# Propagation of optical and infrared waves in the atmosphere

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**Abstract**

Free Space Optical communications (FSO) has attracted considerable attention for a variety of applications in telecommunications field.

This technology uses the transmission of an optical or infrared (IR) signal in the atmosphere to provide high data rate reliable more economically than traditional fiber. Some of FSO advantages are: spectrum licensing, frequency coordination, no interference, fast and easy installation, multi-Gbps high data rate, low cost.

This communication presents various atmospheric considerations relating to the propagation such as absorption and scattering by molecular or aerosols, scintillation due to the air index variation under the temperature effect, attenuation by hydrometeors (rain, snow) like their various modelling (Kim and Kruse, Al Naboulsi, Carbonneau, etc). Some experimental results (attenuation in function of the visibility) are presented. The comparison of measurements with our model shows a good agreement for low visibility where Kruse and Kim models deviate notably from measurements.

**1 - Introduction**

Free Space Optical communication (FSO) has attracted a considerable attention for a variety of applications in telecommunications field. This technology uses the transmission of an optical or infrared (IR) signal in the atmosphere to provide high data rate reliable links in a more profitable way and more rapid than the traditional networks fiber.

The various aspects of the infrared and visible optical waves propagation in the atmosphere are presented (molecular and aerosol absorption, molecular and aerosol scattering, rain and snow attenuation, scintillations effects). They constitute the key of all good comprehension of the future free space optical communication systems (FSO). Fog appears as the more penalizing element in the free space optical link operation.

The comparison of experimental data allows validating the models suggested in the literature. These models allow also the control of the emission power levels of the future free space optical links guaranteeing a sufficient dynamics taking into account the variability of the optical propagation conditions.

**2 - Light propagation in free space**

Free Space Optic (FSO) links involve the transmission, absorption and scattering of the light by the Earth's atmosphere. The atmosphere interacts with light due to the atmosphere composition which, under normal conditions, consists of a variety of different molecular species and small suspended particles called aerosols. This interaction produces of wide variety of optical phenomena: selective attenuation, scattering and scintillations.

A selective absorption of radiations that propagate at specific optical wavelength in the atmosphere results from the interaction between photons and atoms or molecules (N2, O2, H2, H2O, CO2, O3, Ar, etc.) which leads to the disappearing of the incident photon and an elevation of the temperature. The absorption coefficient depends on the type of gas molecules and on their concentration. Molecular absorption is a selective phenomenon which results in a spectral transmission of the atmosphere presenting transparent zones, called atmospheric transmission window, and opaque zones, called atmospheric blocking windows.

Aerosols are extremely fine solids or liquids particles suspended in the atmosphere with very low fall speed by gravity (ice, dust, smoke, etc). Their size generally lies between $10^{-2}$ and 100 µm. Fog, dust and maritime spindrift particles are examples of aerosols. Aerosols influence the conditions of atmospheric attenuation due to their chemical nature, their size and their concentration. In maritime environment, the aerosols are primarily made up of droplets of water (foam, fog, drizzle, rain), of salt crystals and various particles of continental origin. Type and density of continental particles depend on distance and characteristics of the neighbouring coasts.

Atmospheric scattering results from the interaction of a part of the light with the atoms and/or the molecules in the propagation medium. It causes an angular redistribution of this part of the radiation with or without modification of the wavelength.

Aerosols scattering occurs when the particle size are of the same order of magnitude as the wavelength of the transmitted wave. In optics it is mainly due to mist and fog. Attenuation is a function of frequency but also of the visibility related to the particle size distribution. This phenomenon constitutes the most restrictive factor to the deployment of Free Space Optical systems at long distance. The visibility is a concept defined for the needs of the meteorology. It characterizes the transparency of the atmosphere estimated by a human observer. It is measured by the Runway Visual Range (RVP), distance that a parallel luminous ray's beam must travel through the atmosphere until its intensity (or luminous flux) drops to 0.05 times its original value. It is measured using a transmissometer or a diffusiometer.

Under the influence of thermal turbulence inside the propagation medium, random distributed cells are formed. They have variable size (10 cm - 1 km) and different temperature. These various cells have different refractive indexes thus causing scattering, multipath, variation of the arrival angles: the received signal fluctuates quickly at frequencies ranging between 0.01 and 200 Hz. The wave front varies similarly causing focusing and defocusing of the beam. Such fluctuations of the signal are called scintillations

**3 - Modeling**

For optical and IR waves, light propagation through the atmosphere is affected by absorption and scattering by air molecules and absorption and scattering by solid or liquid particles suspended in the air. The transmission of the light in the atmosphere is described by the Beer Lambert law:

$$\tau(\lambda, L) = \frac{P(\lambda, L)}{P(\lambda, 0)} = \exp\left[-\gamma(\lambda) L\right]$$

where:

- $\tau(\lambda)$ is the total transmittance of the atmosphere at wavelength $\lambda$
- $P(\lambda, L)$ is the signal power at distance L from the transmitter,
- $P(\lambda, 0)$ is the emitted power,
- $\gamma(\lambda)$ is the attenuation or the total extinction coefficient per unit of length

Extinction coefficient is composed of absorption and scattering terms. Generally it is the sum of the following terms:

$$\gamma(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda)$$

Where $\alpha_{m,a}$ are molecular and aerosol absorption coefficients respectively and $\beta_{m,a}$ are molecular and aerosol scattering coefficients respectively.

In the spectrum region used by FSO, attenuation coefficient is only approximated by the coefficient of scattering by the particles present in the atmosphere.

**3.1 - Kruse and KIM relations**

Thus, the attenuation coefficient is approximated by the following relation (Kruse relation):

$$\gamma(\lambda) \;;\; \beta_a(\lambda) = \frac{3.912}{V}\left(\frac{\lambda_{nm}}{550}\right)^{-q}$$

The coefficient q depends on the particle size distribution. It is given by [1]:

$$q = \begin{cases} 1.6 & \text{si } V > 50km \\ 1.3 & \text{si } 6km < V < 50km \\ 0.585\, V^{1/3} & \text{si } V < 6km \end{cases}$$

This relation was largely used in the literature with the aim of determining the FSO equipment link budget. From the last two equations, it is clear that, for any meteorological conditions, more the wavelength increases, more the attenuation decreases.

Thus, a recent study proposes another expression for the parameter q. This expression, not yet experimentally checked, is the following one [2]:

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

This last equation implies independence between the atmospheric attenuation values and the wavelength in presence of a dense fog reducing the visibility below 500 m. Beyond 500 m of visibility, this relation respects the conclusion deduced from the previous relations, namely a smaller attenuation for increasing wavelengths.

**3.2 – Al Naboulsi relations**

AL NABOULSI and al. developed from FASCOD simple relations allowing the evaluation of the attenuation in the 690 to 1550 nm wavelength range and for visibilities going from 50 to 1000 m for two types of fog: advection and convection fog [3]:

The advection fog is generated when the warm, moist air flows over a colder surface. The air in contact with the surface is cooled below its dew point, causing the condensation of water vapour. It appears more particularly in spring when southern displacements of warm, moist air masses move over snow covered regions.

The attenuation by an advection fog is expressed by the following relation:

$$\sigma_{advection} = \frac{0.11478\lambda + 3.8367}{V}$$

where:

- $\lambda$ is the wavelength (nanometers),
- V is the visibility (meters).

The radiation or convection fog is generated by radiative cooling of an air mass during the night radiation when meteorological conditions are favourable (very low speed winds, high humidity, clear sky). It forms when the surface releases the heat that is accumulated during the day and becomes colder: the air which is in contact with this surface is cooled below the dew point, causing the condensation of water vapour, which results in the formation of a ground level cloud. This type of fog occurs more particularly in valleys.

The attenuation by a radiation or convection fog is expressed by the following relation:

$$\sigma_{advection} = \frac{0.18126\lambda^2 + 0.13709 + 3.8367}{V}$$

**3.3 – Rain attenuation**

Rain attenuation (dB/km) is generally given by the CARBONNEAU relation [4]:

$$Att_{rain} = 1.076 * R^{0,67}$$

**3.4 – Snow attenuation**

Attenuation in function of snowfall rate is given by the following relation

$$Att_{snow}[dB/km] = aS^b$$

where:

$Att_{snow}$ is attenuation by snow (dB/km)
S is the snowfall rate (mm/h)
a et b are coefficients, function of the wavelength, giving by the following relations ($\lambda$nm in nm):

| | | |
|---|---|---|
| Wet snow | $a = 0,0001023 * \lambda_{nm} + 3,7855466$ | $b = 0,72$ |
| Dry Snow | $a = 0,0000542 * \lambda_{nm} + 5,4958776$ | $b = 1,38$ |

**3.5 - Scintillation attenuation**

Tropospheric scintillations effects are generally studied from the logarithm of the amplitude $\chi$ [dB] of the observed signal ("log-amplitude"), defined as the ratio in decibels between its instantaneous amplitude and its average value. The intensity and the speed of the fluctuations (scintillations frequency) increase with wave frequency. For a plane wave, a low turbulence and a specific receiver, the scintillation variance $\sigma\chi 2$ [$dB^2$] can be expressed by the following relation:

$$\sigma_\chi^2 = 23.17 * k^{7/6} * C_n^2 * L^{11/6}$$

where:

- k[m-1] is the wave number ($2\pi/\lambda$),
- L[m ] is the length of the link,
- $Cn^2$ [$m^{-2/3}$] is the structural parameter of the refractive index, representing the turbulence intensity.

Scintillation peak with peak amplitude is equal to $4\sigma\chi$ and attenuation related to scintillation is equal to $2\sigma\chi$.

**4 – Measurements and results**

We present hereafter experimental results deduced from attenuation measurements in function of the visibility realized within the framework of COST 270 project in collaboration with the University of GRAZ[5].

Figure 1 shows the evolution of the attenuation measured on the site of "La Turbie" of the specific attenuation (dB/km) of the luminous ray at 850 nm and 950 nm according to the visibility in presence of fog. Results are compared to KRUSE and to KIM model.

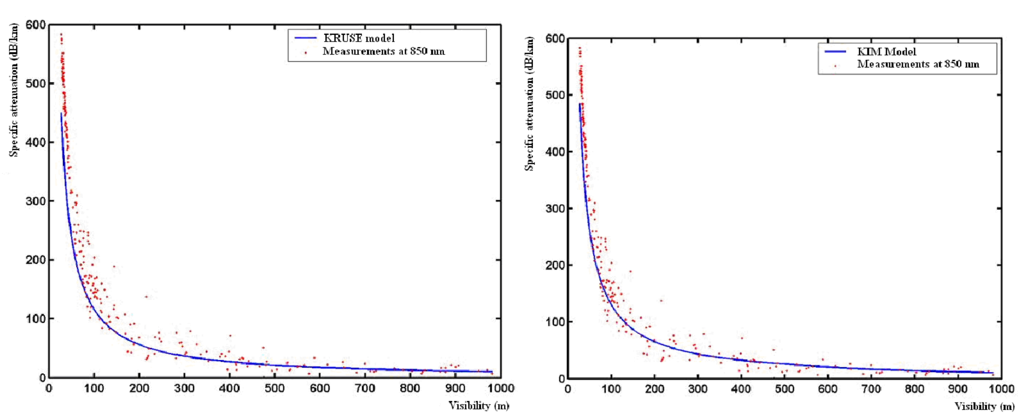


Figure 1: Variation of the attenuation at 850 nm in function of the visibility; Comparison to KRUSE and KIM model.

Figure 2 shows the evolution of the attenuation measured on the site of "La Turbie" of the specific attenuation (dB/km) of the luminous ray at 850 Nm according to the visibility in the presence of fog. The results are compared to the Al Naboulsi model.

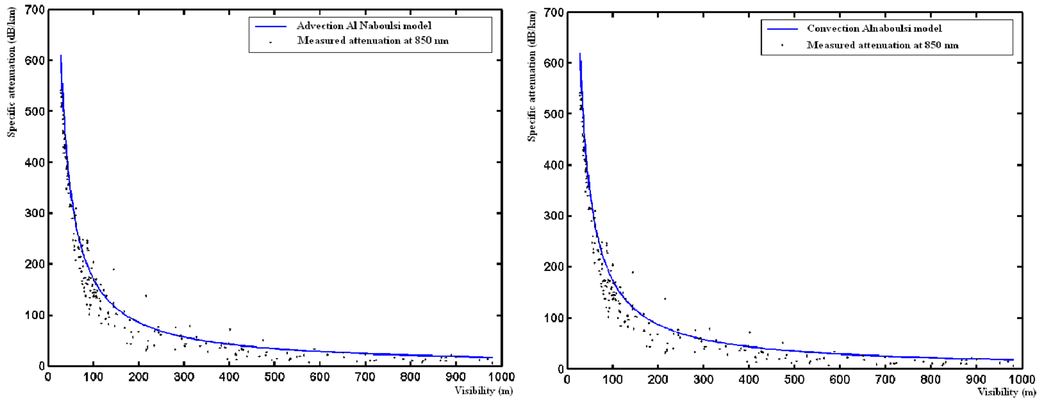


Figure 2: Variation of the attenuation according to the visibility; Comparison to the advection and convection Al Naboulsi model.

The comparison of measurements to models existing in the literature shows a good agreement between measurements and the suggested models. From the analysis of the previous curves, it appears that the Al Naboulsi model, developed from Fascod, is in excellent agreement with experimental measurements for low visibilities where Kruse and Kim models deviate notably from measurements.

## 5 – Conclusion

The various aspects of the propagation of the photons in the Earth's atmosphere were presented (molecular and aerosol absorption, molecular and aerosol scattering, rain and snow attenuation, scintillations effects). They constitute the key of all good comprehension of the future free space optical communication systems. The fog seems the more penalizing element to free space optical links operation.

The comparison of the experimental data allows validating the models suggested in the literature. The latter allow controlling the levels of emission power of the future free space optical links in their guaranteeing a sufficient dynamics taking into account the variability of the optical propagation conditions.

The experimental links allow to show that FSO constitute a reliable alternative broad band to the installation of optical fibres and to lead to a better acceptance of this technology in the industry of the high data rate telecommunications networks.

In order to better apprehend the availability of an atmospheric optical link, the reader will refer to engineering tools to simulate the quality of service. They allow, for a given geographical site, to determine the availability and the reliability of a link according to the parameters systems (power, wavelength, characteristic of the system) and climatic and atmospheric parameters. They integrate the various physical phenomena responsible of the rupture of the link such as the attenuations due to the ambient light, scintillation, the rain, snow and the fog [6].

## 6 - Reference


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