Dramatic Atmospheric Turbulence Effects on Submarine Laser Communication Systems (SLCS) and Free Space Optics (FSO)

Ahmed Nabih Zaki Rashed[1*], and Mohamed S. F. Tabbour[2]
[1,2]Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT

Abstract-This paper has investigated the free space optics and submarine laser communications to be suited Egyptian climate weather. Refractive index fluctuations are deeply investigated for both free space communication systems and submarine laser systems. Optical path length, optical intensity fluctuations, Rayleigh scattering coefficient are the major interesting performance parameters over wide range of temperature , wind speed, signal altitude over ground, and relative humidity variations. Numerical examples are further provided to collaborate on the derived analytical expressions. We have taken into account the analysis of signal to noise ratio (SNR) and the bit error rate (BER) performance of free-space optical (FSO) links and laser submarine communications over atmospheric turbulence channels

Keywords: Wind speed, Temperature variations, Year seasons, Signal altitude, relative humidity, SNR and BER.

I. INTRODUCTION

The Free Space Optical (FSO) communication is also known as Wireless Optical Communication (WOC), Fibreless, or Laser Communication (Lasercom). FSO communication is one of the various types of wireless communication which witnesses a vast development nowadays. FSO provides a wide service and requires point-to-point connection between transmitter and receiver at clear atmospheric conditions. FSO is basically the same as fiber optic transmission. The difference is that the laser beam is collimated and sent through atmosphere from the transmitter, rather than guided through optical fiber [1, 2]. The FSO technique uses modulated laser beam to transfer carrying data from a transmitter to a receiver. FSO is affected by attenuation of the atmosphere due to the instable weather conditions. Since the atmosphere channel, through which light propagates is not ideal. In some mountainous areas, it is difficult to install the technique of fiber optics. But FSO technique will solve this problem with same proficiency and quality provided by fiber optics. FSO systems are sensitive to bad weather conditions such as fog, haze, dust, rain and turbulence [3]. All of these conditions act to attenuate light and could block the light path in the atmosphere. As a result of these challenges, we have to study weather conditions in detail before installing FSO systems [4]. This is to reduce effects of the atmosphere also to ensure that the transmitted power is sufficient and minimal losses during bad weather. There are three factors which enable us to test the FSO performance as: design, uncontrollable and performance. Design factors are relating to FSO design such as light power, wavelength, receiver and transmitter aperture diameter, link range and detector sensitivity. Uncontrollable elements such as rainfall elements include rainfall rate and raindrop radius, haze element include visibility and turbulence element include refractive index structure. Performance of system was tested during the rainy days and hazy days which can be calculated from the effect of scattering coefficient, atmospheric attenuation and total attenuation. However, the system performance in the clear days can be calculated from the effect of variance [5].

II. SCHEMATIC VIEW FREE SPACE OPTICAL TRANSCEIVER LINE OF SIGHT

FSO is a technique used to convey data carried by a laser beam through the atmosphere. While FSO offers a broadband service, it requires Lone of Sight (LOS) communication between the transmitter and receiver as shown in the Fig. 1 [6]. The atmosphere has effects on the laser beam passing through it, so the quality of data received is affected. To reduce this effect, the fundamental system components must be designed to adopt with the weather conditions. This design is mostly related to transmitter and receiver components. In the following subsection, we will tackle discuss the components and the basic system of FSO.

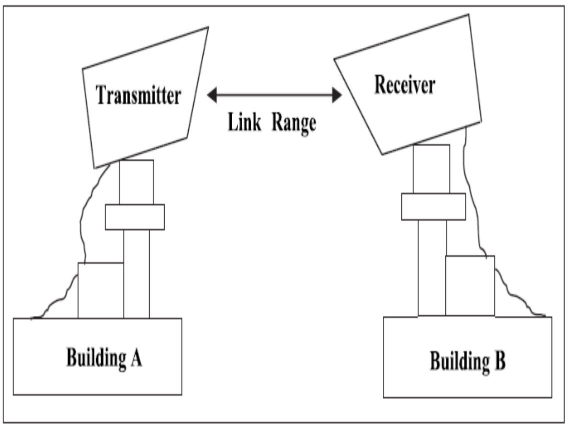

Fig. 1. Schematic showing FSO Transmitter and Receiver LOS.

FSO communication is a line of sight technology that uses laser beam for sending the very high bandwidth digital data from one point to another through atmosphere. This can be achieved by using a modulated narrow laser beam lunched from a transmission station to transmit it through atmosphere and subsequently received at the receiver station [7].

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III. System Model Analysis

In atmospheric turbulence, an important parameter for characterizing the amount of refractive index fluctuation is the index of refraction structure parameter, C_n^2, introduced by [8]. The value of C_n^2 varies with altitude and a commonly used model to describe it is the Hufnagel Valley Day, Hufnagel Valley Night, Greenwood, and submarine laser communication (SLC) Day models with given below as:

$$C_n^2(h) = A\exp\left(-\frac{h}{100}\right) + 5.94x10^{-53}\left(\frac{WS}{27}\right)^2 h^{10}\exp\left(-\frac{h}{1000}\right) + 2.7x10^{-16}\exp\left(-\frac{h}{1500}\right)$$

[HV-day model] (1)

$$C_n^2(h) = 1.9x10^{-15}\exp\left(-\frac{h}{100}\right) + 8.16x10^{-54}h^{10}\exp\left(-\frac{h}{1000}\right) + 3.02x10^{-17}\exp\left(-\frac{h}{1500}\right)$$

[HV-night model] (2)

$$C_n^2(h) = \left[2.2x10^{-13}\,(h+10)^{-1.3} + 4.3x10^{-17}\right]\exp\left(-\frac{h}{1500}\right)$$

[GW-model] (3)

$$C_n^2(h) = 4.008x10^{-13}h^{-1.054},\quad 20\,m \le h \le 230\,m$$

[SLC-model I] (4)

$$C_n^2(h) = 6.352\,x10^{-7}\,h^{-2.966},\quad 850\ m \le h \le 7000\ m$$

[SLC-model II] (5)

$$C_n^2(h) = 6.209x10^{-16}h^{-0.6229},\quad 7000\ \text{m} < h < 20000\ \text{m}$$

[SLC-model III] (6)

Where A is the refractive-index structure parameter at ground level, WS is the velocity of wind in m/s and h is the altitude in meters. On the other hand, when a vertical path is considered, the behavior of C_n^2 is conditioned by temperature changes along the different layers within the Earth's atmosphere, hence, the refractive-index structure parameter becomes a function of the altitude above ground. With taking into account the introduction of the effects of solar radiation and aerosol loading in the atmosphere, as the following expression [9]:

$$C_n^2(T,WS,RH,TCSA,SF) = 5.9x10^{-15}W_{th} + 1.6x10^{-15}T - 3.7x10^{-15}RH - 3.7x10^{-15}WS + 2.8x10^{-14}SF - 1.8x10^{-14}TCSA - 3.9x10^{-13}$$

(7)

Where W_{th} is a temporal hour weight, T is the temperature in K, RH is the relative humidity (%), SF is the solar flux in units of kW/m^2, and TCSA is the total cross sectional area of the aerosol particles and its expression can be found [9]:

$$TCSA = 7.3x10^{-3} + 9.96x10^{-4}RH - 2.75x10^{-5}\,RH^2 - 1.37x10^{-5}\,SF^4$$

(8)

Therefore the refractive index structure parameter, C_n^2 can be given by the following formula:

$$C_n^2 = C_n^2(h) + C_n^2\,(T,WS,RH,TCSA,SF) \quad (9)$$

Another important factor is the rytov approximation which gives relationship between index refraction structure parameter C_n^2 and relative variance of optical intensity fluctuation as the following formula:

$$\sigma_I = \sqrt{0.5\,C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6}} \quad (10)$$

Where λ is the operating optical signal wavelength and L is the link range (distance between transmitter and receiver). Both signal to noise ratio (SNR) and bit error rate (BER) are used to evaluate the quality of optical communication systems. BER performance depends on the average received power, the scintillation strength, and the receiver noise. With appropriate design of aperture averaging the received optical power could be increased as well as reducing the effect of the scintillation. The SNR with turbulence in terms of the mean signal and noise intensity I_0 and I_n, is given as with taken into account the approximation [10]:

$$SNR\,(dB) = 10\,\log\left(\frac{1}{0.31C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6}}\right) \quad (11)$$

For optical wireless links with on-off keying (OOK) modulation scheme the BER is considered [11] as:

$$BER = \frac{\exp(-0.5\,SNR)}{\sqrt{2\pi\,SNR}} \quad (12)$$

The rays leaving the laser source are deflected as they travel through the turbulent atmosphere, some arriving off-axis instead of what is expected without turbulence, represented with the horizontally straight dashed arrow. As the rays may also be interpreted as the wave vector for the traveling wavefront, the variations in the angle respect the optical axis at the receiver represent the concept of angle-of-arrival fluctuations. The expression for the angle-of-arrival fluctuations, that directly depends on the turbulence strength and the optical path length is given by [12]:

$$\beta = \sqrt{2.91C_n^2\,L(2\,W_G)^{-1/3}} \quad (13)$$

Where W_G is the aperture radius and it is related to the receiving aperture, D_R by the following formula [13]:

$$W_G = \frac{D_R}{\sqrt{8}} \quad (14)$$

The Rayleigh scattering coefficient or extinction coefficient can be written by the following relation [14]:

$$\sigma_R = \sqrt{1.23\,C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6}} \quad (15)$$

IV. Simulation Results and Performance Evaluation

FSO system used the laser beam to transfer data through atmosphere. The bad atmospheric conditions have harmful effects on the transmission performance of FSO. These effects could result in a transmission with insufficient quality and failure in communication. So, the implementation of the FSO requires the study of the local weather conditions patterns. Studying of the local weather conditions patterns help us to determine the atmospheric attenuation effects on FSO communication that occurs to laser beam at this area. we shall discuss the effects of atmospheric attenuation, scattering coefficient during rainy and hazy days and atmospheric turbulence during clear days on the FSO system performance. Finally, we will calculate the atmospheric turbulence.

Table 1: Proposed operating parameters for free space optics and laser submarine systems [3, 7, 12, 14, 15].

Operating parameter	Value and unit
Refractive-index structure parameter at	1.7 x 10^{-14} $m^{-2/3}$

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ground level , A		
Operating optical signal wavelength, λ		850 nm ≤ λ ≤ 1550 nm
Link range, L		100 m ≤ L ≤ 1000 m
Wind speed, WS		2 m/s ≤ WS ≤ 20 m/s
A temporal-hour weight, W_{th} (Sunrise)		0.05
A temporal-hour weight, W_{th} (Sunset)		0.1
Solar flux, SF		0.1 kW/m^2
Receiver diameter, D_R		20 cm
Altitude over ground level, h		20 m ≤ h ≤ 20000 m
Average Atmospheric temperature, T	Winter season	287.3 K
	Summer season	299 K
	Spring season	293.8 K
	Autumn season	295.5 K
Average Relative humidity, RH (%)	Winter season	59.33 %
	Summer season	56.66 %
	Spring season	46.66 %
	Autumn season	60 %
Average wind speed	Winter season	3.73 m/sec
	Summer season	3.9 m/sec
	Spring season	4.2 m/sec
	Autumn season	3.5 m/sec

Based on the modeling equations analysis and the assumed set of the operating parameters as shown in Table 1, the following facts are assured as shown in the series of Figs. (2-22):

i) Fig. 2 has assured that laser intensity fluctuations decreases with increasing operating laser signal wavelength for different seasons' year in terrestrial free space optics. It is evident that winter season has presented the lowest laser intensity fluctuations in compared with seasons' year.

ii) Figs. (3, 4) have indicated that signal to noise ratio increases and bit error rate decreases with increasing operating laser signal wavelength for different seasons' year in terrestrial free space optics. It is observed that winter season has presented the highest signal to noise ratio and the lowest bit error rate in compared with seasons' year under the same operating conditions.

iii) Fig. 5 has assured that laser intensity fluctuations increases with increasing optical link range for different seasons' year in terrestrial free space optics. It is evident that winter season has presented the lowest laser intensity fluctuations in compared with seasons' year under the same operating conditions.

iv) Figs. (6, 7) have indicated that signal to noise ratio decreases and bit error rate increases with increasing operating optical link range for different seasons' year in terrestrial free space optics. It is theoretically found that winter season has presented the highest signal to noise ratio and the lowest bit error rate in compared with seasons' year under the same operating conditions.

v) Fig. 8 has assured that angle of arrival fluctuations increases with increasing operating optical link range for different seasons' year in terrestrial free space optics. It is evident that winter season has presented the lowest arrival of angle fluctuations in compared with seasons' year under the same operating conditions.

vi) Figs. (9, 16) have assured that laser intensity fluctuations decreases with increasing operating laser signal wavelength for different seasons' year in submarine laser communications. It is evident that winter season has presented the lowest laser intensity fluctuations in compared with seasons' year.

vii) Figs. (10, 11, 17, 18) have indicated that signal to noise ratio increases and bit error rate decreases with increasing operating laser signal wavelength for different seasons' year in submarine laser communications. It is observed that winter season has presented the highest signal to noise ratio and the lowest bit error rate in compared with seasons' year under the same operating conditions.

viii) Figs. (12, 19) have assured that laser intensity fluctuations increases with increasing optical link range for different seasons' year in submarine laser communications. It is evident that winter season has presented the lowest laser intensity fluctuations in compared with seasons' year under the same operating conditions.

ix) Figs. (13, 14, 20, 21) have indicated that signal to noise ratio decreases and bit error rate increases with increasing operating optical link range for different seasons' year in submarine laser communications. It is theoretically found that winter season has presented the highest signal to noise ratio and the lowest bit error rate in compared with seasons' year under the same operating conditions.

x) Figs. (15, 22) has assured that angle of arrival fluctuations increases with increasing operating optical link range for different seasons' year in submarine laser communications. It is evident that winter season has presented the lowest arrival of angle fluctuations in compared with seasons' year under the same operating conditions.

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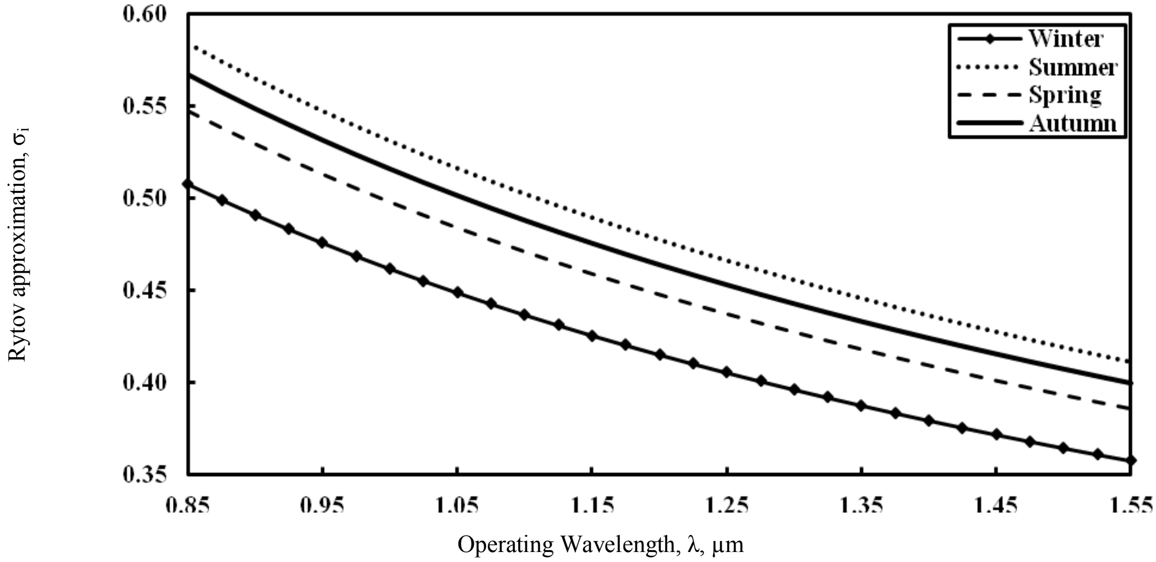

Fig. 2. Variations of the Rytov approximation against the operating wavelength for terrestrial free space optics communication at the assumed set of parameters.

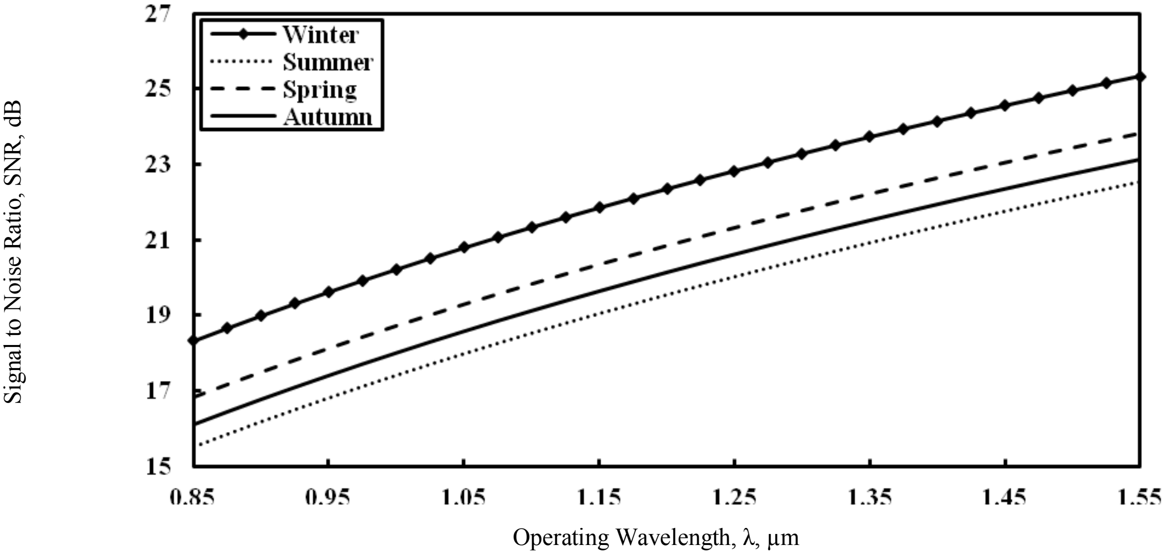

Fig. 3. Variations of the signal to noise ratio against the operating wavelength for terrestrial free space optics communication at the assumed set of parameters.

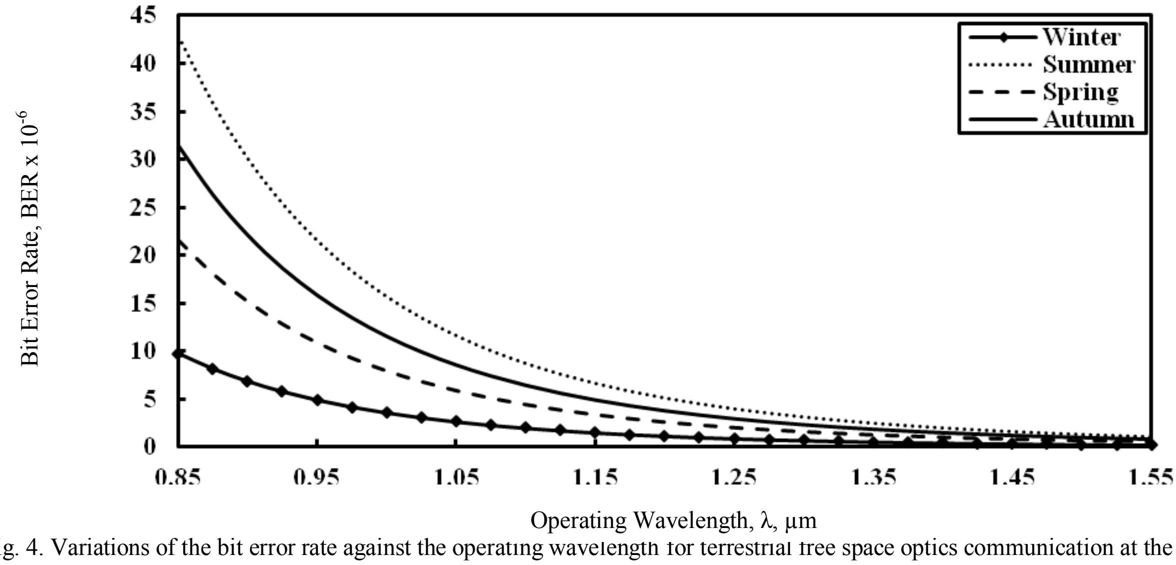

Fig. 4. Variations of the bit error rate against the operating wavelength for terrestrial free space optics communication at the assumed set of parameters.

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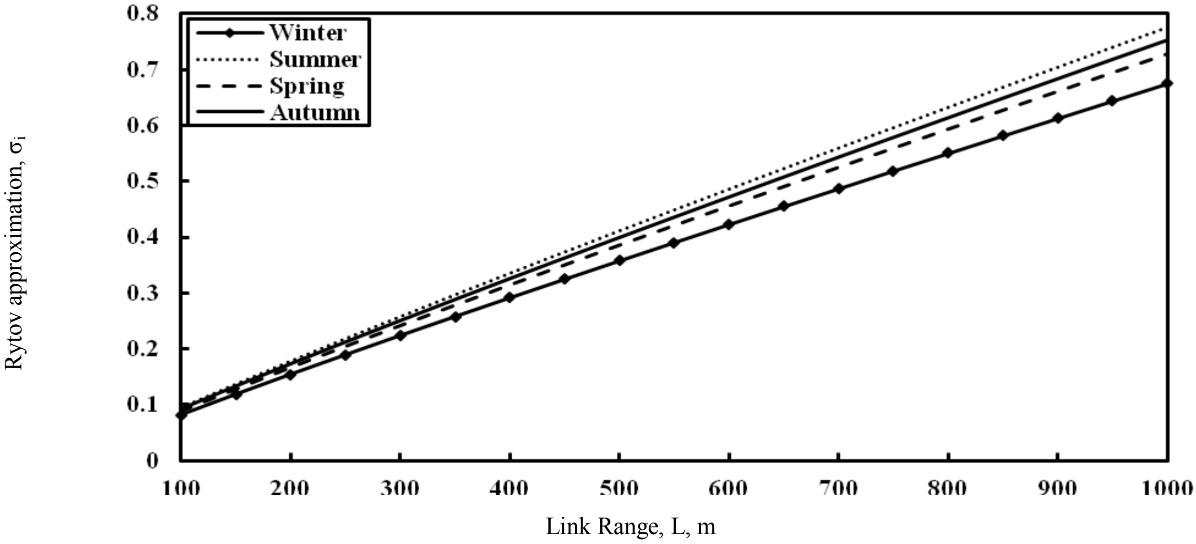

Fig. 5. Variations of the Rytov approximation against the link range for terrestrial free space optics communication at the assumed set of parameters.

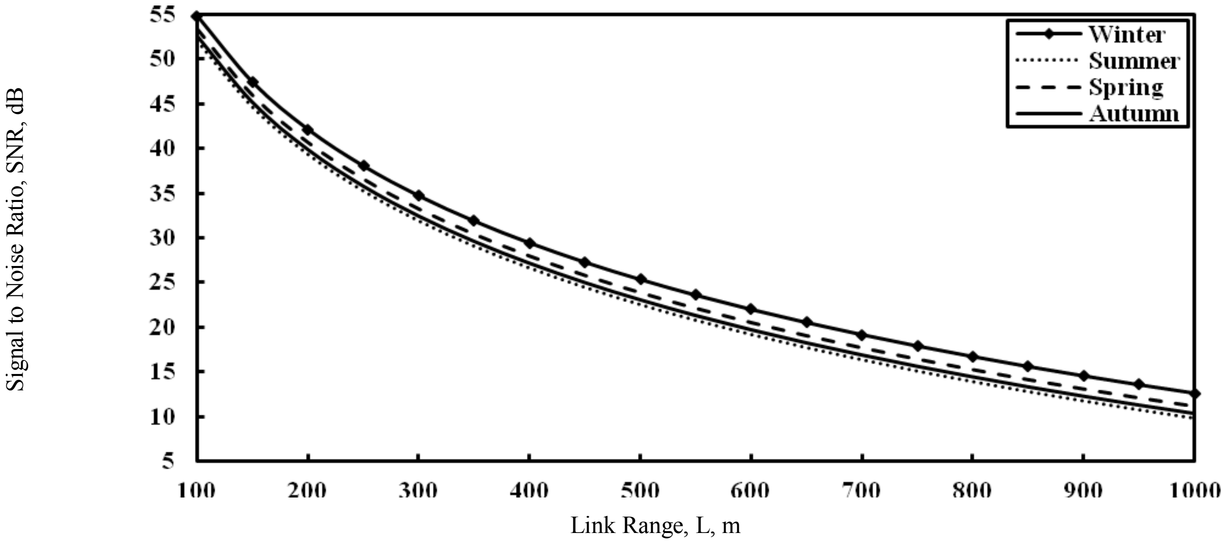

Fig. 6. Variations of the signal to noise ratio against the link range for terrestrial free space optics communication at the assumed set of parameters.

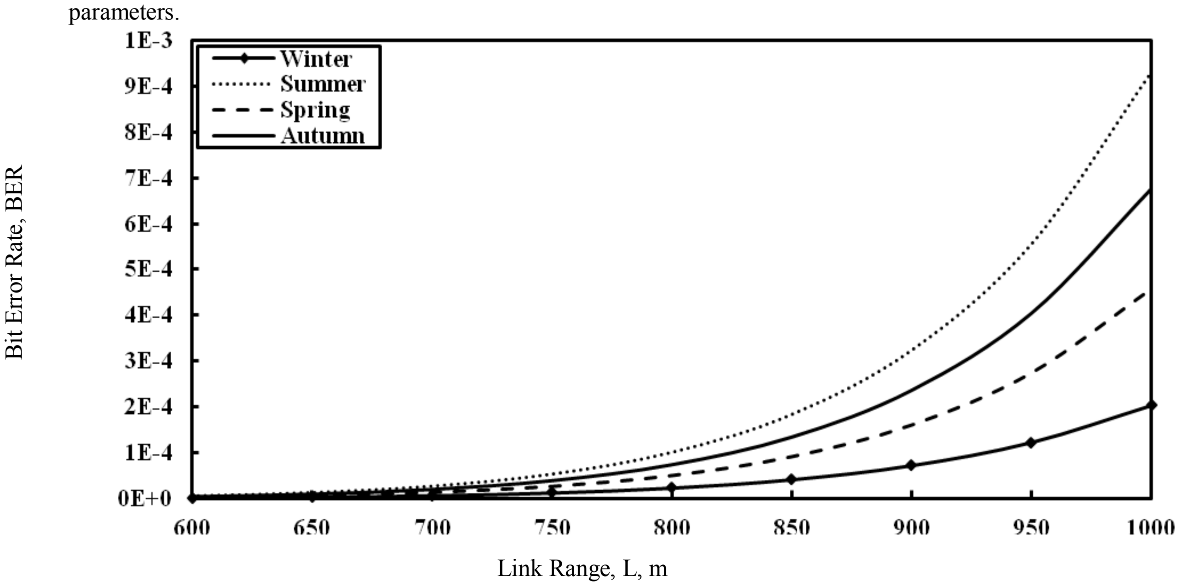

Fig. 7. Variations of the bit error rate against the link range for terrestrial free space optics communication at the assumed set of parameters.

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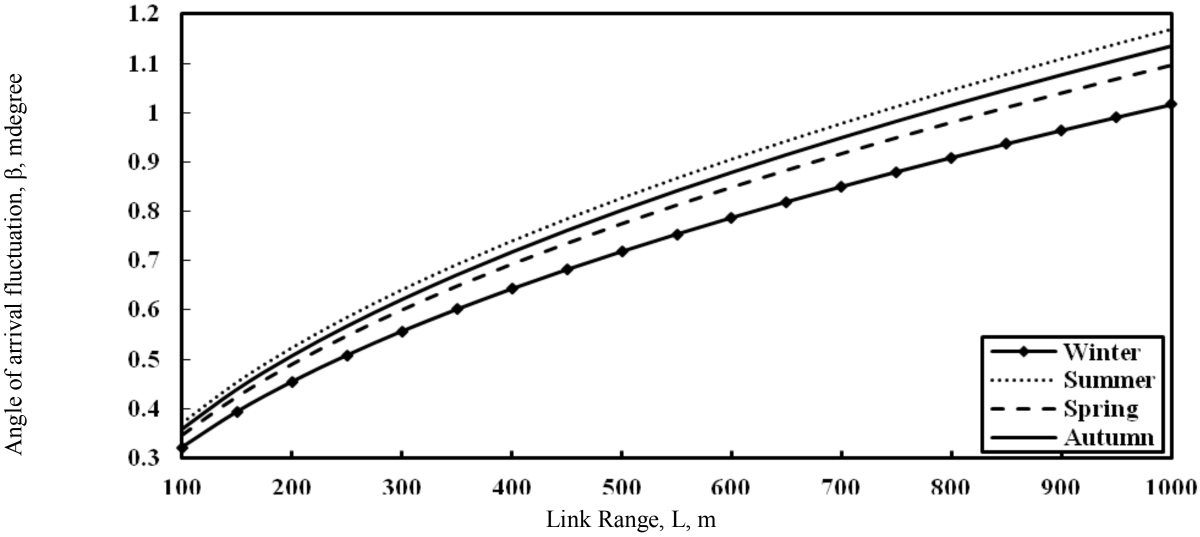

Fig. 8 Variations of the angle of arrival fluctuation against the link range for terrestrial free space optics communication at the assumed set of parameters.

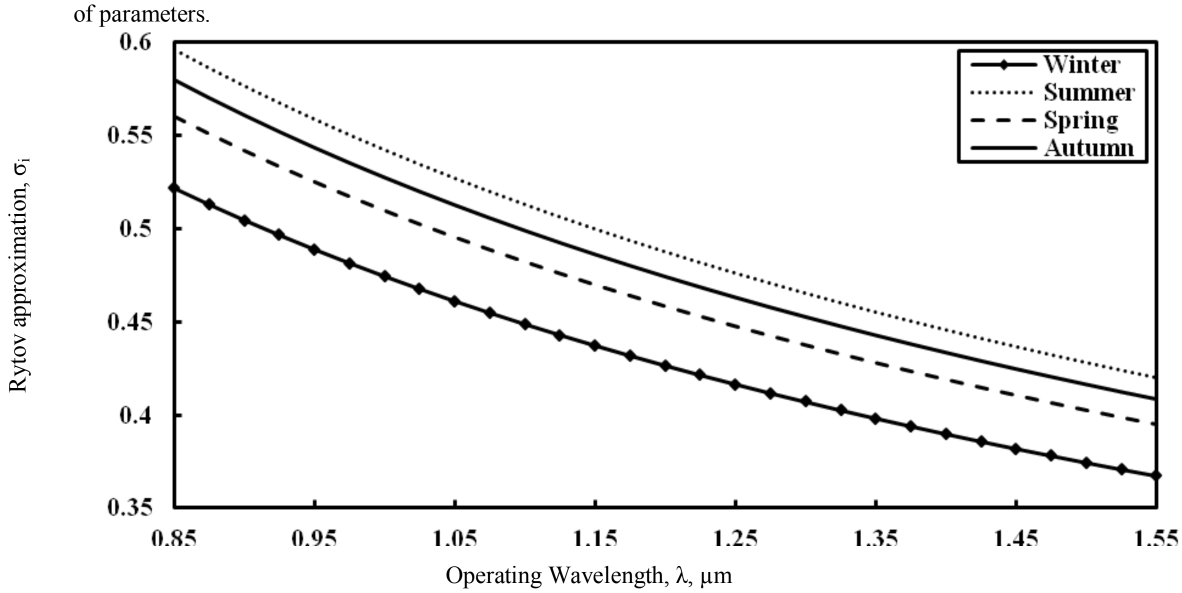

Fig. 9. Variations of the Rytov approximation against the operating wavelength for submarine laser communication modeling one at the assumed set of parameters.

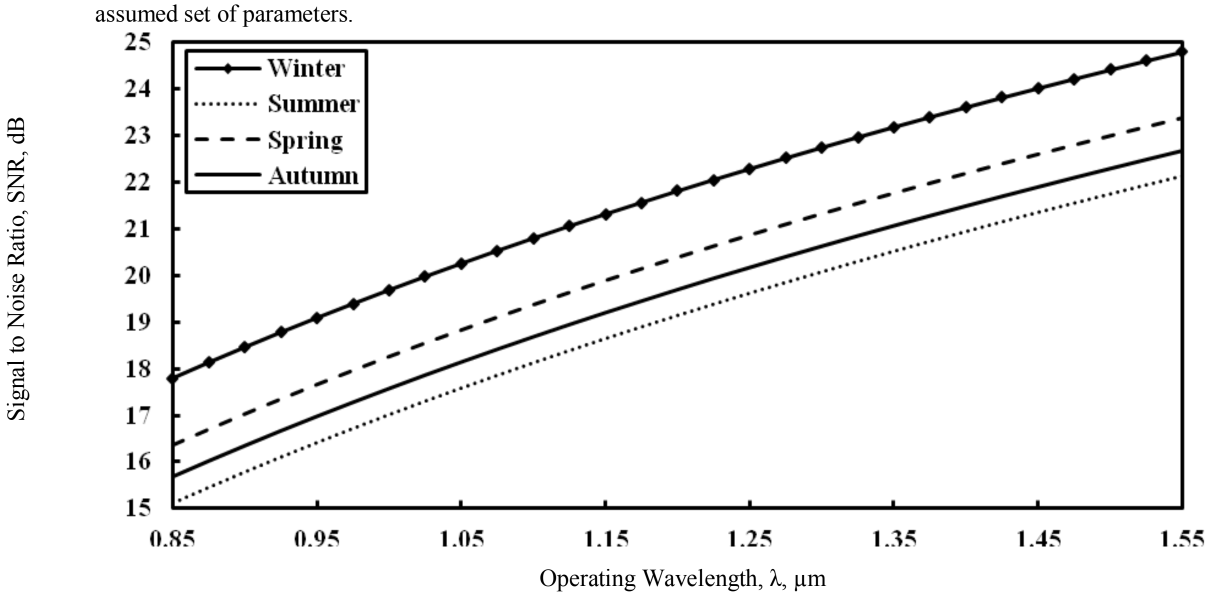

Fig. 10. Variations of the signal to noise ratio against the operating wavelength for submarine laser communication modeling one at the assumed set of parameters.

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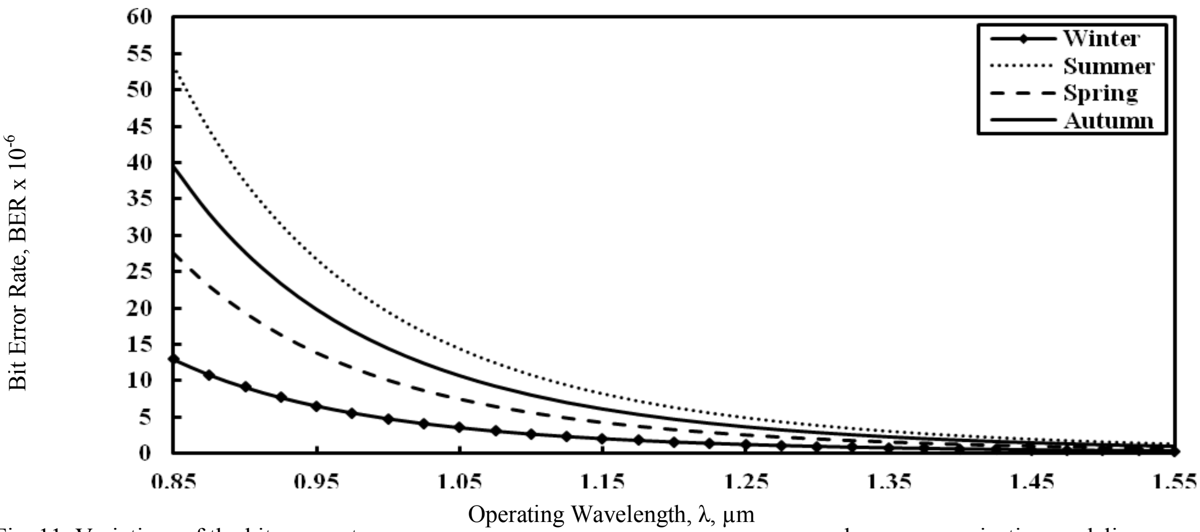

Fig. 11. Variations of the bit error rate against the operating wavelength for submarine laser communication modeling one at the assumed set of parameters.

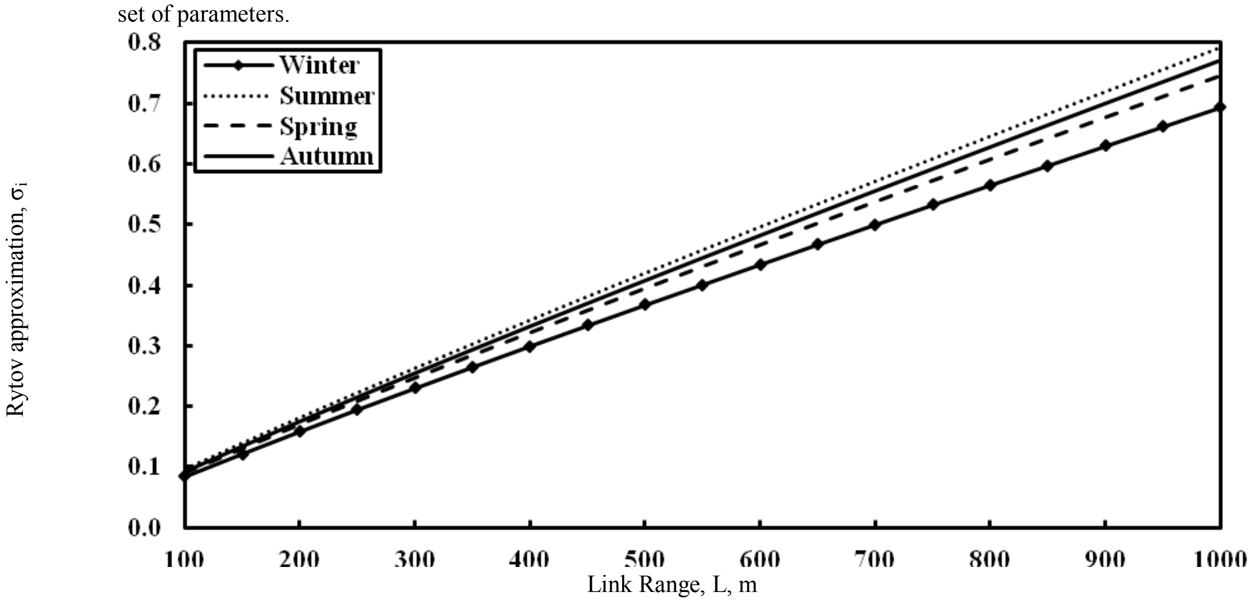

Fig. 12. Variations of the Rytov approximation against the link range for submarine laser communication modeling one at the assumed set of parameters.

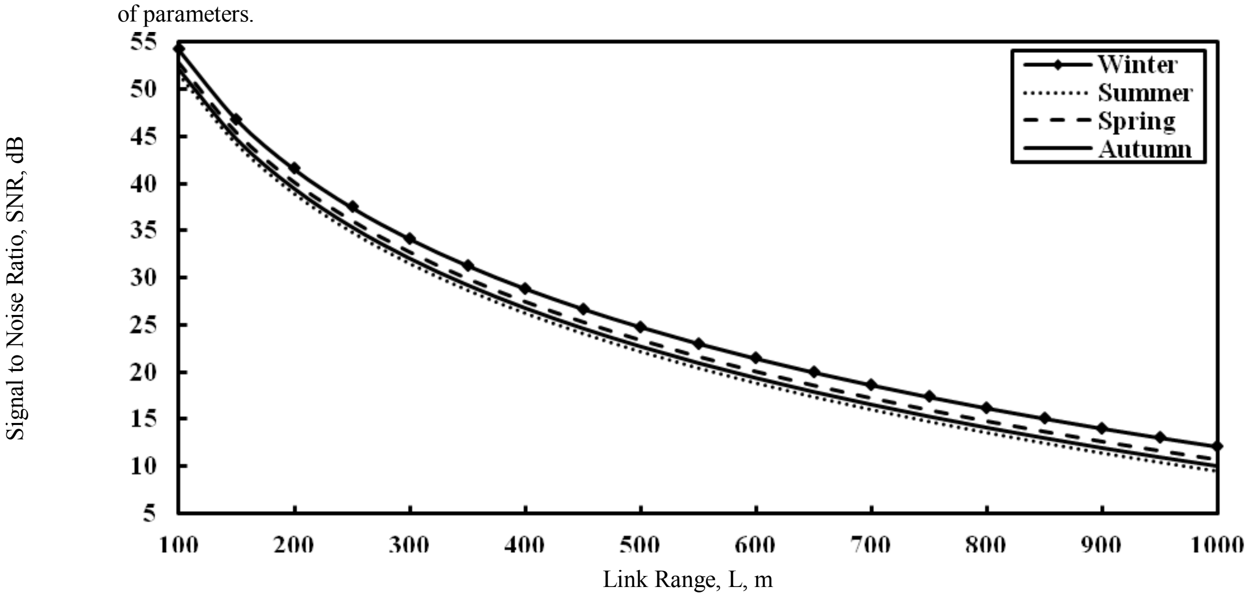

Fig. 13. Variations of the signal to noise ratio against the link range for submarine laser communication modeling one at the assumed set of parameters.

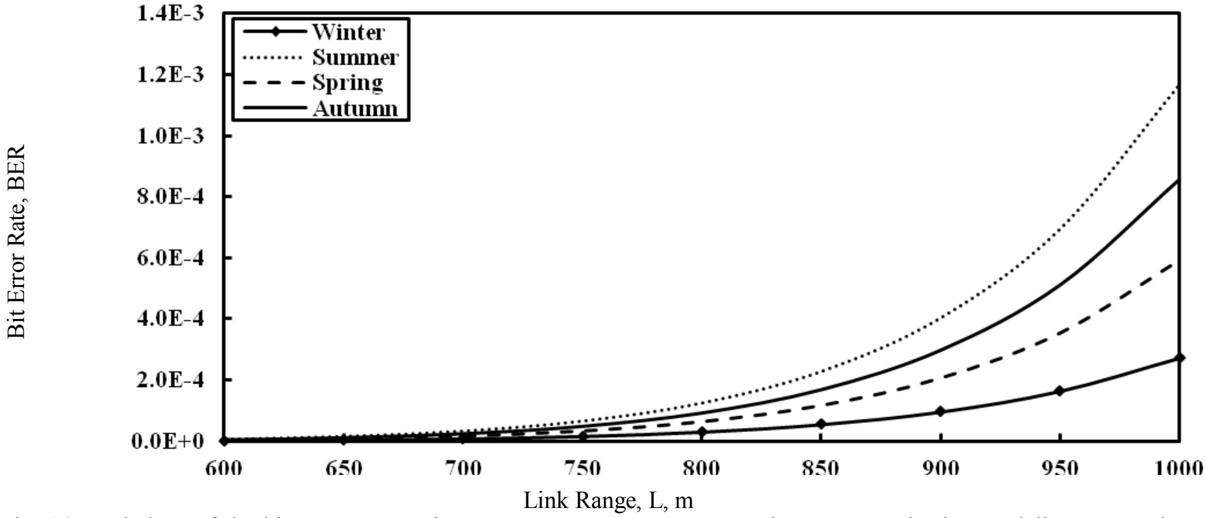

Fig. 14. Variations of the bit error rate against the link range for submarine laser communication modeling one at the assumed set of parameters.

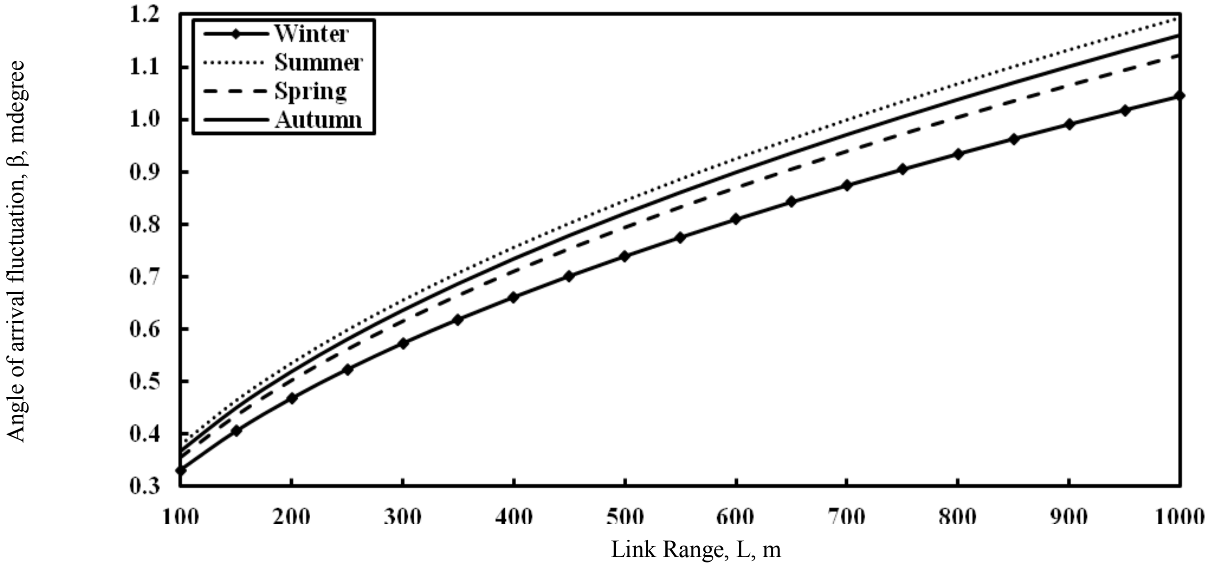

Fig. 15 Variations of the angle of arrival fluctuation against the link range for submarine laser communication modeling one at the assumed set of parameters.

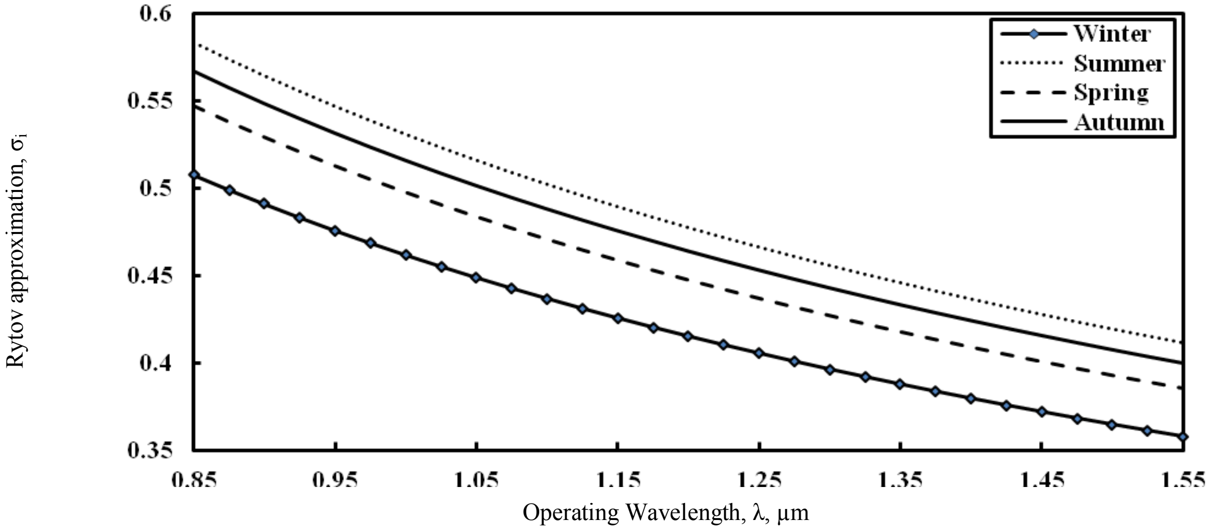

Fig. 16 Variations of the Rytov approximation against the operating wavelength for submarine laser communication modeling three at the assumed set of parameters.

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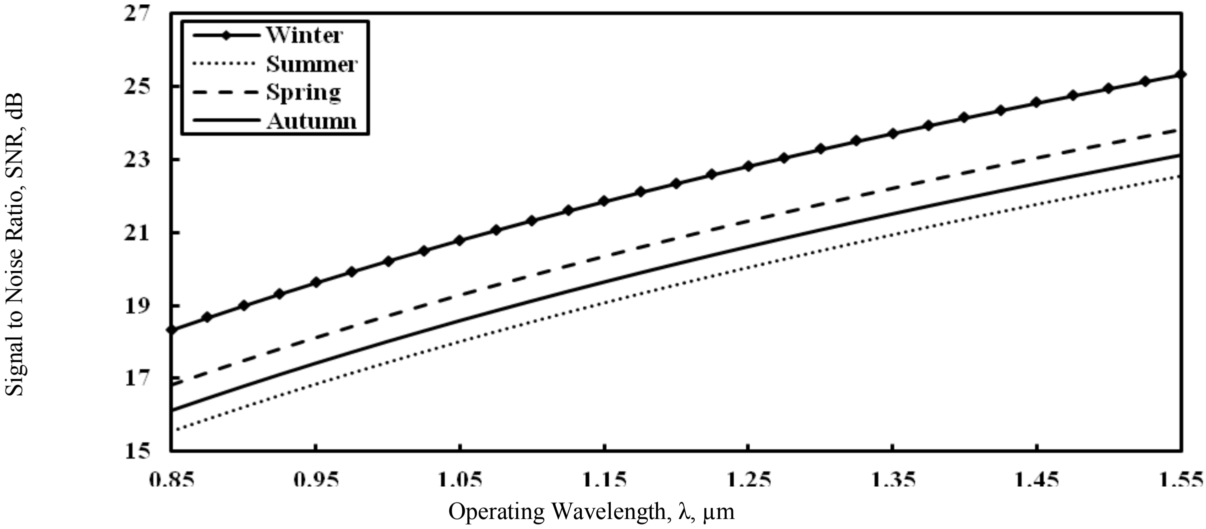

Fig. 17. Variations of the signal to noise ratio against the operating wavelength for submarine laser communication modeling three at the assumed set of parameters.

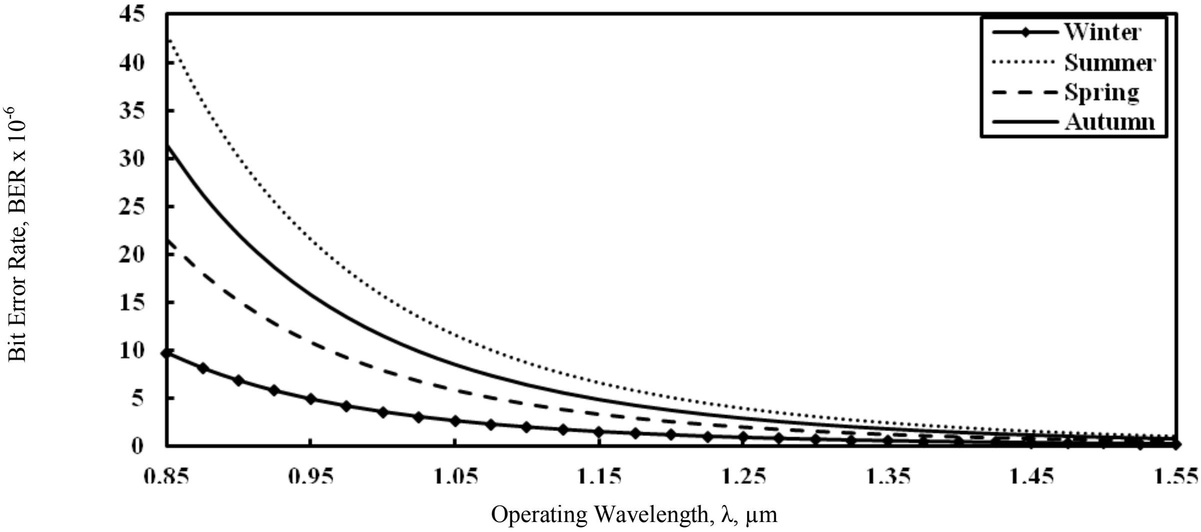

Fig. 18. Variations of the bit error rate against the operating wavelength for submarine laser communication modeling three at the assumed set of parameters.

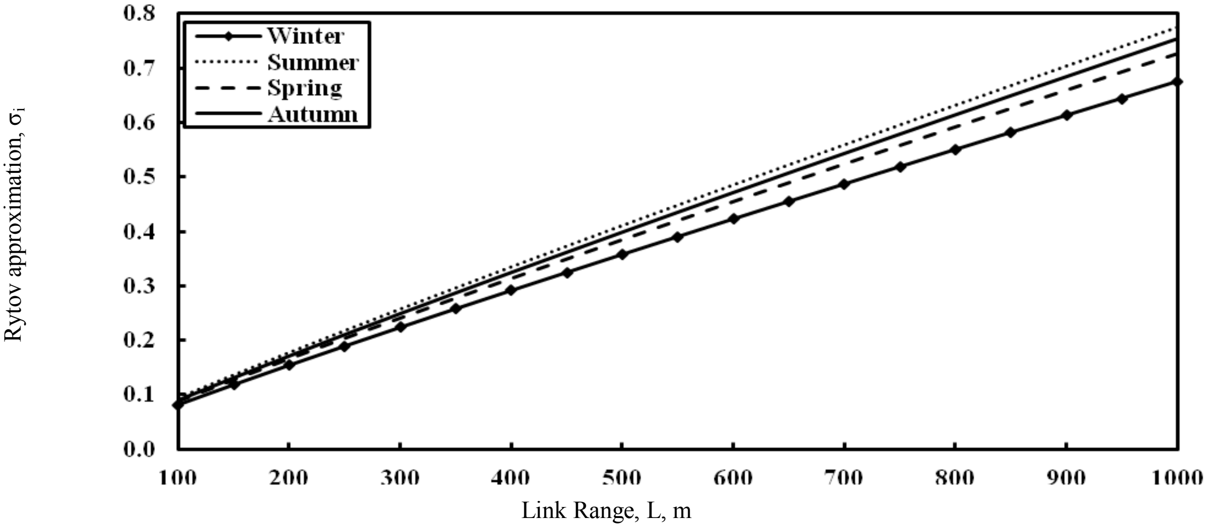

Fig. 19. Variations of the Rytov approximation against the link range for submarine laser communication modeling three at the assumed set of parameters.

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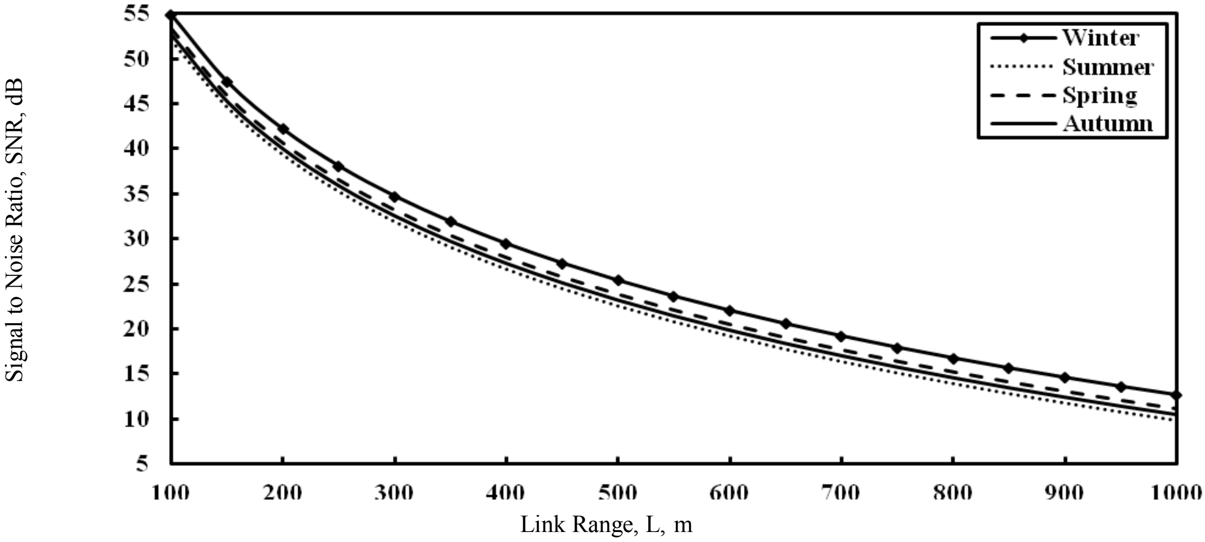

Fig. 20. Variations of the signal to noise ratio against the link range for submarine laser communication modeling three at the assumed set of parameters.

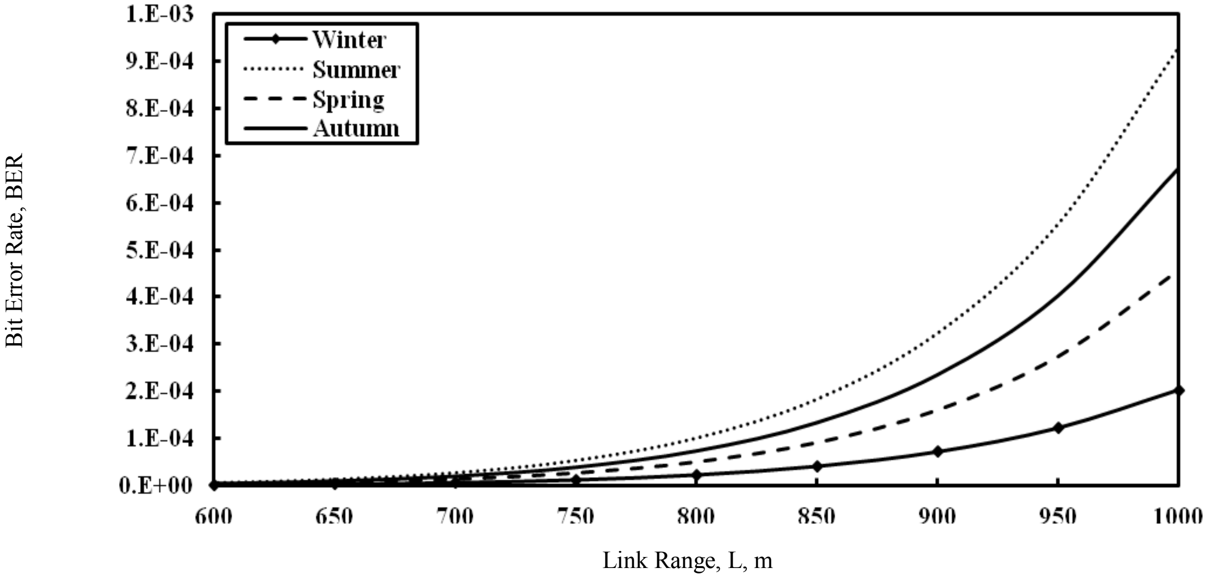

Fig. 21. Variations of the bit error rate against the link range for submarine laser communication modeling three at the assumed set of parameters.

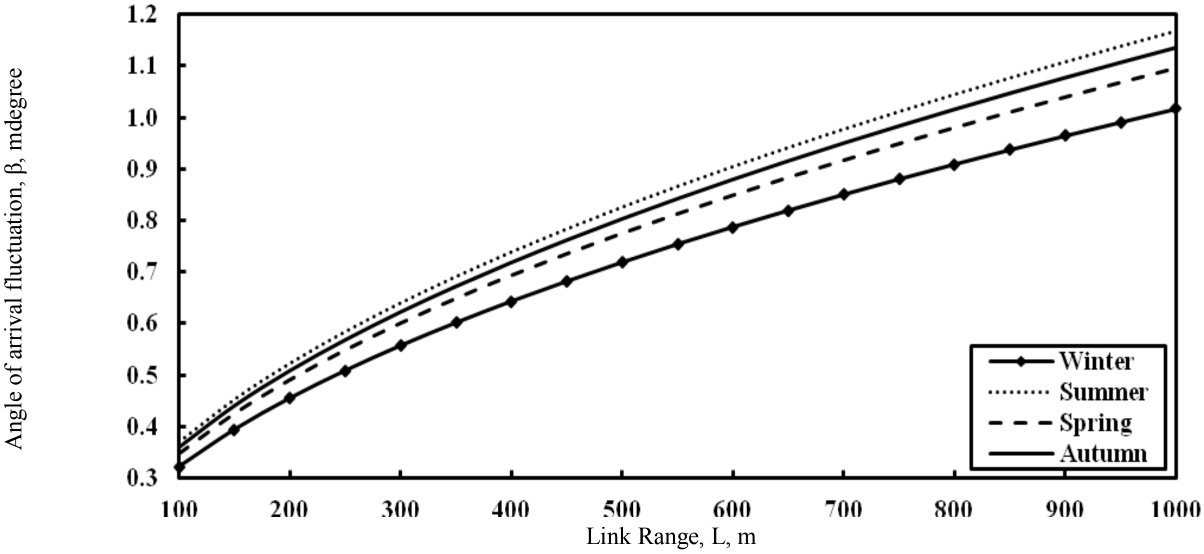

Fig. 22. Variations of the angle of arrival fluctuation against the link range for submarine laser communication modeling three at the assumed set of parameters.

V. CONCLUSIONS

In a summary, we have deeply investigated the terrestrial and submarine free space optics over atmospheric channels for different seasons' year in Egypt. It is theoretically found that the dramatic effects of increasing optical link range on the free space optic terrestrial and submarine laser communications on the decreases signal to noise ratio, increased both bit error rate and laser intensity and angle of arrival fluctuations. As well as it is observed that the increased operating optical laser wavelength, this results in increasing signal to noise ratio and decreasing bit error rate and laser intensity, arrival angle fluctuations. So it is recommended for operation at the window transmission at 1.55 micrometer for both terrestrial and submarine free space optics.

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Author's Profile

Dr. Ahmed Nabih Zaki Rashed was born in Menouf city, Menoufia State, Egypt country in 23 July, 1976. Received the B.Sc., M.Sc., and Ph.D. scientific degrees in the Electronics and Electrical Communications Engineering Department from Faculty of Electronic Engineering, Menoufia University in 1999, 2005, and 2010 respectively.
Currently, his job carrier is a scientific lecturer in Electronics and Electrical Communications Engineering Department, Faculty of Electronic Engineering, Menoufia university, Menouf. Postal Menouf city code: 32951, EGYPT. His scientific master science thesis has focused on polymer fibers in optical access communication systems. Moreover his scientific Ph. D. thesis has focused on recent applications in linear or nonlinear passive or active in optical networks. His interesting research mainly focuses on transmission capacity, a data rate product and long transmission distances of passive and active optical communication networks, wireless communication, radio over fiber communication systems, and optical network security and management. He has published many high scientific research papers in high quality and technical international journals in the field of advanced communication systems, optoelectronic devices, and passive optical access communication networks. His areas of

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interest and experience in optical communication systems, advanced optical communication networks, wireless optical access networks, analog communication systems, optical filters and Sensors, digital communication systems, optoelectronics devices, and advanced material science, network management systems, multimedia data base, network security, encryption and optical access computing systems. As well as he is editorial board member in high academic scientific International research Journals. Moreover he is a reviewer member and editorial board member in high impact scientific research international journals in the field of electronics, electrical communication systems, optoelectronics, information technology and advanced optical communication systems and networks. His personal electronic mail ID (E-mail:ahmed_733@yahoo.com). His published paper under the title "**High reliability optical interconnections for short range applications in high speed optical communication systems**" has achieved most popular download articles in Optics and Laser Technology Journal, Elsevier Publisher in year 2013.

Dr. Mohamed Salah Tabbour was born in 30-10-1976. Received the **B.Sc.**, **M.Sc.**, **Ph.D.** in Electronics & Electrical Communications Engineering Department from Faculty of Electronic Engineering (FEE), Menoufia University, Egypt in 1999, 2005, and 2013 respectively. Currently, his job carrier is a lecturer in Electronics & Electrical Communications Engineering Department, FEE, Egypt. His interest research mainly focuses on the transmission capacity, data rate product and long transmission distances of the radio over fiber optical communication networks. His areas of interest and experience are in Optical communication systems, Advanced Optical communication networks, Wireless optical access networks, Analog communication systems, Optical Sources, detectors, and sensors, digital communication systems, optoelectronic devices.

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