

Study The Effects of Atmospheric Turbulence
on Propagation of Laser Beam

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by

Gailan Asad Kazem

Diyala university ,college of science ,physics department

gailanasad@yahoo.com

Abstract

Two theoretical methods for the calculation of turbulence attenuation to laser beam are used, the Rytov's approximation and Andrews's method. These calculations were performed for some important communication wavelengths of $0.86 \mu\text{m}$, $1.55 \mu\text{m}$, $3.50 \mu\text{m}$ and $10.6 \mu\text{m}$. The distance between the optical transmitter and receivers system of horizontal links was set to values ranging from (0 to 3000) m. We have taken into account the homogenous turbulence at low and high values for structure parameter of refractive index.

Keywords: Free space optical links, laser beam propagation in the atmosphere , turbulence attenuation .

دراسة تأثير الاضطراب الجوي على انتشار الحزمة الليزرية

كيلان اسعد كاظم

جامعة ديالى، كلية العلوم، قسم الفيزياء

الخلاصة

تم استخدام طريقتين نظريتين لحساب توهين الاضطرابات لشعاع الليزر هي تقريب ريتوف وطريقة أندروز، نفذت العمليات الحسابية لبعض الطوال الموجية المهمة في الاتصالات هي $0.86 \mu\text{m}$ ، $1.55 \mu\text{m}$ ، $3.50 \mu\text{m}$ و $10.6 \mu\text{m}$ مايكرو متر، تم تعيين المسافات بين الإرسال والاستقبال في المنظومة البصرية في الروابط الأفقية لقيم تتراوح بين (0 إلى 3000) متر. أخذنا بعين الاعتبار الاضطراب المتجانس لقيم منخفضة وعالية في مؤثر البناء لمعامل الانكسار.

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

1. Introduction

Optical wave propagation through the turbulent atmosphere is a significant topic and of high interest for science and engineering applications such as in physics, meteorology, remote sensing, astronomy, and communication applications^[1]. When a laser beam propagates through the atmosphere, its quality will be affected by turbulence. As consequences, the laser beam will have many distorted terms such as random time delay, pulse spread, beam wander, spread and scintillation^[2]. the theoretical studies is discuss the propagation laser beam either the horizontal or slant path ,and it centered on the spherical or infinite plane-wave forms^[3,4]. The temporary redistribution of the intensity known as scintillation, results from the chaotic flow changes of air and from thermal gradients within the optical path caused by the variation in air temperature and density^[5].

2- Atmospheric Turbulences Theory

Atmospheric turbulence, generated by a temperature differential between the Earth's surface and the atmosphere, causes effects on optical waves. during daytime, the Earth is hotter than the air, causing the air nearest the

ground to be hotter than that above. This negative temperature gradient causes light rays parallel to the earth to bend upwards. If the negative temperature gradient is sufficiently strong, it can result in an inverted image known as a mirage. Temperature gradients are positive during nighttime hours, resulting in downward bending of light rays^[1,2]. In addition, atmospheric turbulence disrupts the coherence of laser radiation and optical wave. Wave front distortions in the optical wave induced by atmospheric turbulence result in a broadening of the beam, random variations of the position of the beam centroid called beam wander, and redistribution of the beam energy within a cross section of the beam leading to irradiance fluctuations Atmospheric temperature variations and wind speed fluctuations create local unstable air masses, causing them eventually to break up into turbulent eddies or cells of many different scale sizes. These in homogeneities range in size from a micro scale to a macro scale, and hence, in effect form a continuum of decreasing "eddy" size^[3]. Turbulent cells can occur in the whole path length or just in the few sections Fig(1-b) ,Variance in the refraction index is characteristic for atmospheric turbulences media and its value depends on the local temperature, atmospheric pressure or particle density at specific location^[4,5].

3. Models of Atmospheric Turbulence

In the this research we can descript some important Atmospheric turbulence parameters that have directly relation on propagation of laser beam where Atmospheric turbulence containing random or nonhomogeneities medium. There are several ways of statistically expressing the characteristics of fluctuations in the refractive index field. Most important are the variance, the structure function, Statistical character of refraction index is measured as refraction index structure function(D_n)^[1,5,6]:

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

$$D_n = \begin{cases} C_n^2 \cdot r^{2/3} & \dots \dots \dots l_0 \ll r \ll L_0 \\ C_n^2 \cdot l_0^{-4/3} \cdot r^2 & \dots \dots r \ll l_0 \end{cases} \dots (1)$$

Where (C_n^2) is refractive index structure parameter [$\text{m}^{-2/3}$], The structure parameter is also called in the structure coefficient or structure constant.

also (l_0) presents inner scale of the turbulent cell measured in meter unit [m] and L_0 signifies turbulent cell outer scale measured in meter unit [m] as shown in the fig(1-a). The inner scale (l_0) is typically in the range of 1mm to 1cm, while the outer scale is in the range of 10 m to 100 m. Both the inner scale and the outer scale have an impact on wave propagation^[6]. Eddies of scale sizes much smaller than (L_0) are assumed to be statistically homogeneous and isotropic, whereas those equal to or larger than (L_0) are generally non-isotropic, and their structure is not well defined. As the turbulent eddies become smaller and reach the size of the inner scale (l_0), the relative amount of energy dissipates by viscous forces. The inner scale is typically of the order of some millimeters near the ground and will be described^[1,7]. The refractive-index structure constant (C_n^2) can be expressed in terms of the temperature structure constant C_T by^[8,9]:

$$C_n^2 = \frac{77.6P}{T^2} \left(1 + \frac{0.00753}{\lambda^2}\right) \times 10^{-6} C_T^2 \dots \dots \dots (2)$$

Where temperature $T(K^0)$, pressure $P(\text{mb})$, and wavelength λ (μm)

The values of C_T^2 and C_n^2 vary both with height and in horizontal directions, thereby mirroring the presence of inhomogeneities of the wind velocity and temperature gradients in space and time.

The atmospheric structure constant, (C_n^2), has been measured by the use of one of the following two methods^[9].

(1) Optical method (scintillometer), (2) Thermal method (micro thermometer)

The refractive-index structure parameter (C_n^2) is measured in units of $\text{meters}^{-2/3}$. Its value varies from 10^{-17} or less when the turbulence is extremely weak, and to 10^{-13} or more when the turbulence, generated near the ground in direct sunlight, is strong as in Table (1). The analysis of the fluctuating optical signal (scintillation) was performed by computing the first five statistical moments of the beam intensity. The moments were then normalized by dividing the m th moment $\langle I^m \rangle$ by the average value $\langle I \rangle$ raised to the m th power, i.e., $\langle I^m \rangle / \langle I \rangle^m$. This normalization process permits us to discern the inherent statistics of the scattering process independently of the power of the laser beam and also allows for a comparison of the statistics at different ranges^[1,4]. The variance or probability distribution of the intensity fluctuations are important for laser systems designed for laser communication

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

Systems^[4,6], the probability distribution and normalized moment are dependent on variance (σ_I^2) or relative variance of optical intensity (σ_{Ir}^2) in the detected signal. Relative variation of optical intensity (σ_{Ir}^2) can be expressed as^[6,8].

$$\sigma_{Ir}^2 = \frac{\sigma_I^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \dots \dots \dots (3)$$

Where I is optical intensity of the received signal, and $\langle \quad \rangle$ signifies mean value. when relative variance of optical intensity much less than one ($\sigma_I^2 \ll 1$) then Rytov approximation is used and the relative variation of optical intensity and refractive index structure parameter are relation by^[2,8,6]:

$$\sigma_{Ir}^2 = A \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \dots \dots \dots (4)$$

where (A) is the constant and equal 1.23 for the plane wave, and 0.5 for the spherical wave, and (k) wave number, and (L) signifies the distance between the transmitter and receiver of the optical wireless link. the variance of an electromagnetic wave is σ_x^2 variance of the log-amplitude scintillation variance and is related to relative variation of optical by^[6,7]:

$$\sigma_x^2 = \frac{1}{4} \ln\left(\frac{\sigma_{Ir}^2}{I^2} + 1\right) \dots \dots \dots (5)$$

An optical beam propagation in the earth's atmosphere often can be approximated by a plane or spherical wave. When a laser beam transmitted from a spacecraft behaves almost as a plane wave when it reaches the earth's atmosphere, and a laser beam emitted from a small aperture in the earth's atmosphere behaves as a spherical wave^[3,9].

4. The Theoretical Models for Atmospheric Turbulence

Attenuation of Laser Beam.

There are many method to determined the atmospheric turbulence attenuation of laser beam, such as following^[5,7,10]:

a-The Rytov Approximation

this method work with the idea of homogenous atmospheric transmission media, The Rytov approximation starts from the premise that an air mass behaves as a fluid, The intensity and the speed of the fluctuations (scintillation frequency) increase with wave frequency. For a low turbulence, the scintillation variance (σ_x) in [dB²] can be expressed by the relation^[6,7,10]:

$$\sigma_x^2 = 23.17 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \dots \dots \dots (6)$$

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

the relation for calculation the turbulence attenuation (α_{RY}) according to the Rytov's approximation method expressed by:

$$\alpha_{RY} = 2(23.17 C_n^2 k^{7/6} L^{11/6})^{1/5} \dots\dots (7)$$

The optical signal attenuation and atmospheric turbulences are stronger during sunny days^[6,10]. this method is not concerned with the effect of aperture averaging. The aperture averaging factor is defined as the ratio of the intensity variance for an aperture (D) to that for a point on the detector^[7]. the variance of optical intensity can cause errors in the communications channel and degrade the performance of the link. However these random fluctuations can be averaged out by increasing the size of the receiving aperture^[7,11].

b- Andrews's Method

This method is derived on the basis of a detailed mathematical analysis of the turbulence in atmospheric transmission media presented by Larry C. Andrews. the resultant expression for the theoretical mean variance of optical intensity is given as^[7]:

$$\bar{\sigma}^2(D_{RXA}) = \exp \left[\frac{0.49\beta_o^2}{(1+0.18d^2+0.56\beta_o^{12/5})^{7/5}} + \frac{0.51\beta_o^2(1+0.69\beta_o^{12/5})^{-5/6}}{1+0.9d^2+0.62d^2\beta_o^{12/5}} \right] - 1 \dots\dots (8) \text{The}$$

Parameters (d) are related with wavelength of optical laser source by the relation^[7]:

$$d = \sqrt{\frac{2\pi}{4L\lambda}} \cdot D_{RXA} \dots\dots (9)$$

while the second parameter (β) is given by the relation:

$$\beta_o^2 = 0.5 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \dots\dots (10)$$

Where (L) is the distance between transmitter and receiver and (D_{RXA})

is diameter of receiving optical lens and (β_o) which is formally the same as the Rytov relative variance of optical intensity for spherical waves.

According to this method the turbulence attenuation in dB is given by the relation^[7,10,11].

$$\alpha_{AN} = 10 \cdot \text{Log} \left| 1 - \sqrt{\bar{\sigma}_I^2(D_{RXA})} \right| \dots\dots \dots (11)$$

The two methods mentioned above work with the idea of homogenous atmospheric transmission media.

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

5. Results And Discussions

In this research the results and discussions are involving the following:

A- Calculations of Atmospheric Turbulence Attenuation(α)

We calculated turbulence attenuation using the Rytov approximation, and Andrews's method. Atmospheric windows with $0.86\ \mu\text{m}$, $1.55\ \mu\text{m}$, $3.50\ \mu\text{m}$ and $10.6\ \mu\text{m}$ wavelengths are used in the computations. Refractive index structure parameters C_n^2 were set to be $(10^{-17}, 10^{-16}, 10^{-15}, 10^{-14}$ and $10^{-13})\ \text{m}^{-2/3}$. All simulations were run in Matlab and the resultant values of the turbulence attenuation that obtain are compare with other publishers such as Lucie Dordová, Otakar Wilfert^[6,7]. The first calculation represent by fig. (2). Attenuation laser wavelength by atmospheric turbulence proceeded with the following parameters: propagation range $L = (0-3000)\ \text{m}$ and for different wavelength ($0.86\ \mu\text{m}$, $1.55\ \mu\text{m}$, $3.50\ \mu\text{m}$ and $10.6\ \mu\text{m}$) and also for Refractive index structure parameters C_n^2 (10^{-13} to 10^{-17}) $\text{m}^{-2/3}$, by the Rytov's method (RY). According to the results obtained it is clear from fig. (2) many conclusions: the attenuation laser beam by atmospheric turbulence (α in dB) are increase with increase the laser range, and they increase with increase the laser wavelength (λ) and also it see that the Refractive index structure parameters C_n^2 is effect directly on the attenuation (α) this parameter represent the atmospheric status for very weak turbulence at ($10^{-17}\ \text{m}^{-2/3}$) and very strong turbulence at ($10^{-13}\ \text{m}^{-2/3}$) which means a higher volume of atmospheric turbulence. this method is not concerned with the effect of aperture averaging.

Also by using the Andrews's method Attenuation laser wavelength by atmospheric turbulence proceeded with the same parameter as in the Rytov's method in addition to the other parameter (d) and (D_{RXA}) where (d) related with wavelength (λ) and range (L) while (D_{RXA}) is diameter of receiving optical lens its value is $10\ \text{cm}$, as shown in the fig. (3) the curves of attenuation laser beam by atmospheric turbulence (α in dB) that obtain by Andrews's method have same behavior as in the Rytov's method but if compared between of them fig. (2) and fig. (3) we will see some different in scales or values in the (α) at a given (λ) and same (C_n^2) and this appear clearly at higher volume of atmospheric turbulence mean at (C_n^2) equal to 10^{-13} , 10^{-14} , and $10^{-15}\ \text{m}^{-2/3}$ while at the lower turbulence (10^{-16} and 10^{-17}) $\text{m}^{-2/3}$ the curves of (α) in the tow figuration (2 and 3) approximately have small different or analogous because at the lower (C_n^2) the effect of turbulence is very weak, so the difference between turbulence attenuation calculated by the Rytov approximation and that calculated by the method Andrews's method is negligible in this case.

The different between in the values of attenuation laser beam by atmospheric turbulence (α in dB) in the tow figures (2 and 3) at higher volume of atmospheric turbulence are caused by that the Andrews's method take in to account the parameter of receiver's aperture (D_{RXA}) or aperture averaging fig. (3) while Rytov's method (RY) is not. The aperture averaging factor is

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

defined as the ratio of the intensity variance for aperture of optical receiver (D_{RXI}) to that for a point on the detector. In all the cases presented the highest turbulence attenuation occurs when the method of Rytov's method (RY) is used while Andrews's method gives the smallest values of this attenuation in all cases.

b-Comparison of Turbulence Attenuations

It is evident that the influence of optical source wavelength is of utmost importance. This fact is well known and it results from the equations introduced in particular presentations of the method applied for the calculation of turbulence attenuation. For each method we compare the differences between turbulence attenuations in the case of wavelengths $1.550 \mu\text{m}$, and $3.50 \mu\text{m}$ when the refractive index structure (C_n^2) has value $10^{-17} \text{ m}^{-2/3}$, $10^{-16} \text{ m}^{-2/3}$, $10^{-15} \text{ m}^{-2/3}$, $10^{-14} \text{ m}^{-2/3}$ and $10^{-13} \text{ m}^{-2/3}$, and the distance between the optical transmitter and receiver is from 0 m to 3000 m. The difference can be evaluated mathematically by the following equation^[7,10]:

$$\Delta\alpha = \alpha(1.55 \mu\text{m}) - \alpha(3.50 \mu\text{m}) \dots\dots\dots (12)$$

where $\alpha(1.55 \mu\text{m})$ signifies the calculated turbulence attenuation when the wavelength $1.55 \mu\text{m}$ is considered, and $\alpha(3.50 \mu\text{m})$ represents the same parameter for calculations with the wavelength $3.50 \mu\text{m}$. these wavelengths are very important for many purpose as in communication system, therefore it is important to do a comparison between them. the comparisons were of course made for calculations made by the Rytov approximation (Fig.4-a), and Andrews's method (Fig. 4-b). Particular characteristics for different refractive index structure parameters are distinguished by different colors as well as by a different line style. Calculating according to the Rytov approximation (Fig.4-a) we obtain for $C_n^2 = 10^{-16} \text{ m}^{-2/3}$ a difference between the characteristics ($1.55 \mu\text{m}$) and for ($3.50 \mu\text{m}$) which is under 3.45 dB, for $C_n^2 = 10^{-15} \text{ m}^{-2/3}$ the difference is a little higher than 10 dB. In atmospheric transmission media with a high volume of atmospheric turbulence with $C_n^2 = 10^{-14} \text{ m}^{-2/3}$ the differences in turbulence attenuation reach as much as 34.5 dB for an optical path length of 3000 m.

Considering the resultant difference between the turbulence attenuations ($\Delta\alpha$) given by Andrews's method (Fig.4-b) we can say that this difference is unimportant due to resultant values being lower than (3 dB) even in the case of high turbulences and at weak turbulences the difference is less than (0.2 dB) for the distance between the optical transmitter and receiver increasing up to 3000 m. according to the calculations by the tow method the wavelength $3.5 \mu\text{m}$ is of greater advantage than the wavelength $1.55 \mu\text{m}$.

Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

6. Conclusion

In all method applied for the calculation of turbulence attenuation It is found that the optical laser beam in the turbulent atmospheric transmission medium using the (10.6 μ m) wavelength is less attenuated than when using the (0.86 μ m) wavelength. the result of Andrews's method is the lowest possible turbulence attenuation. On the other hand, the method of Rytov approximation gives the worst case of turbulence attenuation as the result, and it is not concerned with the effect of aperture averaging. In the case of calculating turbulence attenuation by Andrews's method we find that the difference between the attenuations of (1.5 μ m) and (3.5 μ m) wavelengths is minimal, While the method of Rytov approximation is used, the calculated difference is very pronounced, especially for a higher volume of atmospheric turbulence. Considering high atmospheric turbulences and an optical wireless link with a range of 3000 m, we have to take into account the fact that the difference between the minimal and the maximal turbulence attenuation can be as much as 35 dB. This can be a problem in free space optical links operating in areas with a higher or unstable volume of atmospheric turbulences.

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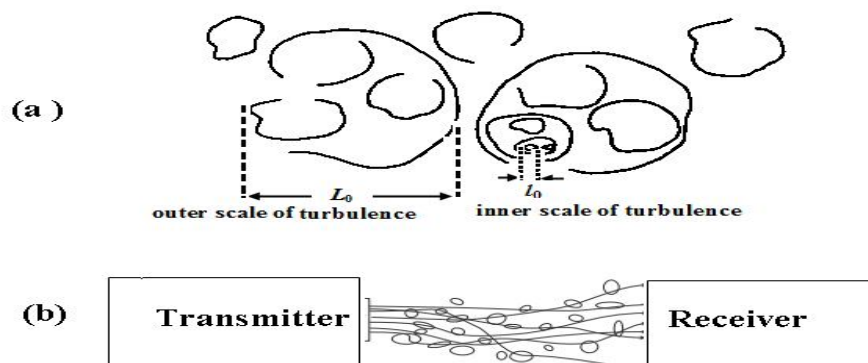
Study The Effects of Atmospheric Turbulence
on Propagation of Laser Beam

Gailan Asad Kazem

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Table (1)Refractive index structure parameter influence on the atmosphere^[1,7,6]

In (meter) ^{-2/3} C_n^2	Atmospheric Turbulence descriptions
10^{-17}	Very weak
10^{-16}	Weak
10^{-15}	Mean
10^{-14}	Strong
10^{-13}	Very strong

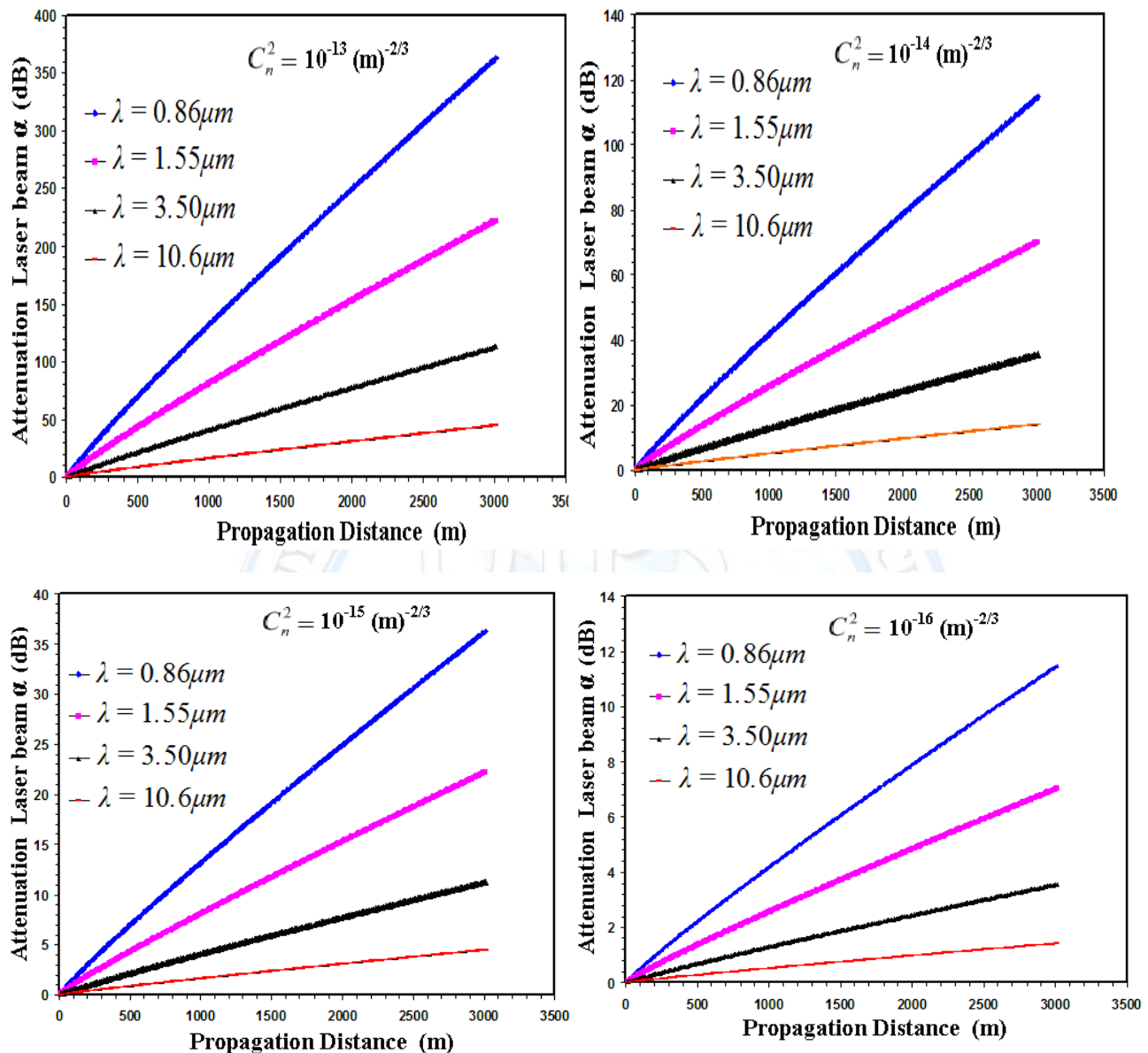


Fig(1)a-Turbulent eddies showing outer and inner scales^[1,7]

b-Atmospheric transmission media with turbulent cells^[6,7].

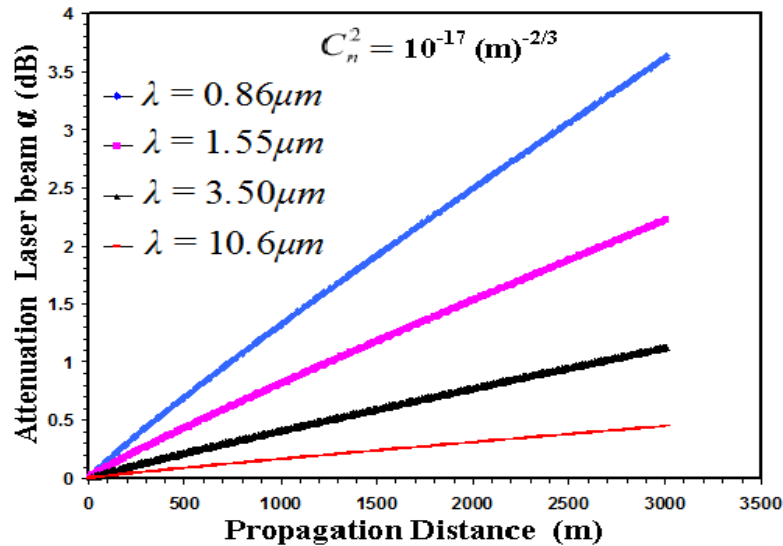
Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

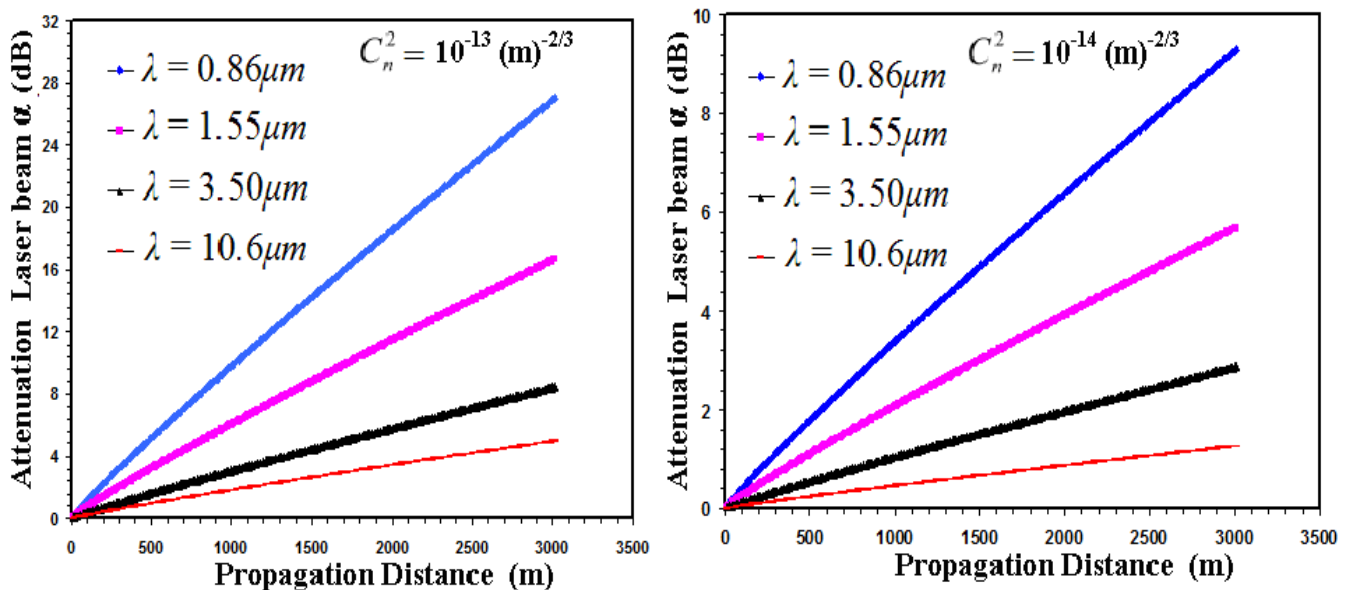


Study The Effects of Atmospheric Turbulence on Propagation of Laser Beam

Gailan Asad Kazem

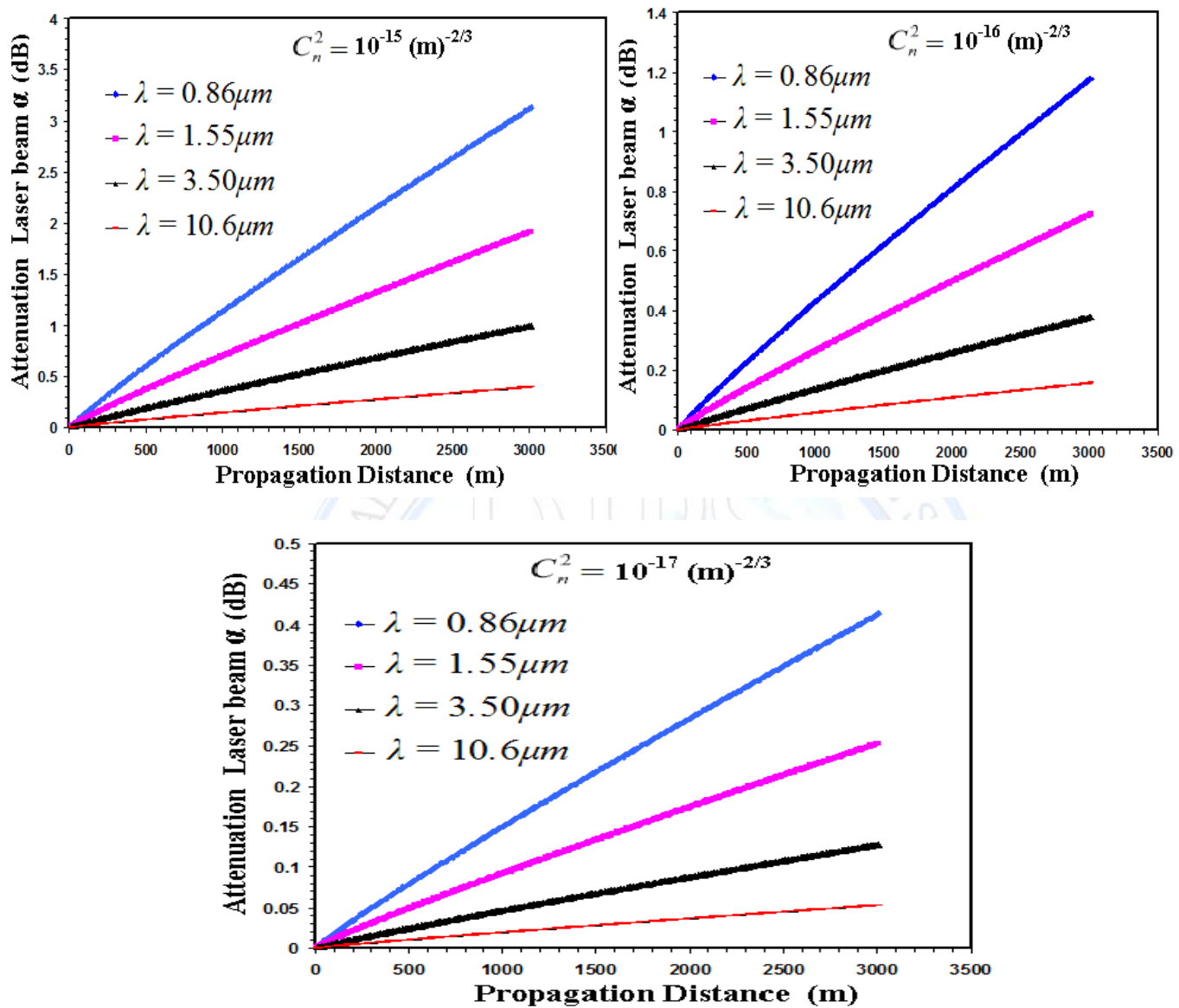


Fig(2) Attenuation laser beam by atmospheric turbulence as a function of propagation range for different wavelength, by Rytov's method (RY).



**Study The Effects of Atmospheric Turbulence
on Propagation of Laser Beam**

Gailan Asad Kazem



Fig(3) Attenuation laser beam by atmospheric turbulence as a function of propagation range for different wavelength ,by Andrews's method (AN).

Study The Effects of Atmospheric Turbulence
on Propagation of Laser Beam

Gailan Asad Kazem

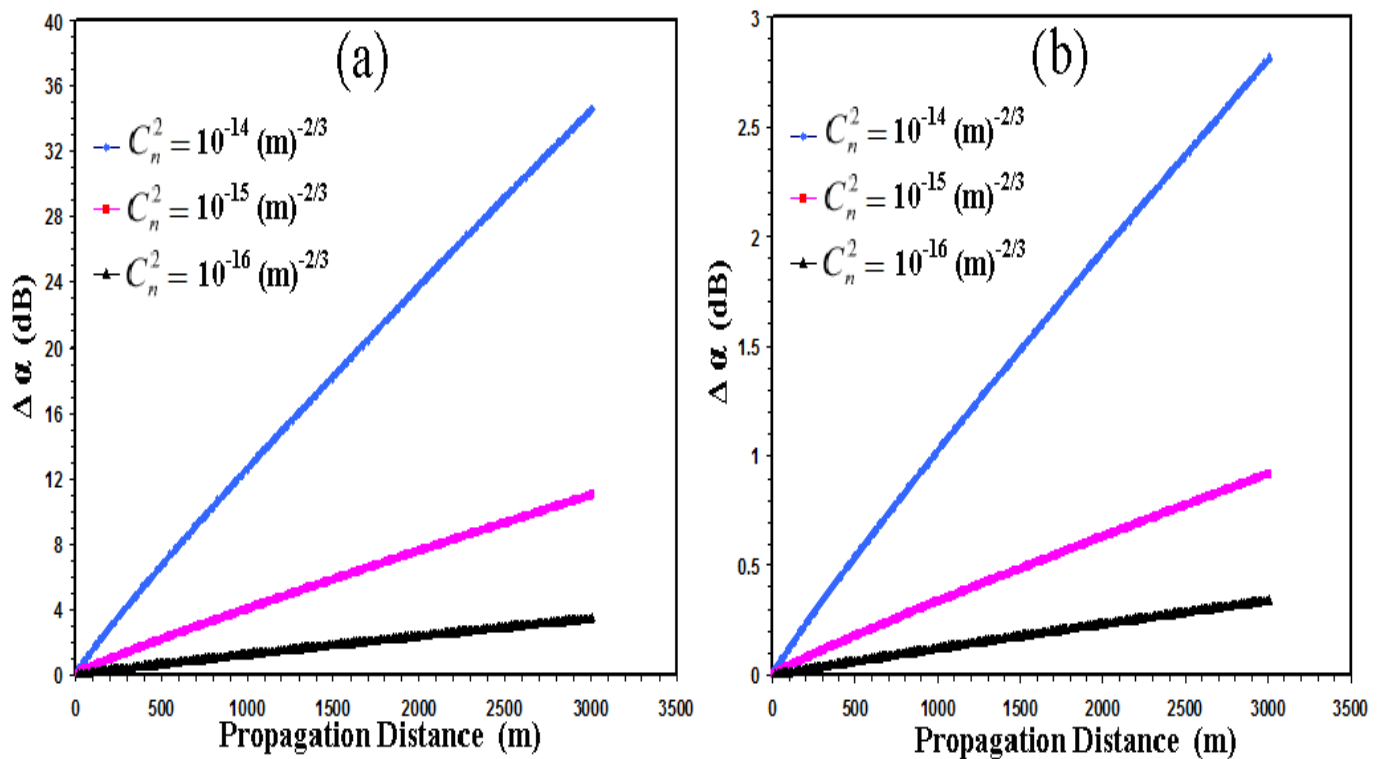


Fig. (4). Difference between attenuation of laser beam with wavelength $3.5\mu\text{m}$ and $1.55\mu\text{m}$ turbulent atmosphere calculated by Rytov's method (a), and Andrews's method (b)