

## RECOMMENDATION ITU-R P.1814\*

**Prediction methods required for the design  
of terrestrial free-space optical links**

(Question ITU-R 228/3)

(2007)

**Scope**

This Recommendation provides propagation prediction methods for planning terrestrial free-space optical systems. It includes methods to estimate attenuation in clear air, fog, and rain and snow precipitation. It also covers scintillation and impairments by sunlight.

The ITU Radiocommunication Assembly,

*considering*

- a) that the visible optical and infrared spectrum is available for radiocommunications in the Earth's environments;
- b) that for the proper planning of free-space optical (FSO) radiocommunication systems operating in visible optical and infrared spectrum, it is necessary to have appropriate propagation data;
- c) that methods have been developed that allow the calculation of the most important propagation parameters needed in planning free-space optical systems operating in the visible optical and infrared spectrum;
- d) that these methods have been tested against available data and have been shown to yield an accuracy that is both compatible with the natural variability of propagation phenomena and adequate for most present applications in the planning of systems operating in visible optical and infrared spectrum,

*recognizing*

- a) that No. 78 of article 12 of the ITU Constitution states that a function of the Radiocommunication Sector includes, "... carrying out studies without limit of frequency range and adopting recommendations ...",

*recommends*

- 1** that the methods for predicting the propagation parameters given in Annex 1 should be adopted for planning free-space optical systems, in the respective ranges of validity indicated in the Annex.

NOTE 1 – Supplementary information related to propagation prediction methods in visible optical and infrared spectrum may be found in Recommendation ITU-R P.1817 – Propagation data required for the design of terrestrial free-space optical links.

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\* This Recommendation should be brought to the attention of Radiocommunication Study Groups 1 and 9.

## Annex 1

### 1 Introduction

In the design of FSO links several effects must be considered including the losses due to atmospheric absorption, scattering and turbulence, microclimate environment and localized effects, link distance and link misalignment. The selection of wave length, data rate, eye-safety issues, and ambient solar radiation must also be considered.

FSO system operation requires line-of-sight (LOS). When testing for LOS, as FSO systems use beam expansion and a collimated beam, the clearance needed between the centre of the beam and any obstructions is essentially equal to the beam radius. This is in contrast to RF systems where Fresnel zone clearance is needed.

The primary disadvantage of FSO systems are their vulnerability to atmospheric effects such as attenuation and scintillation, which can reduce link availability. The narrow beam also makes alignment of the laser communications terminal more critical than is usual for RF systems.

A key parameter in the design of FSO links is the consideration of the power budget. The link margin,  $M_{link}$  (dB), which is the power available above the sensitivity of the receiver, can be found from equation (1):

$$M_{link} = P_e - S_r - A_{geo} - A_{atmo} - A_{scintillation} - A_{system} \quad (1)$$

where:

- $P_e$  (dBm): total power of the emitter
- $S_r$  (dBm): sensitivity of the receiver which also depends on the bandwidth (Data rate)
- $A_{geo}$  (dB): link geometrical attenuation due to transmit beam spreading with increasing range
- $A_{atmo}$  (dB): atmospheric attenuation due to absorption and scattering
- $A_{scintillation}$  (dB): attenuation due to atmospheric turbulence
- $A_{system}$  (dB): represents all other system dependent losses including misalignment of the beam direction, receiver optical losses, loss due to beam wander, reduction in sensitivity due to ambient light (solar radiation), etc.

The definition and computation of these terms and the initial consideration for planning an FSO link are given in the following sections.

### 2 Initial considerations in designing an FSO link

The choice of a suitable link location is an important issue for a successful operation of an FSO system. The installation of FSO links has to account for prevailing weather conditions, physical obstructions and surface types along the path, and transceiver mounting arrangements to ensure optimum link performance.

#### 2.1 Weather

- Weather conditions, and in particular the local climate, in the vicinity of the chosen link path will influence the occurrence of snow, rain, drizzle fog, haze, aerosol and dust/sand that will lead to absorption and scattering of the transmitted signal.

## 2.2 Path characteristics

- Physical obstructions to the path between emitter and receiver are clearly to be avoided. It is well worth noting that mature trees can increase in height by between 0.5 and 1 m in one year and vary in foliage density over the year.
- Links between buildings should account for thermal vents that could result in hot air rising through the link path, and the resulting turbulence could lead to significant scintillation at the receiver.
- The topography and the type of surface beneath an FSO line-of-sight path can significantly impact the performance of the link. FSO links across river valleys, or across areas of open sea, will often experience increased incidents of fog. Building structures beneath the link may cause additional thermal activity in the air above them that may then lead to increased scintillation on the received signal.

## 2.3 Transceiver mounting

- Most FSO systems have very narrow beam widths, and, as a result, the accurate alignment of the emitter and receiver is critical; any misalignment causes significant signal loss. The telescope mounts must be stable and direct mounting to substantial walls, or to the top of a single column, is considered essential for reliable performance over a period of time. Movement as the result of differential thermal expansion, or buffeting by wind, should be minimized.

## 3 Geometrical attenuation

Even in clear weather conditions, the beam diverges and, as a result, the detector receives less signal power. The attenuation due to transmit beam spreading with increasing range is called geometrical attenuation and is given by the formula (2):

$$A_{geo}(\text{dB}) = 10 \log_{10} \left( \frac{S_d}{S_{capture}} \right) \quad (2)$$

where:

$S_{capture}$ : receiver capture surface (m<sup>2</sup>)

$S_d$ : surface area of transmit beam at range  $d$ , which is approximated by:

$$S_d = \frac{\pi}{4} (d \cdot \theta)^2$$

where:

$\theta$ : beam divergence (mrad)

$d$ : emitter-receiver distance (km).

It is possible on short links for the capture area to be greater than the beam area. In these cases the value of  $A_{geo}$  should be set to zero as all of the beam energy is collected.

#### 4 Specific atmospheric attenuation due to absorption and scattering $\gamma_{atmo}$

The specific atmospheric attenuation  $\gamma_{atmo}$  (dB/km) can be written as the sum of two terms:

$$\gamma_{atmo} = \gamma_{clear\_air} + \gamma_{excess} \quad (3)$$

where:

- $\gamma_{clear\_air}$ : specific attenuation under clear air (due to the presence of gaseous molecules)
- $\gamma_{excess}$ : specific attenuation due to the occasional presence of fog, mist, haze, drizzle, rain, snow, hail, etc.

The atmosphere is a time-varying transmission medium and as a result  $\gamma_{atmo}$  is a stochastic process. However, as shown in equation (1), imposing limits on system availability and its effects are generally treated statistically. Link margin,  $M_{link}$ , represents the amount of attenuation which can be tolerated by a given system at a given range.

##### 4.1 Specific clear-air attenuation $\gamma_{clear\_air}$

Attenuation under clear-air conditions is mainly the attenuation due to the absorption by gaseous molecules. Atmospheric absorption at specific optical wavelengths results from the interaction between photons and atoms or molecules ( $N_2$ ,  $O_2$ ,  $H_2$ ,  $H_2O$ ,  $CO_2$ ,  $O_3$ , etc.) which leads to the absorption of the incident photon and an elevation of the temperature. The absorption coefficient depends on:

- the type of gas molecules; and
- their concentration.

Molecular absorption is a wavelength-selective phenomenon which results in atmospheric transmission windows, and atmospheric absorbing regions. The important atmospheric molecules that have high absorption in the IR band include water,  $CO_2$ ,  $O_3$  and  $O_2$ .

Because the size of the gaseous molecules is much smaller than the wavelength, scattering attenuation from the gaseous molecules is negligible.

Usually the laser wavelengths are selected to fall inside atmospheric transmission windows, so  $\gamma_{clear\_air}$  is negligible. The wavelengths generally used in FSO systems are near 690, 780, 850, and 1 550 nm. However, in comparison to relatively unpolluted suburban locations, applications in dense urban areas with high aerosol contents might benefit from a different wavelength.

##### 4.2 Specific excess attenuation

Excess attenuation is the attenuation caused by the occasional presence of fog, mist, haze, drizzle, rain and snow particles. The presence of these particles causes an angular redistribution of the incident flux, known as scattering, and reduces the flux propagation in the original direction. However, there is no loss of energy similar to absorption. The physical size of the scatterers with respect to the transmission laser wavelength determines the type of scattering. Table 1 shows the three different scattering regimes depending on the scatter's size and the approximate relationship between wavelength and scatter's attenuation coefficient (effective-cross section). Also shown in Table 1 are the type of scatters in each regime for the visible and IR wavelengths.

TABLE 1

Scattering regimes depending on the scatter's size  $r$  with respect to the transmission laser wavelength  $\lambda$ . Also shown is the approximate relationship between wavelength and scatter's attenuation coefficient  $Q(\lambda)$

	Rayleigh scattering	Mie scattering	Non-selective or geometrical scattering
	$r \ll \lambda$ $Q(\lambda) \sim \lambda^{-4}$	$r \approx \lambda$ $Q(\lambda) \sim \lambda^{-1.6}$ to $Q(\lambda) \sim \lambda^0$	$r \gg \lambda$ $Q(\lambda) \sim \lambda^0$
Type of scatter	Air molecules Haze	Haze Fog Aerosol	Fog Rain Snow Hail

Because of the  $Q(\lambda) \sim \lambda^{-4}$  relationship of the Rayleigh regime the air molecular scattering contribution to the total attenuation coefficient is negligible.

For particles that are much larger than the wavelength, scattering can be described by geometric optics which is independent of laser wavelength. Rain drops, snow, hail, cloud droplets and heavy fog will geometrically scatter laser light.

For particles whose size is comparable to the laser wavelength, Mie scattering theory can be applied. Fog and aerosol particles are the major contributors to the Mie scattering process.

An analytical approach can be used in which computation predictions of the specific attenuation are made based on the theoretically derived effective cross sections of atmospheric particles with assumed particle size distributions. However, the particle size distributions of either aerosol or fog, which is a key parameter to determine their physical and optical properties, are difficult to model and measure.

#### 4.2.1 Estimation of specific attenuation due to fog $\gamma_{fog}$ (Mie scattering)

Since an analytical approach is often not practical to compute the attenuation due to Mie scattering, empirical methods have been adopted by the FSO community. In these methods, the attenuation coefficient due to Mie scattering is related to visibility.

The technical definition of *visibility* or visual range is the distance that light decreases to 2% of the original power or qualitatively visibility is the distance at which it is just possible to distinguish a dark object against the horizon. The visibility parameter is easily measured and stored in meteorological stations or airports databases, which allows geo-local performance evaluation of these telecommunication systems using the distribution of this parameter. However, the visibility data collected at airports may not necessarily represent conditions found in either urban or rural environments, which can be very different in terms of topography and proximity to water.

An empirical simplified formula, which has been used in the FSO community to calculate the specific attenuation due to fog,  $\gamma_{fog}(\lambda)$  (dB/km), is:

$$\gamma_{fog}(\lambda) = \frac{3.91}{V} \left( \frac{\lambda}{550 \text{ nm}} \right)^{-q} \quad (4)$$

where:

$V$  : visibility (km)

$\lambda$  : wavelength (nm)

$q$  : a coefficient dependent on the size distribution of the scattering particles. It has been determined from experimental data and given by:

$$\begin{aligned} q &= 1.6 & V > 50 \text{ km} \\ &= 1.3 & 6 \text{ km} < V < 50 \text{ km} \\ &= 0.585V^{1/3} & V < 6 \text{ km} \end{aligned} \quad (5)$$

To obtain the attenuation value exceeded for a given percentage of time  $p$  (i.e. for a given probability), the value of the visibility that was not exceeded for this percentage  $p$  is required for equation (4).

#### 4.2.2 Specific attenuation due to rain $\gamma_{rain}$

Specific rain attenuation  $\gamma_{rain}$  (dB/km) is given by the relation:

$$\gamma_{rain} = k \cdot R^\alpha \quad (6)$$

Recommendation ITU-R P.837 provides the rainfall rate  $R(p)$  (mm/h) exceeded for any given percentage of the average year,  $p$ , and for any location, and equation (6) provides the specific attenuation exceeded for the time percentage  $p$ .

The parameters  $k$  and  $\alpha$  depend on the rain characteristics, and some values determined from measurements are given in Table 2. Figures 1 and 2 illustrate the relationship between  $\gamma_{rain}$  and rainfall rate,  $R$ , using the parameters in Table 2 for Japan.

TABLE 2  
Parameters used for the estimation of the specific  
attenuation due to rain

Location	$k$	$\alpha$
Japan	1.58	0.63
France	1.076	0.67

FIGURE 1

Atmospheric attenuation due to rainfall

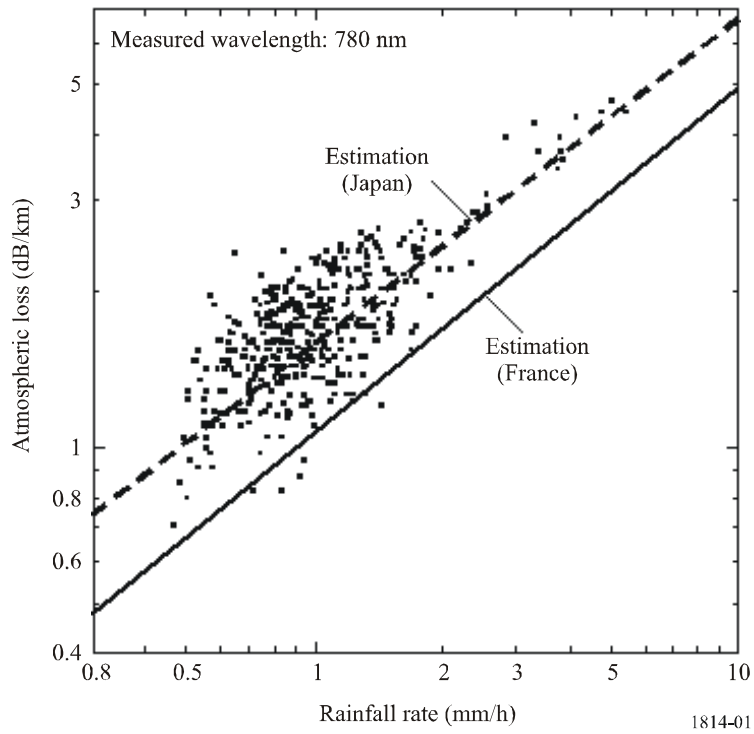
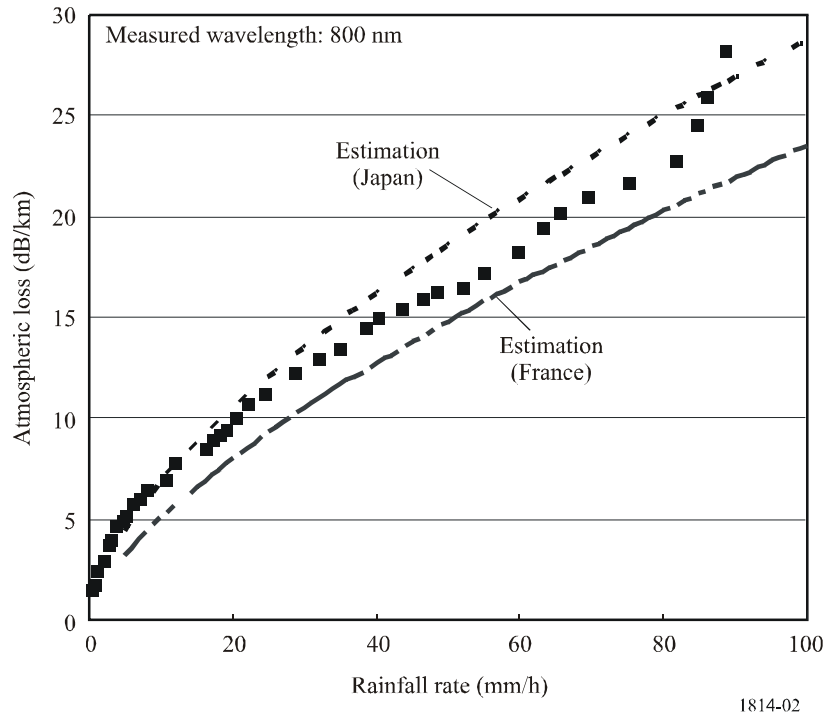


FIGURE 2

Atmosphere attenuation due to rainfall



### 4.2.3 Specific attenuation due to snow $\gamma_{snow}$

Attenuation as a function of snowfall rate is given by the following relation:

$$\gamma_{snow} = \alpha \cdot S^b \quad (7)$$

where:

- $\gamma_{snow}$ : specific attenuation due to snow (dB/km)
- $S$ : snowfall rate (mm/h)
- $\alpha$  and  $b$ : functions of the wavelength,  $\lambda$  (nm). Estimated values for wet and dry snow are given in Table 3.

TABLE 3  
Parameters used for the estimation of the specific  
attenuation due to snow

	$\alpha$	$b$
Wet snow	$0.000102\lambda + 3.79$	0.72
Dry snow	$0.0000542\lambda + 5.50$	1.38

## 5 Scintillation effects

A second major atmospheric process that affects the performance of laser communication systems is turbulence-induced atmospheric scintillation which causes severe fluctuations in the received signal power.

Atmospheric turbulence produces temporary pockets of air with slightly different temperatures, different densities, and different indices of refraction. Data can be lost due to beam wander and scintillation as the laser beam becomes deformed propagating through these index of refraction inhomogeneities. The significance of each effect depends on the size of these turbulence cells with respect to the laser beam diameter.

If the sizes of the turbulence cells are larger than the beam diameter, the laser beam as a whole randomly bends, causing signal loss if the beam wanders off the receiver aperture. Longer wavelengths will have less beam wander than shorter wavelengths, although the wavelength dependence is weak.

More commonly, if the sizes of the turbulence cells are smaller than the laser beam diameter, ray bending and diffraction cause distortions in the laser beam wave front. This results in temporal fluctuations in the laser beam intensity, known as scintillation, at the receiver with a frequency spectrum from 0.01 Hz to 200 Hz.

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 fluctuation rate (scintillation frequency) increase with wavelength. For a plane wave and weak turbulence, the scintillation variance  $\sigma_x^2$  (dB<sup>2</sup>) can be expressed by the following relation:

$$\sigma_x^2 = 23.17 \cdot k^{7/6} \cdot C_n^2 \cdot L^{11/6} \quad (8)$$



where:

$$k = \frac{2\pi}{\lambda} : \text{ wave number (m}^{-1}\text{)}$$

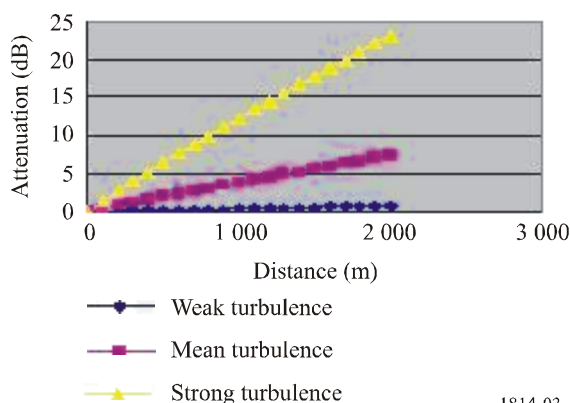
$L$ : length of the link (m)

$C_n^2$ : refractive index structure parameter ( $\text{m}^{-2/3}$ ).

The scintillations have peak amplitude of  $4\sigma_\chi$  and the attenuation due to scintillation is  $2\sigma_\chi$ . For strong turbulence, saturation of the variance given by the above relation is observed. The parameter  $C_n^2$  has a different value at optical wave lengths than at millimetre wavelengths. Scintillation at millimetre wavelengths are primarily due to humidity fluctuations, while at optical wavelengths scintillation is primarily a function of the temperature. At millimetre wavelengths,  $C_n^2$  is approximately equal to  $10^{-13} \text{ m}^{-2/3}$  (in general, at millimetre wavelengths  $C_n^2$  is between  $10^{-14}$  and  $10^{-12} \text{ m}^{-2/3}$ ) and at optical wavelengths a value of  $C_n^2$  is approximately equal to about  $2 \times 10^{-15} \text{ m}^{-2/3}$  for weak turbulence (in general at optical wavelengths  $C_n^2$  is between  $10^{-16}$  and  $10^{-13} \text{ m}^{-2/3}$ ).

Figure 3 illustrates the variation of the attenuation of a 1 550 nm wavelength optical beam for weak, mean, and strong turbulence at distances up to 2 000 m. Clearly, attenuation increases as turbulence increases. Table 4 shows the turbulence effect on optical and radio waves propagation. Scintillation is stronger on longer optical wavelengths.

FIGURE 3  
Variation of the attenuation due to scintillation according to distance for various turbulence types at 1 550 nm



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TABLE 4  
Table of scintillation fade depths expected for 1 km path length

	Turbulence		
	Low	Moderate	High
$C_n^2$ optic waves ( $\text{m}^{-2/3}$ )	$10^{-16}$	$10^{-14}$	$10^{-13}$
Attenuation (0.98 $\mu\text{m}$ ) (dB)	0.51	5.06	16.00
Attenuation (1.55 $\mu\text{m}$ ) (dB)	0.39	3.87	12.25
$C_n^2$ millimetre waves ( $\text{m}^{-2/3}$ )	$10^{-15}$	$10^{-13}$	$10^{-12}$
Attenuation (40 GHz) (dB)	0.03	0.09	0.27
Attenuation (60 GHz) (dB)	0.03	0.11	0.35

Scintillation can be reduced by using either multiple transmit beams or large receiver apertures. Also to minimize the effects of scintillation on the transmission path, FSO systems should not be installed close to hot surfaces. Because scintillation decreases with altitude it is recommended that FSO systems should be installed a little higher above the rooftop (>1 m) and away from a side wall if the installation takes place in a desert-like environment.

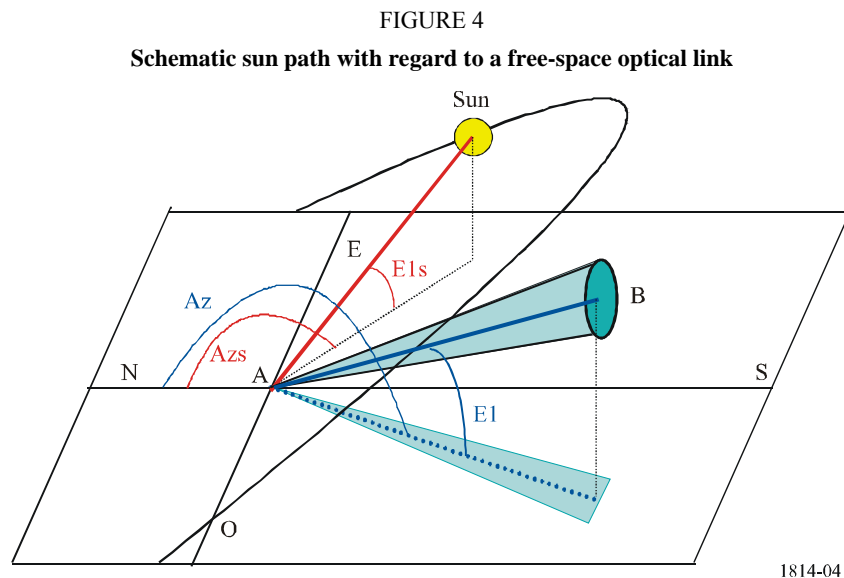
Margins allocated to compensate for fog or rain attenuation can compensate also for scintillation effects.

## 6 Ambient light effect

Solar conjunction occurs when the sun or a reflected image of the sun is in or near the instantaneous field of view (IFOV) of an optical receiver. The receive IFOV is generally at least as large as the transmit divergence. The problem becomes severe when the sun position is parallel to the optical link and the sun power penetrating inside the receiver is greater than the power received from the emitter.

Solar interference is usually reduced by arranging for the receiver to be positioned so that the sun is always off-axis.

Figure 4 represents the geometry of the sun path in the sky with regard to a free-space optical link (A is the receiver, B the emitter).



The power radiated by the sun,  $P_{radiated}$  ( $\text{W}/\text{m}^2$ ) is defined by the following relation:

$$P_{radiated} = 1\,200 \cdot \cos\left(\frac{\pi}{2} - E_{Is}\right) \quad (9)$$

where  $E_{Is}$  is the sun height (rad).

The received power is given by:

$$P_{solar} = F_{solar} \cdot P_{radiated} \cdot S_{capture} \cdot W_{receiver} / 100 \quad (10)$$

where:

- $F_{solar}$ : solar spectral power as a function of wavelength
- $S_{capture}$ : receiver capture surface area (m<sup>2</sup>)
- $W_{receiver}$ : receiver bandwidth (nm)
- $F_{solar}$ : modelled by the following curve fit:

$$F_{solar} = 8.97 \times 10^{-13} \lambda^5 - 4.65 \times 10^{-9} \lambda^4 + 9.37 \times 10^{-6} \lambda^3 - 9.067 \times 10^{-3} \lambda^2 + 4.05 \lambda - 5.70 \quad (11)$$

where:

- $\lambda$ : wavelength (nm).

## 7 Link margin calculation

The link fade margin for an FSO system with a receiver at a distance  $d$  (km) from the emitter can be estimated using the following steps:

*Step 1:* The geometrical attenuation  $A_{geo}$  can be obtained from equation (1).

*Step 2:* Laser wavelengths are usually selected to fall inside atmospheric transmission windows so  $\gamma_{clear\_air}$  can be considered negligible. However, estimates of the specific clear-air attenuation can be obtained from Recommendation ITU-R P.1817.

*Step 3:* The specific attenuation due to fog  $\gamma_{fog}$  can be obtained from equations (4) and (5). In the absence of local data typical values of visibility can be found in Recommendation ITU-R P.1817.

*Step 4:* The specific attenuation due to rain  $\gamma_{rain}$  can be obtained from equation (6) and Table 2.

*Step 5:* The specific attenuation due to  $\gamma_{snow}$  can be obtained from equation (7) and Table 3.

*Step 6:* The fade margin  $M_{link}$  (dB) is given by:

$$M_{link} = P_e - S_r - A_{system} - A_{geo} - \gamma_{clear\_air} \cdot d - \gamma_{fog} \cdot d - \gamma_{rain} \cdot d - \gamma_{snow} \cdot d$$

where:

- $P_e$  (dBm): total power of the emitter
- $S_r$  (dBm): sensitivity of the receiver
- $A_{system}$  (dB): represents all other system dependent loss. These include loss due to misalignment link, receiver optical loss, beam wander loss, ambient light attenuation (solar radiation), etc.

## 8 Other issues

Other factors that should be taken into account when an FSO system is designed include the following:

International safety regulations strictly limit the maximum output power of optical systems. At 1 550 nm, the regulatory agencies allow approximately 100 times more power than for “eye safe” shorter wavelengths. The disadvantage of this laser type is mainly their cost when compared to shorter wavelengths lasers operating around 850 nm.

FSO transceivers can be located behind windows. The angle the beam makes with the window is critical. The angle should be as perpendicular as possible, yet slightly angled (5 degrees) to reduce bounce-back of the beam to its receptor. Also some windows contain glass or glass coating that reduce glare. Because these windows are often specifically designed to reject infrared, the coatings can reduce the signal by 60% or more.

Low visibilities will decrease the effectiveness and availability of FSO systems. Low visibility can occur during a specific time period within a year or day. Also low visibility can be a localized phenomenon (coastal fog). One solution to the negative impact of low visibility is to shorten the distance between the terminals which provides a greater link margin to handle bad weather conditions.

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