, these effects on optical wave propagations are still permanent hindering the optimal use of optical waves through the atmosphere.

1.2 Turbid atmosphere effects

On the other hand, molecular and particle scattering add to the problem of optical wave communications. The main gas absorbent at optical wave length is water vapor. Fortunately, the near infrared wavelengths used for communications are all in optical windows were absorption is negligible.

Furthermore, particles absorption by water drops is also negligible, relatively to loss due to scattering effects, at optical wavelengths. Thus the main concern is extinction due to scattering. To this regard high attenuations are observed in dense fog, high intensity rain and clouds.

Attenuation due to above mentioned phenomena are investigated at optical wavelengths with the use of the rigorous Mie theory. Calculations of specific attenuations are performed with regard to the scattering cross section of the particle and the rain drop size distribution.

Mainly there is four drop size distributions commonly used in the literature. Marshall and Palmer exponential distribution was the earliest and is the main distribution that is still used in mid-high latitudes. Another distribution is the modified gamma distribution obtained from gamma distrigution.

Measurements have shown that the above mentioned distributions are unsuitable for characterizing precipitation at tropical regions. This could be logic due to the fact that rain in the tropical regions is of warm cloud type forming at temperatures above $0°C$ and starts as water drop whereas that of mid-high latitudes form at temperatures levels below freezing and therefore starts as ice crystals changing to its liquid form as it falls to the ground.

All investigations of drop size distribution at tropical regions recommend use of the three parameters lognormal drop size distribution. This conclusion was due to measurements carried out in Japan, Nigeria, Brazil, India, and Malaysia all confirming and recommending the use of the lognormal distribution.

Fog attenuation, on the other hand can be easily calculated by knowledge of visibility which can easily be obtained and data are available in all airports and weather centers. This visibility value will be directly used in the calculation of specific attenuation for a particular wavelength. The same is also true for haze by using the same formula.

1.3 Objective and Scope of the Research

The following research work aims at the investigation of atmospheric attenuation on free space optics communication link. A refine understanding of various effects on optical wave propagation in the free atmosphere is an essential element so as to carry the task of investigating the specific rain attenuation on free space optics communication link effectively and efficiently. Therefore an understanding of turbulence and its effects on optical wave propagation will help furnishing the ground for a better analysis of the different theories characterizing this propagation phenomenon.

Investigation of the effects of molecular and particles absorption and scattering of optical wave propagation in a turbid media is then crucial for assessing the attenuation effects of precipitation on the free space optics link. This then will bring the focus on the main objectives of this study listed as follows:

I. To measure rain attenuation on the free space optics link at $850\,nm$ optical wavelength for Malaysian weather.

II. To infer new drop size distribution parameters for the optical wavelength from attenuation measurements.

III. To derive a new power-law relation for calculations of specific attenuation for $850\,nm$ optical wavelength.

IV. To derive a mathematical relation between the measured packet's latency and rain rates.

1.4 Outline of the Thesis

Building of the thesis is carried out with the objective of providing a refine understanding of various atmospheric effects on free space optics communication link. Thus the effects of the atmosphere are divided into two categories namely turbulent effects and turbid effects.

Chapter 2 lays down the basics of turbulence and its characteristics that have major effects on wave propagation. The refractive index of the atmosphere fluctuations are discussed and analyzed. The randomness of the atmosphere and its characterization with the moments of the field is presented. The correlation and structure functions of the refractive index fluctuations are discussed. Finally, the different refractive index spectrums are given and explained.

Classical theories of wave propagation in turbulent media are presented in Chapter 3. The method of small perturbation and Rytov's method are mathematically explained and analyzed. The shortcomings of these theories are discussed. Theories for the strong fluctuations regime are also presented and compared.

Chapter 4 gives qualitative analysis of the effects of the turbulent atmosphere on optical wave propagation. Effects of intensity scintillation, beam wander, angle of arrival fluctuations, among others, are discussed and mathematical expressions are given.

Propagation of optical waves in turbid media are the subject of Chapter 5 with the effects of molecular and particles absorption and scattering reviewed. Drop size distributions for rain, fog, and haze are presented and analyzed. Effects of rain, haze, and fog on optical propagation are discussed and their attenuation's expressions are given.

The instrumentations used, set-up of equipment, and method of measurements are presented in Chapter 6. Wiring and the software used for this link are also presented.

Chapter 7 presents the results and discussion of the thesis. The achieved objectives are explained in this chapter. The new drop size distribution's parameters are derived. A new power-law relation for specific attenuation is mathematically derived. Furthermore, the relation between packet's latency and rain rates is explained and formulated by a mathematically derived equation using regression analysis.

Chapter 8 includes the final conclusion and outlook of the study.

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