THE INFLUENCE OF ATMOSPHERIC ATTENUATION ON FREE SPACE OPTICAL COMMUNICATION

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Abstract

In this research project we are concentrating on investigating the losses affecting a Free Space Optical communication system. Losses are mainly atmospheric attenuation and geometric losses. The several types of atmospheric attenuation: absorption, scattering and scintillations are introduced. Several types of absorption molecules which causes the most absorption at specific wavelengths are given. Also we have investigated the possibility of neglecting the attenuation due to absorption by choosing the suitable wavelength. Attenuation due to scattering are introduced and treated. Relationships which describe Rayleigh scattering and Mie scattering are also given. The effect of each type of scattering on an FSO are discussed and why we can neglect Rayleigh scattering is justified. Analytical study which was carried out according to experimental data was taken from the Civil Aviation & Meteorology Authority – Yemen Meteorological Service. The Mie scattering coefficient or aerosols scattering are calculated at several ranges of visibilities. The scattering coefficient due to rain is calculated as a Non-selective scattering. The attenuation due to hazy days and rainy days are also calculated. The analytical study also discuss the variation of geometric loss according to the variation of transmitter, receiver aperture and the beam divergence. Finally the total attenuation is calculated.

1. Introduction

The atmosphere is a mixture of gases and aerosols that influences light propagation by absorption, scattering and turbulences (scintillations) effects. A major restriction on the outdoor terrestrial use of optical frequencies is the major variability of the atmospheric attenuation with changing meteorological conditions. It has to be accepted that under particular conditions of fog or heavy rain or snow that the system is rendered inoperative. The atmosphere is considered as a challenging dynamical channel for electromagnetic waves propagation. *Scattering*, *absorption* and *turbulences* are the dominant mechanisms of signal loss and distortion. *Scattering* process occurs when light waves encounter particles or molecules of different sizes and shapes. *Absorption*, on the other hand, is a quantum effect that is described by wavelength-based atmospheric windows. *Turbulences* are caused by hot pockets of air that distort the optical signal.

2. Types of scattering particles

In the atmospheric model structure, the layer referred to as troposphere, is considered as the lowest layer that extends from ground level to around 11 Km (36,000 feet or 7 miles). The first class of atmospheric constituents is particles of maximum 1 μm in radius, due to their small sizes and very lightweight. These particles are suspended in the air to form the continuum called *aerosol*. Scattering by aerosol is called *haze*, with highest level of haze occurring near the surface of the earth. Aerosol particles are smog (smoke + fog), fine soil particles, cosmic dust, clouds, fog and others. Particles that contain moisture contribute to attenuation due to humidity factors. The second class of particles consists of water-based particle called hydrometers. These particles could be in liquid state (clouds, mist, fog, rain, ocean spray), or solid state (hail or snow). Typically, these particles are larger than 1 μm in radius and exist over a shorter period of time than the smaller particles. The different types of atmospheric constituents sizes and concentrations are listed in Table (1) [Achour M, Part II, 2002 & Kim I. , 2000].

Table (1) : Radius ranges for various types of particles.

Type	Radius (μm)	Concentration (in cm^{-3})
Air molecules	10^{-4}	10^{19}
Aerosol	10^{-2} to 1	10 to 10^{3}
Fog	1 to 10	10 to 100
Cloud	1 to 10	100 to 300
Raindrops	10^{2} to 10^{4}	10^{-5} to 10^{-2}
Snow	10^{3} to $5*10^{3}$	N/A
Hail	$5*10^{3}$ to $5*10^{4}$	N/A

3. Atmospheric attenuation

The molecules and aerosols in the atmosphere attenuate the transmission of light by *absorption* and *scattering*. In general, the atmospheric transmission is given by the following *Beer's law* equation [F.T.Arecchi , 1972] :

$$\tau = \exp(-\mu R) \qquad (1)$$

Where:

μ : Is the total extinction coefficient and equals to the sum of absorption and scattering coefficients. It can be estimated from the following equation:

$$\mu=\beta_{abs}+\beta_{sca} \quad \text{..........} \quad (2)$$

R : Is the distance between (Tx) and (Rx) in kilometer.

3.1 Absorption

When a beam of optical radiation passes through a heterogonous medium, part of it is absorbed and part is scattered. Absorption is caused primarily by the water vapor (H_2O) and carbon dioxide (CO_2) in the air along the transmission path. Gases in the atmosphere have many resonant bands, called transmission windows, which allow specific frequencies of light to pass through. These windows occur at various wavelengths. Absorption is proportional to the absolute humidity. With an increase in the humidity an environment will realize more absorption and thus higher attenuation rates. However, the use of appropriate power based on atmospheric condition helps maintain the required level of network availability. The most abundant gases existing in the atmosphere are nitrogen, oxygen and argon. All of them are symmetrical molecules and produce no absorption. Therefore there are no absorption bands for these gases. Water vapor (H_2O) and carbon dioxide (CO_2) are responsible for most of the absorption of radiant energy by earth's atmosphere. These gases have absorption bands in the infrared spectrum [Willebrand, 2001].

CO_2 and H_2O vapor also exhibit distinctive absorption patterns as a function of wavelength, pressure, temperature and path length. As the pressure of gas increases due to high temperature, the number of molecular collisions and the interaction between molecules increase, the molecules in the absorption band are broadened, smeared out and finally disappear entirely. Thus the wavelength appears to be missing from the beam. If pressure is reduced due to low temperature, the transmittance increases and bands become narrower, resulting in lower attenuation rates. Since the temperature and pressure effects are very small, they are usually ignored.

A curve of absorption of CO_2 against wavelength is shown in Figure (1). Strong absorption occurs near the region of 2.7 μm and 4.3 μm. Figure (2) shows the curve for water vapor. The absorption lines are at 1.4, 1.9, 2.7 and 6.3 μm [Schlessinger,1994]. The principal absorption lines for other atmospheric constituents are shown in Figure (3).

It is possible to calculate an absorption coefficients from the concentration of the particulate and the effective cross section such as [Arnon S. , 2003]:

$$\beta_{abs} = \sigma_{abs} N_{abs} \quad [1/\text{km}] \quad \text{..........} \quad (3)$$

Where:

σ_{abs} : Is the effective cross section of the absorption particles [km^2].

N_{abs} : Is the concentration of the absorption particles [1/km^3].

Absorption lines at visible and near infrared wavelengths are narrow and generally well separated. Thus, absorption can generally be neglected at wavelength of interest for free space laser communication [F.T.Arecchi , 1972].

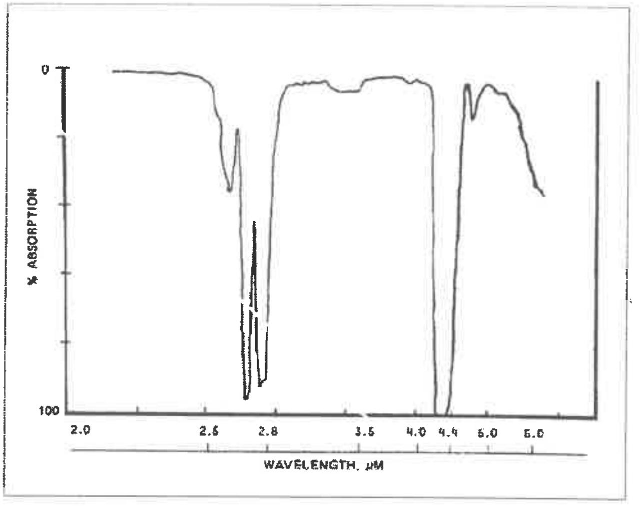

Figure (1) : Absorption curve for CO_2. [adapted from Schlessinger, 1994]

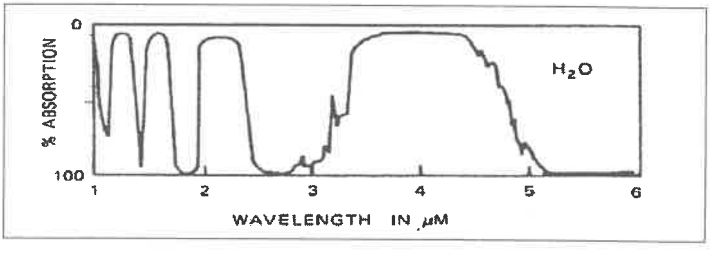

Figure (2) : Absorption curve for water vapor. [adapted from Schlessinger, 1994]

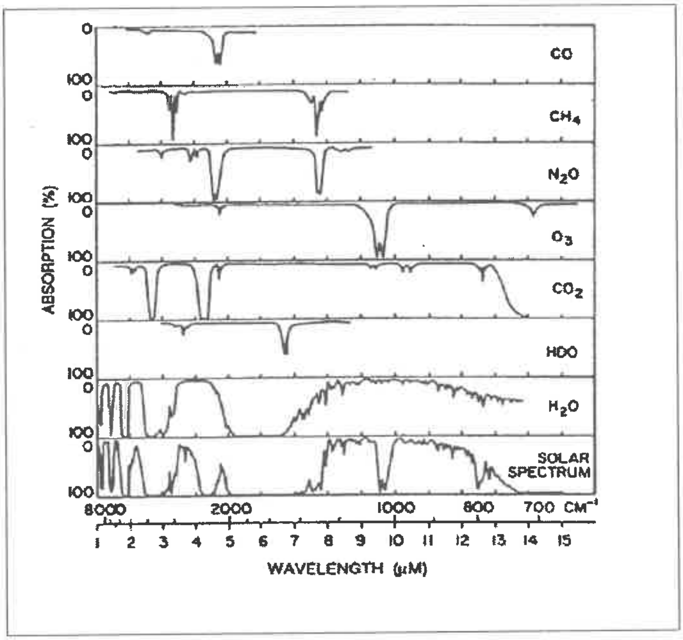

Figure (3) : Atmosphere absorption for solar energy. [adapted from Schlessinger, 1994]

Another reason for ignoring absorption effect is to select wavelengths that fall inside the transmittance windows in the absorption spectrum [Hudson, 1969]. The wavelengths of 785 nm, 850 nm, 1550 nm and 10 μm fall inside the transmittance window. In a very narrow window this result is for transmission through heavy rain and hazy days. The longer the wavelength, the higher the transmitting energy and the higher the reliability provided by the link. This is because the longer wavelength is able to pass directly through suspended particles, resulting in minimal atmospheric attenuation [Mohd Zaatari, 2003].

In Figure (4) the atmospheric transmittance with approximately all the interesting absorption molecules are shown.

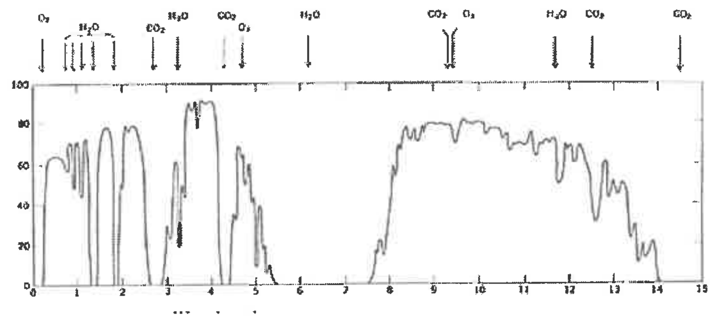

Figure (4) : The atmospheric transmittance window. [adapted from Ghuman B , 2002]

3.2 Scattering

It is interesting to note that most of the light which reaches our eyes comes indirectly by means of scattering. Fine particles or bits of matter standing in the path of continuous transmission of electromagnetic waves abstract energy from the incident wave and re-radiate it in different directions. Figure (5) is extracted from reference [Earl J. , 1976] to illustrate the re-distribution of radiation once a particle is hit by an electromagnetic wave. Forward scattering becomes more significant when particle sizes exceed the incident wavelength. Scattering of infrared signals by raindrops is illustrated in Figure (5-C).

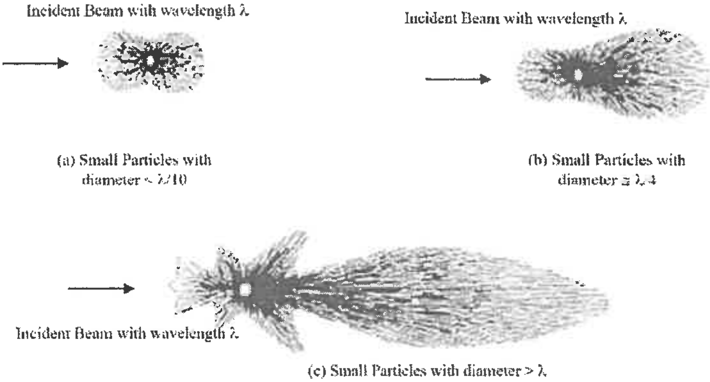

Figure (5) : Scattering patterns of electromagnetic waves by spherical particles. [Earl J. , 1976].

Scattering has a greater effect than absorption on laser beam propagation at visible and near infrared wavelengths. The atmospheric scattering of light is a function of its wavelength and the number and size of scattering elements in the air. Accordingly, we can divided the scattering of light into three types [Achour M, Part II, 2002]:

1. Rayleigh (Molecular) scattering.
2. Mie (Aerosoles) scattering.
3. Non-selective scattering.

The most common scattering elements in the air that affect laser beam transmission are fog, smog, rain, and snow. It is possible to calculate the scattering coefficients from the concentration of the particles and the effective cross section such as: [Arnon S. , 2003]

$$\beta_{sca} = \sigma_{sca} N_{sca} \quad \textbf{[1/km]} \quad \text{.......} \quad \textbf{(4)}$$

Where:

σ_{sca} : Is a cross-section parameters [km^2].
N_{sca} : Is a particle concentrations [$1/km^3$].

and β_{sca} is either Rayleigh (Molecular) β_m or Mie (Aerosols) β_a scattering. The total scattering can be written as:

$$\beta = \beta_m + \beta_a \quad [1/\text{km}] \qquad (5)$$

3.2.1 Rayleigh (molecular) scattering

Rayliegh scattering refers to scattering by molecular and atmospheric gases of sizes much less than the incident light wavelength. It is inversely proportional to the fourth power of the wavelength and plays a significant part only in the ultraviolet part of the spectrum or at high altitudes where the number of aerosol particles becomes negligible. The Rayliegh scattering coefficient β_m [1/km] is given by: [Arnon S. , 2003]

$$\beta_m = \sigma_m N_m \quad [1/\text{km}] \qquad (6)$$

Where:

σ_m : Is the Rayleigh scattering cross-section [km^2], and is proportional to λ^{-4} (λ is the wavelength for the laser beam).

N_m : Is the number density of air molecules [$1/km^3$].

The Rayleigh scattering cross section is given by the following relationship:

$$\sigma_m = \frac{8\pi^3 \left(n^2 - 1\right)^2}{3N^2 \lambda^4} \quad [\text{km}^2] \qquad (7)$$

where:

n : Is the index of refraction (in air is usually assumed to be 1).

λ : Is the incident light wavelength [m].

N : Is the volumetric density of the molecules [$1/km^3$].

3.2.2 Mie (aerosols) scattering

Mie scattering occurs when the particle diameter is larger than one-tenth of the incident laser beam wavelength and don't exceed it. Mie theory is applicable for scattering by isotropic spherical elements without quantum consideration of particle radiation by incident monochromatic light. Mie scattering is the main cause of attenuation at laser wavelength of interest for free space laser communication at terrestrial altitude. It depends on the particle size distribution of the present aerosols. The Mie scattering coefficient is given by: [Arnon S. 2003]

$$\beta_a = \sigma_a N_a \quad [1/\text{km}] \qquad (8)$$

Where:

σ_a : Is the Mie scattering cross-section [km^2].
N_a : Is the number density of air particles [1/km^3].

The Mie scattering cross section follows the following relationship:

$$\sigma_a = \pi r^2 \left(2 - \frac{4}{\varphi} \sin(\varphi) + \frac{4}{\varphi^2} (1 - \cos(\varphi)) \right) [\text{km}^2] \quad \text{.................} \quad (9)$$

Where:

r : Is the aerosol radius.
φ : Is the normalized size parameter which is given by :

$$\varphi = 4\pi r (n_0 - 1) / \lambda \quad \text{..} \quad (10)$$

n_0 : Is the stationary refractive index of the marine atmosphere and is a function of temperature, pressure, wavelength, and humidity:

$$n_0 \approx 1 + \frac{77p}{T} \left(1 + \frac{7.53 \times 10^{-3}}{\lambda^2} - 7733 \frac{q}{T} \right) \times 10^{-6} \quad \text{...........} \quad (11)$$

Where:

p : Is the air pressure [mbar].
T : Is the temperature [K].
q : Is the specific relative humidity [g/m^3].
λ : Is the incident laser beam wavelength.

Due to the fact that the visibility is an easily obtainable parameter, either from airport or weather data, it is easy to calculate the Mie scattering coefficient by using the following relationship:

$$\beta_a = \left(\frac{3.91}{V} \right) \left(\frac{0.55\mu}{\lambda} \right)^i \quad [1/\text{km}] \quad \text{...} \quad (12)$$

Where:

V : Is the visibility (Visual Range) in kilometer.
λ : Is the incident laser beam wavelength in micrometer.
i : Is a parameter which typically varies from 0.7 to 1.6 corresponding to visibility conditions from poor to excellent and is called the size distribution of the scattering particles.
Where:

- $i = 1.6$ for $V > 50$ km.
- $i = 1.3$ for $6 \text{ km} \le V \le 50$ km.
- $i = 0.585\ V^{1/3}$ for $V < 6$ km.

For Mie scattering coefficient (also called Mie attenuation coefficient) the relationship between the transmitted power and received power is given by:

$$P_r = P_t \tau \quad \text{(13)}$$

Since we are neglecting the absorption attenuation at wavelength of interest and Rayleigh scattering at terrestrial altitude and according to equations (2) and (5) then :

$$\mu = \beta_a \quad \text{(14)}$$

The atmospheric transmission τ is given as:

$$\tau = \exp(-\beta_a R) \quad \text{(15)}$$

Equation (13) becomes:

$$p_r = p_t \exp(-\beta_a R) \quad \text{(16)}$$

Using the change of base theorem

$$\log_a N = \frac{\log_b N}{\log_b a} \quad \text{(17)}$$

We can express the equation (17) in decibel as following

$10 \log_{10}(p_r) = 10 \log_{10}(p_t) + 10 \log_{10}(\exp(-\beta_a R))$

$10 \log_{10}(p_r) = 10 \log_{10}(p_t) + 10 (\log_e(\exp(-\beta_a R))/\log_e(10))$

$10 \log_{10}(p_r) = 10 \log_{10}(p_t) - R * 4.3429\, \beta_a$

$$10 \log_{10}(p_r) = 10 \log_{10}(p_t) - R\, \beta_{a\,\text{(dB)}} \quad \text{(18)}$$

Where:

p_r : Is the received power (W).
p_t : Is the transmitted power (W).
$\beta_{a\,\text{(dB)}} = 4.3429\, \beta_a$ (attenuation dB/km)
R : Range in kilometer.

The atmospheric attenuation in dB τ can be calculated as follows:

$$\tau = 4.3429 \beta_a R \quad \text{(19)}$$

3.2.3 Non-selective (geometric) scattering

The Non-selective scattering concept applies for particle sized larger than the incident laser beam wavelength. In this case, Mie theory is approximated by the principles of reflection, refraction and diffraction. The name Non-selective refers to the fact that scattering is independent of wavelength.

Non-selective scattering exists due to rainfall. The drop rain size is much larger than incident wavelength. Scattering due to rainfall is called Non-selective scattering [Achour M. , Part II 2002]. The radius range of different types of particles is shown in Table (1).

In scattering there is losses in power due to directional redistribution of energy that may have a significant loss in beam intensity for longer distances. Figure (6) illustrate the pattern of Rayleigh, Mie and Non-Selective scattering and Figure (7) portrays the process of scattering.

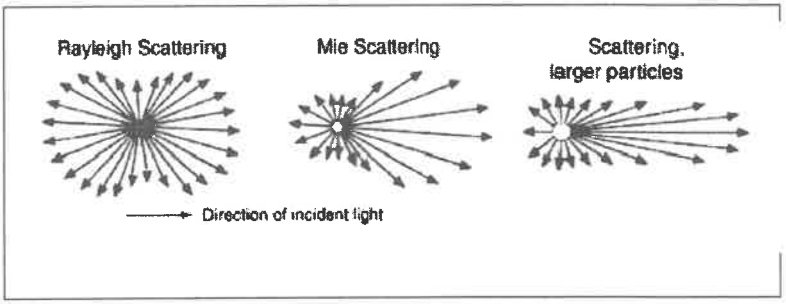

Figure (6) : Patterns of Rayleigh, Mie and Non-selective scattering. (Scattering large particles)

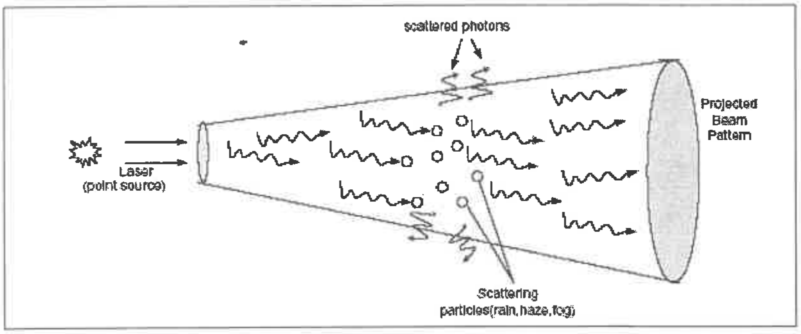

Figure (7) : The process of scattering.

The type of scattering is determined by the size of the particular atmospheric particle with respect to the transmitted laser wavelength. This is described by a dimensionless number called the size parameter α:

$$\alpha = \frac{2\pi r}{\lambda} \qquad (20)$$

Where:

r : Is the radius of the scattering particle.

λ : Is the laser wavelength.

The size parameters are plotted in Figure (8) along with the corresponding regions for Rayleigh, Mie, and Non-selective scattering [Kim I. , 2000].

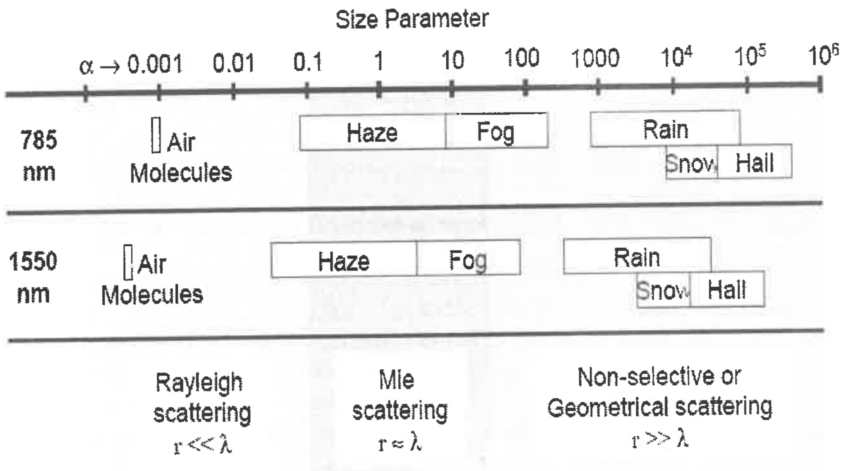

Figure (8) : Size parameters of atmospheric scattering particles in table (1) for laser wavelengths of 785 nm and 1550 nm. Also plotted are the corresponding regions for Rayleigh, Mie, and Non-selective or geometric scattering. For each type of scattering, the approximate relationship between the particle size and wavelength.

3.3 Turbulence Or Scintillation

The variation of refractive index along the propagation path caused by slight temperature variations among different air pockets acts like series of small lenses. It deflect the beam into and out of the transmission path causes amplitude fluctuations at the receiver. These fluctuations can vary orders of magnitude during a hot day (typically worst at midday) and can impact the burst errors performance on a milliseconds timescale. The effect of scintillation is less for short distance links but drastically increases with distance.

The turbulence effect on the laser beam occurs because of small-scale dynamic changes in the index of refraction of the atmosphere. Atmospheric turbulence produces temporary pockets of air (turbulence cells) with slightly different indices of refraction. If the size of the turbulence cells is larger than the beam diameter, the whole laser beam bends. This effect is illustrated in Figure (9).

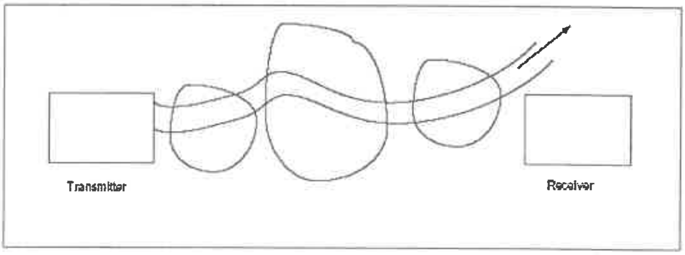

Figure (9) : Laser beam wander due to turbulence cells that are large than the beam diameter.

It is common that the sizes of the turbulence cells are smaller than the beam diameter and so the laser beam bend and become distorted. Small variations in the arrival time of various components of the beam wavefront produce constructive and destructive interference and result in temporal fluctuations in the laser beam intensity at the receiver. Figure (10) graphically examines what happens in this occurrence.

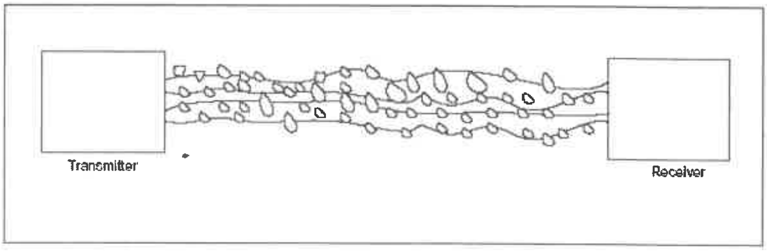

Figure (10) : Scintillation or fluctuations in beam intensity at the receiver due to turbulence cells that are smaller than the beam diameter.

We can reduce the effect of scintillation by using multiple beam technology to increase the received power at the received terminal or large receiver apertures. The large aperture approach is more effective for scintillation reduction than multiple transmitter beams.

4. Visibility

Visibility is defined as the maximum distance along which a 550 nm visible laser beam wavelength travels while being able to distinguish between the target object and its background with 2% contrast. For visibilities above 4 km, attenuation is mainly due to haze and semi-clear weather condition, and is less than 5 dB/km depending on the visibility value and wavelength. For visibilities less than 4 km, attenuations not only depend on visibility but also on droplet sizes and distributions (or their corresponding equivalent water contents). For these low visibility values, attenuation can reach hundreds of dB per km and is higher at shorter wavelength. Visibility is useful to calculate the atmospheric attenuation probability. It is taken from airport visual range technique measurement all over the world with very good resolution (every half hour or less) [Srinivasa G.]. Visibility related to atmospheric attenuation parameter (aerosols and particles) at terrestrial altitude can be calculated using Mie scattering coefficient at λ=0.55 μm as follows:

$$V = \beta_a^{-1} \ln\left(\frac{1}{0.02}\right) = \frac{3.912}{\beta_a} \text{ [km]} \quad \text{(21)}$$

Where:

V : Is the visibility (visual rang) [km].

β_a : Is the Mie scattering coefficient [1/km].

5. Rainfall Rate

Rain consists of separate drops of water falling to the Earth's surface from clouds. Not all rain reaches the surface, some evaporates while falling through dry air. Small raindrops are nearly spherical. Larger ones become increasingly flattened, like a hamburger; very large ones are shaped like a parachute. The larger raindrops fall faster than the smaller ones.

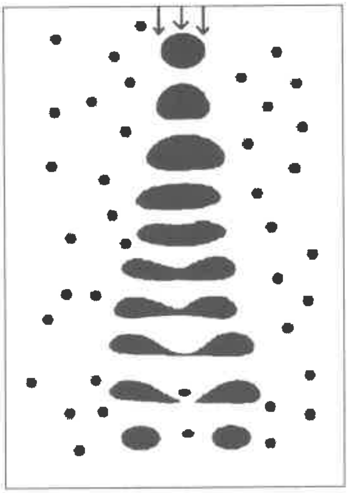

Figure (11) : Several rain droplets process. [Brown 2003]

Raindrops usually start out close to spherical in shape but as they begin to fall faster the drag from surrounding air tends to change their shape. If a droplet has grown large enough through collision and coalescence, it may break apart and form several smaller droplets that will begin the collision and coalescence process all over again. This process is shown in Figure (11) [Brown 2003].

5.1 Effect of Rainfall Rate on FSO System

In an atmosphere containing only scattering (no absorption), the spectral transmittance over a path of length R is: [Hudson , 1969]

$$\tau = \exp\left(-\beta_{rain\ scat}\ R\right) \qquad (22)$$

Where: $\beta_{rain\ scat}$: Is the scattering coefficient due to rain.

The scattering coefficient can be calculated by using Stroke Law: [Nevers , 2000 & Achour M. 2002]

Limiting speed of raindrop:

$$V_a = \frac{2a^2 \rho g}{9\eta} \qquad (23)$$

Where:

Droplet radius, a = 0.001 cm to 0.1 cm
Water density, ρ = 1 g/cm^3
Gravitational constant , g = 980 cm/sec^2
Viscosity of air, η= 1.8 * 10^{-4} g/cm.sec

The raindrop distribution:

$$N_a = \frac{Z_a}{4/3\left(\pi a^3\right)V_a} \qquad (24)$$

Where Z_a is the rainfall rate (cm/sec)

Scattering coefficient by rain:

$$\beta_{Rain\ scat} = \pi a^2 N_a\, Q_{scat}\left(\frac{a}{\lambda}\right) \qquad (25)$$

Where :

Q_{scat} : Scattering efficiency
a : Radius of raindrop (cm)
N_a : Number of water droplets contained in the atmosphere (cm^3)

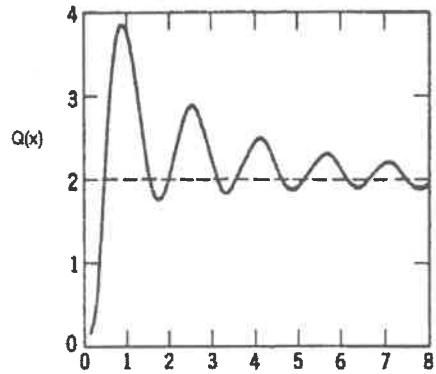

Figure (12) : Scattering Efficiency (Q(x)) versus Ratio of Raindrop radius to wavelength (a/λ).
[Hudson , 1969]

Figure (12) shows that *Q (x)* changes rapidly at the beginning of droplet growth and strongly dependent on wavelength. For further droplet growth, the value of *Q(x)* oscillates slightly and finally assumes a value of 2, with no wavelength dependence. Therefore the scattering efficiency, *Q(a/λ)* in Equation (25), is assumed to be 2. Large particles like rain give transmissions that are wavelength independent. Scattering due to rainfall is called Non-selective scattering since the drop size is much larger than wavelength. Rayleigh scattering due to rain has very little effect at FSO wavelength of 1.55 μm. The wavelengths of FSO signals, on the order of 0.001 mm are too short to be affected by Rayleigh scattering.
In general, the raindrop radius range seems to vary between 10 μm and 1000 μm. The radius of aerosol is about 0.01 μm to 1 μm. The radius of a raindrop is about 1000 times that of an aerosol droplet. The laser is able to pass through the raindrop particle, with less scattering effect occurring. The haze particles are very small and stay longer in the atmosphere. Therefore more scattering effect will occur. This is the primary reason that attenuation via rain is less than haze [Hill , 2001]. Thus rain has less impact on FSO compared to haze.

6 Different weather conditions and associated particle types

The several weather conditions and the corresponding visibility at various wavelengths are listed in the table below.

Table (2) : Weather conditions and associated particle types, sizes and concentrations. [I. I. Kim. , 1998]

Weather Condition	Precipitation			Visibility	dB loss/km		
			mm/hr		0.785 μm	1.55 μm	10 μm
Dense Fog				0 m			
				50 m	314.5487	271.6509	181.7669
Thick Fog				200 m	75.1741	59.5645	31.4769
Moderate Fog				500 m	28.7903	20.9923	8.8332
Light Fog		Cloudburst	100	770 m	18.223	12.6531	4.6565
				1 km	13.7902	9.2624	3.1122
Thin Fog	Snow	Heavy Rain	25	1.9 km	6.9064	4.2187	1.0928
				2 km	6.532	3.9562	1.0012
Haze		Medium Rain	12.5	2.8 km	4.5227	2.581	0.5549
				4 km	3.0508	1.622	0.2872
Light Haze		Light Rain	2.5	5.9 km	1.976	0.9626	0.1341
				10 km	1.0693	0.4416	0.0391
Clear		Drizzle	0.25	18.1 km	0.5908	0.244	0.0216
				20 km	0.5346	0.2208	0.0196
Very Clear				23 km	0.4649	0.192	0.017
				50 km	0.2139	0.0883	0.0078

7. Geometric loss

Geometric loss is the ratio of the surface area of the receiver aperture to the surface area of the transmitter beam at the receiver. Since the transmit beams spread constantly with increasing range at a rate determined by the divergence, while geometric loss depends primarily on the divergence and the range, geometric losses can be determined with the formula stated as: [Kim I. , 2002]

$$\text{Geometric Loss} = \frac{d_2^2}{\left(d_1 + (\theta R)\right)^2} \quad \text{.......} \quad (26)$$

where:

d_2 : Diameter receiver aperture (m)
d_1 : Diameter transmitter aperture (m)
θ : Beam divergence (mrad)
R : Link range (km)

8. Total Attenuation

Atmospheric attenuation of FSO system is typically dominated by haze and fog, but is also dependent upon rain and dust. The total attenuation is a combination of atmospheric attenuation in the atmosphere and geometric loss.
Total attenuation for FSO system is actually very simple at a high level (leaving out optical efficiencies, detector noises, etc). The equation is: [Brown , 2003]

$$\frac{P_{received}}{P_{transmitted}} = \frac{d_2^2}{\left(d_1 + (\theta R)\right)^2} \times \exp(-\beta R) \quad \text{.......} \quad (27)$$

Where:

d_2 : Diameter receiver aperture (m)
d_1: Diameter transmitter aperture (m)
θ : Beam divergence (mrad)
R : Link range (km)
β : Total scattering coefficient (1/km)

Looking at this equation, the variables that can be controlled are the aperture size, the beam divergence and the link range. The scattering coefficient is uncontrollable in an outdoor environment. In real atmospheric situations, for availabilities at 99.9% or better, the system designer can choose to use huge transmitter laser powers, design large receiver apertures, design small transmitter apertures and employ small beam divergence. Another, other variable that can be controlled is link range, which must be of a short distance to ensure that the atmospheric attenuation is not the dominant term in the total attenuation [Brown , 2003 & Bloom S. , 2002].

9. Simulation and Results

Our simulations based on data taken from the Civil aviation & Meteorology Authority – Yemen Meteorological Service. The work involved analyzing the real data. The data analysis focuses on the Sana'a, Aden, Taiz, Hodidah, Ibb and Haja provinces in the year 2003 for rainy and hazy days only. The atmospheric attenuation due to scattering coefficient will be determined in this section.

9.1 Atmospheric Attenuation in Hazy Days

Figure (13) shows the atmospheric attenuation versus high visibility. To obtain atmospheric attenuation in dB (Decibels), we multiply the scattering coefficient by the factor 4.3429 as in equation 18. Link range between transmitter and receiver is in kilometers. The atmospheric attenuation is inversely proportional to the high visibility.

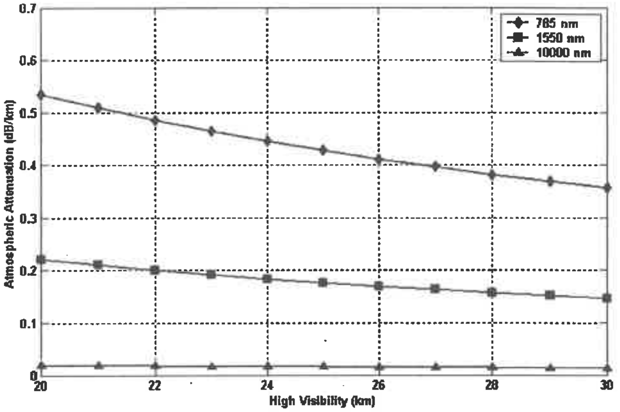

Figure (13): Atmospheric attenuation versus high visibility.

The atmospheric attenuation for high visibility of 20 km is about 0.5346 dB/km, 0.2208 dB/km and 0.0196 dB/km for 785 nm, 1550 nm and 10 μm wavelengths respectively. For the high visibility of 30 km, the atmospheric attenuation is approximately to 0.3564 dB/km (785 nm), 0.1472 dB/km (1550 nm) and 0.0130 dB/km (10 μm). This shows that atmospheric attenuation in hazy days is wavelength dependent. The wavelength of 785 nm provides higher atmospheric attenuation than the wavelength of 1550 nm and 10 μm.

In Figure (14) the atmospheric attenuation versus average visibility was explained.

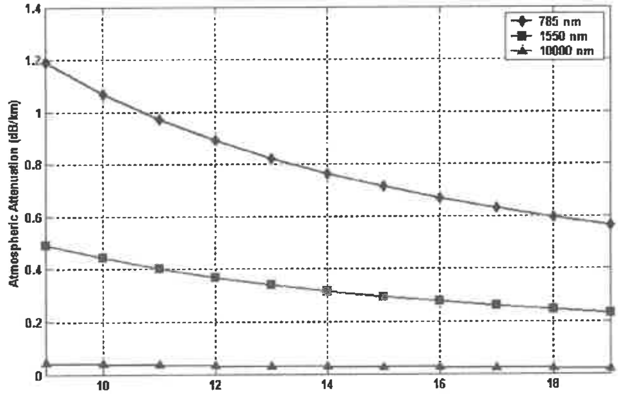

Figure (14) : Atmospheric attenuation versus average visibility.

The atmospheric attenuation for average visibility of 9 km is about 1.1881 dB/km, 0.4906 dB/km and 0.0435 dB/km for 785 nm, 1550 nm and 10 μm wavelengths respectively. For the average visibility of 19 km, the atmospheric attenuation is approximately to 0.5628 dB/km (785 nm), 0.2324 dB/km (1550 nm) and 0.0206 dB/km (10 μm). This shows that atmospheric attenuation in hazy days is also wavelength dependent. Also the wavelength of 785 nm provides higher atmospheric attenuation than the wavelength of 1550nm and 10 μm.

The x-axis represents low visibility and the y–axis corresponds to atmospheric attenuation. Figure (15) indicates the atmospheric attenuation is inversely proportional to the low visibility. As the visibility increases, the atmospheric attenuation decrease.

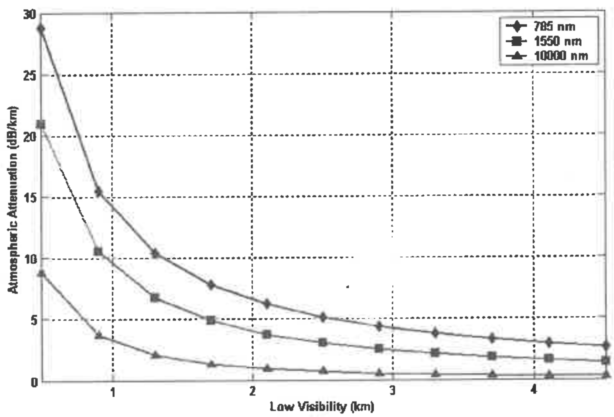

Figure (15) : Atmospheric attenuation versus low visibility.

The critical low visibility is 0.5 km and produces about 28.79 dB/km (for wavelength 785 nm), 20.99 dB/km (for wavelength 1550 nm) and 8.83 dB/km (for wavelength 10 μm). This reading shows that the wavelength of 10 μm is able to reduce the atmospheric attenuation effect on the FSO system. To ensure a minimal amount of atmospheric attenuation, FSO systems suggest operation in the 10 μm wavelength.

The atmospheric attenuation effect in low visibility has greater than the atmospheric attenuation in average visibility and high visibility. This is because more haze particles stay in the atmosphere under low visibility conditions. The aerosols particles in low visibility conditions can redirect or redistribute more laser light. FSO wavelengths, which are on the order of 0.001 mm, are close enough to the size of aerosols particles, which range from 0.01μm to 1μm, to be significantly scattered. The laser light scattering will have a drastic impact as the laser light tries to pass through the aerosols particles in the atmosphere. The haze scattering or Mie scattering is the dominant factor in atmospheric attenuation (see Equation 15). As the scattering coefficient increases the atmospheric effect will increase on the FSO systems.

The graph in Figure (16) indicates the atmospheric attenuation over the transmission range of 0.5km to 5km. The atmospheric attenuation (dB) can be obtained by using Equation (19). As the link range between transmitter and receiver increases, the atmospheric attenuation increases too. This means that the increment of link range is able to decrease the effectiveness and transmission quality of FSO systems.

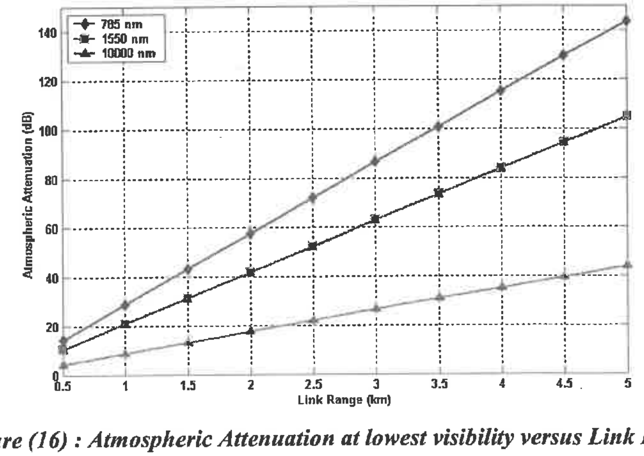

Figure (16) : Atmospheric Attenuation at lowest visibility versus Link Range.

From the obtained results, the impact of atmospheric attenuation in low visibility is to shorten the desirable distance between the transmitter and receiver. For low visibility at 0.5 km, the atmospheric attenuation is about 14.40 dB (for 785 nm wavelength), 10.50 dB (for 1550 nm wavelength) and 4.42 dB (for 10 μm wavelength) at a distance of 0.5 km. The atmospheric attenuation is about 143.95 dB (for wavelength 785 nm), 104.95 dB (for wavelength 1550 nm) and 44.15 dB (for wavelength 10 μm) at a link range of 5 km. From the obtained results, it is recommended to shorten the distance between the transmitter and the receiver to improve the FSO transmission systems. Another solution to improve the atmospheric attenuation is by using the 10 μm wavelength. The laser light with wavelength of 10 μm suffers less atmospheric attenuation than the 785 nm wavelength.

9.2 Atmospheric Attenuation in Rainy Days

Figure (17) shows the result of atmospheric attenuation due to light rainfall, moderate rainfall and heavy rainfall. The atmospheric attenuation can be calculated by using Beer's Law as stated in Equation (22). The raindrop radius is 0.05cm and link range is 1km. From this equation the dominant atmospheric attenuation effect that impacts FSO is attenuation of signal by scattering. As the rainfall rate increases, the losses due to atmospheric attenuation also increase.

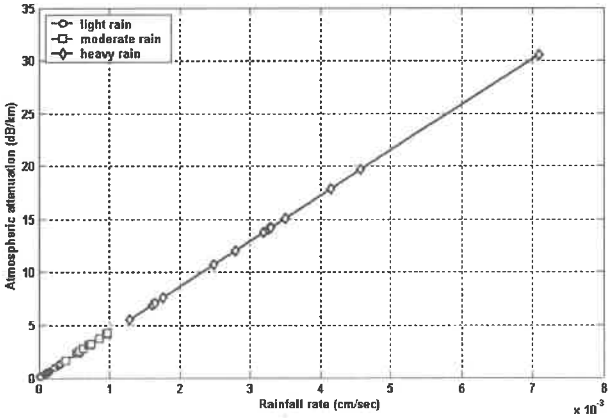

Figure (17) : Atmospheric Attenuation versus Rainfall Rate.

The dominant atmospheric attenuation effect that impacts FSO is attenuation of signal by scattering. Therefore the atmospheric effects also increase as the rainfall rate increases. The atmospheric attenuation is between 0.0956 dB/km to 1.32 dB/km in light rainfall, 1.64 dB/km to 4.2 dB/km in moderate rainfall and 5.51 dB/km to 30.54 dB/km in heavy rainfall.

Table (1) : The scattering coefficient and the corresponding attenuation at each rain state

Rain state	*From*		*To*	
	Scattering (km^{-1})	*Attenuation (dB/km)*	*Scattering (km^{-1})*	*Attenuation (dB/km)*
Light rain	0.0220	0.0956	0.3035	1.32
Moderate rain	0.3779	1.64	0.9670	4.2
Heavy rain	1.2696	5.51	7.0321	30.54

The Graph in Figure (18) presents the atmospheric attenuation at the end rang of light, moderate and heavy rainfall rate versus link range. The raindrop radius is 0.05cm. It shows that atmospheric attenuation increases linearly as the link range increases.

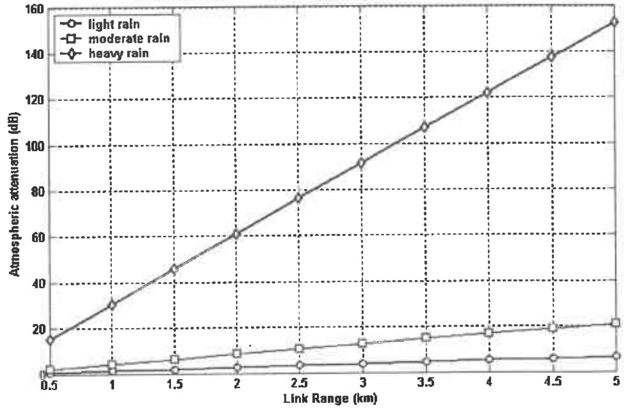

Figure (18) : Atmospheric Attenuation versus Range.

If the FSO system is deployed with a distance of 0.5km, the atmospheric attenuation is only 0.66 dB, 2.1 dB and 15.27 dB at the end range of light, moderate and heavy respectively. When the link range increases up to 5km, the atmospheric attenuation reaches up to 6.59 dB, 21 dB and 152.7 dB at the end range of light, moderate and heavy respectively. Shortening the range in the system might produce less atmospheric attenuation.

9.3 Geometric loss

Figure (19) shows a graph of geometric loss versus diameter of transmitter aperture. Equation (26) was used to calculate geometric loss for two designs as given in table(4) The divergence angle and the link range are assumed to be 1 mrad and 1 km respectively.

Table (4) : Diameter of transmitter and receiver aperture of an FSO system.

Design	Diameter transmitter aperture	Diameter receiver aperture
Design 1	18 cm	18 cm
Design 2	3.5 cm	20 cm

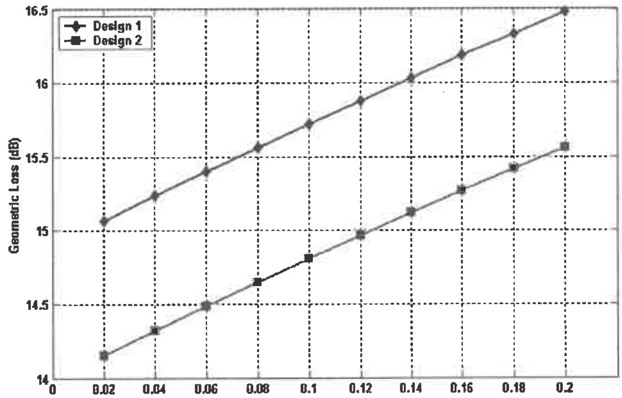

Figure (19) : Geometric Loss versus Diameter of Transmitter Aperture.

From analysis of the graph, is shown that as the diameter of transmitter aperture is increases, the geometric loss increases too. This means that by using a small diameter of transmitter aperture in FSO systems, geometric loss effect is minimized. By minimizing geometric loss effect, the quality of FSO transmission is improved. The effect of geometric loss on the diameter of receiver aperture size is presented in Figure (20). It shows that as the diameter of receiver aperture increases, geometric loss decreases.

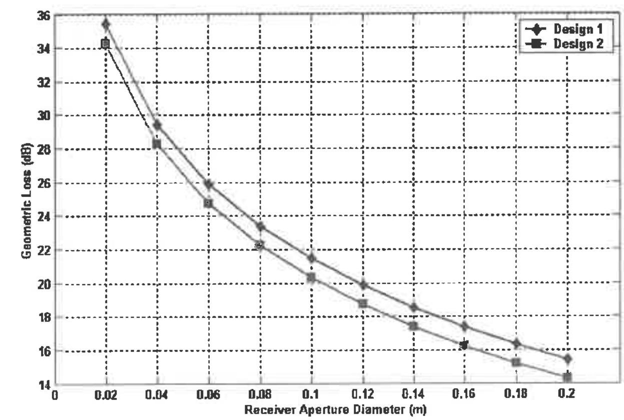

Figure (20) : Geometric Loss versus Diameter Receiver Aperture.

The relationship of geometric loss to diameter of receiver aperture is inversely proportional. This means that FSO designed with large diameter of receiver aperture will result in less geometric loss. By reducing the effect of geometric loss, the FSO system is able to optimize transmission quality.

9.4 Total Attenuation in Hazy Days

The graph in Figure (21) shows the total attenuation of hazy days under average visibility conditions. The graph shows that as the average visibility increases, the total attenuation will decrease. The total attenuation is plotted based on Equation (27). Link range is 1km and beam divergence is 1mrad. The total attenuation calculation is based on specifications of Design 1 and Design2.

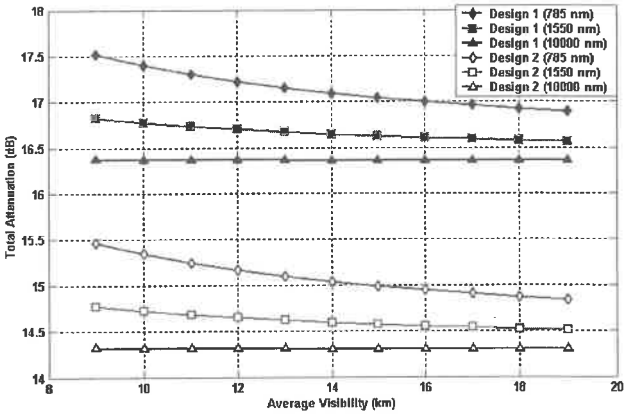

Figure (21) : Total Attenuation versus Average Visibility.

The average visibility is defined as the weather condition where the visibility is between 9 km to 19 km. The total attenuation under Design 1 specifications can run from 17.52 dB to 16.90 dB (for wavelength 785 nm), 16.82 dB to 16.57 dB (for wavelength 1550 nm) and 16.38 dB to 16.35 dB (for wavelength 10 μm) at 1km link range and 1mrad beam divergence. For Design 2 the total attenuation is about 15.47 dB to 14.84 dB (for 785 nm), 14.77 dB to 14.51 dB (for 1550nm) and 14.32 dB to 14.30 dB (for 10 μm).

The wavelengths of 10 μm with Design 2 produce the least total attenuation. By minimizing attenuation effect, the quality of FSO system transmission can be improved.

Figure (22) depicts the performance of total attenuation for a 1km link range and 1mrad beam divergence. The x-axis represents low visibility. The low visibility range is 0.5 km to 4.5 km. The total attenuation is plotted based on Equation (27).

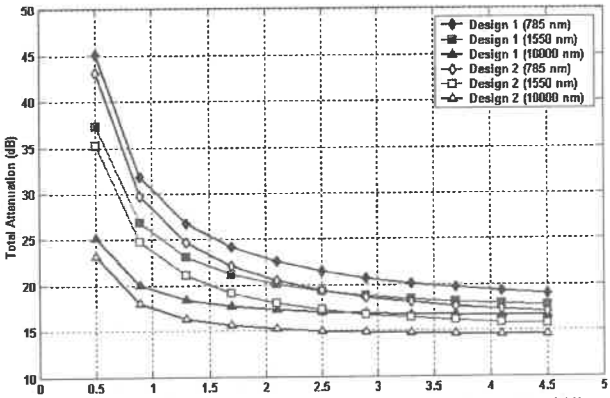

Figure (22) : Total Attenuation versus Low Visibility.

By comparing Figure (21) and Figure (22), it is shown that low visibility has a greater effect of total attenuation compared to average visibility. As mentioned in the previous section, more haze particles stay in the atmosphere during low visibility compared to average visibility. As the particles size approach the laser light, the scattering process became dominant. The atmospheric attenuation is increased due to increasing of scattering coefficient. This will lead to increase of total attenuation effect in the low visibility conditions.

The aperture size also influences the effect of total attenuation. The design with small transmitter aperture and large receiver aperture (Design 2) produces less total attenuation compared to the design with transmitter and receiver of same size (Design 1). Therefore a Design 2 specification is preferred. It is found that forward scattered laser light may be collected within large receiver apertures.

The system with wavelength of 785 nm provides higher total attenuation than the wavelength of 1550 nm and 10 μm. The maximum total attenuation in Design 1 is about 45.12 dB (for 785 nm wavelength), 37.33 dB (for 1550 nm wavelength) and 25.17 dB (for 10 μm wavelength). Meanwhile in Design 2, the maximum effect of total attenuation is about 43.07 dB (for 785 nm wavelength), 35.27 dB (for 1550 nm wavelength) and 23.11 dB (for 10 μm wavelength).

Figure (23) indicates the total attenuation over a transmission range of 0.5 km to 5 km. The calculation is based on critical low visibility of 0.5 km. The beam divergence is assumed to be 1mrad. As the distance increases, the total attenuation increases too.

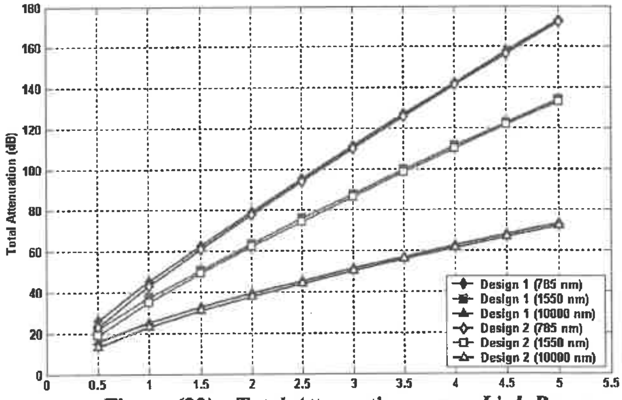

Figure (23) : Total Attenuation versus Link Range.

The total attenuation for the link range of 0.5 km is 25.94 dB (for 785 nm wavelength), 22.04 dB (for 1550 nm wavelength) and 15.96 dB (for 10 μm wavelength) for Design 1 specifications. The total attenuation in Design 2 is approximately 22.94 dB (for 785 nm wavelength), 19.04 dB (for 1550 nm wavelength) and 12.96 dB (for 10 μm wavelength). For the distance of 5km in Design 1, the total attenuation increases up to 173.13 dB (for 785 nm wavelength), 134.14 dB (for 1550 nm wavelength) and 73.34 dB (for 10 μm wavelength). Meanwhile in Design 2, the total attenuation runs up to 171.97 dB (for 785 nm wavelength), 132.98 dB (for 1550 nm wavelength) and 72.19 dB (for 10 μm wavelength). This means that in FSO, a short distance is necessary to meet the lower total attenuation effect in the transmission link. The total attenuation which effects the 1550 nm wavelength is less for the 785 nm wavelength.

The light beam has a cone shape. Because of this, the light gets more spread out as the link range increases. Consequently, not all the light in the beam hits the receiver aperture. Much of laser light gets wasted around the side of the receiver. As mentioned before, the increase of link range leads to larger spot size. Therefore, short link range is recommended for FSO systems.

Figure (24) presents total attenuation versus beam divergence in low visibility (0.5 km) conditions. The link distance is about 1km. Large beam divergence produces higher total attenuation.

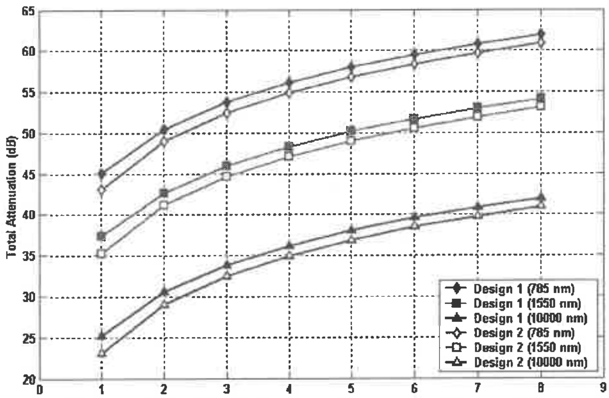

Figure (24) : Total Attenuation versus Beam Divergence.

For 1 mrad beam divergence, the total attenuation of Design 1 is about 45.12 dB (for 785 nm wavelength), 37.33 dB (for 1550 nm wavelength) and 25.17 dB (for 10 μm wavelength). Meanwhile for Design 2, the total attenuation is approximately 43.07 dB (for 785 nm wavelength), 35.27 dB (for 1550 nm wavelength) and 23.11 dB (for 10 μm wavelength). If the beam divergence is 8 mrad, the total attenuation for Design1 is about 61.94 dB (for 785 nm wavelength), 54.14 dB (for 1550 nm wavelength) and 41.98 dB (for 10 μm wavelength). The total attenuation in Design 2 is about 60.87 dB (for 785 nm wavelength), 53.07 dB (for 1550 nm wavelength) and 40.91 dB (for 10 μm wavelength).

From the statement of S=θR, the increment value of beam divergence lead to large spot size. If the spot size is larger than receiver aperture, the problem of 'overfill' energy loss occurs.

Using small transmitter apertures and large receiver apertures as stated in Design 2 specifications can reduce the total attenuation effect. Smaller beam divergence also contributes to less total attenuation effect.

9.5 Total attenuation in rainy days

Figure (25) shows the result of total attenuation due to light rainfall, moderate rainfall and heavy rainfall. The total attenuation can be calculated by using Equation (27). The transmitter and receiver diameter used in this calculation are based on size as specified in Design 1 and Design 2 (as mentioned Table 4). The beam divergence and link range are assumed to be 1 mrad and 1 km respectively.

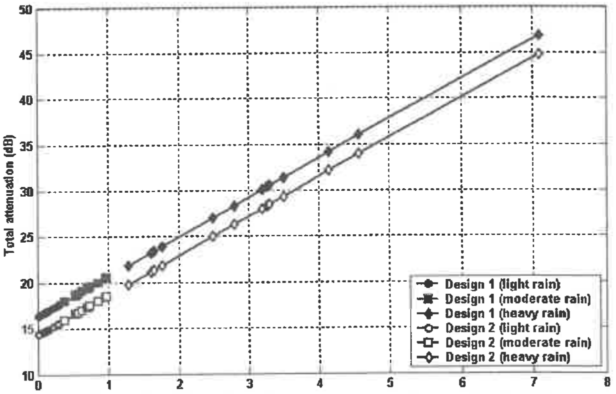

Figure (25) : Total Attenuation versus Rainfall rate.

As the rainfall rate increases, the losses due to attenuation increase. The total attenuation under Design 1 specifications in light rainfall is about 16.43 dB to 17.65 dB, in moderate rainfall about 17.97 dB to 20.53 dB and in heavy rainfall about 21.85 dB to 46.87 dB. For Design 2, the total attenuation in light rainfall is about 14.37 dB to 15.60 dB, in moderate rainfall about 15.92 dB to 18.48 dB, and in heavy rainfall about 19.79 dB to 44.82 dB.

From the analysis above, it can be concluded that Design 2 has a small attenuation than Design 1. This means that FSO design with a smaller transmitter aperture and larger receiver aperture (Design 2) will be able to minimize the attenuation effect on the transmission.

The Graph in Figure (26) presents total attenuation in the heaviest rainfall rate at range of 0.5km to 5km. It is shown that attenuation increases exponentially as the link range increases. The beam divergence is assumed to be 1mrad.

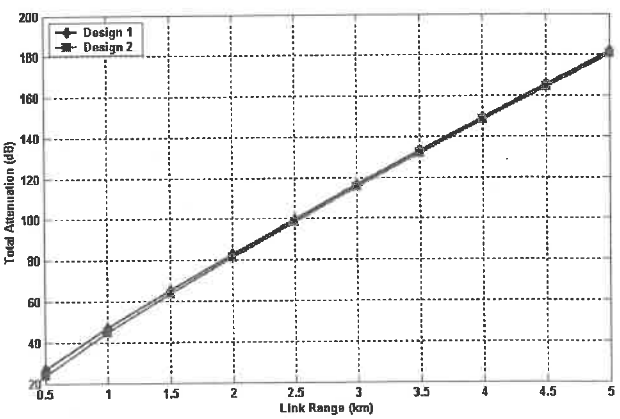

Figure (26) : Total Attenuation versus Link Range in Heavy Rain.

The total attenuation which is produced in Design 1 is about 26.82 dB to 181.88 dB for link range of 0.5km to 5km. Meanwhile in Design 2, the total attenuation affecting the FSO system is about 23.82 dB to 180.72 dB for link range of 0.5 to 5km. This shows that the FSO design with small transmitter aperture and large receiver aperture should be able to reduce the attenuation effect for long distance applications.

Theoretically, S = θR, where S = spot size(m), θ = beam divergence (mrad) and R = link range (km). As the range increases, the spot size spreads to a larger size. The beam may spreads to a size larger than receiver aperture, and this "overfill" energy is lost.

From the result obtained, it can be concluded that FSO is suitable for short distance deployment. The link range increment will lead to more attenuation effect and energy loss.

The x axis represents the beam divergence. The y axis corresponds to the total attenuation. Figure (27) represents the total attenuation for the heaviest rainfall rate. The link range is 1km. From the result obtained, as the beam divergence increases, the total attenuation increases too. As mentioned previously, S=θR. This mean that as the beam divergence size increases, the spot size will increase too. If the beam divergence spreads larger than the receiver aperture size, the same problem as discussed in the previous section (Figure 25) will occur, that is "overfill" energy loss.

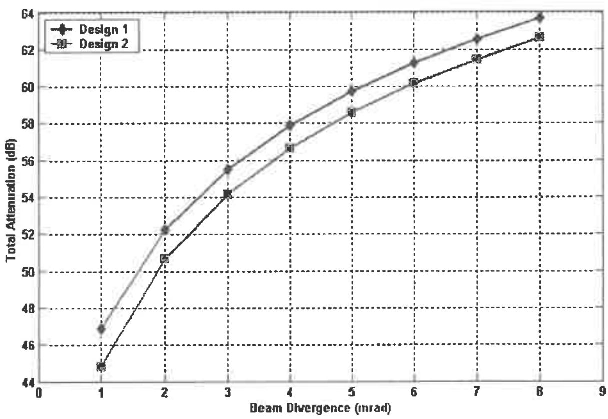

Figure (27) : Total Attenuation versus Beam Divergence.

Total attenuation in beam divergence of 1 mrad is about 46.87 dB and 63.69 dB for 8 mrad beam divergence. This value is calculated based on Design 1 specification. For design 2, total attenuation is about 44.82 dB to 62.62 dB for beam divergence of 1 mrad to 8 mrad. From the result obtained, it is shown that Design 2 and small beam divergence produce less total attenuation.

The transmission with large beam divergence is able to cover a large area at the receiver, but it will increase attenuation loss. If a beam of a small divergence is used, attenuation loss will be low.

10. Discussions

10.1 Haze Effect on FSO System

The scattering coefficient of haze on low visibility has a greater effect than the heaviest rainfall conditions except at Ibb city which is less than the scattering coefficient at heaviest rainfall in Aug. FSO wavelengths are closer to the size of haze particles, which range from 0.01 μm to 1 μm, causing them to be significantly scattered. The haze consists of suspended particles, which settle so slowly that they may be considered to remain in the atmosphere. The suspended particles can increase the scattering effect on the transmission process. The radius of raindrop particles is 100 to 10000 μm, which is much larger than the haze particles size. The raindrop will fall to the ground and is not suspended in the atmosphere. Therefore, the haze conditions will interfere with FSO transmissions more than in the rain conditions. The scattering process in the haze can substantially attenuate FSO transmissions. The scattering coefficient in low visibility is higher than in average visibility. This is because low visibility conditions consist of more haze particles than average visibility. The atmospheric attenuation will be increased due to the increased effect of the scattering coefficient. From the result analysis, the preferred transmission wavelength is 1550 nm. FSO systems with wavelength of 1550 nm produce less scattering and atmospheric attenuation compared to wavelength of 785 nm.

10.2 Rain Effect on FSO System

Scattering coefficient is subject to rainfall rate conditions and radius of raindrop. Raindrop size is inversely proportional to scattering coefficient. Big drops fall faster than small drops. The scattering coefficient is greater in heavy rainfall compared to moderate and light rainfall. In heavy rainfall, more raindrop particles will interfere with the FSO system transmission. The scattering process occurs more in heavy rain. This is because the liquid contents in heavy rain are more than in moderate and light rain. The liquid contents consist of particles or molecules of different sizes and shapes. More scattering occurs when light waves encounter these particles and molecules. The scattering due to rainfall is called Non-selective scattering. This is because the raindrop size is larger than the incident wavelength. The Non-selective scattering effects are wavelength independent. The drop size is much larger than the wavelengths, making scattering effects wavelength independent. From the last the scattering efficiency $Q_{scat}\left(\frac{a}{\lambda}\right)$ will be approximately equal to 2. The ratio of a/λ >30, $Q_{scat} \cong 2$ The radius of particles grows until equilibrium between the droplets and the surroundings is attained. Therefore wavelength does not influence the scattering process much. Figure (12) shows the scattering efficiency graph. The performance of (a/λ) will continuously oscillate until the steady state is assumed to be 2.

Atmospheric attenuation can be calculated by using Beer's Law. The atmospheric attenuation depends on scattering coefficient and link range. The atmospheric attenuation effect can be minimized by reducing scattering coefficient and link range. But the scattering depends on weather conditions and is uncontrollable. The link range is the only design parameter that can be reduced. The atmospheric attenuation greatly reduced for short link range applications such as 0.5 km to 1 km.

10.3 Geometric Loss on FSO System

Figures (19) and (20) show the geometric loss effect for different transmitter apertures and diameter of receiver apertures. From both graphs, it is shown that FSO design with small diameter of transmitter aperture and large diameter of receiver aperture results in less geometric loss effect. In addition, FSO performance can be improved and system operation optimize.

10.4 Total Attenuation Effect in Hazy and Rainy Days

Total attenuation depends on geometric loss and atmospheric attenuation loss. Design parameters such as transmitter and receiver size, beam divergence and link range can be controlled. Rain and haze conditions are based on environmental factors and are uncontrollable. From the results obtained, the total attenuation effect is less in smaller transmitter sizes and larger receiver sizes (as specified under Design 2), shorter link ranges and smaller beam divergences.

References

Achour M., "Simulating Atmospheric Free Space Optical Propagation Part II: Haze, Fog and Low Clouds Attenuation" , Optical Wireless Communications V. Proceedings of the SPIE , Volume 4873, pp. 1-12 , October 2002. http://www.ulmtech.com/Downloads/UlmTechFogWP.pdf. Accessed on July 2004

Isaac I. Kim , Bruce McArthur , and Eric Korevaar "Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications" , Optical Wireless Communications III , Proc. SPIE , 4214 , pp. 26-37 , 2000. http://www.freespaceoptic.com/WhitePapers/Comparison_Of_Beam_in_Fog.pdf Accessed on March 2005

F.T.Arecchi , E.O.Schulz-Dubois "Laser Handbook" , volume 2 , North_Holland Publishing Company , Amesterdam , 1972

Willebrand, Heinz A., Ghuman Barksheesh S. (2001). Fiber Optic Without Fiber. LightPointe Communications Inc. , 2001 http://freespaceoptic.com/Fiber_Optics_Without_Fiber.htm. Accessed on February 2005

Schlessinger,M. , "Infrared Technology Fundamentals" , Marcel Dekker Inc , 1994

Arnon S., Ben-Gurion University of the Negev , Beer-Sheva , Zionist entity , "Optical Wireless Communications" , Encyclopedia of Optical Engineering , R. G. Driggers, ed. (Marcel Dekker , NewYork , to be published) , 2003.
http://www.ee.bgu.ac.il/~shlomi/publication/chapter-optical wireless communication.pdf
Accessed on December 2004

Hudson, Richard D. Infrared System Engineering. John Wiley & Sons, New York/London/Sydney/Toronto. , 1969

Mohd O. Zaatari. , " Wireless Optical Communications System in Enterprise Networks" , The Telecommunications Review , 2003
http://www.mitretek.org/publications/2003_telecomm-review/06_Zaatari_2003.pdf
Accessed in July 2005.

Earl J. McCartney, "Optics of the Atmosphere: Scattering by Molecules and Particles", Wiley & Sons, New York, 1976.

Srinivasa G. Narasimhan and Shree K. Nayar "Vision and the Atmosphere".

Brown, Derek W. Terminal Velocity and The Collision/Coalescence Process, 2003
http://vortex.plymouth.edu/precif/terminalvelocity.html.
Accessed on February 2005

Nevers, N.D. Air Pollution Control Engineering, McGRAW-HILL , 2000

I. Kim , R. Stieger , J. Koontz , C. Moursund , M. Barclay , P. Adhikari , J. Schuster , and E. Korevaar , "Wireless optical transmission of Fast Ethernet, FDDI, ATM, and ESCON protocol data using the TerraLink laser communication system" , Opt. Eng. , 37 , 3143-3155 , 1998.

Bloom S. Eric Korevaar , John Schuster , Heinz Willebrand. "Understanding the Performance of free space optics" [Invited] , Journal of Optical Networking, Vol.2 , No. 6 , 2003
http://www.wcai.com/pdf/2004/fso_osa.pdf
Accessed on December 2004