Influence of Atmospheric Attenuation of Laser Beam on performance of Free Space Optics System

Gailan Asad Kazem
Diyala university ,college of science ,physics department

Abstract

In this research the optical parameters that effect on the performance of the free space optics (FSO) system such as wavelength ,transmitted optical power, aperture averaging factor, and power margin for different paths links have been discussed. also the scintillation index caused by atmospheric turbulence and the atmospheric attenuation of laser beam due to the scattering by fog, mist, and haze have been discussed for these systems, the simulations are performed for a horizontal-path propagation of the Gaussian-beam wave and for two wavelengths 780 nm, and 1600 nm.

1.Introduction

The free space optics (FSO) communication is a recent and growing technology that has found application in many areas of the short- and long communications space from intersatellite links to interbuilding links. the (FSO) applications systems are most frequently used as the last-mile telecommunications link or as the LAN link between buildings[1]. A disadvantage of (FSO) is a fluctuation of atmospheric attenuation caused by a number of phenomena in the atmosphere, such as scattering, absorption, and turbulence. Scattering in particular, which is a product of fog, haze, or low clouds, causes large variation in the received optical power and markedly limits the availability of (FSO) for a given transmission range[2], the only turbulence and scattering are appropriate to be taken into consideration due to the negligible absorption effect. the most important effects of atmospheric turbulence on the laser beam are phase-front distortion, beam broadening, beam wander and redistribution of the intensity within the beam. 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[3]. the eddies of various sizes and differing densities act as lenses scattering light off its intended path then Particular parts of the laser beam travel on slightly different paths and combine, the recombination is destructive or constructive at any particular moment and results in spatial redistribution of signal and consequently in lowering the received optical power[4].

2. Gaussian Beam Description of Optical System

Two types of beams are used in FSO the Gaussian beam and the top-hat beam. Most lasers produce Gaussian beams that have point-source spatial qualities[5,11]. A beam with an ideal Gaussian intensity profile corresponding to the theoretical TEM00 mode is the most frequently used model for the real laser-beam description. But most FSO systems use large divergence beams of the order of milliradians to allow easy alignment. In the case of relatively large divergence angles and relatively large link distances this model can be considerably simplified without any notable loss of accuracy .The Gaussian beam that propagates along the **(z)** axis as shown in **Fig. 1** can be characterized at the transmitter (**z = 0**) by the beam spot radius (W_0), at which the optical intensity falls off to the ($1/e^2$)of the maximum on the beam axis, by the wave number $k = 2\pi/\lambda$ (where λ is the wavelength), and by the radius of curvature F_0, which specifies the beam forming. The cases $F_0 = \infty$, $F_0 > 0$ **and** $F_0 < 0$ correspond to collimated, convergent and divergent beam forms, respectively. These parameters are usually used to describe the beam at a given position **z = L** and it called input-plane beam parameters[2,6] :

$$\Theta_0 = 1 - \frac{1}{F_0}, \Lambda_0 = \frac{2L}{kW_0} \text{.......... .....}(1)$$

Where (Θ_0) the curvature parameter , (Λ_0) the Fresnel ratio at the input plane,(W_0) beam spot radius and(F_0)the radius of curvature,

The output plane beam parameters corresponding to the input-plane beam parameter is[2,6]:

$$\Theta = 1 - \frac{1}{F} = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2}, \Lambda = \frac{\Lambda_0}{\Theta_0^2 + \Lambda_0^2} \text{........}(2)$$

Where (F) is the radius of curvature at the receiver.

The beam spot radius at the receiver $W(L)$ can be expressed as [1]:

$$W(L) = W_0[\Theta_0^2(L) + \Lambda_0^2(L)]^{1/2} \text{......}(3)$$

An additional parameter useful for beam description is the divergence half-angle *(θ)*, which defines the spreading of the beam when propagating toward infinity. It is given by[2]:

$$\theta = \frac{\lambda}{\pi W_B} \text{............}(4)$$

Where(W_B) is the spot size radius at the beam waist give as[6]:

$$W_B = W_0[(\frac{kW_0^2}{2F_0})^2 + 1]^{-1/2} \text{.......}(5)$$

3.The Loss of Laser Power by propagation

The optical intensity in the Gaussian beam at radial distance (***r***)from the optical axes given as[2]:

$$I^0(r,L) = I_0[\frac{W_0}{W(L)}]^2 \exp[\frac{-2r^2}{W^2(L)}] \ldots\ldots\ldots\ldots(6)$$

where $\boldsymbol{I^0 = I_0(0,0)}$ is the transmitter output irradiance at the centerline of the beam and the superscript denotes the irradiance in a free space (without turbulence). The relation between the intensity of the optical wave and the total power in the beam for the case($\boldsymbol{r = 0}$) can be written in the form[5].

$$I^0(0,L) = I_0 \frac{W_0^2}{W^2(L)} = \frac{2P_0}{\pi W^2(L)} \ldots\ldots\ldots\ldots(7)$$

where $\mathbf{P_0}$ is the total power transmitted by the beam.

The incident Power ***P(D,L)*** on the circular receiver lens of aperture diameter (**D**) situated at distance (**L**) is[6]:

$$P(D,L) = P_0[1 - \exp(\frac{-D^2}{2W^2(L)})] \ldots\ldots\ldots\ldots(8)$$

In a real situation, a relatively large divergence angle (1 mrad ≤ θ ≤ 10 mrad) causes that $kW_0^2 >> 1$, and the divergence as in Eq(4)and Eq(5) reduces to $\theta = W_0/|F_0|$. Similarly, equation (3) could be expressed in a simplified form, $W_L = W_0 + L\theta$. On the assumption that the beam radius at the receiver position is much greater than the diameter of the receiver lens, the optical intensity at the lens can be regarded as uniformly distributed as shown in Fig. (1),Then the received optical power is [4]:

$$P(D,L) = I^0(0,L)\frac{\pi D^2}{4} = \frac{D^2 P_0}{2(W_0 + L\theta)} \ldots\ldots\ldots\ldots(9)$$

The propagation loss of laser power can be express as[2]:

$$A_{prop},(D,P) = 10\log(\frac{P_0}{P(D,L)}) = 20\log\left(\frac{\sqrt{2}(W_0 + L\theta)}{D}\right) \ldots\ldots(10)$$

The laser power, beam divergence, receiver sensitivity , coupling losses, and receiver lens area is define how the FSO able to eliminate atmospheric effects. They are summarized in the power link margin ***M(L)*** taking into account the condition($\boldsymbol{W_0 << L\theta}$) the power link margin ***M(L)*** is given by[2,3,5]:

$$M(L) = P_0 - 20\log\left(\frac{\sqrt{2}L\theta}{D}\right) - \Pr \ldots\ldots\ldots\ldots(11)$$

4-The scintillation index of Gaussian beam propagation through turbulent atmosphere

Atmospheric scintillation can be defined as the changing of beam intensities in time and space or redistribution of intensity beam at the plane of a receiver that is detecting a signal from a transmitter located at a distance . The received signal at the detector fluctuates as a result of the thermally induced changes in the index of refraction of the air along the transmit path. These index changes cause the atmosphere to act like a series of small lenses that deflect portions of the light beam into and out of the transmit path[11]. In the case of strongly divergent beam, scintillation is the most significant source causing a loss of power. The intensity of the optical wave(I)propagating through turbulent atmosphere is a random variable. The normalized variance of optical wave intensity, referred to as the scintillation index, is defined by[1,4,6]:

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle} - 1 \qquad \text{.....(12)}$$

The scintillation index indicates the strength of irradiance fluctuations. For weak fluctuations, it is proportional, and for strong fluctuations, it is inversely proportional to the Rytov variance for a plane wave as[5,7]:

$$\sigma_1^2 = 1.23 . C_n^2 . k^{7/6} . L^{11/6} \qquad \text{...(13)}$$

where C_n^2 ($m^{-2/3}$) is the refractive-index structure parameter.

The refractive-index structure parameter is very difficult to measure as it also depends on the temperature, wind strength, altitude, humidity, atmospheric pressure, etc. For a homogenous turbulent field, which can be assumed for near-ground horizontal-path propagation, the refractive-index structure parameter is constant. According to the modified Rytov theory, intensity(I) is defined as a modulation process in the form[2]:

$$I = x.y \qquad \text{.(14)}$$

where x and y are statistically independent unit mean random variables representing fluctuations caused by small-scale (diffractive) and large-scale (refractive) turbulence eddies. the scintillation index can be expressed in the form[2]:

$$\sigma_I^2 = (1+\sigma_x^2)(1+\sigma_y^2) - 1 = \exp(\sigma_{\ln x}^2 + \sigma_{\ln y}^2) - 1 \qquad \text{.....(15)}$$

where σ_x^2 and σ_y^2 are normalized variances , $\sigma_{\ln x}^2$ and $\sigma_{\ln y}^2$ are log-irradiance variances of x and y [1,2,7].

Optical scintillations can be reduced by increasing the collecting area of the receiver lens by the integration of various intensities incident on particular parts of the lens. This phenomenon is known as aperture averaging and it given by[8]:

$$A = \frac{\sigma_I^2(D)}{\sigma_I^2(D=0)} = \left[1 + 1.06\left(\frac{D^2 k}{4L}\right)\right]^{-7/6} ....(16)$$

Where (D) is the receiver diameter .

when aperture averaging is assumed, the log-irradiance variances are given by[2,3,7,8]:

$$\sigma_{\ln x}^2(D,L) = 0.49\sigma_1^2\left(\frac{\Omega_G - \Lambda_1}{\Omega + \Lambda_1}\right)^2\left(\frac{1}{3} - \frac{1}{2}\overline{\Theta} + \frac{1}{5}\overline{\Theta}^2\right)\eta_x^{7/6}\left(1 + 0.4\eta_x\frac{2-\overline{\Theta}}{\Omega_G + \Lambda_1}\right)^{-7/6} ..(17) \text{ And}$$

$$\sigma_{\ln y}^2(D,L) = \frac{1.27\sigma_1^2\eta_y^{-5/6}}{1 + 0.4\eta_y}(\Omega_G + \Lambda_1)............(18)$$

Where $\overline{\Theta} = 1 - \Theta$, and $\Omega_G = \frac{16L}{KD^2}$

also the artificial variables are:

$$\eta_x = \left(\frac{1}{3} - \frac{1}{2}\overline{\Theta} + \frac{1}{5}\overline{\Theta}^2\right)^{-6/7}\left(\frac{\sigma_B^2}{\sigma_1^2}\right)^{6/7}.\left(1 + 0.56\sigma_B^{12/5}\right)^{-1} ..(19) \quad \text{and}$$

$$\eta_y = \left(\frac{\sigma_B^2}{\sigma_1^2}\right)(1 + 0.69 .\sigma_B^{-12/5}).........\ .....(20)$$

The Rytov variance for a Gaussian-beam wave is[2]:

$$\sigma_B^2 = 3.86\sigma_1^2\left(\frac{2}{5}\left[(1+2\Theta)^2 + 4\Lambda^2\right]^{5/12}\cos\left[\frac{5}{6}\tan^{-1}\left(\frac{1+2\Theta}{2\Lambda}\right)\right] - \frac{11}{16}\Lambda^{5/6}\right)..(21)$$

4.Attenuation by Scattering

The attenuation of laser beam through the atmosphere is described by exponential Lambert law[9,10].

$$\tau_L = \frac{P_L}{P_0} = \exp^{-\alpha L} ....(22)$$

Where(τ_L) Transmittance at ranger (L), Where P_L Laser power at range (L) and (α) is total attenuation coefficient per unit length.

In the spectrum region used by FSO, attenuation coefficient is only approximated by the coefficient of scattering by the particles present in the atmosphere[6,7].The type of scattering is determined by the size of the atmospheric particle with respect to the laser wavelength. The size of the atmospheric particle described by a dimensionless number called size parameter (***a***) [3]:

$$a = \frac{2\pi r}{\lambda} \text{........(23)}$$

Where r = radius of scattering particle,

The general relation between wavelength and scattering coefficient is {3, 6,].

$$\alpha_\lambda = d\lambda^{-q} \text{..........(24)}$$

Where, **d** = constant parameter , **q = a** parameter whose value depends on type of scattering

There are three type of scattering occurs in the atmosphere, Rayleigh, Mie and Non-selective or Geometrical scattering. Rayleigh scattering occurs when wavelength is much larger than the particle size (**λ >> r**), in this kind of scattering (**q**) is equal to such scattering would be present even in completely clear atmosphere, because the gas molecules themselves would scatter the radiation. the effect of Rayleigh scattering on the total attenuation is very small, so it can be neglected[3, 6,10] .As the particle size approaches laser wavelength (**λ≈r**), scattering of radiation off the larger particles becomes more dominate in the forward direction as opposed to the backward direction. this type of scattering, where the size parameter **(a)** varies between (**0.1, 50**) such as fog, smoke, haze and dust is called Mie scattering , where the value of (**q**) varies from (**0 to 1.6**) The third generalized scattering occurs when the atmospheric particles are much larger than laser wavelength (**r >> λ)** size parameter grater than 50, the scattering is called Geometrical or Nom-selective scattering, the scattering particles are larger enough so that the angular distribution of scattered radiation can be described by geometric optics .the Rain drops Nom-selective scattering of laser wavelength . the scattering is called Nom-selective because there is no dependence of the attenuation coefficient on laser wavelength ,where (**q=0**)[3,6,10]. Kruse formula is an empirical relation often used to calculate the atmospheric attenuation is [2, 3, 4, 6]:

$$\alpha = \frac{13}{V}\left(\frac{\lambda_{(\mu m)}}{0.55}\right)^{-q(V)} \text{.......... ....(25)}$$

Where, (α) in dB/Km and(V) visibility in (Km) and

$$q(V) = \begin{cases} 1.6 \text{................} For V > 50 Km \\ 1.3 \text{................} For 6 < V < 50 Km \text{...........(26)} \\ 0.585 V^{1/3} \text{....} For 0 < V < 6 Km \end{cases}$$

We can use this formula when **λ** = (350 to 1640) nm[12] .The value of **q(v)** is very important because it determines the wavelength dependence of the attenuation coefficient and the type of scattering[9] .The latest investigations indicate no wavelength dependence of the atmospheric attenuation coefficient in foggy conditions, where the visibility is less than 5 Km. A new method for evaluating the particle size distribution coefficient that respects this fact was proposed by Kim as[10,11]:

$$q(V)=\begin{cases}1.6\text{.......... ....} For\ .(V>50\,Km)\\ 1.3\text{.......... ....} For\ (6<V<50\,Km)\\ 0.16V+0.34\text{.......... ..}For\ (1<V<6Km)\text{......... ....}(27)\\ V-0.5\text{.......... ....}For\ (0.5<V<1Km)\\ 0\text{.......... ....}For\ (V<0.5Km)\end{cases}$$

Further studies of attenuation due to scattering were conducted by a other authors. Naboulsi proposed relations for attenuation caused by radiation and advection fog and for visibilities ranging from 50 to 1000 m. Radiation fog generally forms during the night when the temperature of the ground surface drops due to the radiation of the heat accumulated during the day. When the air is cooled by the ground surface below the dew point, the condensation of water vapor and, consequently, the formation of ground fog occur. The attenuation coefficient for radiation fog is[11,12]:

$$\alpha(V)=4.343\,\frac{0.11478\,\lambda+3.8367}{V}\text{.......... ...}(28)$$

Advection fog is formed when the warm and wet air moves above colder maritime or terrestrial (e.g., snow covered) surfaces. As in the previous case, the air in contact with the ground surface can be cooled below the dew point, which causes the condensation of water vapor. The attenuation
coefficient for advection fog is given by[10,11,12]:

$$\alpha(V)=4.343\,\frac{0.18126\,\lambda^2+0.13709\,\lambda+3.7205}{V}\text{............}(29)$$

Where(λ) in equations (25,28and 29)are in microns unite.

The unit that is used in this research to measure the attenuation is Decibel per unit length, from equation (25) the Decibel unit (**dB**) is defined as[12] :

$$\tau_R=10Log_{10}\frac{P_R}{P_0}=(10Log_{10}e)\alpha R=4.34\alpha R=4.34\tau_R\,(30)$$

5. Results and discussion

Although there are a few optical wavelengths suitable for transmission through the atmosphere, FSO designers usually use near-IR spectral as windows from 780 nm, to 1600 nm. The reason for this choice is the good availability of lasers and photodiodes for these wavelengths. Which spectral window is more appropriate for operation of FSO in turbulence[11].To demonstrate the effects of turbulence and scattering on laser-beam propagation the FSO systems may be characterized by the receiver lens area and by the power link margin $M(L)$. there are three typical FSO representatives, differing in the optical parameters, theses parameters are summarized in Table (1), As shown in the Fig. 2. at very short link distances, the power link margin has maximum value because is not affected by the propagation loss where the beam spot diameter at the receiver position is lower than the diameter of the receiver lens, while at long distance the power link margin will be decrease where the (FSO A) be more decreasing from the others types of (FSO B or FSO C) because the beam spot be increasingly with increasing the distance due to the divergence and then intensity will be decrease at the receiver . A.Prokes (Reference 2) find that the maximum values for $M(L)$ are(45,35,25) dB for(FSO C , FSO B and FSOA) respectively while our results are (50,44,32) dB for(FSO C , FSO B and FSOA) respectively. From fig.3 it can be seen the largest receiver lens area as in (FSO C) the lowest power loss due to propagation ,while the(FSO A) give a more loss power due to propagation than other systems because it has diameter of receiver less than other systems .The scintillation index shown in Fig. 4 was evaluated for λ = 780nm ,and 1600nm and for the refractive-index structure parameter C_n^2 10^{-14} $m^{-2/3}$ as strong turbulence , the scintillation index for λ = 1600nm has larger scintillation index value than λ = 780nm, and (FSO A) also has large scintillation index value from the (FSO) systems B and (C).also the scintillations index can be reduced by increasing the collection area of the receiver lens, this area causes an integration of various intensities incident on particular parts of the lens, this phenomenon is known as aperture averaging. according to these rustles the aperture averaging factor is shown in the fig.5 and it is clears from Fig.5.that for large area of the receiver as in (FSO C) system with λ = 780nm the aperture averaging factor has less value than (FSO C) system with λ = 1600nm ,while aperture averaging factor for (FSO A) system be more increased form other systems where the scintillations is increase for this system .for this purpose the λ = 780nm is give the best results than λ = 1600nm to operate the (FSO) system . Fig.6.(a & b) show the attenuation by scattering as a function of visibility range for two wavelength (780 nm and 1600nm),in this Fig. we split the scale of visibility range in order to see easily all the behavior of Attenuation curves at low values ,as shown the class of fog, mist, and haze in relation to the visibility corresponds to the classification given in Equations (26,27,28&29). It is clear that the two Naboulsi formulas show higher atmospheric attenuation compared to the Kim and Kruse relations for two wavelength . it can be noted that the energy loosing from the laser beam through the atmosphere decreases with increasing the visibility, where the visibility represents the weather conditions, this means there is a visual range which is related to weather condition specially related to radius and distribution of the atmospheric particles. It can be concluded from Fig.6.that the attenuation at a given visibility value decreases with increasing the wavelength. For compare , there are not large different attenuation between two wavelengths(780 nm and 1600nm) for operation the (FSO)systems.

6. Conclusion

The power link margin decrees with increasing the link distance and it decrees with decreasing the diameter of the receiver. The received optical power, which decreases with increasing link distance ,where the increase in the diameter of the receiver lead to decrease in loss of power. the scintillation index is reduced a lot by increasing the diameter of the receiver. and the scintillation index increasing with link distance firstly grows rapidly in the weak fluctuation and then decreases slowly with increasing the distance. The attenuation at a given visibility value decreases with increasing the wavelength. there are not large different in value of attenuation for 780 nm or 1600nm for operation the (FSO)systems. the correct operation of (FSO)in foggy conditions need a large power link margin to overcome of beam attenuation by scattering.

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Tab. 1. Parameters of the FSO systems used for calculations[2].

Parameters	FSO A	FSO B	FSO C
P_0 [dB.m]	10	10	13
P_r [dB.m]	-27	-30	-30
W_0[mm]	10	10	20
F[m]	-5	-10	-20
D[mm]	75	100	150
2θ[mrad]	4	2	2

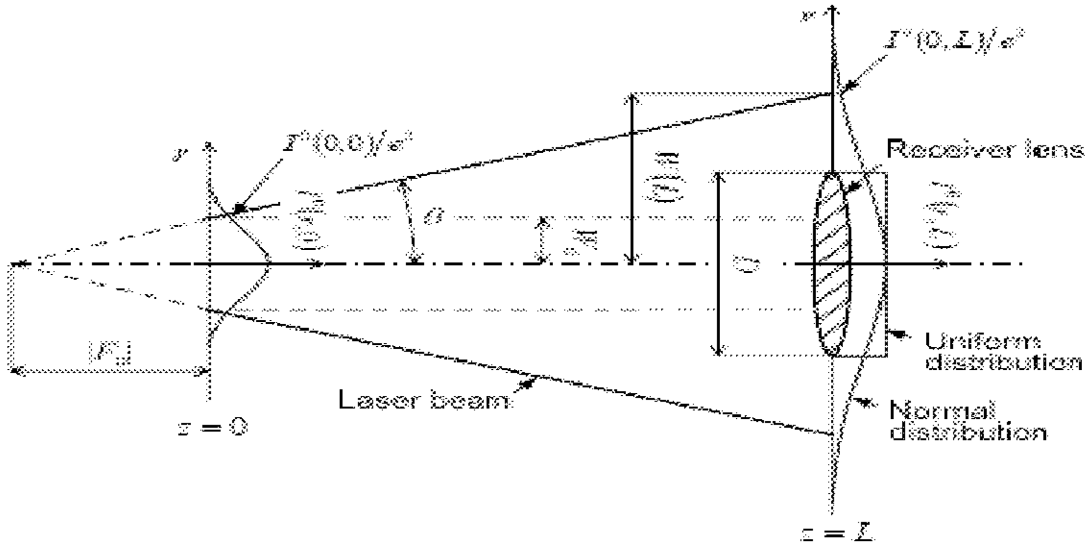

Fig. 1. Definition of the Gaussian beam's parameters [2,6,8].

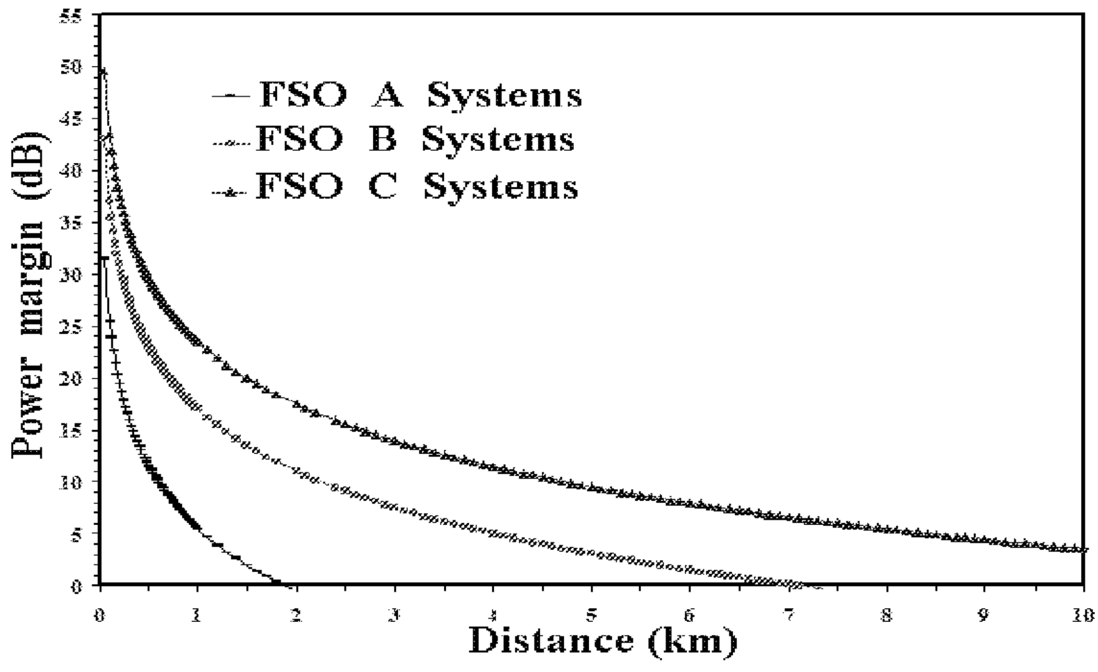

Fig. 2. Power margin as function of propagation range.

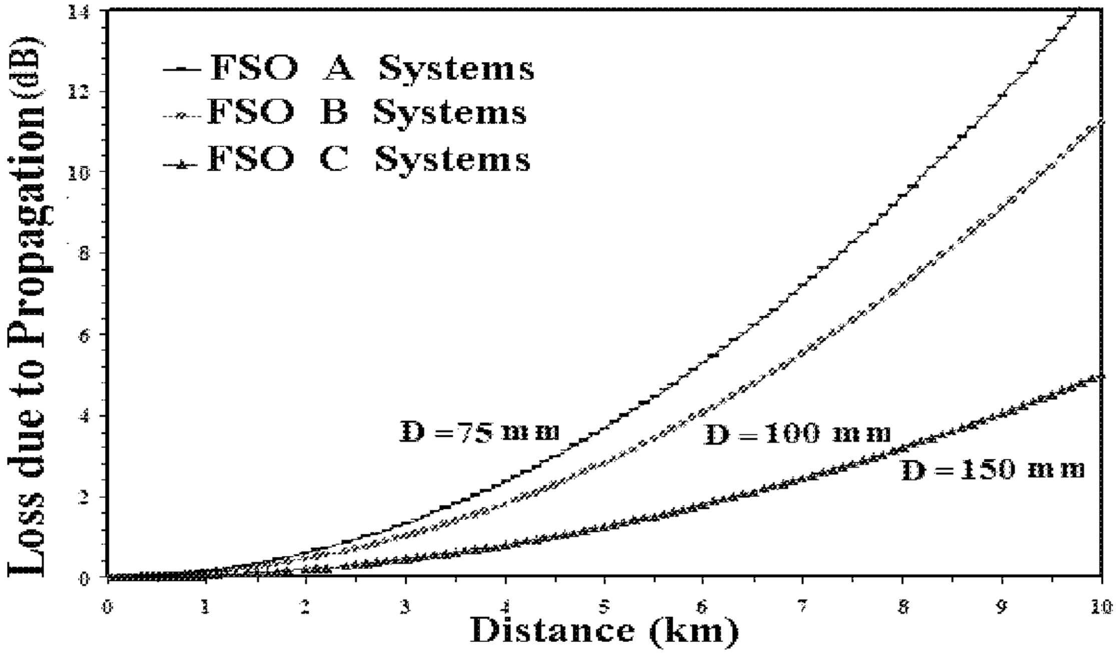

Fig. 3. Power loss due to propagation as function of propagation range for FSO systems.

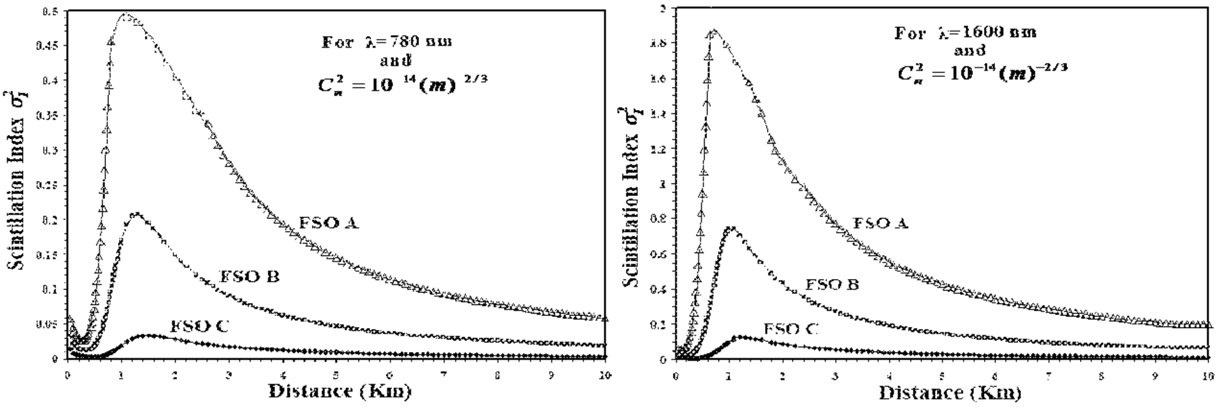

Fig. 4. Scintillation index as a function of propagation range for FSO systems

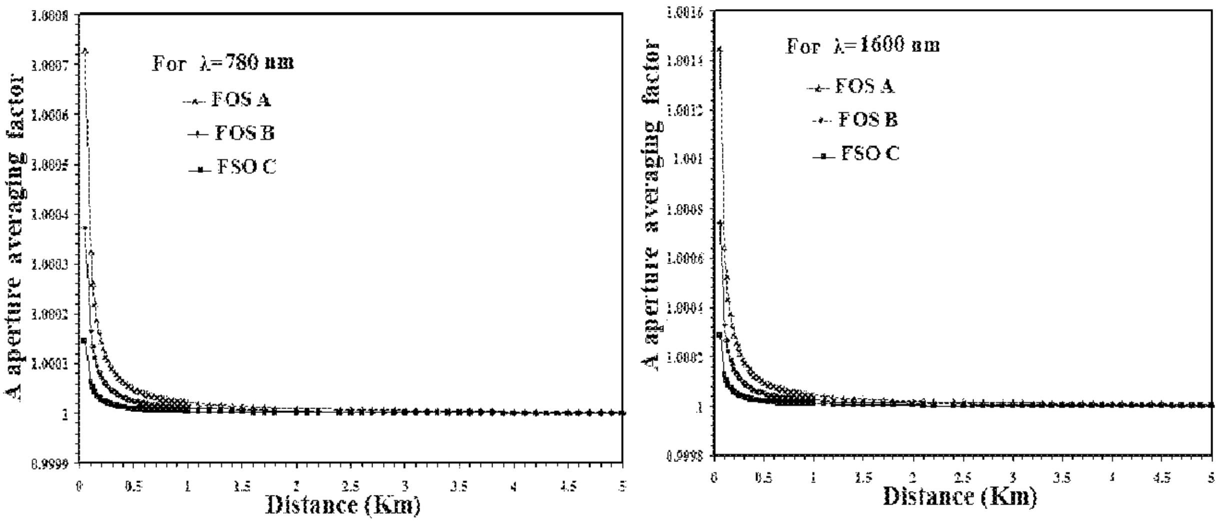

Fig. 5. aperture averaging factor as a function of propagation range for FSO systems

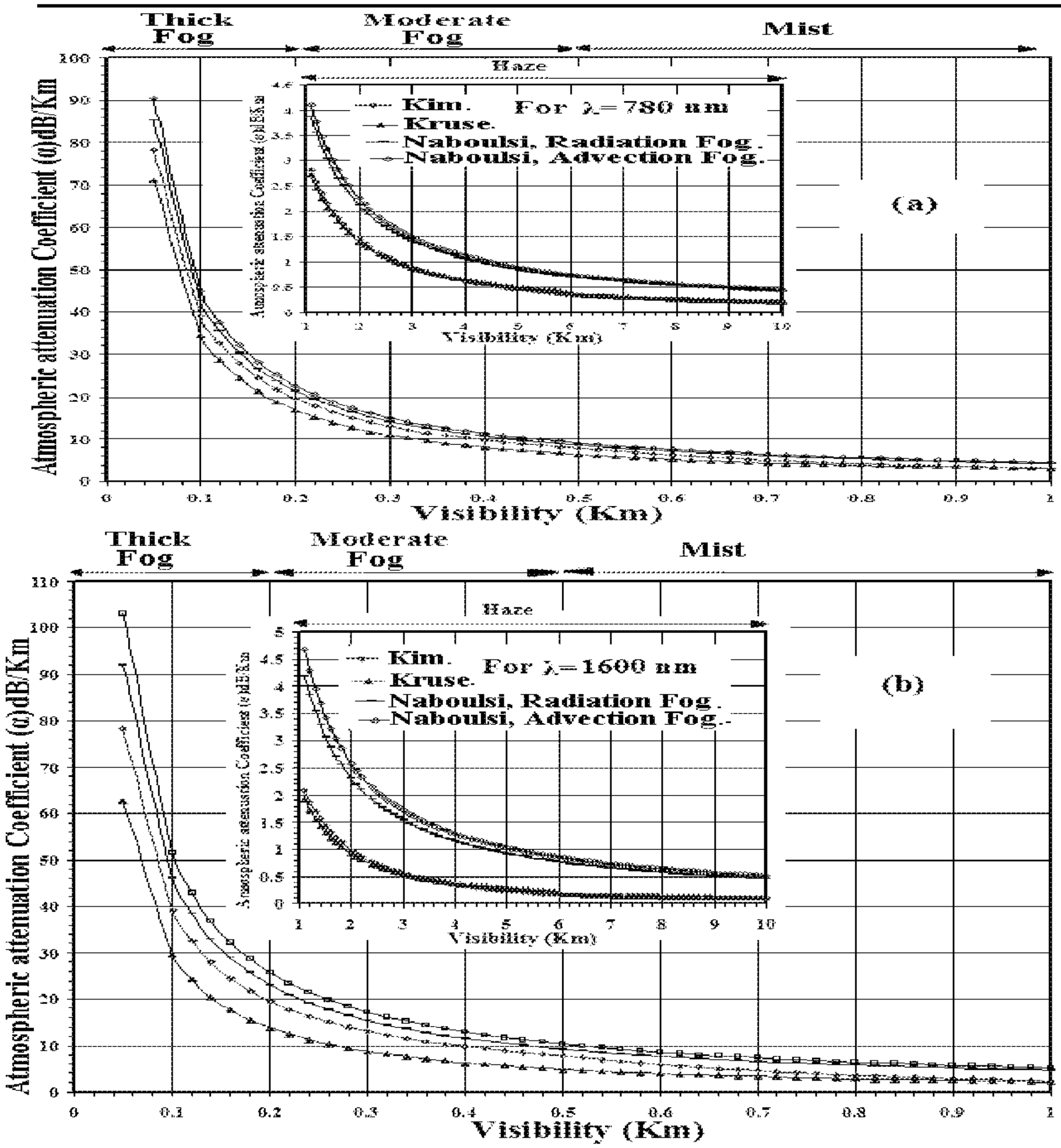

Fig. 6. Attenuation due to Scattering as a function of Visibility range.

الخلاصة

في هذا البحث تم مناقشة المعلمات البصرية التي تؤثر على أداء منظومة الاتصالات البصرية في الفضاء (FSO) المتمثلة بالطول الموجي، القدرة الضوئية النافذة ،عامل توسيط الفتحة و حد القدرة لمسارات روابط مختلفة . كما تم مناقشة معمل التلألؤ الناجم عن الاضطراب في الغلاف الجوي والتوهين الجوي للحزمة الليزرية نتيجة الاستطارة بواسطة الضباب الكثيف والضباب الخفيف لهذه المنظومة، نفذت عمليات المحاكاة للانتشار الأفقي للحزمة الكاوسية ولطولين موجيين 1600 nm, and . 780nm