Optical Laser Sources Selection Criteria for High Transmission Capacity Free Space Optical Communications and Eye Safety through Atmospheric Conditions

Ahmed Nabih Zaki Rashed
Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT

Abstract— *This paper has presented the free space transmission and atmospheric transmission limitations. As well as we have studied quality factor and bit error rate at the receiver side under the atmospheric conditions for different optical transmission regions.*

Keywords- Eye safety, Laser selection criteria, Atmospheric conditions, Free space optics, and Laser communication.

I. INTRODUCTION

Free-space optical communication has attracted a lot of attentions recently. A lot of groups have conducted many experiments on the FSO (free-space optical) communication [1]. As for the terrestrial applications it is always used for providing communication links for up to several kilometers. Together with the advancement of optical fiber technology, free-space optical communication system requires even faster communication speed [2]. In order to enhance the communication speed it is a good idea to use full-optical free-space optical communication system. In the past, the free-space optical communication systems always used photo detectors as the receiver. As there are limitations in using the photo detectors, we use optical fiber as the receiver in the next generation free space optical communication systems. We defined the systems that use optical fiber as the receiver as full-optical free-space optical communication systems. We can use the erbium-doped fiber amplifiers (EDFAs) and wavelength division multiplexing (WDM) technology to achieve higher communication capacities [3]. Using this full-optical technology it is easy to connect with existing widely deployed optical fiber network. For the next generation free space optical communication system full-optical is very attractive technology. When the free space optical communication system is used in the terrestrial application, it is deeply influenced by the atmospheric turbulence. From 1960s, many scientists have done a lot of works on the optical wave propagation through atmosphere turbulence [4]. They have given some models about the optical wave propagation through random media. For an optical wave propagating about 1 km, we can use Rytov method to calculate the effect of the atmosphere turbulence on the optical wave propagation. And it gives quite good agreement with the experiment data [5]. Ronald has summarized many important results about the properties of wave propagation in random media. In recent years some researchers use the theory to analyze intensity fluctuations when the receiving aperture is small and for the full-optical free-space optical system, the received fiber core is very small. It has influenced not only the intensity fluctuation as a result of atmospheric turbulence but also the angle-of arrival fluctuation. The AOA (angle-of-arrival) fluctuation has more influence on the full-optical system.

Wireless networks offer the user increased mobility and flexibility, allowing information to be accessed or exchanged anywhere, without the need for a physical connection to a network. Early wireless radio LAN products operated in the unlicensed 900 MHz and 2.4 GHz Industrial-Scientific-Medical (ISM) bands [6]. However, the bandwidths available at these frequencies are limited, and must be shared with other products on the market, such as cordless telephones, baby monitors and microwave ovens, which gives rise to the use of robust anti-interference spread spectrum techniques. In applying wireless infrared communication, non-directed links, which do not require precise alignment between transmitter and receiver, are desirable. They can be categorized as either line-of-sight (LOS) or diffuse links. LOS links require an unobstructed path for reliable communication, whereas diffuse links rely on multiple optical paths from surface reflections. On the other hand, FSO communication usually involves directed LOS and point to-point laser links from transmitter to receiver through the atmosphere. FSO communication over few kilometer distances has been demonstrated at multi-Gbps data rates [2]. FSO technology offers the potential of broadband communication capacity using unlicensed optical wavelengths. However, in-homogeneities in the temperature and pressure of the atmosphere lead to refractive index variations along the transmission path.

These refractive index variations lead to spatial and temporal variations in optical intensity incident on a receiver, resulted in fading. In FSO communication, faded links caused by such atmospheric effects can cause performance degradation manifested by increased bit error rate (BER) and transmission delays [3].

II. BEAM FORMING OPTICS AND LASER SOURCE SELECTION CRITERIA FOR FSO

The key element in any optical communication system is an optical source that can easily be modulated. Such a source should produce energy concentrated in a narrow wavelength band, and should be capable of being modulated at very high rates. One of the primary sources of light in modern optical systems is the semiconductor laser. Their basic principles and characteristics, such as their output beam profile, will be important in assessing their performance when used in a free space optical (FSO) system. In long-range FSO communications, light fields from optical sources can be collected and refocused using beam forming optics, which will orient the light into particular directions. A combination of converging and diverging lenses placed at the source is used to produce a collimated beam.

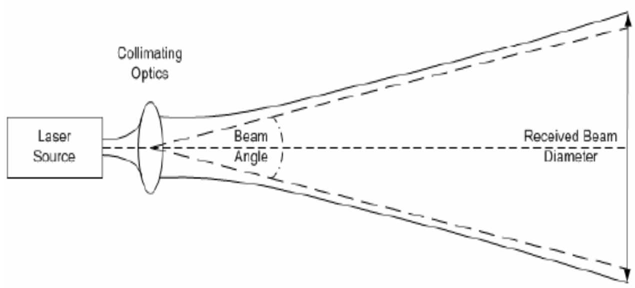

Fig. 1. Laser beam collimation in long range FSO links.

Figure 1 shows a simple type of beam collimation commonly used in long-range links. For short-range links, in order to obtain omni directionality, the optical light needs to emerge over a wider angle, but at the expense of rapid beam expansion with distance In an ideal collimation process, the converging lens focuses the light source to a point and the diverging lens expands it to a perfect beam. In practice, the source field is instead focused to a spot, and the expanded beam spreads during propagation with a planar beam diameter [7]. Optical source may be a laser diode (LD) or light emitting diode (LED), which used to convert the electrical signal to optical signal. A laser diode is a device that produces optical radiation by the process of stimulated emission photons from atoms or molecules of a lasing medium, which have been excited from a ground state to a higher energy level. A laser diode emits light that is highly monochromatic and very directional. This means that the LD's output has a narrow spectral width and small output beam angle divergence. LDs produce light waves with a fixed phase relationship between points on the electromagnetic wave. There are two common types of laser diode: Nd:YAG solid state laser and fabry perot and distributed-feedback laser (FP and DFB) The selection of a laser source for FSO applications depends on various factors. They factors can be used to select an appropriate source for a particular application. To understand the descriptions of the source performance for a specific application, one should understand these detector factors. Typically the factors that impact the use of a specific light source include the following [8]: price and availability of commercial components; transmission power and lifetime; modulation capabilities; Eye safety, and physical dimensions and compatibility with other transmission media [9].

III. SYSTEM MODEL ANALYSIS

With indoor wireless communications using infrared beams, eye safety issues must be addressed. The International Electro technical Commission (IEC) document IEC 825-1 defines the maximum exposure limits. This standard does not distinguish between the laser and LED emission level. The following formulae were established by the American National Standards Institute as a guideline for the safe use of lasers [4]. The maximum permissible exposure (MPE) values of intrabeam viewing for a nearly point source are [10]:

$$MPE = 1.8\, C_A\, t^{-0.25}\ \ mW/cm^2 \tag{1}$$

$$MPE = 0.32\, C_A\ \ mW/cm^2 \tag{2}$$

Where t is the irradiation exposure time in sec, which ranges from 50 μsec to 1000 sec, and the parameter C_A can be given by the following formula [11, 12]:

$$C_A = 10^{0.002\,(\lambda - 700)} \tag{3}$$

The attenuation of laser power through the atmosphere is described by the exponential Beers-Lambert Law [13]:

$$T_S = \exp\left(-\sigma L\right) \tag{4}$$

Where T_S is the signal transmittance, L is the link range, and σ is the signal attenuation per unit length. The attenuation coefficient has contributions from the absorption and scattering of laser photons by different aerosols and gaseous molecule in the atmosphere. Since lasercom wavelengths (typically 850 nm, 1300 nm and 1550 nm) are chosen to fall inside transmission windows within the atmospheric absorption spectra, the contributions of absorption to the total attenuation coefficient are very small. The effects of scattering, therefore, dominate the total attenuation coefficient. The type of scattering is determined by the size of the particular atmospheric particle with respect to the transmission laser wavelength. This is described by a dimensionless number called the size parameter, α which is given by:

$$\alpha = \frac{2\pi r}{\lambda} \quad (5)$$

Where r is radius of the scattering particle, and λ is the laser wavelength. Where the signal attenuation σ can be given by the MATLAB curve fitting program to get [14]:

$$\sigma(dB) = 10 \log\left(\frac{3.91\alpha}{\lambda^{1.6}}\right) \quad (6)$$

To determine whether the atmospheric attenuation critical for lasercom is wavelength dependent or not, we first go to scattering first principles. A scattering particle will have an effective scattering cross section C, which will vary depending on size parameter, which is the ratio of the size of the particle to the radiation wavelength, and the difference in index of refraction between the scattering particle and the ambient air. The scattering efficiency Q is defined as the scattering cross section normalized by the particle cross-sectional area [15]:

$$Q = \frac{C}{2\pi r} \quad (7)$$

Another approach to determine the wavelength dependence of atmospheric attenuation is to perform the full Mie calculation for some known particle size distributions. A popular analytic size distribution model for atmospheric particles is the modified gamma distribution [16]:

$$n = a\, r^{\Gamma} \exp\left(-b\, r^{\gamma}\right) \quad (8)$$

Where n is the particle concentration per unit volume per unit increment of the radius, r is the radius of the particle a, α, b, γ are positive and real constants, and α is an integer which is taken average value of a=633.35, Γ=2.8, γ=0.7, and b=6.26. Generally, the distinction between the two cases of weak and strong turbulence are made by considering the Rayleigh scattering, σ_R which is given by [17]:

$$\sigma_R = \sqrt{1.23 C_n^2 \left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6}} \quad (9)$$

Where C_n^2 is the turbulence strength in $m^{-2/3}$, λ is the laser wavelength, and L is the link range. Based n the data clarified in Ref. [17], the fitting relationship between quality factor (QF), bit error rate (BER) with divergence angle θ in mrad can be given by the following formula [18]:

$$QF(dB) = 1.342\, P_T \exp(-0.652\theta) \quad (10)$$

For optical wireless links or free space optics, the bit error ate (BER) is considered by the following formula:

$$BER = \frac{\exp(-0.5\, QF)}{\sqrt{2\pi QF}} \quad (11)$$

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

We have deeply investigated the optical laser sources selection criteria for high transmission capacity free space optical communications and possible Eye Safety ranges through atmospheric conditions for different particle size distribution over wide range of the affecting parameters which are completely shown in Table 1. Aw well as we have analyzed the general acceptance of free space laser communication (lasercom) or optical wireless as the preferred wireless carrier of high bandwidth data has been hampered by the potential downtime of these lasercom systems in heavy, visibility limiting, and weather conditions.

Table 1: Proposed operating parameters for short range wireless optical communication links [1, 4, 7, 12, 15].

Operating parameter	Value and unit
Propagation length, L	100 m ≤ L ≤ 1000 m
Irradiation exposure time, t	50 μsec ≤ t ≤ 1000 sec
Ultra violet laser wavelength, λ_{UV}	200 nm ≤ λ_{UV} ≤ 400 nm
Visible laser wavelength, λ_{Vis}	400 nm ≤ λ_{Vis} ≤ 700 nm
Near infrared laser wavelength, λ_{NIR}	700 nm ≤ λ_{NIR} ≤ 1600 nm
Turbulence strength, C_n^2	$10^{-17} \le C_n^2 \le 10^{-12}$
Transmitted Laser power, P_T	100 mW
Divergence angle, θ	1 mrad ≤ θ ≤ 6 mrad
Particle type	Particle Radius (μm)
Haze particle	0.0001 - 10
Fog droplet	5 to 20
Hail	5000 to 10000

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. (2-21):

i) Figs. (2-5) have assured that maximum permissible exposure increases with increasing both operating laser signal wavelength for different operating signal transmission regions and laser irradiation exposure time.
ii) Figs. (6-8) have indicated that atmospheric signal attenuation increases with increasing particle radius, propagation length and decreasing operating laser signal wavelength. It is observed that in the case of hail particles have presented the highest atmospheric signal attenuation in compared with other particles radius under the same operating conditions.
iii) As shown in Figs. (9-17) have demonstrated that atmospheric signal transmission decreases with increasing particle radius, propagation length and decreasing operating laser signal wavelength. It is observed that in the case of hail particles have presented the lowest atmospheric signal transmission in compared with other particles radius under the same operating conditions.

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iv) Figs. (18-20) have indicated that laser beam scattering increases with increasing both propagation length and refractive index structure turbulence strength and decreasing operating laser signal wavelength.

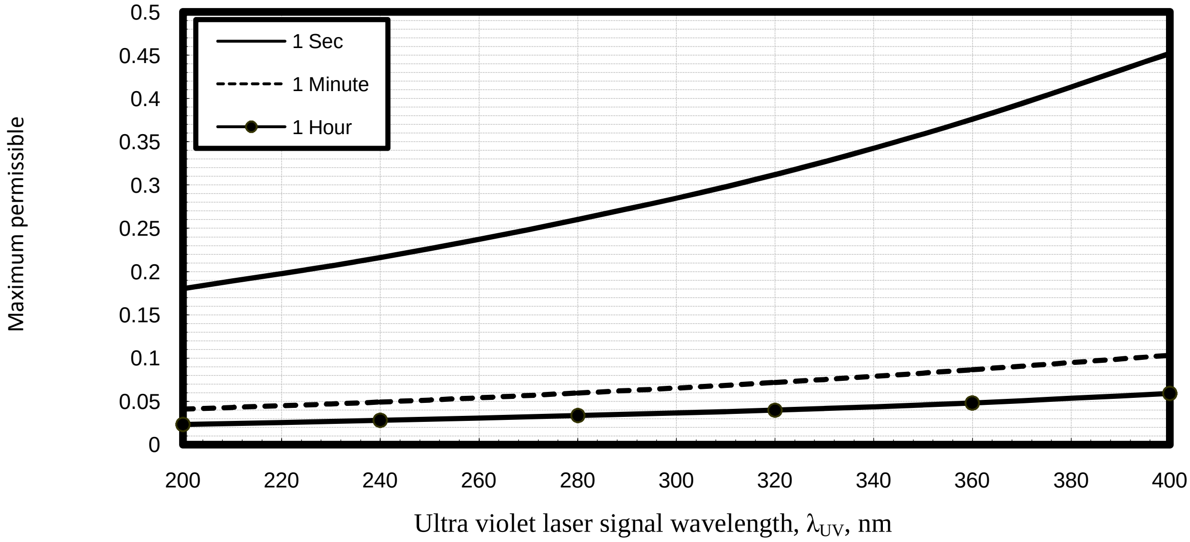

Fig. 2. Maximum permissible exposure in relation to ultraviolet laser signal wavelength and laser exposure irradiation time at the assumed set of the operating parameters.

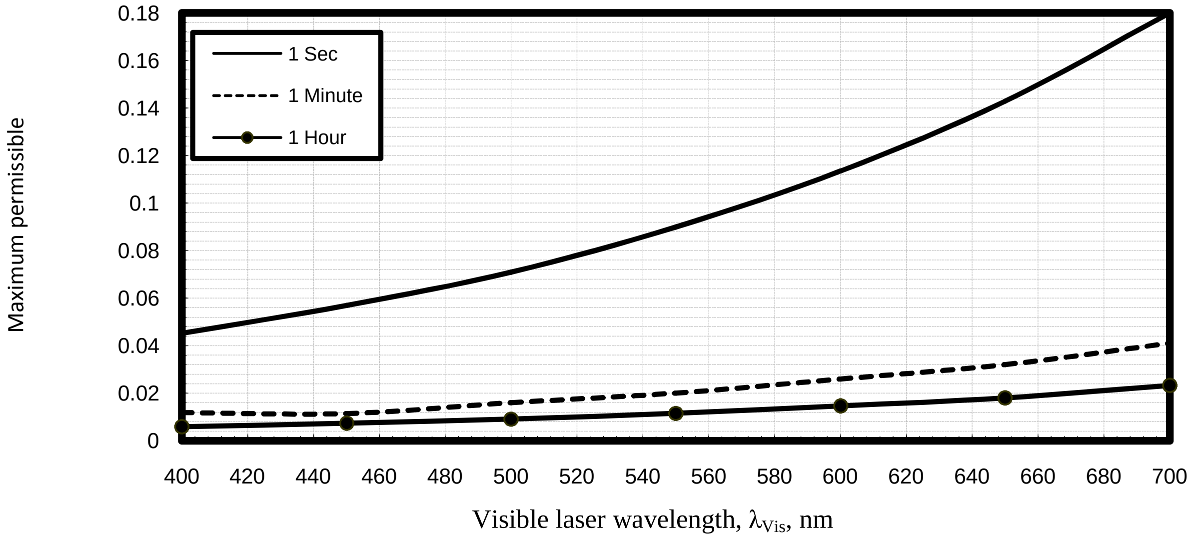

Fig. 3. Maximum permissible exposure in relation to visible laser signal wavelength and laser exposure irradiation time at the assumed set of the operating parameters.

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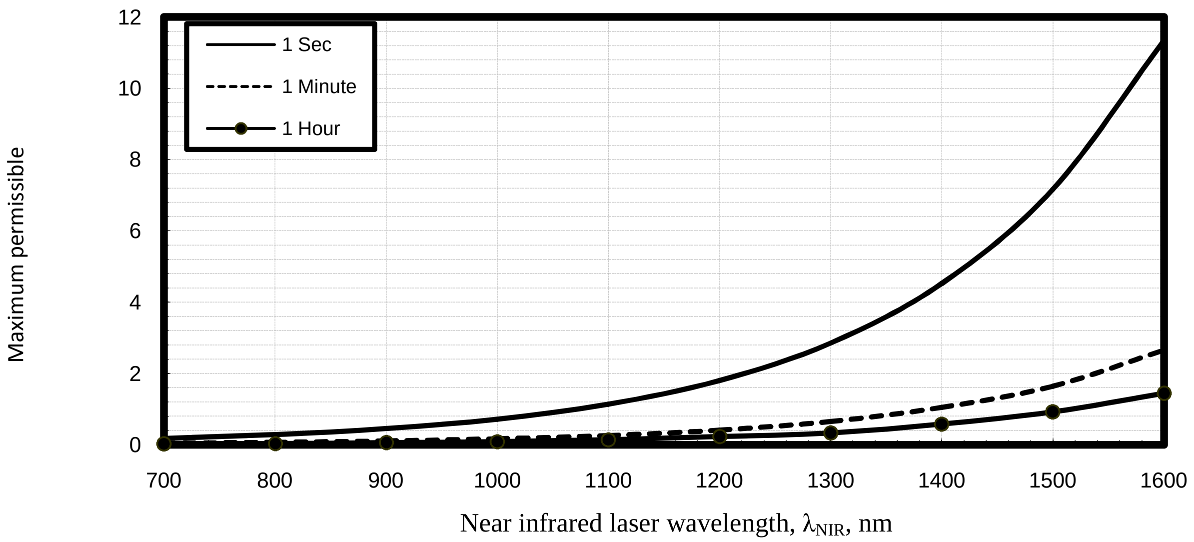


Fig. 4. Maximum permissible exposure in relation to near infrared laser signal wavelength and laser exposure irradiation time at the assumed set of the operating parameters.

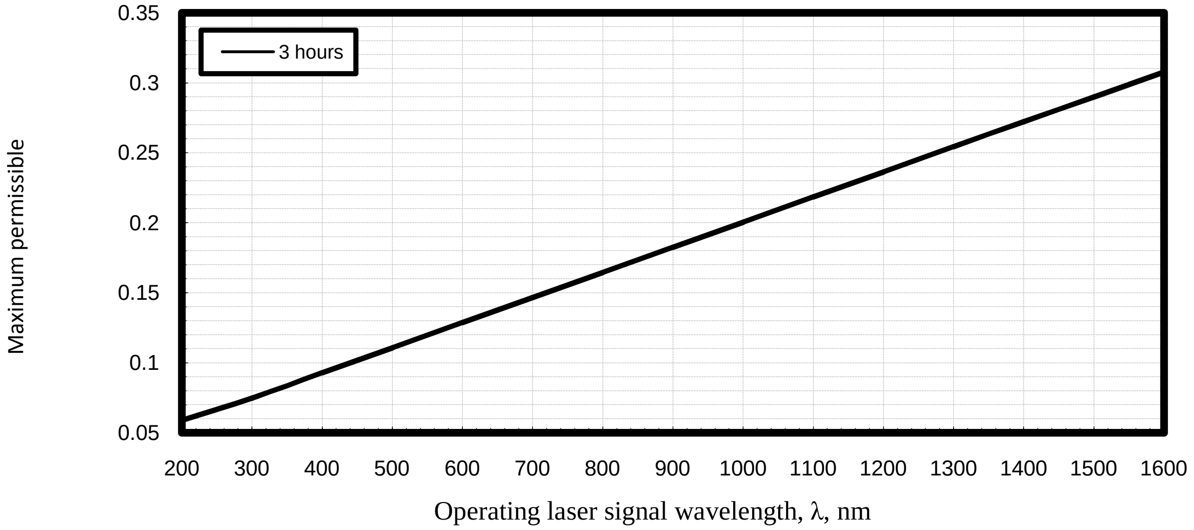


Fig. 5. Maximum permissible exposure in relation to different operating laser signal wavelength transmission regions and laser exposure irradiation time of 3 hours at the assumed set of the operating parameters.

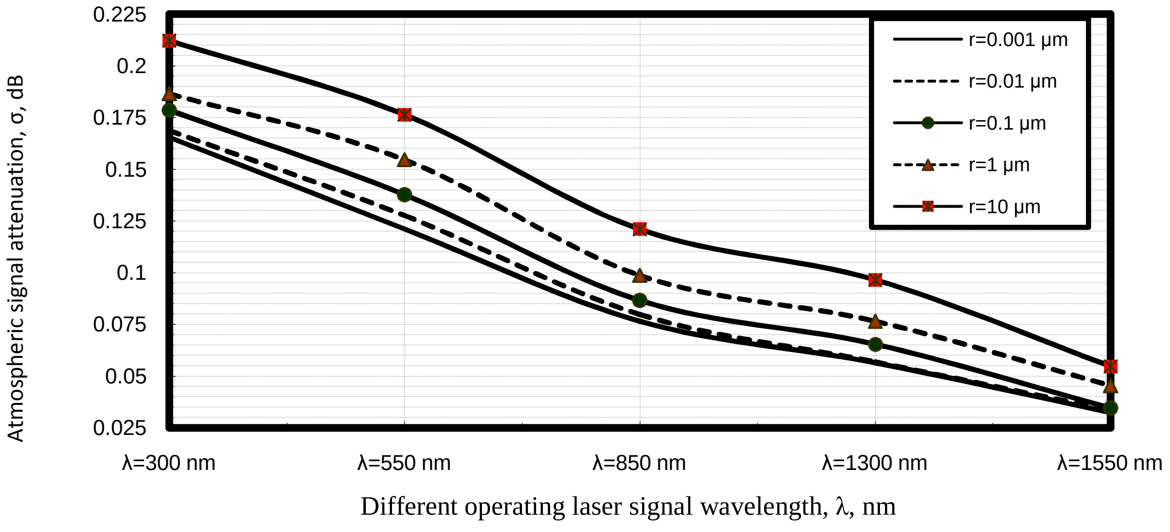


Fig. 6. Atmospheric signal attenuation against different operating laser signal wavelength and haze particle radius at the assumed set of the operating parameters.

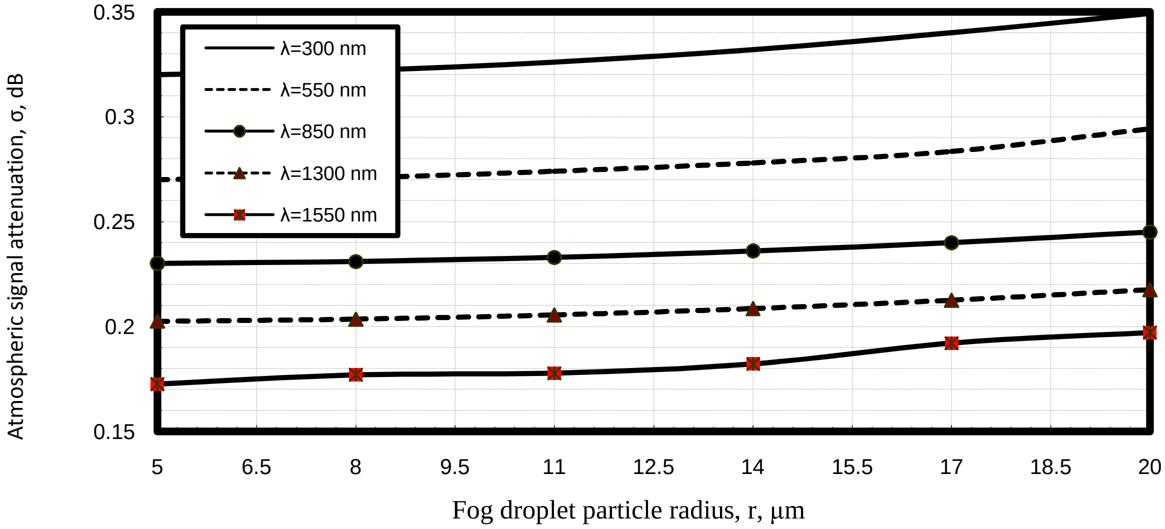


Fig. 7. Atmospheric signal attenuation against and fog droplet particle radius and different operating laser signal wavelength at the assumed set of the operating parameters.

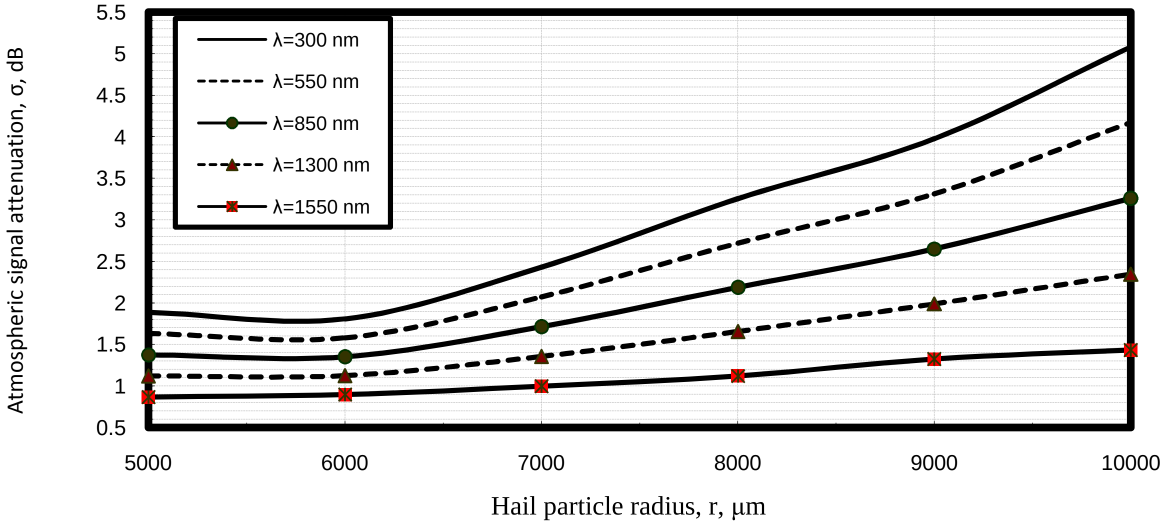
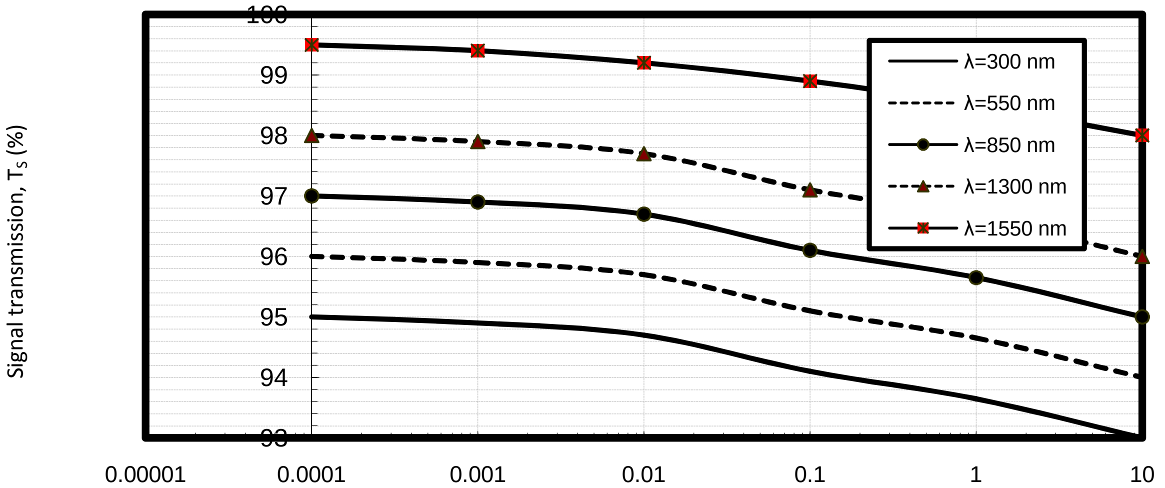
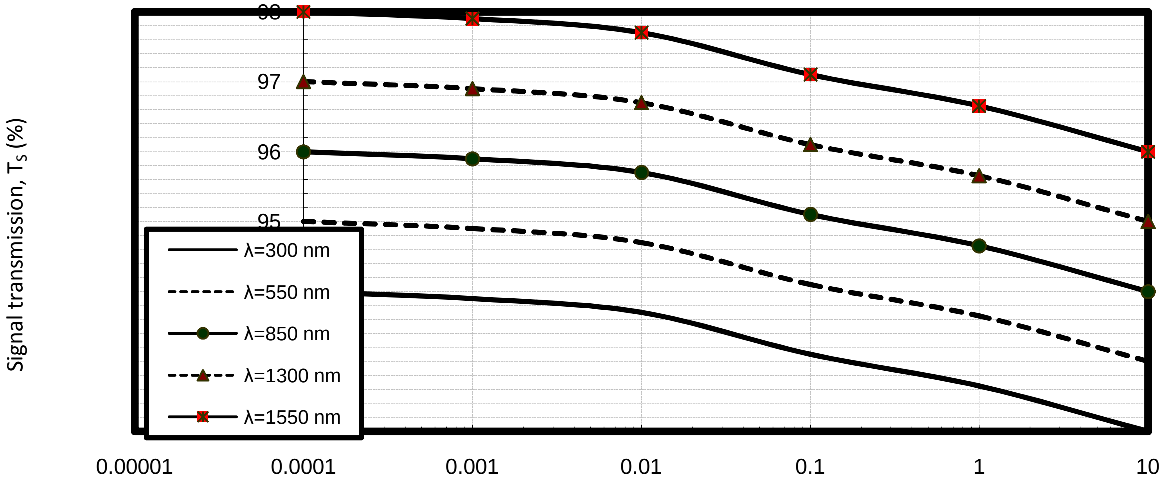


Fig. 8. Atmospheric signal attenuation against and hail particle radius and different operating laser signal wavelength at the assumed set of the operating parameters.



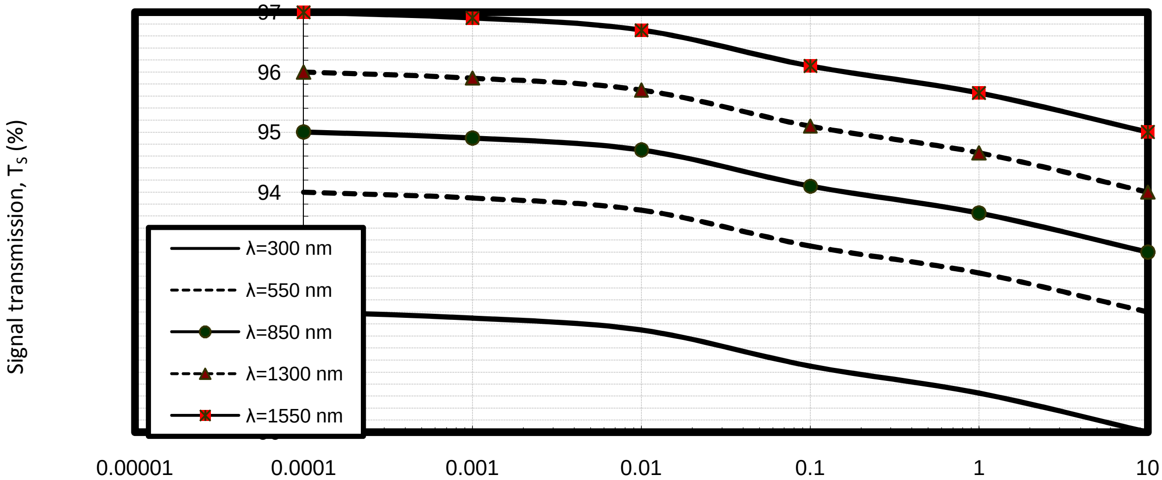
Haze particle radius, r, μm

Fig. 9. Signal transmission in relation to haze particle radius and different operating laser signal wavelength with propagation length (L=100 m) at the assumed set of the operating parameters.



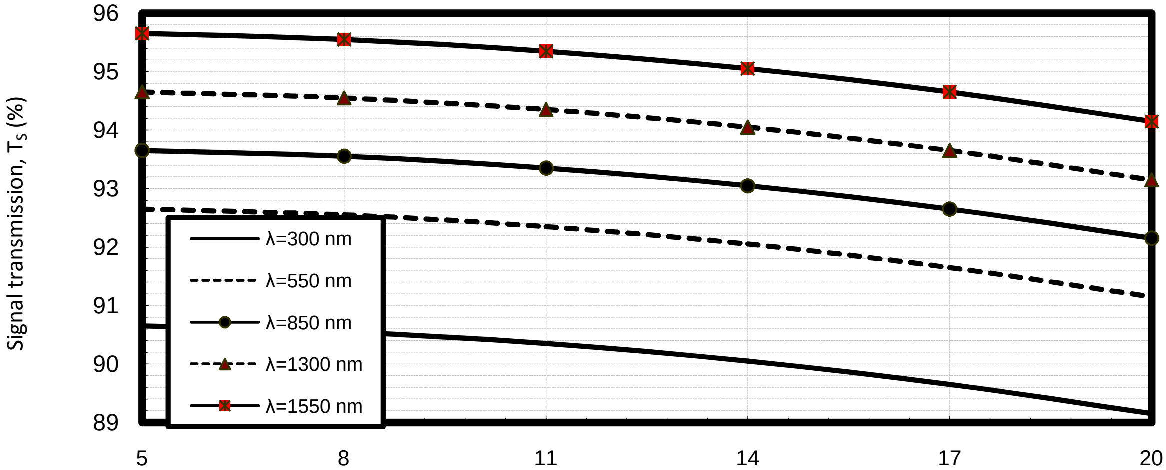
Haze particle radius, r, μm

Fig. 10. Signal transmission in relation to haze particle radius and different operating laser signal wavelength with propagation length (L=500 m) at the assumed set of the operating parameters.



Haze particle radius, r, μm

Fig. 11. Signal transmission in relation to haze particle radius and different operating laser signal wavelength with propagation length (L=1000 m) at the assumed set of the operating parameters.



Fog droplet particle radius, r, μm

Fig. 12. Signal transmission in relation to fog droplet particle radius and different operating laser signal wavelength with propagation length (L=100 m) at the assumed set of the operating parameters.

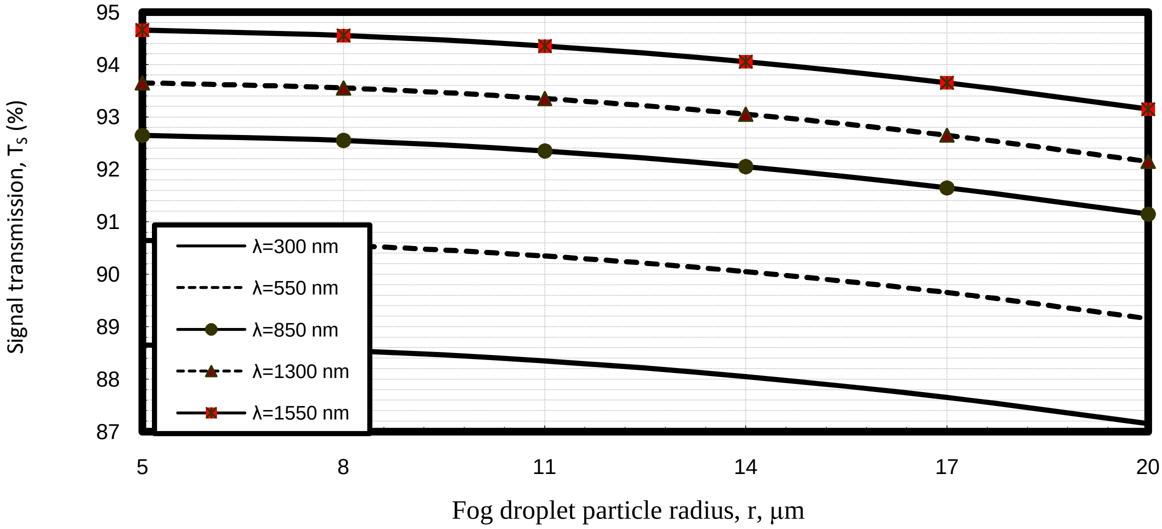


Fig. 13. Signal transmission in relation to fog droplet particle radius and different operating laser signal wavelength with propagation length (L=500 m) at the assumed set of the operating parameters.

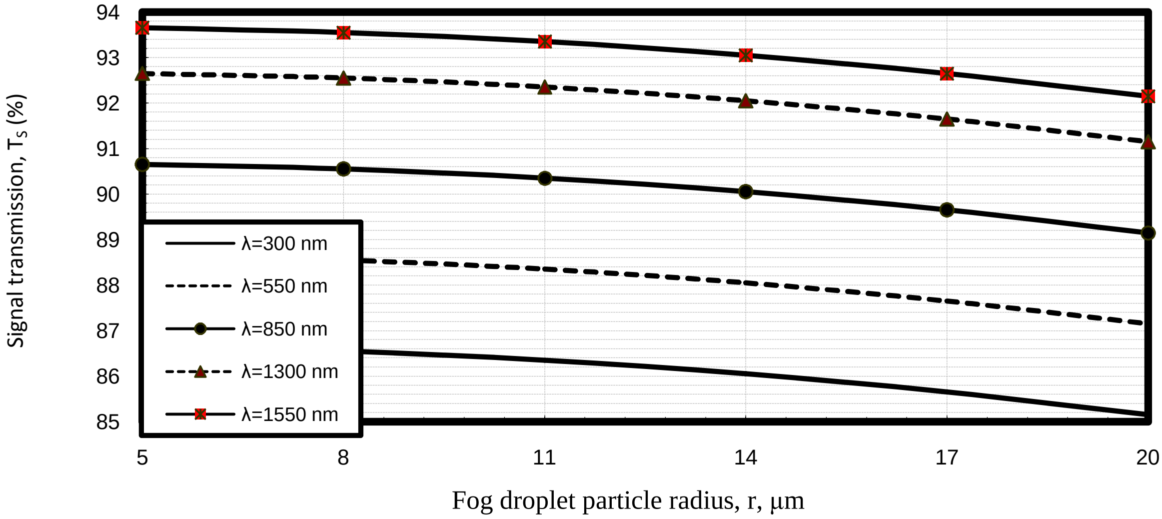
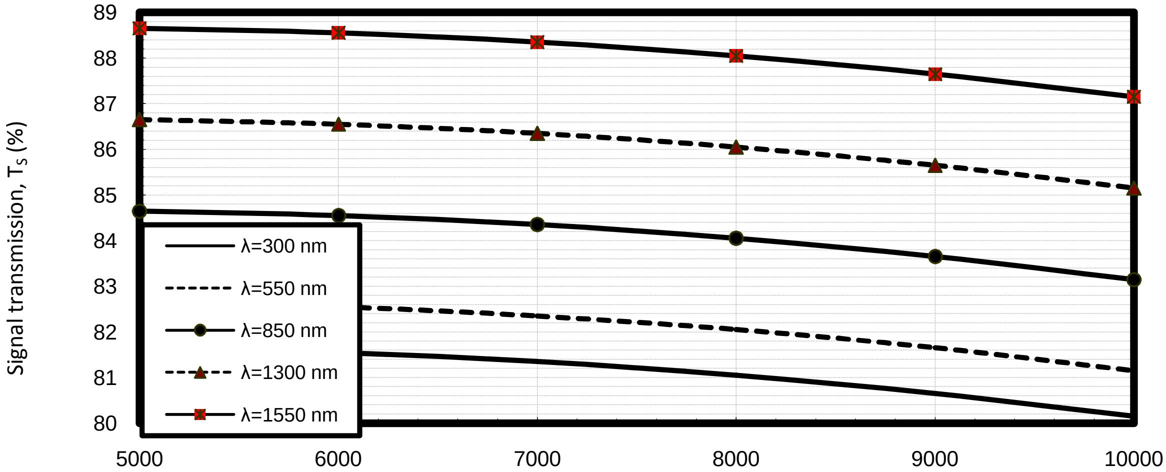


Fig. 14. Signal transmission in relation to fog droplet particle radius and different operating laser signal wavelength with propagation length (L=1000 m) at the assumed set of the operating parameters.



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Hail particle radius, r, µm

Fig. 15. Signal transmission in relation to hail particle radius and different operating laser signal wavelength with propagation length (L=100 m) at the assumed set of the operating parameters.

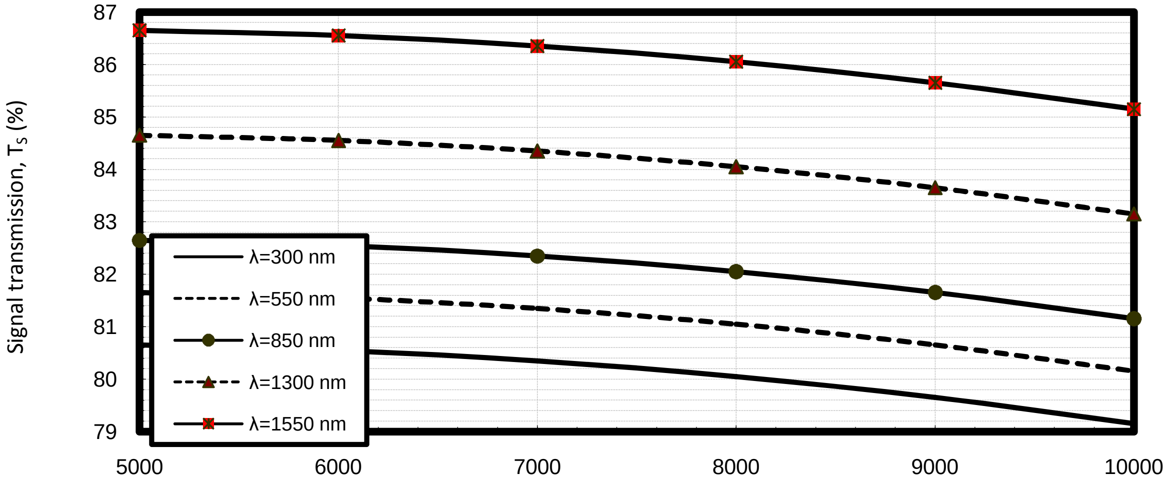


Fig. 16. Signal transmission in relation to hail particle radius and different operating laser signal wavelength with propagation length (L=500 m) at the assumed set of the operating parameters.

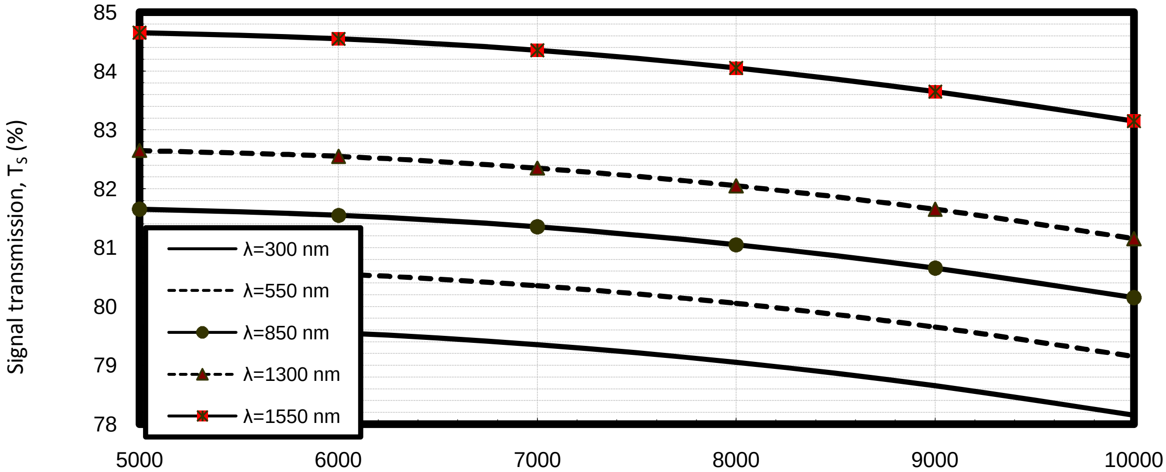
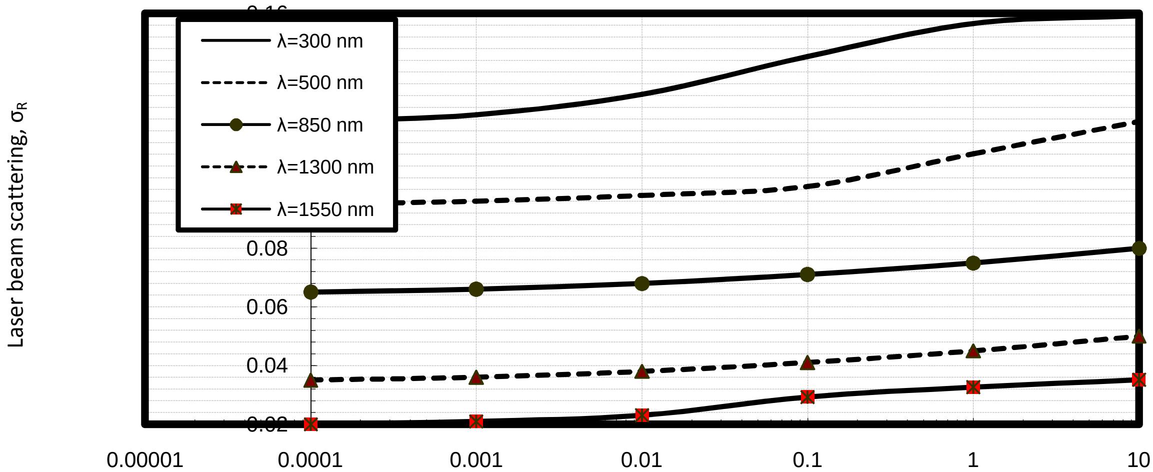


Fig. 17. Signal transmission in relation to hail particle radius and different operating laser signal wavelength with propagation length (L=500 m) at the assumed set of the operating parameters.



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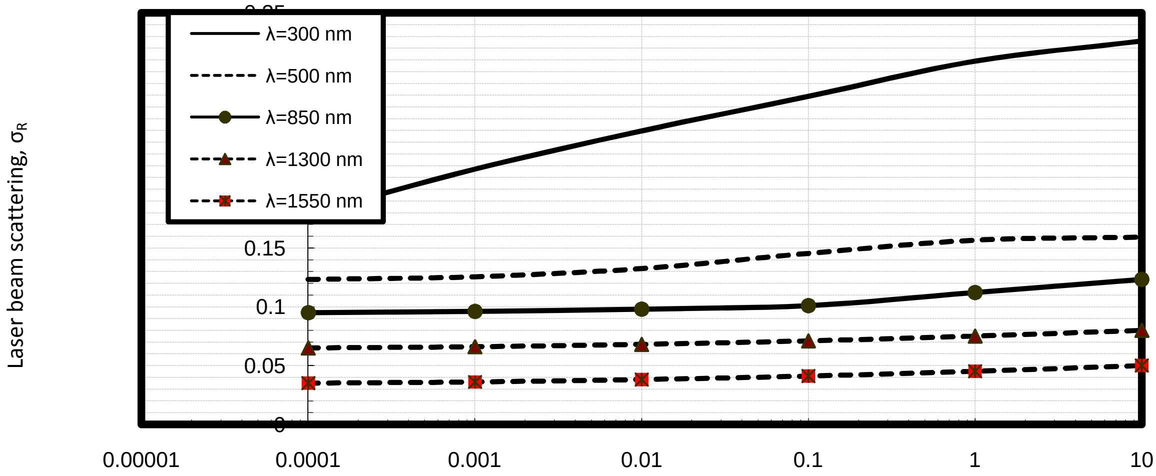
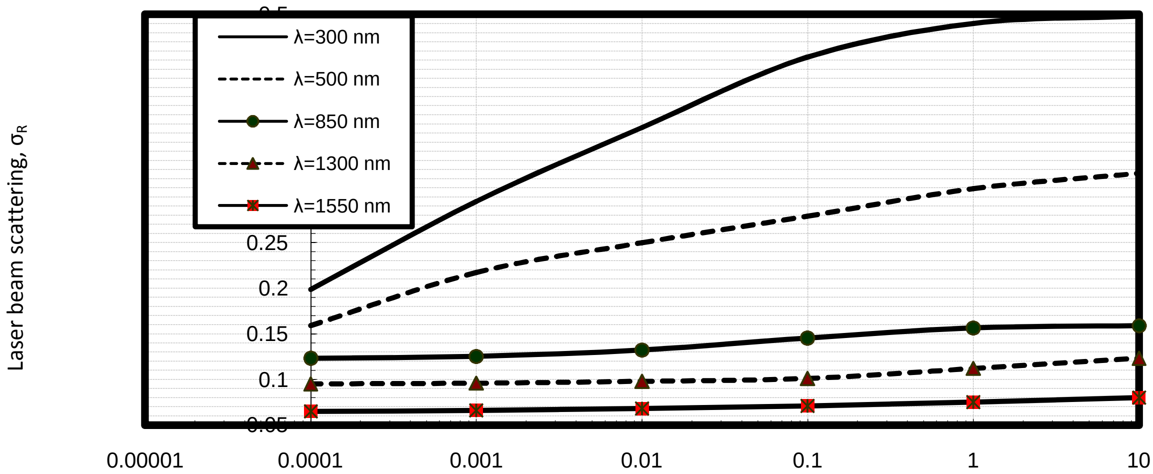
Refractive index turbulence strength, $C_n^2 x10^{-13}$, $m^{-2/3}$

Fig. 18. Laser beam scattering coefficient in relation to refractive index structure turbulence strength and different transmission laser signal wavelengths with propagation length (L=100 m) at the assumed set of the operating parameters.



Refractive index turbulence strength, $C_n^2 x10^{-13}$, $m^{-2/3}$

Fig. 19. Laser beam scattering coefficient in relation to refractive index structure turbulence strength and different transmission laser signal wavelengths with propagation length (L=500 m) at the assumed set of the operating parameters.



Refractive index turbulence strength, $C_n^2 x10^{-13}$, $m^{-2/3}$

Fig. 20. Laser beam scattering coefficient in relation to refractive index structure turbulence strength and different transmission laser signal wavelengths with propagation length (L=1000 m) at the assumed set of the operating parameters.

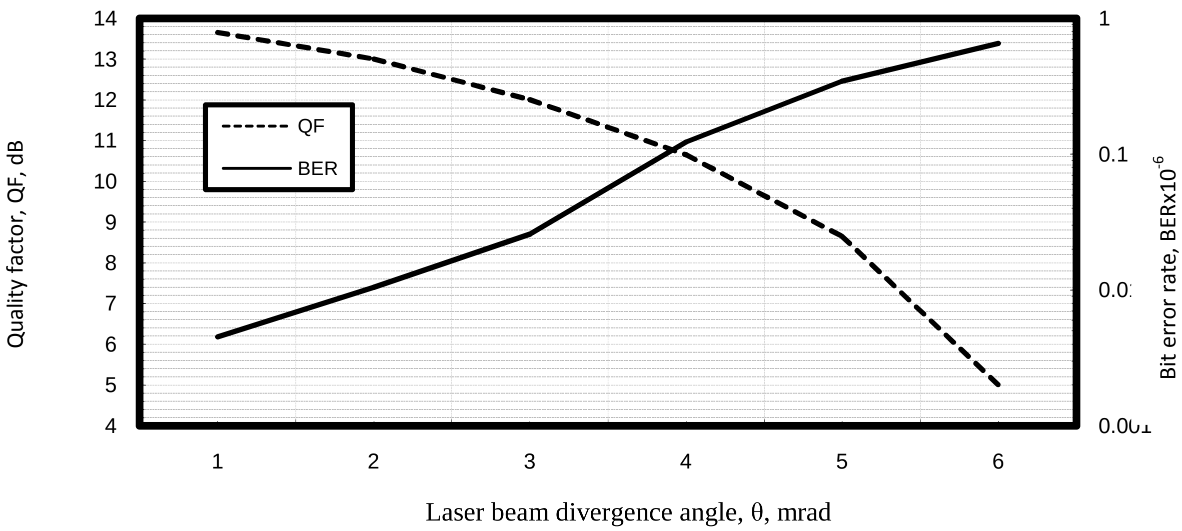


Fig. 21. Laser signal Quality factor and bit error rate in relation to laser beam divergence angle at the assumed set of the operating parameters.

v) Fig. 21 has assured that signal quality factor decreases and bit error rate increases with increasing laser beam divergence angle.

V. CONCLUSIONS

In a summary, we have been investigated the best selection criteria for laser diode sources operating conditions at near infrared operating transmission windows. It is theoretically found that the increased laser beam divergence angle, this results in the increased bit error rate and the decreased signal to noise ratio. As well as it is indicated that the dramatic effects of propagation length, refractive index structure turbulence strength on the laser beam scattering. Moreover it is observed that the dramatic effects of increasing particle radius, its concentration and propagation length on the atmospheric signal transmission and increased atmospheric signal attenuation.

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