

# Terrestrial Free-Space Optics systems: Wavelength Considerations: 10 $\mu\text{m}$ vis-a-vis Shorter Wavelengths

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**Abstract-** This paper presents analytical study of Free-Space Optics (FSO) at 10  $\mu\text{m}$  vis-a-vis conventionally used shorter wavelengths like 850, 1350 and 1550 nm under different weather attenuating conditions like fog, rain, snow and turbulence etc. while taking in to consideration maximum allowable laser power transmission from eye safety perspective and background radiations received from celestial and other hot bodies.

**Index Terms-** Free-space optics, optical wireless, atmospheric modeling, 10 micron FSO, 10  $\mu\text{m}$  FSO systems, wavelength considerations, FSO propagation

## 1 INTRODUCTION

The media for high bit rate communication being used generally is either optical fiber or RF transmission. But, there could be situations where a dark spare fiber is not available and laying of the new cable is not feasible from techno-commercial considerations. On the other hand, RF communication being prone to interference, low security, and low bandwidth and requiring a spectrum license for its usage imposes its own limitations. In such situations, FSO technology appears as a viable candidate. Free space optic (FSO) can provide line of sight, wireless, high bandwidth multi Giga bits per second links to fulfill high data rate requirements for future communication applications. However, the widespread growth of FSO has been hampered by availability and reliability issues. FSO links are highly vulnerable to weather conditions like fog etc. and results in reduced link availability for considerable amount of time. One of the solutions is to use RF back up links that are less susceptible to weather attenuations specially fog etc. The second choice calls for extensive weather database and proper understanding of fog types in the region. In this paper, we address a possible third choice that may eliminate the need for a backup link and exhibits improved fog penetration. It is based on selecting 10  $\mu\text{m}$  as the carrier wavelength over the current shorter 0.85  $\mu\text{m}$ , 1.3  $\mu\text{m}$  and 1.55  $\mu\text{m}$  wavelengths.

This paper is divided into four sections. In section two, we review the FSO technology in general, while in section three we present the analytical results of atmospheric

effects at different wavelengths and finally in section four, considerations for using 10 $\mu\text{m}$  wavelength are presented.

## 2 FSO TECHNOLOGIES

FSO system works on the principle of transmission of information using light as a carrier. FSO is a line-of-sight wireless technology which uses optical transceiver with a laser as a transmitter and a Photo detector as a receiver operating in full duplex mode. Information is transmitted between the two transceivers using the On-and-Off Keying (OOK) technique, which is a basic modulation scheme that transmits a signal when the bit "1" is transmitted and transmits nothing for "0" bits.

Being portable and compact, it can be installed easily over rooftops or behind windows and does not require a spectrum licence for its usage. It is much secured due to very narrow beam width and cost effective. It has a larger bandwidth, provides high data transmission rates up to several Gbps. FSO finds a wide variety of applications in defence, space communication, LAN to LAN connection, temporary network installation and many more. In spite of its major advantages over RF links, its widespread use is hampered by several challenges in practical deployment. For example, aerosol scattering caused by rain, snow and fog results in performance degradation leaving it vulnerable to adverse weather conditions.

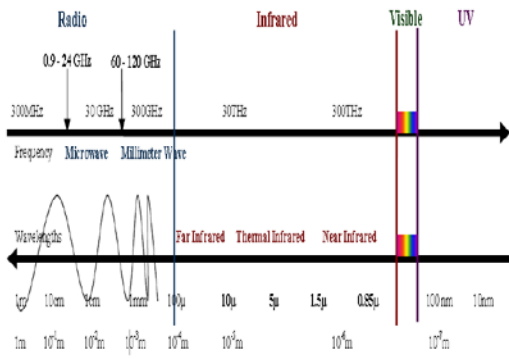


Figure 1: The electromagnetic spectrum and corresponding applications

As plainly visible in the Fig.1 above, the infrared frequency, i.e., 30THz to 300THz is used as a medium in FSO. For a convenient and analytical edge, we will be talking in the terms of wavelengths rather than frequencies for the rest of this paper.

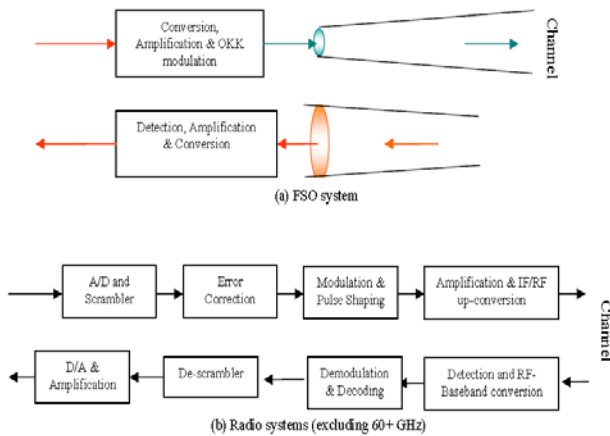


Figure 2: High layer view of FSO and Radio Systems

### 3 ATMOSPHERIC EFFECTS

The performance of FSO Link is subject to several atmospheric factors like environmental temperature, fog, smoke, haze and rain, but it is typically dominated by fog. Atmospheric attenuation is mainly caused when the optical signal encounters air molecules and other particles suspended in the air having size comparable to the optical wavelengths that are normally used for FSO transmission.

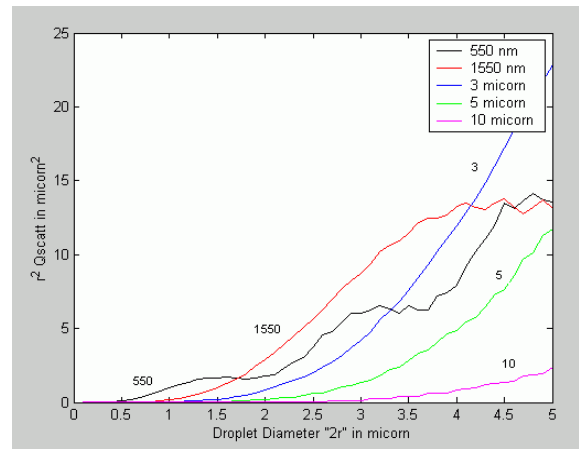


Fig. 3 Attenuation versus droplet size diameter for different wavelengths

Unlike fog, rain has a little effect on FSO and is not a major factor while considering FSO availability, but heavy rains may attenuate the strength of the transmitted beam along the path. Like rains, snow has a little effect on FSO link but this effect could increase in heavy snow. These are discussed in detail in following sub-sections.

#### 3.1 Attenuation due to fog:

Fog is the most important among the various atmospheric attenuation causing factors. The attenuation due to fog happens because of absorption and scattering of beam propagating through water particles. Fog is characterized by a number of physical parameters such as particle size distribution, liquid water content, fog temperature and humidity. Since the size of fog particles is comparable to wavelength used (near infrared window), it causes attenuation due to Mie scattering. Mie scattering is the most accurate way to calculate the attenuation in case of fog droplets but this calculation requires detailed information of fog parameters like particle size, its distribution, refractive index etc. which may not be available at the given location of FSO link and moreover it requires complex computations. Therefore an alternative method to predict specific attenuation (dB/km) due to fog, which uses visibility data, is employed. The models proposed by Kruse, Kim [1, 2] use visibility data.

The visibility can be defined as the greatest distance under given weather conditions to which it is possible to see with out instrument assistance. The visibility range is the distance that a parallel luminous beam travels through in the atmosphere until its intensity drops to 5% of its original value [3].

From Kruse model [1], the scattering coefficient in terms of visibility(V in Km) is given by

$$\alpha_{\text{scattering}} = 3.91/V \times (0.55/\lambda\mu\text{m})^q \geq 0 \quad \dots\dots\dots(1)$$

where 'q', the exponent is given by

$$q = \begin{cases} 1.6 & V > 50\text{Km} \\ 1.3 & 6\text{Km} < V < 50\text{Km} \\ 0.585V^{1/3} & V < 6\text{Km} \end{cases} \dots\dots\dots(2)$$

Further, Kim [2] proposed another expression for the parameter 'q', as a modification to the one given by Kruse above and is given as

$$q = \begin{cases} 1.6 & \text{if } V > 50\text{km} \\ 1.3 & \text{if } 6\text{km} \leq V \leq 50\text{km} \\ 0.16V + 0.34 & \text{if } 1\text{km} < V < 6\text{km} \\ V - 0.5 & \text{if } 0.5\text{km} < V < 1\text{km} \\ 0 & \text{if } V < 0.5\text{km} \end{cases}$$

..... (3)

And specific attenuation/km is given as  $= 10 \log(e)^{\alpha_{\text{scattering}}}$

Using the Kruse model, specific attenuation is approximately 16.5, 93 and 210 dB/km at 1.550μm wavelengths with visibility equal to 500 m, 100 m and 50 m respectively whereas similar attenuation is much less at 10 μm[fig. 4].

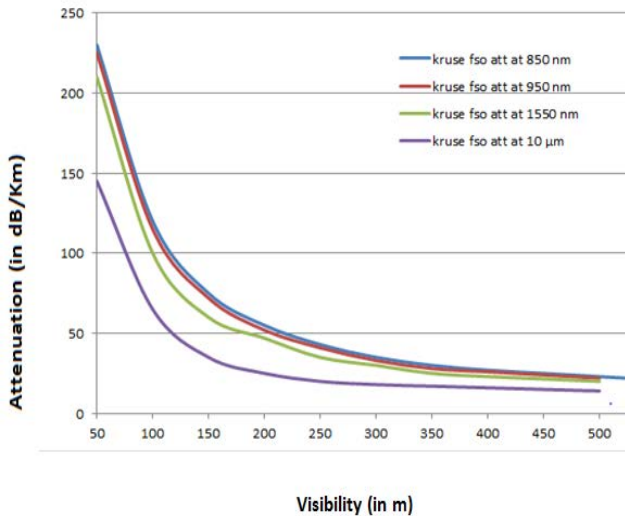


Fig 4. Attenuation measurements due to fog at different wavelengths

**3.2 Attenuation due to rain:**

The increase in rainfall rate causes linear increase in attenuation, as the size of the water droplets increases with increased rain rate. The increase results in excessive reflections and refractions.

The specific rain attenuation is related to rain fall rate as:[4]

$$\alpha_{\text{Rain}} = 1.076R^{0.67}$$

Where R is rainfall rate in mm/hr and specific attenuation in dB/km.

From the above expression, it can be seen that specific attenuation for rainfall rate of 50, 100, 200 mm/hr will be equal to 14.44, 22.978 and 36.55 dB/km respectively.

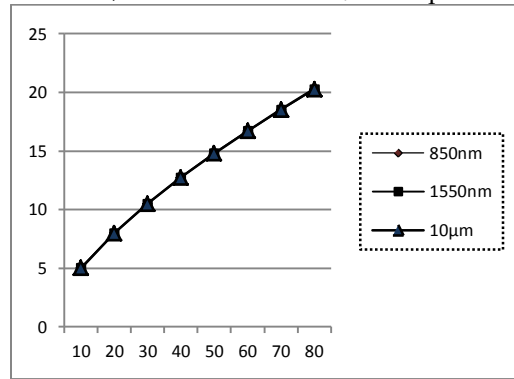


Fig 5. Attenuation due to rain at different wavelength The attenuation due to rain is independent of wavelengths as used in FSO systems

**3.3 Attenuation due to snow:**

Snow can be categorized as dry and wet snow. Dry snow is similar to fog and whereas wet snow to rain. If S is the snow rate in mm/hr, then specific attenuation due to snow is given as: [4]

$$\alpha_{\text{Snow}} = a.S^b \quad \dots\dots (4)$$

Where a and b are given for dry and wet snow respectively as:

For dry snow,

$$a = 5.42 \times 10^{-5} \lambda + 5.4958776, \quad b = 1.38; \quad \lambda \text{ in nm}$$

and for wet snow,

$$a = 1.023 \times 10^{-4} \lambda + 3.7855466, \quad b = 0.72$$

From the above, we can visualize that the specific attenuation due to dry snow (fog) can be much greater as compared to wet snow (rain) for a given snow rate.

For 10μm, when we consider snow rate as 2mm/hr, the specific attenuation constant for

dry and wet snow will be 14.30157 and 6.235 dB/km respectively and similar results are

obtained at 850 nm.

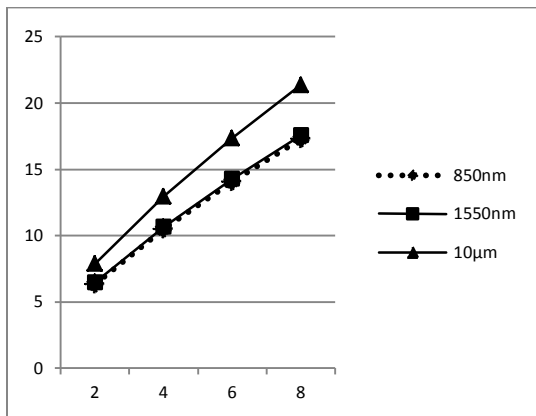
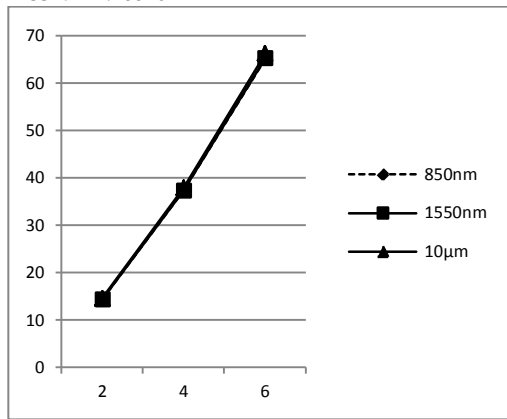


Fig. 6 Attenuation due to dry and wet snow at different wavelengths

From the above plots, we can thus infer that attenuation due to dry snow does not change with wavelength whereas attenuation due to wet snow does change. For example, the attenuation at 850 nm and 10µm are 17.27 and 21.36 dB/km respectively at 8mm/hr wet snow rate.

### 3.4 Attenuation due to scintillation: [5-7]

Atmospheric turbulence causes scintillation. It can be defined as the changing of light intensities in time and space domain at the plane of a receiver that is detecting a signal received 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. The time scale of these fluctuations is of the order of milliseconds, approximately equal to the time that it takes a volume of air the size of the beam to move across the path, and therefore is related to the wind speed.

As the refractive index structure along the path is time dependent because of the turbulent mixing of refractive index cells, the spatial intensity distribution at the receiver plane varies. The temporal variation of intensity observed

at an infinitely small point and the spatial variation of intensity within the receiver aperture are commonly described as "scintillation". The intensity and the speed of scintillation (fluctuation) increases with wave frequency. [7] For a plane wave, at low turbulence and with a specific receiver, the scintillation attenuation can be expressed as [7]

$$\alpha_{scin} = 2\sqrt{23.17(2\pi/\lambda * 10^9)^{(7/6)} * Cn^2 * l^{11/6}} \dots\dots\dots(5)$$

Where 'l' is channel length in meters,  $C_n^2$  is the refractive index structure parameter in  $[m^{-2/3}]$  and its values are given as  $10^{-16}$ ,  $10^{-14}$  and  $10^{-13}$  for low, moderate and high turbulence respectively. We can see its strong dependence on wavelength used.

Using equation (5), the calculated value of attenuation at different values are given in table 1 below.

Wavelength	Scintillation Attenuation	Remarks
850 nm	26.16 dB/km	Length of link taken as 1000 meter and $C_n^2 = 10^{-13}$
1550 nm	8.98 dB/km	
10000 nm(10µm)	3.54 dB/km	

Thus we can see the strong dependence of attenuation due to scintillation with wavelength which is significantly less by the order of magnitude compared to 850nm.

## 4 10 µm TECHNOLOGY

The selection of optical wavelength for FSO systems is primarily based on the atmospheric effects and on the availability of receiver and transmitter components, eye safety reasons and of course cost. On the basis of atmospheric propagation conditions and laser safety regulations, longer wavelengths (beyond the "dangerous" wavelengths for eye safety) are the preferred option. Nearly all currently available commercial FSO system are using wavelength between 0.78 µm up to 1.55 µm. The key benefit of using such wavelengths is that components are readily available since they are similar to the components used in fibre optic communications and other industrial and consumer applications, but they perform badly ( higher attenuation and low availability) in foggy weather conditions, as discussed in section 3 above.

When talking about FSO communications using lasers, one has to consider an important issue namely eye safety regulations. The International Electro-technical Commission and related institutions developed standards for an eye-safe transmission of optical power. All laser products are classified in different levels depending on the greatest possible hazard. Laser classes range from "Class 1" (not dangerous to "Class 4" (very hazardous, emit power exceeding 0.5 Watt).

The cornea, the outer layer of the eye, acts like a band pass filter and passes only wave lengths between 400 nm to 1400 nm [8]. This means that the energy of emitted light outside of this region is absorbed and does not reach the retina. In other words, laser communication with wavelengths below approximately 400 nm and beyond 1400 nm can have the advantage of using higher energy densities within the laser beam. Laser sources operating in visible light domain (380nm -780nm) can be detected by eye and it can take counter measures like the normal eye shut-reflex, but within boundary limits of emitted power and exposure time. This fact makes other wavelength like 1064 nm potentially hazardous because the laser light is still focused directly on the retina, but it cannot be detected. When a person is exposed to this kind of irradiation, adverse effects can not be ruled out. The characteristic quantity is called Maximum Possible Exposure (MPE). It specifies a certain level to which a person could be exposed without any hazardous effect or long term effects like biological changes within eye or skin [10] It depends on the laser wavelength, the emitted power and the duration of exposition. Information about the methods to calculate the MPE is available in [12]. It clearly shows that the earlier systems (around 850 nm) are basically more dangerous than newer developments like 10  $\mu$ m. These are orders of magnitude better than 850 nm systems. 10  $\mu$ m systems have a much higher MPE level compared to 850 nm[11]. Nevertheless, the risk of concentration of irradiation with collection optics should not be ignored.

Moreover, the reduced background light from celestial bodies, clouds and Earth further reinforces the use of 10  $\mu$ m which reduces the blinding of tracking sensors thus allows sensors with a wider field-of-view [13]. Although the use of 10  $\mu$ m wavelengths was reported in the 1980's, but evolving interest has been encountered in recent years. One reason for this can be attributed to accelerated advances in Quantum Cascade Lasers (QCL) as well as the progress in mercury cadmium telluride photo-diodes and quantum well infrared photo-detectors [14]. Earlier CO<sub>2</sub> lasers were tried at 10 $\mu$ m but experienced practically difficulties in operating FSO link with this laser type. It required elaborate cooling arrangements and it was not easy to tune the laser. Moreover, the lifetime of the said laser was limited.

QCL sources have drastically improved in price and performance. They belong to the family of semiconductor lasers and emit light in the 10  $\mu$ m band. It was first demonstrated in 1994 at the Bell Laboratories with output power in excess of 180 mW. QCLs score with excellent lifetime. At this rate, it is expected that output power of even 500 mW could be achieved shortly. QCL sources having a wavelength of 8  $\mu$ m – 10  $\mu$ m can operate at room temperature. The necessary cooling can be realized by a

solid state thermoelectric cooler. The QCLs can be modulated directly and problems like extinction ratio and limited bandwidth are also taken care by it.

## 5 CONCLUSIONS

Performance of FSO system at different wavelengths spanning from 850 nm to 10 $\mu$ m were analyzed under different atmospheric conditions like fog, rain, snow and turbulence. On the basis of our analysis, we conclude that attenuation at longer wavelength like 10 $\mu$ m is much less than that at 0.85  $\mu$ m and 1.55  $\mu$ m under foggy conditions. Similarly the effective attenuation due to scintillation is significantly less at 10 $\mu$ m compared to 0.85  $\mu$ m and 1.55  $\mu$ m. Also, higher allowable laser transmission power at 10  $\mu$ m from the perspective of the eye safety considerations, improves the system availability despite of the similar specific attenuation during rain and snow at the two wavelengths. Moreover, the reduced background light from celestial bodies, clouds and Earth encourages the use of 10  $\mu$ m which reduces the blinding of tracking sensors thus allows sensors with a wider field-of-view. Finally it is expected that due to the better availability light sources and detectors at 10  $\mu$ m like QCL lasers and mercury cadmium telluride photo-diodes and quantum well infrared photo-detectors, it will be possible to construct a second-generation reliable FSO systems. However, it is still at research stage and more work need to be done before commercial systems can be expected to appear at this wavelength.

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