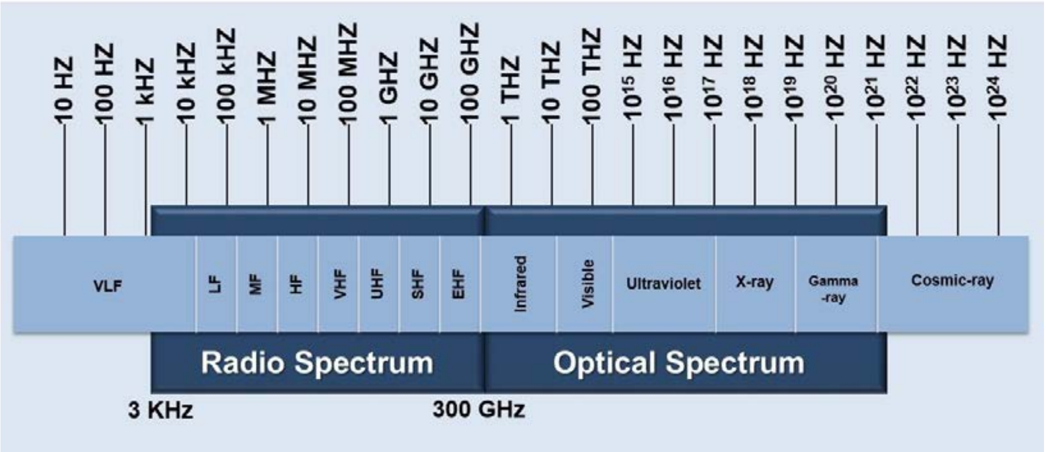
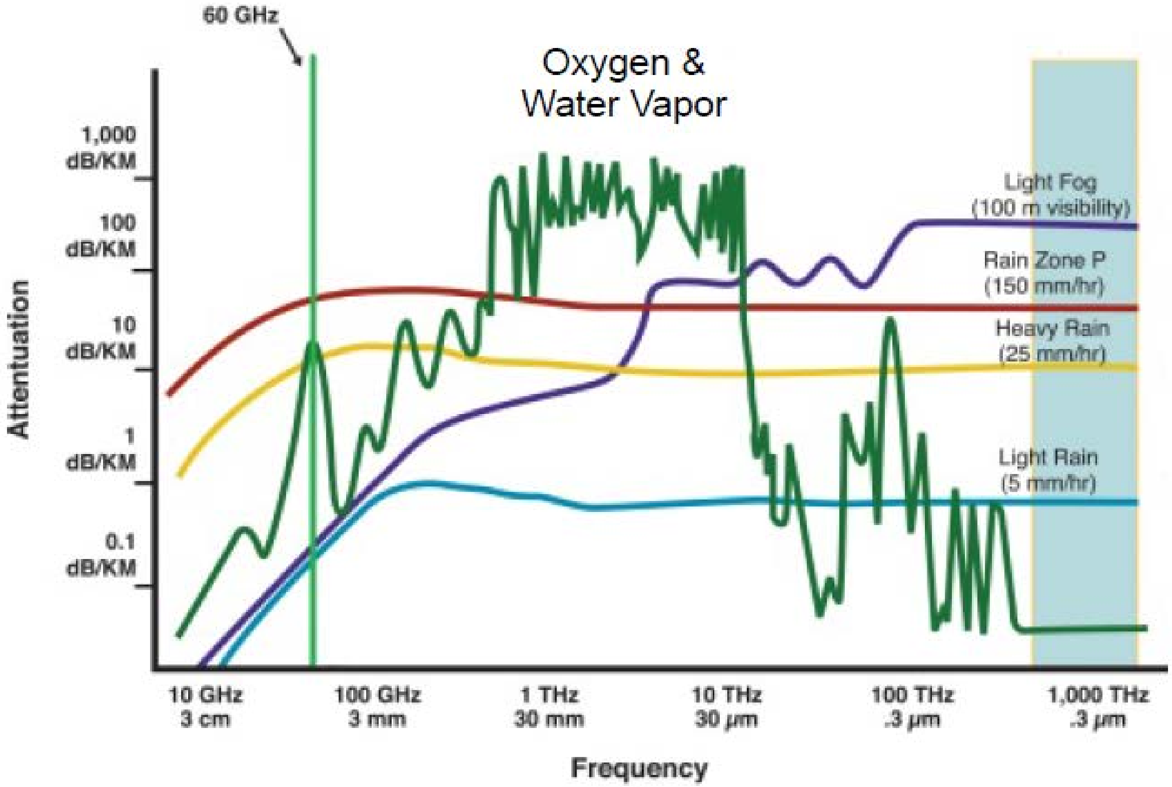
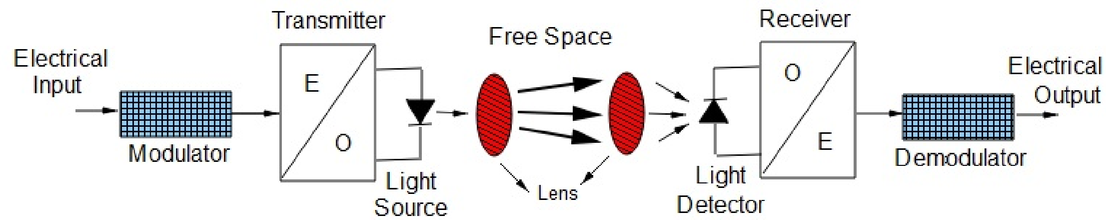
Free Space Optics (FSO)

- Introduction to
  - FSO link power budget
  - Atmospheric effects
  - Relevant ITU-R Rec. P.x





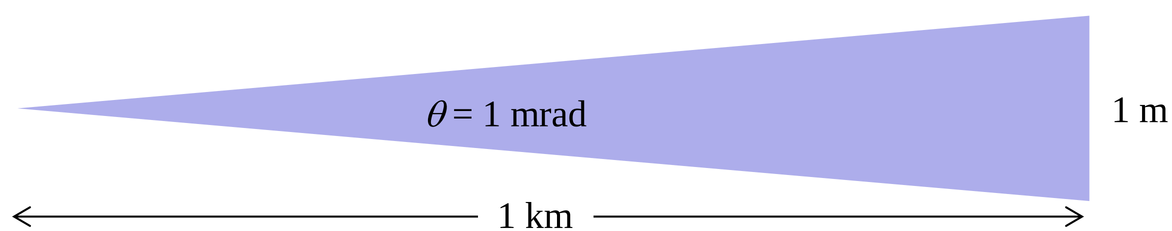
FSO links challenges



R.Ramirez-Iniguez at al. Optical Wireless Communications IR for Wireless Connectivity. CRC Press, 2007.

- Atmosphere
  - Gas composition
  - Aerosols (small particles 0.01 – 100 µm)
  - Hydrometeors (rain, snow, hail, ...)
  - Lithometeors (dust, smoke, sand, ...)
  - Refractive index modifications (turbulence)

  =>
  - Molecular absorption
  - Atmospheric scattering and absorption
  - Scintillation
- Other issues
  - Alignment
  - Building motion
  - Window attenuation
  - Birds, etc.



angle θ (mrad) * range (km) = spot size (m)

Beer–Lambert law in the atmosphere

$$P_R = P_T \frac{S_R}{(\theta d)^2} \mathrm{e}^{-\sigma d} \qquad \sigma = \sigma_m + \sigma_n + \beta_m + \beta_n$$

S_R … receiver capture surface
θ … beam divergence (specific attenuation)
d … distance (specific attenuation)

σ … extinction coefficient (specific attenuation)
σ_m … molecular absorption coef. (gas composition)
σ_n … aerosols absorption coef. (ice, dust, smoke…)
β_m … Rayleigh scattering coef. (particles $< \lambda$)
β_n … Mie scattering coef. (particles $\sim \lambda$)

Absorption dominates in IF region
Scattering dominates in visible and UV regions

RECOMMENDATION ITU-R P.1817-1*

Propagation data required for the design of terrestrial free-space optical links

(Question ITU-R 228/3)

(2007-2012)

Scope

This Recommendation provides propagation data required for the design of free-space optical (FSO) links and planning of free-space optical systems, in the respective ranges of validity indicated in the Recommendation.

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 optic (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 visible optical and infrared spectrum;

d) that, as far as possible, 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 the 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 for frequencies in visible and infrared spectrum may be found in an ITU-R Recommendation on prediction methods required for the design of terrestrial free-space optical links.

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.

FSO link budget (ITU-R Rec. P.1814)

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):

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

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.

FSO link budget (ITU-R Rec. P.1814)

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):

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

where:

$S_{capture}$: receiver capture surface (m^2)

S_d: surface area of transmit beam at range d, which is approximated by: $S_d = \frac{\pi}{4}(d \cdot \theta)^2$

where:

θ : 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.

FSO link budget (ITU-R Rec. P.1814)

4 Specific atmospheric attenuation due to absorption and scattering γ_{atmo}

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

$$\gamma_{atmo} = \gamma_{clear\_air} + \gamma_{excess} \tag{3}$$

where:

γ_{clear_air}: specific attenuation under clear air (due to the presence of gaseous molecules)

γ_{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 γ_{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.

FSO link budget (ITU-R Rec. P.1814)

4.1 Specific clear-air attenuation γ_{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_2, 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.

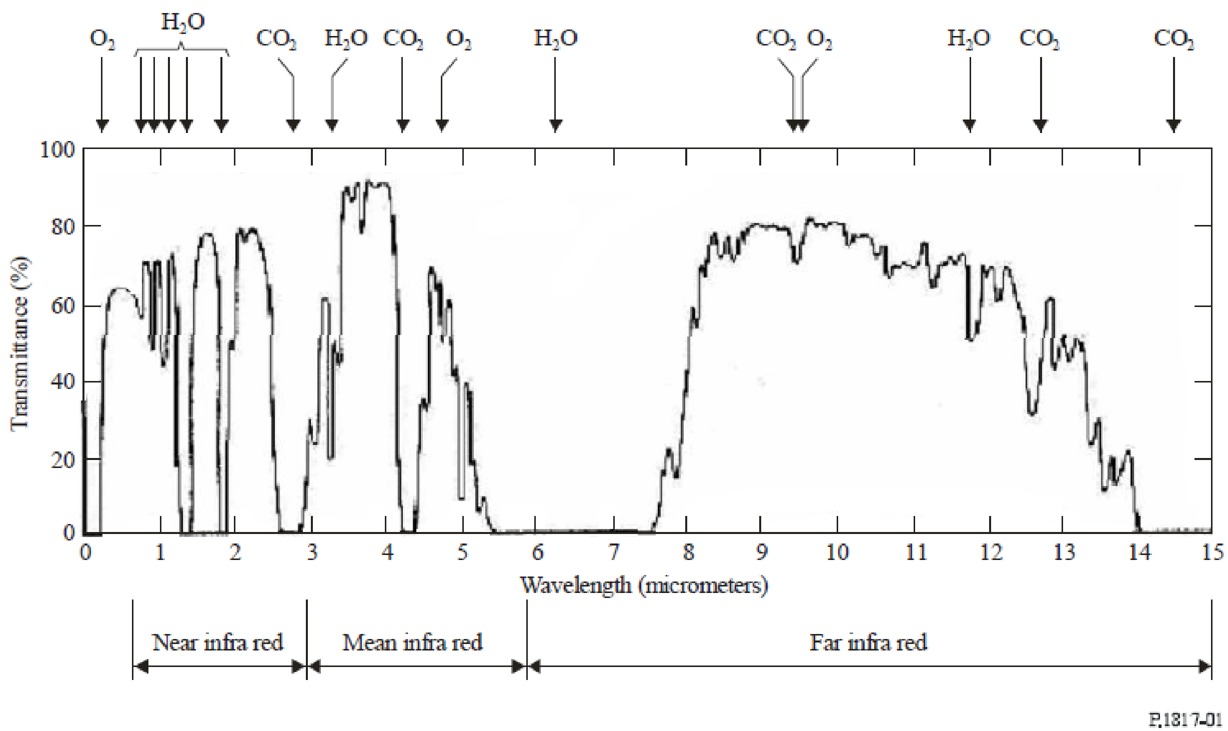
Because the size of the gaseous molecules is much smaller than the wavelength, scattering attenuation from the gaseous molecules is negligible.

Usually the laser wavelengths are selected to fall inside atmospheric transmission windows, so $\gamma\gamma_{clear\_air}$ 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.

Molecular absorption

- Interactions between the photons and the atoms and/or molecules of the atmosphere (gas attenuation)

Transmittance of the atmosphere due to molecular absorption

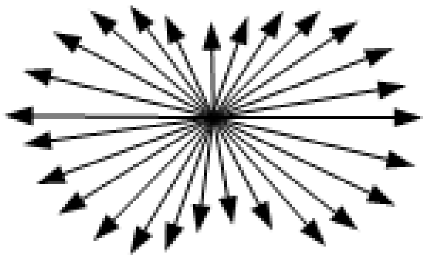


The transmission windows in the optical range are:

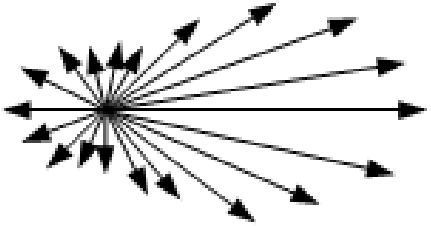
–	Visible and very-near IR:	from 0.4 to 1.4 µm
–	Near IR or IR I:	from 1.4 to 1.9 µm and 1.9 to 2.7 µm
–	Mean IR or IR II:	from 2.7 to 4.3 µm and 4.5 to 5.2 µm
–	Far IR or IR III:	from 8 to 14 µm
–	Extreme IR or IR IV:	from 16 to 28 µm.

Atmospheric scattering

- Interactions between the photons and the atoms and/or molecules of the atmosphere causing an angular redistribution of the radiation (can also modificate the wavelength λ)
- Molecular scattering
  - Light vs. particles (gas molecules) smaler than λ
  - Rayleigh scattering => attenuation
  - Affects ultraviolet up to visible λ
  - Negligible at IR
  - (=> blue sky)



- Aerosol scattering
  - Light vs. fine solid or liquid particles (ice, dust, mist, fog, smoke...) of the same order of magnitude as λ
  - Mie scattering => attenuation (function of λ and visibility)
  - Key factor for long distance FSL
  - Additional attenuation is caused by the aerosol absorption



FSO link budget (ITU-R Rec. P.1814)

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.

Scattering regimes depending on the scatter's size r with respect to the transmission laser wavelength λ. 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

FSO link budget (ITU-R Rec. P.1814)

4.2.1 Estimation of specific attenuation due to fog γ_{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:

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

where:

V : visibility (km)

λ : wavelength (nm)

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

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

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).

International visibility code

Weather conditions	Precipitation		mm/h	Visibility (m)	Attenuation (dB/km)
				0	
Dense fog				50	315
Thick fog				200	75
Moderate fog				500	28.9
Light fog		Storm	100	770	18.3
Very light fog				1 000	13.8
	Snow	Strong rain	25	1 900	6.9
Light mist				2 000	6.6
		Average rain	12.5	2 800	4.6
Very light mist				4 000	3.1
		Light rain	2.5	5 900	2
				10 000	1.1
Clear air		Drizzle	0.25	18 100	0.6
Very clear air				20 000	0.54
				23 000	0.47
				50 000	0.19

FSO link budget (ITU-R Rec. P.1814)

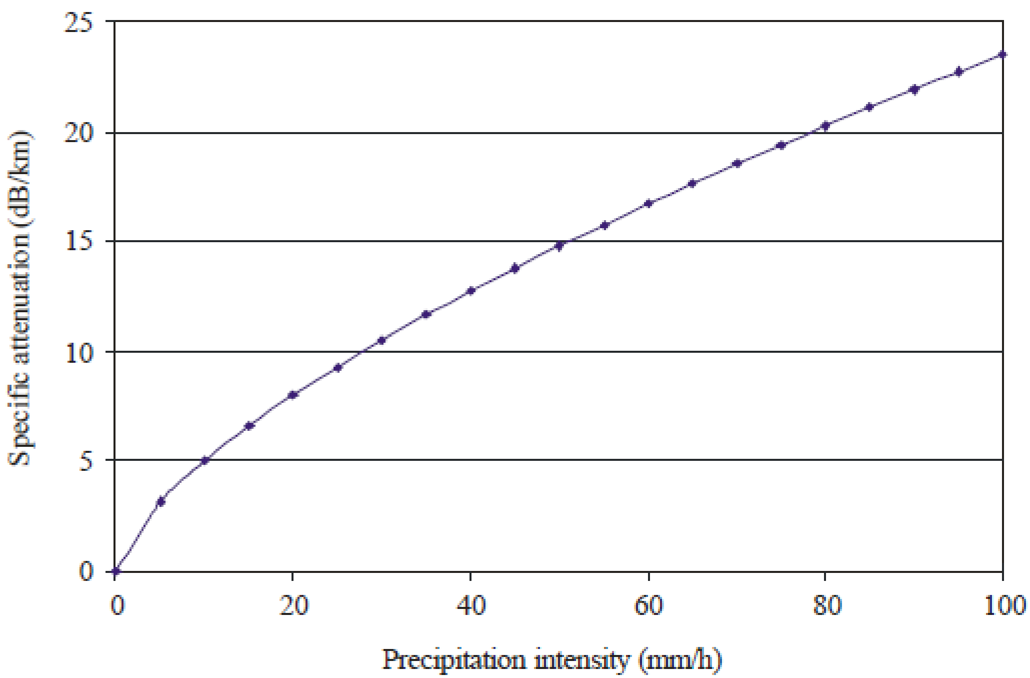
4.2.2 Specific attenuation due to rain γ_{rain}

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

$$\gamma_{rain} = k \cdot R^{\alpha} \tag{6}$$

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.

Specific attenuation (dB/km) due to precipitation in optical and infrared ranges



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4.2.3 Specific attenuation due to snow γ_{snow}

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

$$\gamma_{snow} = \alpha \cdot S^b \tag{7}$$

where:

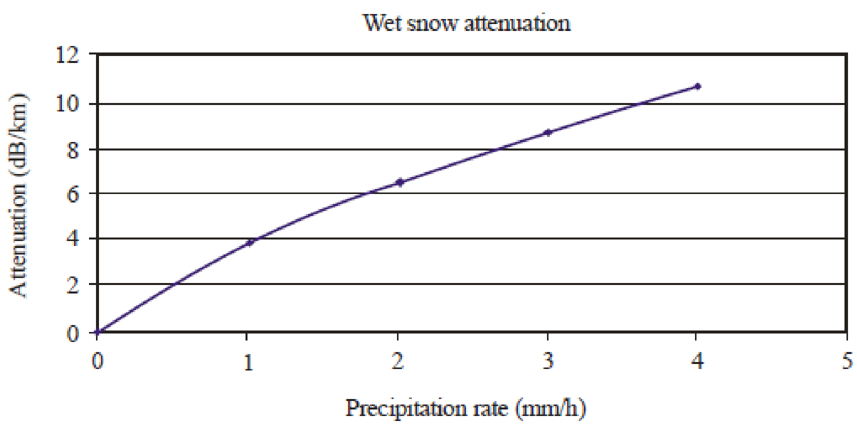
- γ_{snow}: specific attenuation due to snow (dB/km)
- S: snowfall rate (mm/h)
- α and b: functions of the wavelength, λ (nm). Estimated values for wet and dry snow are given in Table 3.

TABLE 3

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

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

Wet snow attenuation vs. snowfall precipitation rate for λ = 1.55 μm



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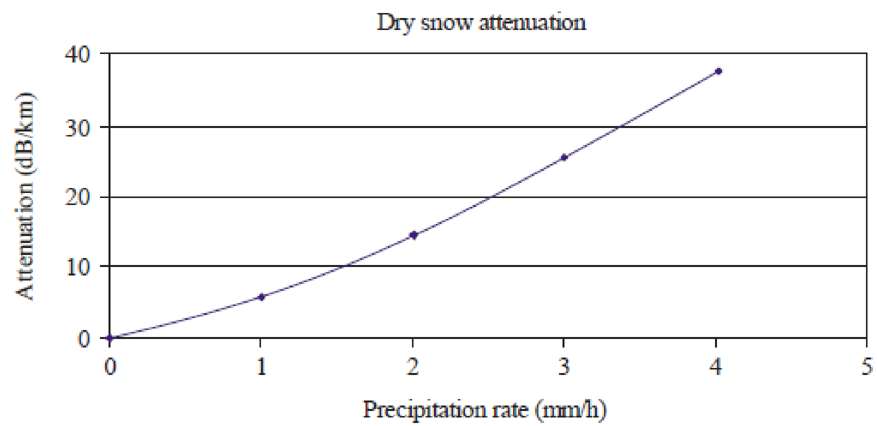
Dry snow attenuation vs. snowfall precipitation rate for λ = 1.55 μm

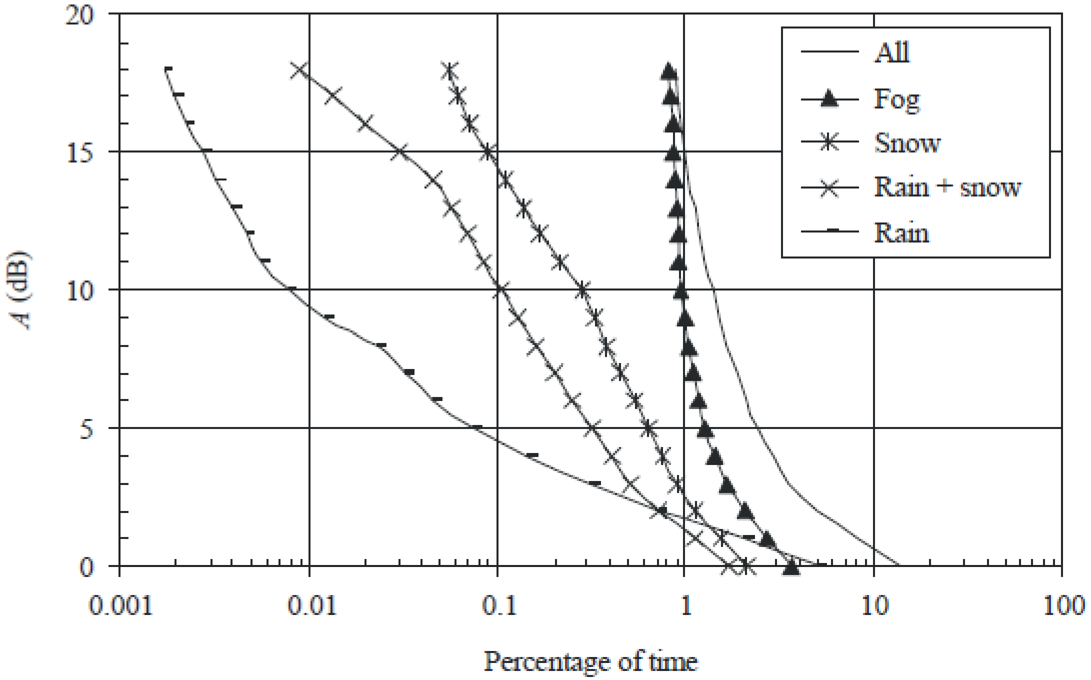


P.1817-11

Hydrometeors

Cumulative distributions of attenuation measured at 860 nm on a 853m path due to: all hydrometeors, fog, rain, rain + snow, and snow in Prague, Czech Republic, during a 6-year period are shown in Fig. 12. All fading events were classified according to the meteorological conditions causing a particular fade event. The meteorological conditions were identified using a camera image of the area between the transmitter and the receiver and using data obtained from an automatic meteorological station located near the receiver. Fading events caused by fog and by snow were the most serious.

Cumulative attenuation distributions for different path conditions



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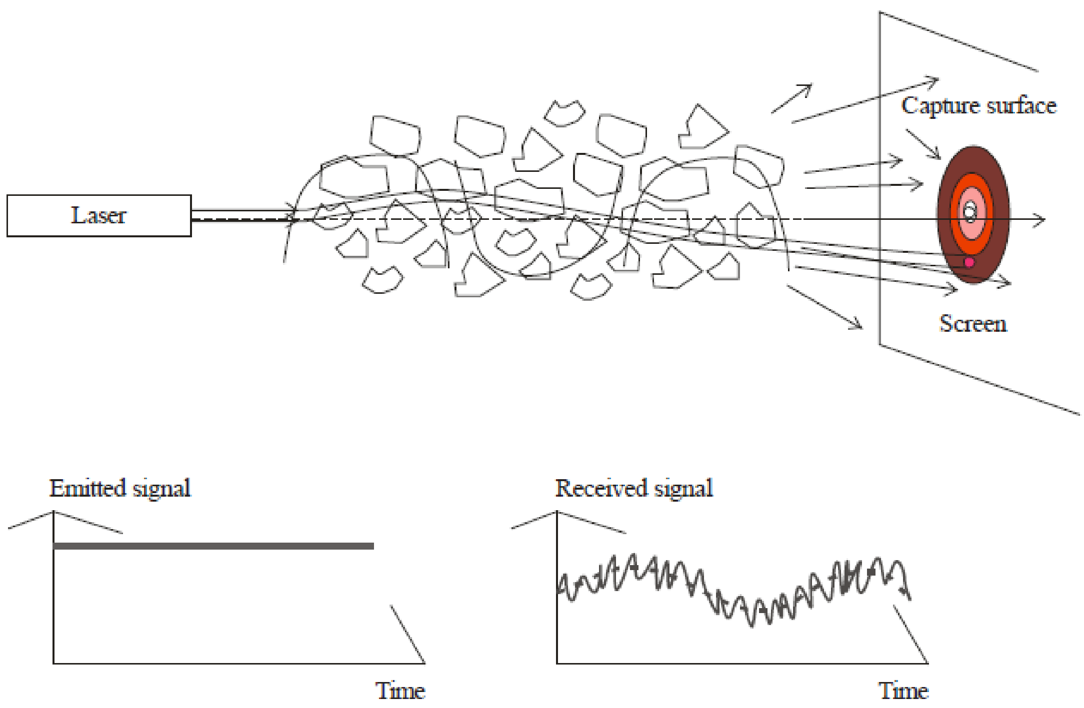
Scintillation

- Randomly distributed cells of different size (10 cm – 1 km) and refractive index due to thermal turbulence in the atmosphere

  => scattering, multipath, angle of arrival variations

  => amplitude fluctuations (0.01 – 200 Hz)

  => wave front distortion = beam defocusing



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Tropospheric scintillations effects are generally studied from the logarithm of the amplitude χ (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 σ_x^2 (dB^2) can be expressed by the following relation:

$$\sigma_\chi^2 = 23.17 \cdot k^{7/6} \cdot C_n^2 \cdot L^{11/6} \tag{8}$$

where:

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

L: length of the link (m)

$C_n{}^2$: refractive index structure parameter (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} m$^{-2/3}$ (in general, at millimetre wavelengths $C_n{}^2$ is between 10^{-14} and 10^{-12} m$^{-2/3}$) and at optical wavelengths a value of $C_n{}^2$ is approximately equal to about 2×10^{-15} m$^{-2/3}$ for weak turbulence (in general at optical wavelengths $C_n{}^2$ is between 10^{-16} and 10^{-13} m$^{-2/3}$).

Table of scintillation fade depths expected for 1 km path length

	Turbulence		
	Low	**Moderate**	**High**
C_n^2 optic waves ($m^{-2/3}$)	10^{-16}	10^{-14}	10^{-13}
Attenuation (0.98 μm) (dB)	0.51	5.06	16.00
Attenuation (1.55 μm) (dB)	0.39	3.87	12.25
C_n^2 millimetre waves ($m^{-2/3}$)	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.

FSO power budget (ITU-R Rec. P.1814)

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 γ_{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 γ_{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 γ_{rain} can be obtained from equation (6) and Table 2.

Step 5: The specific attenuation due to γ_{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:

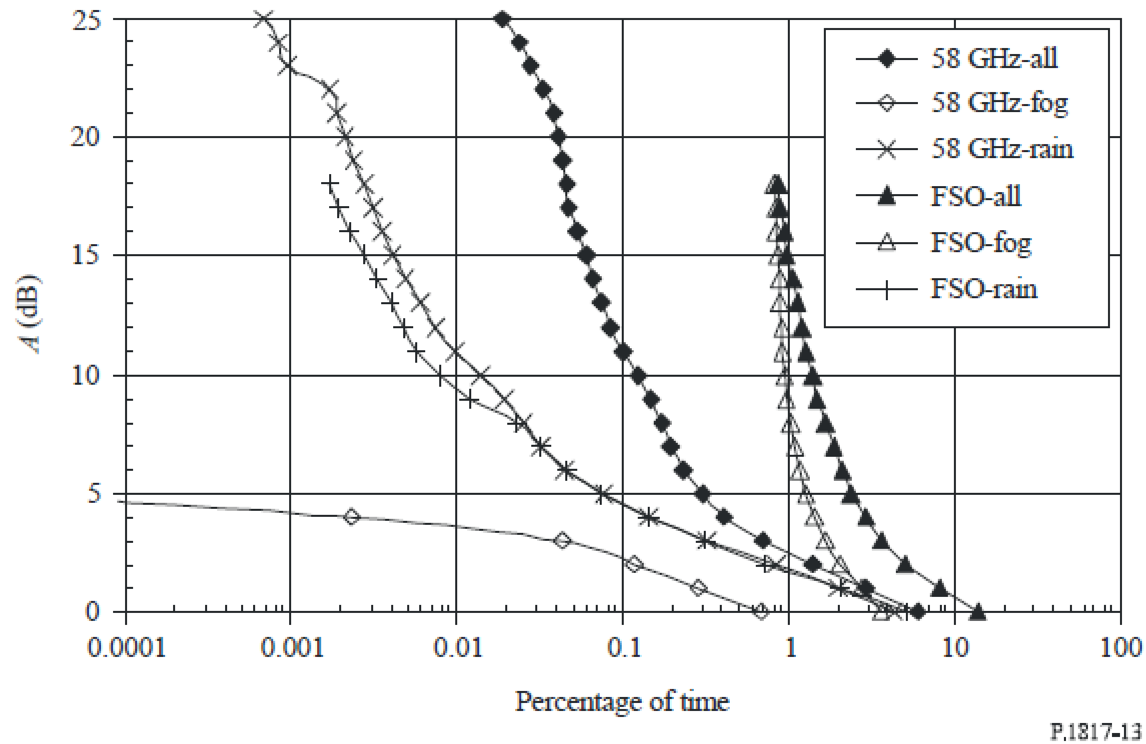
P_e (dBm): total power of the emitter

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.

Hybrid RF / FSO links

RF and FSO attenuations exceeded for different time percentages



Availability ratio comparison of RF, FSO and hypothetical RF/FSO hybrid systems

System	AR (%)
FSO part (850 nm)	99.1340
RF part (58 GHz)	99.9547
Hybrid RF/FSO	99.9989