



Recommendation ITU-R P.1817-1
(02/2012)

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

P Series
Radiowave propagation



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Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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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.

* This Recommendation should be brought to the attention of Radiocommunication Study Groups 1 and 5.

Annex 1

1 Atmospheric considerations

FSO links are impaired by absorption and scattering of light by the Earth's atmosphere. The atmosphere interacts with light due to the composition of the atmosphere, which normally consists of a variety of different molecular species and small suspended particles called aerosols. This interaction produces a wide variety of phenomena: frequency selective absorption, scattering, and scintillation.

- Frequency selective absorption at specific optical wavelengths results from the interaction between the photons and atoms or molecules that leads to the extinction of the incident photons, elevation of the temperature, and radiative emission.
- Atmospheric scattering results from the interaction between the photons and the atoms and molecules in the propagation medium. Scattering causes an angular redistribution of the radiation with or without modification of the wavelength.
- Scintillation results from thermal turbulence within the propagation medium that results in randomly distributed cells. These cells have variable sizes (10 cm-1 km), temperatures, and refractive indices causing scattering, multipath and variation of the angles of arrival. As a result, the received signal amplitude fluctuates at frequencies ranging between 0.01 and 200 Hz. Scintillation also causes wave front distortion resulting in defocusing of the beam.

In addition, sunlight can affect FSO performance when the sun is co-linear with the direction of the free-space optical link.

2 Molecular absorption

Molecular absorption results from an interaction between the optical radiation and the atoms and molecules of the medium (N_2 , O_2 , H_2 , H_2O , CO_2 , O_3 , Ar, etc.). The absorption coefficient depends on the type and concentration of gas molecules. The spectral variations of the absorption coefficient determine the absorption spectrum. The nature of this spectrum is due to the variations of possible energy levels of the gas generated essentially by the electronic transitions, vibrations of the atoms, and rotation of the molecules. An increase in the pressure or temperature tends to widen the spectral absorption lines by excitation of higher energy levels and by the Doppler effect. Molecular absorption is a selective phenomenon that results in relatively transparent atmospheric transmission windows, and relatively opaque atmospheric absorption bands.

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 .

The gaseous molecules have quantified energy levels proper to each species, and can absorb energy (or photons) under the influence of an incident electromagnetic radiation and transition from an initial energy level, e_i , to a higher energy level, e_f . The radiation energy is then attenuated by the loss of one or more photons.

This process only occurs if the incident wave frequency corresponds exactly to one of the resonance frequencies of the considered molecule, given by:

$$\nu_0 = \frac{e_f - e_i}{h} \quad (1)$$

where:

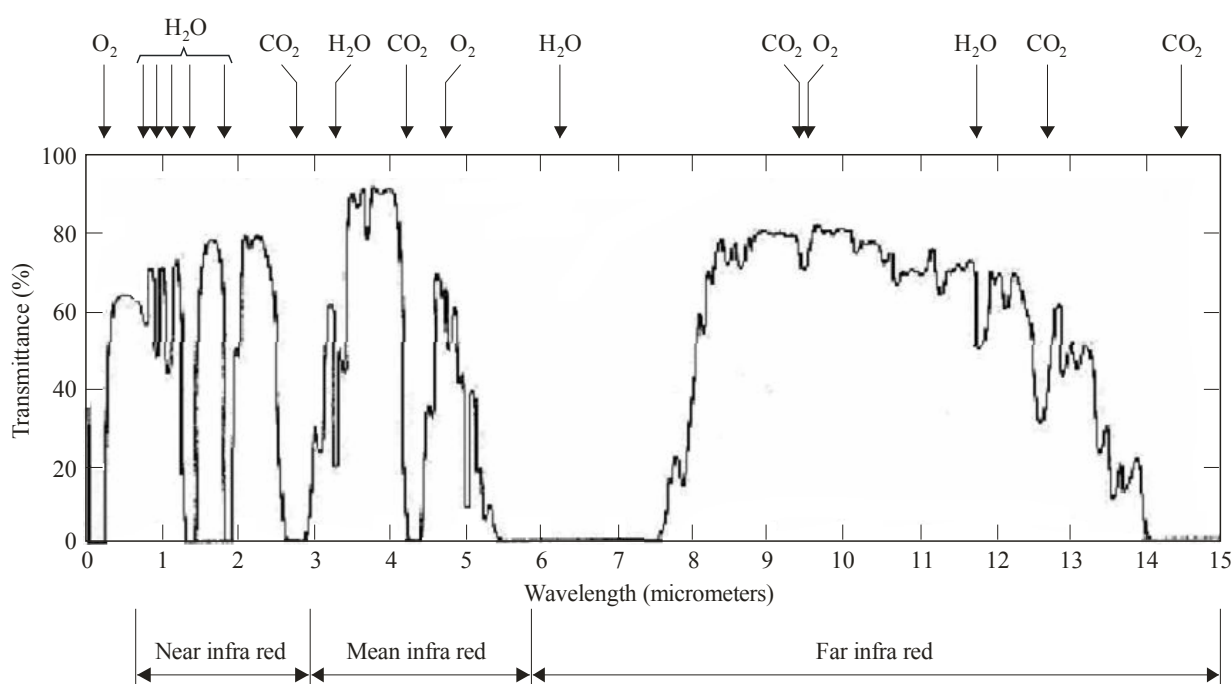
ν_0 : incident wave frequency (Hz);

h : Planck's constant, $h = 6.6262 \cdot 10^{-34}$ J-s.

The fundamental parameters that determine the absorption generated by molecular resonance are: the possible energy levels for each molecular species the probability of transition from an energy level e_i to an energy level e_f , the intensity of resonance lines, and the natural profile of each line.

Generally, the profile of each absorption line is modified by the Doppler effect when the molecules are moving relative to the incident wave, and by the collision effect due to the interaction of the molecules. These phenomena lead to a spectral widening of the natural line of each molecule. For certain molecules, such as in carbon dioxide (CO_2), water vapour (H_2O), nitrogen (N_2) and oxygen (O_2), the absorption line profiles can extend sufficiently far from each central line. This property leads to an absorption continuum. Figure 1 shows the nominal measured atmosphere transmittance due to molecular absorption on a 1 820 m horizontal link at sea level.

FIGURE 1
Transmittance of the atmosphere due to molecular absorption



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3 Molecular scattering

Molecular scattering results from the interaction of light with atmospheric particles whose sizes are smaller than the wavelength of the incident light. Scattering by atmospheric gas molecules (Rayleigh scattering) contributes to the total attenuation of the electromagnetic radiation.

The extinction coefficient due to molecular scattering, $\beta_m(\lambda)$, is:

$$\beta_m(\lambda) = \frac{24\pi^3}{\rho\lambda^4} 10^3 \left(\frac{[n(\lambda)]^2 - 1}{[n(\lambda)]^2 + 2} \right) \left(\frac{6 + 3\delta}{6 - 7\delta} \right) \quad (2)$$

where:

- $\beta_m(\lambda)$: molecular scattering coefficient (km^{-1});
- λ : wavelength (μm);
- ρ : molecular density (m^{-3});
- δ : depolarization factor of the air ($\cong 0.03$);
- $n(\lambda)$: refractive index of air.

An approximate value of $\beta_m(\lambda)$ is:

$$\beta_m(\lambda) = A\lambda^{-4} \quad (3)$$

where:

$$A = 1.09 * 10^{-3} \frac{P}{P_0} \frac{T_0}{T} \quad \text{km}^{-1} \text{ m}^4 \quad (4)$$

and

- P : atmospheric pressure (mbar);
- P_0 : 1 013 mbar;
- T : atmospheric temperature (K); and
- T_0 : 273.15 K.

Molecular scattering is negligible at infrared wavelengths, and Rayleigh scattering primarily affects ultraviolet wavelengths up to visible wavelengths. The blue colour of the clear-sky background is due to this type of scattering.

4 Aerosol absorption

Aerosols are extremely fine solids or liquids particles suspended in the atmosphere with very low fall speed (ice, dust, smoke, etc). Their size generally lies between 10^{-2} and $100 \mu\text{m}$. 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 environments, the aerosols are primarily made up of droplets of water (foam, fog, drizzle, rain), salt crystals, and various particles of continental origin. The type and density of continental particles depend on the distance from, and characteristics of, the neighbouring coasts.

The extinction coefficient due to aerosol absorption, $\alpha_n(\lambda)$, is:

$$\alpha_n(\lambda) = 10^5 \int_0^\infty Q_a \left(\frac{2\pi r}{\lambda}, n'' \right) \pi r^2 \frac{dN(r)}{dr} dr \quad \text{km}^{-1} \quad (5)$$