PROCEEDINGS OF SPIE

Laser Communication and Propagation through the Atmosphere and Oceans II

Alexander M. J. van Eijk
Christopher C. Davis
Stephen M. Hammel
Editors

26–27 August 2013
San Diego, California, United States

Sponsored and Published by
SPIE

Volume 8874

Proceedings of SPIE 0277-786X, V. 8874

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Laser Communication and Propagation through the Atmosphere and Oceans II, edited by Alexander M. J. van Eijk, Christopher C. Davis, Stephen M. Hammel,Proc. of SPIE Vol. 8874, 887401 ·© 2013 SPIE CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2048479

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Author(s), "Title of Paper," in *Laser Communication and Propagation through the Atmosphere and Oceans II*, edited by Alexander M. J. van Eijk, Christopher C. Davis, Stephen M. Hammel, Proceedings of SPIE Vol. 8874 (SPIE, Bellingham, WA, 2013) Article CID Number.

ISSN: 0277-786X
ISBN: 9780819497246

Published by
SPIE
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Printed in the United States of America.

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Detection of non-standard atmospheric effects in FSO systems

Otakar Wilfert[*a], Juraj Poliak[a], Peter Barcík[a], José Luis Arce-Diego[b],
Félix Fanjul-Vélez[b], Irene Salas-García[b], Noé Ortega Quijano[b]
[a] Institute of Radio Electronics, Brno University of Technology, Technicka 12,
616 00 Brno (Czech Republic)
[b] Applied Optical Techniques Group, TEISA Department, University of Cantabria;
ETSII y de Telecomunicación, Av. de los Castros s/n, 39005 Santander (Cantabria), Spain

ABSTRACT

Modern free-space optical (FSO) communication systems in many aspects overcome wire or radio communications. They offer a license-free operation and a large bandwidth. Operation of outdoor FSO links struggles with many atmospheric phenomena that deteriorate phase and amplitude of the transmitted optical beam. Thanks to the recent advancing development, these effects are more or less well understood and described. Goal driven research increased the link availability.

Besides increasing the availability of data links it is necessary to focus on the accuracy and reliability of testing optical links. Research of the data optical links is focused on the transmission of a large amount of data whereas the testing FSO link is designed to achieve maximal resolution and sensitivity thus improving accuracy and repeatability of the atmospheric effects measurement. Given the fact that testing links are located in the measured media, they are themselves influenced by it. Phenomena such as the condensation on transceiver windows (rain, frost) and the deviation of the optical beam path caused by the wind are referred to as non-standard effects. Non-standard effects never occur independently; therefore we must always verify the cross-sensitivity of the testing link.

In the paper we respond to an increasing number of articles dealing with influence of the atmosphere on the link but ignoring the cross-sensitivity of the testing link on other variables than tested. In conclusion, we carry out qualitative and quantitative analysis of self-identified non-standard effects.

Keywords: Testing FSO link, Non-standard effects, Atmospheric effects, Complex FSO link model

1. INTRODUCTION

Advantages and disadvantages of the FSO link are at a focus of many research teams and they have been covered in many sources. Nevertheless, some new aspects appeared: First, after we have investigated hybrid system with optical and RF channel, we found out that microwave link can work at a comparable data rate as the FSO link, decreasing the data rate gap between them. So high bit rate already does not belong to the basic advantages of the FSO link. Another new aspect arose during the study of the real availability of FSO links by means of a dedicated testing FSO (TFSO) link which have a function of an optical atmospheric sensor. These links should not be influenced by errors occurring due to the influence of the parameters which are not tested. Such influences (e.g. rain, snow, frost on the glass aperture of the transceiver, vibrations and deviations of the transceiver due to wind) need to be identified during the measurement as the data might be misinterpreted (problem of cross-sensitivity). In the paper we address such effects and show the modelling of FSO links taking into account these effects which not only deteriorate the data transmission capability of the FSO link, but mainly increase the measurement error of the atmospheric transmissivity measurements, which are essential for proper understanding and modelling of FSO links in general.

Recent development in the field of free-space optical (FSO) communications has led to an increasing availability of FSO links. However, there is still a need to increase the precision of models of the optical beam propagation in the atmosphere which would lead to an optimal link design and increased reliability. To study atmospheric effects on FSO link

*wilfert@feec.vutbr.cz; phone 421 5 4114-6565; fax 421 5 4114-6597; http://www.urel.feec.vutbr.cz/OptaBro/

Laser Communication and Propagation through the Atmosphere and Oceans II, edited
by Alexander M. J. van Eijk, Christopher C. Davis, Stephen M. Hammel,Proc. of SPIE Vol.
8874, 88740S · © 2013 SPIE CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2023207

parameters, optical testing links are used. These testing links themselves are exposed to the atmospheric effects; rain, humidity and wind decrease the transmittance of the glass cover and cause the deviation of the beam direction. All these effects belong to non-standard effects, which are analyzed both qualitatively and quantitatively in order to reduce cross-sensitivity of the testing link.

2. FSO TEST LINK

The quality of transmission of an FSO link is mainly influenced by the atmosphere, specifically by the troposphere and by the effects occurring in it. The tropospheric layer reaches altitudes up to 10 km above surface and is characteristic by non-stationary and inhomogeneous distribution of the atmospheric refraction index n causing turbulence effects and by random occurrence of various aerosols causing attenuation of the optical wave power. Moreover, the turbulence effects causing additional random attenuation. To evaluate the quality of transmission of an FSO link, random character of the atmospheric attenuation and random rate of the atmospheric turbulence at the given location are measured.

By the atmospheric optical communication evaluation by means of a TFSO link, definition of the link specification and its stationary parameters is essential. It is undesirable to test statistical properties of the atmosphere of a "general" FSO link since there is no such thing. The FSO link is always dedicated to a given service (broadcasting, data transmission, multimedia) and is defined by its stationary parameters. The atmospheric properties are also individual for a given link location.

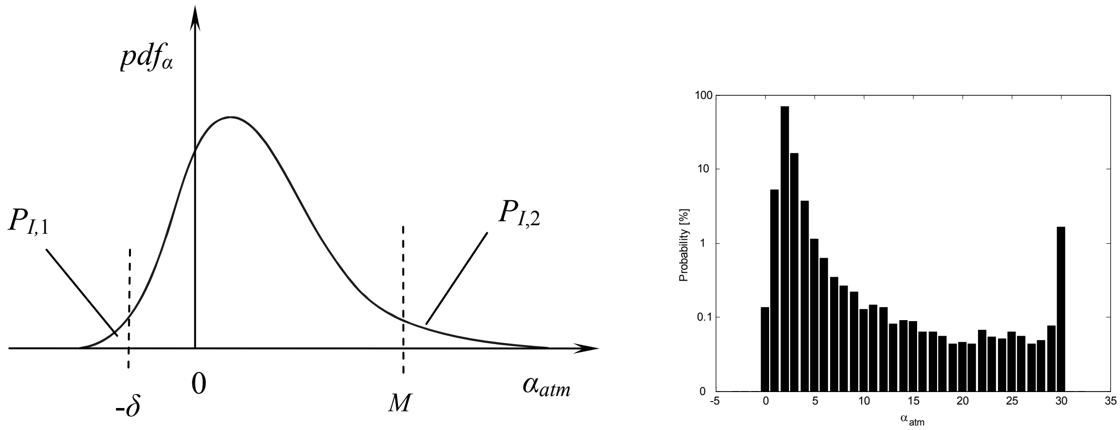
As was already mentioned, the main testing of the atmospheric optical communication is carried by means of the dedicated TFSO link. Measured is the statistics of the additional random atmospheric attenuation α_{atm} in the timeframe of several years. A significant result of the measurement is identification of the worst month within a year, i.e. a month, when a relatively high attenuation was measured for a relatively long period of time. The statistical model of an FSO link is developed based on the measurement and the result for a given location is a probability density function pdf [1] as a function of the attenuation: $pdf_{\alpha} = f(\alpha_{atm})$. An example of a location with an FSO link is shown in Fig.1.

a)

b)

Figure 1. (a) Place with one of the harshest meteorological conditions in the Czech Republic (Milesovka).
(b) High probability of low clouds, rain, hail and fog.

Research into statistical properties of FSO links can be carried out on the basis of the properties of random additional attenuation α_{atm}. Its probability density function pdf_{α} corresponds to that of received optical power. Fig. 2(a) shows a theoretical estimation of the shape of typical probability density function pdf_{α} including both long-term and short-term fades. A histogram obtained from practical measurements is shown in Fig. 2(b). A particular empirically obtained characteristic of $P_{m,RXA}$ depends, of course, on the geographical location of the link, path length and total period of observation.



a) b)

Figure 2. (a) Theoretical shape of pdf_α . (b) Estimation of pdf_α from our test site.
(Negative values of attenuation α_{atm} can theoretically occur due to the constructive interference of waves in the turbulent atmosphere. When received power exceeds saturation level $P_{\text{sat,RXA}}$ the corresponding attenuation α_{atm} is equal to -δ.)

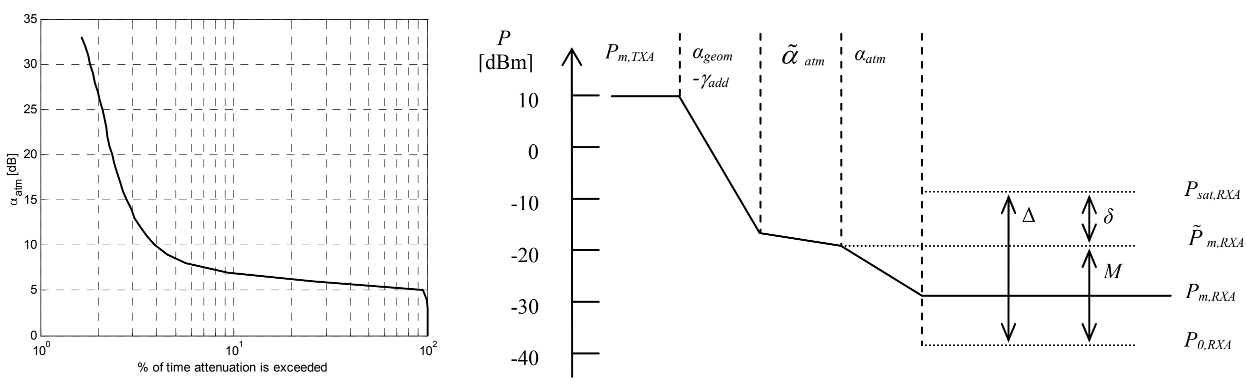
The link is interrupted when the received optical power exceeds the dynamic range Δ of the receiver. This event occurs with the probability (Fig. 2(a) and (1))

$$P_I = P_{I,1} + P_{I,2} = 1 - \int_{-\delta}^{M} pdf_\alpha(\alpha_i)d\alpha_i = 1 + E_\alpha(M) - E_\alpha(-\delta) \approx \frac{T_I}{T_M}, \tag{1}$$

where α_{i} is the given value of attenuation; E_α is the exceedance probability of M or -δ; T_I is the overall measured fade duration and T_M is the overall measurement time [2].

Fig. 3a shows the exceedance probability E_α as usually used in the area of radio-relay links [3]. This quantity determines the probability P that the random attenuation α_{atm} exceeds the given value, i.e. $E_\alpha(\alpha_i) = P(\alpha_{atm} \geq \alpha_i)$. Its relation to classical cumulative distribution function D_α is obvious, $E_\alpha(\alpha_i) = 1 - P(\alpha_{atm} < \alpha_i) = 1 - D_\alpha(\alpha_i)$.

Stationary model of a given FSO link is characterised by its link budget shown as an example in Fig.3b.



(a) (b)

Figure 3. (a) Statistical model of the link (cumulative exceedance probability of the total additional random attenuation α_{atm}).
(b) Steady model of the FSO link ($\tilde{\alpha}_{atm}$ - attenuation of standard clear atmosphere).

The largest positive value of α_{atm} that does not make the received power fall below $P_{0,RXA}$ is equal to M (link margin). Synthesis of the stationary and the statistical model of the FSO link leads to a complex FSO link model. To carry out the synthesis a normalised link margin M_1 is used. For this purpose, M_1 is defined as

$$M_1 = \frac{M}{L_{12}}, \tag{2}$$

where L_{12} is the distance between the transmitter TXA and the receiver aperture RXA (see Fig. 4).

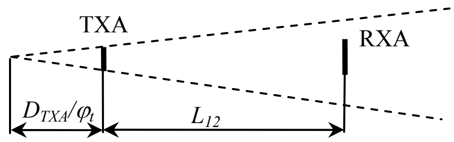


Figure 4. Geometry of the beam propagating from the transmitter aperture TXA to the receiver aperture RXA. (D_{TXA} is the diameter of the TXA and φ_t is the optical beam divergence.)

The definition of the system margin M_S allows us to divide the link model in two parts; part containing only stationary parameters of given transceivers (transmitter output power, receiver sensitivity, diameter of the transmitter aperture and beam divergence) and part related somehow to the atmosphere and the free space (link distance, exceedance probability of a given value at a given location). Normalised link margin M_1 represents exceeded attenuation coefficient α_1 (numerically $M_1 = \alpha_1$). Graphical representation of the stationary and statistical model synthesis is the nomogram [4] in Fig.5.

Particular transceivers are characterised by the system margin (3)

$$M_S = P_{m,TXA} - P_{0,RXA} + 20 \cdot \log \frac{D_{RXA}}{\phi_t} \tag{3}$$

which does not depend on L_{12}. It represents the steady model of a link, which is combined with statistical parameters of the installation site, i.e. with the exceedance probability of α_1. The procedure for evaluating the probability of unavailability P_{un} of a given link at a chosen installation site is as follows: First, for a given system margin M_S and transceiver distance L_{12} we can find the normalized link margin M_1. The value of M_1 also represents the greatest value of atmospheric attenuation $\alpha_{1,atm}$. Second, for a chosen installation site we can find the link unavailability. Fig. 5 is drawn for typical values of the system margin M_S for semiconductor laser links and for the best and the worst atmospheric conditions observed.

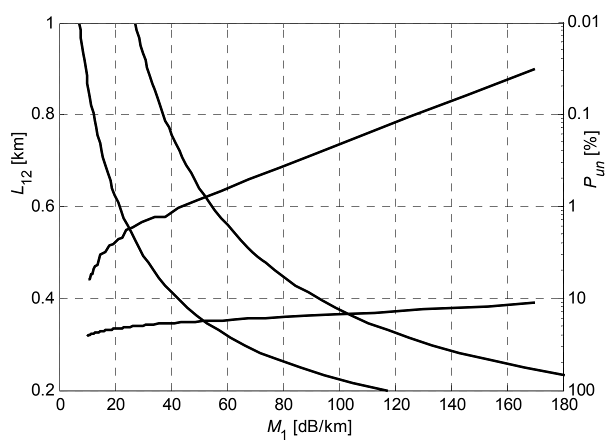


Figure 5. Nomogram for calculation of the link unavailability P_{un}.

The above mentioned method of the FSO link modelling shows, that in order to develop the model of a system with given parameters operating at a given location one must measure the statistical behaviour of the atmospheric attenuation. However, such a simplification of the FSO link modelling leads to incorrect results of the availability P_{av} or of the unavailability P_{un}. There are many other influences (non-standard) to be taken into account when the FSO link availability is analysed.

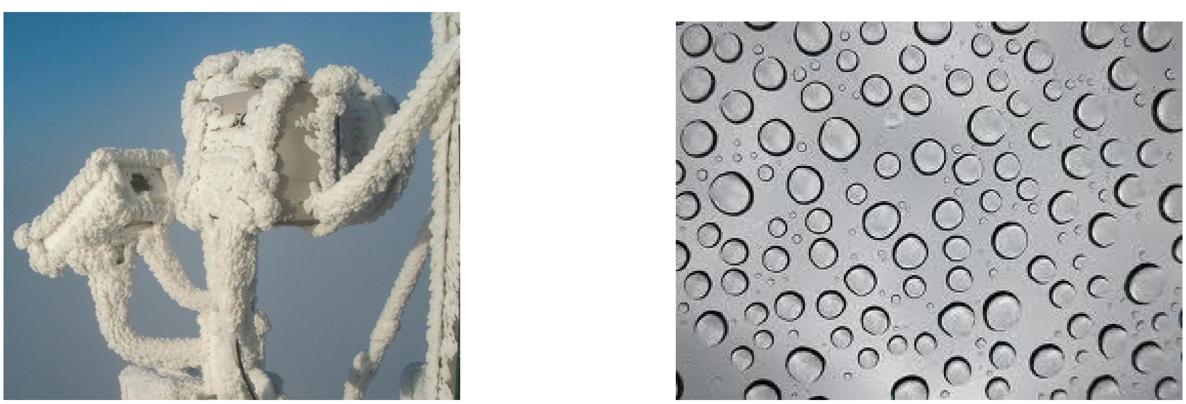
3. FSO TESTING LINK AND NON-STANDARD EFFECTS

Measurement of the statistical behaviour of the atmosphere showed, that the measurement results had been influenced not only by the atmosphere between the transceivers, but also by the influence of aerosols on the transceivers' aperture windows, effect of the wind on the mechanical brackets and also the diffraction of the beam on the transmitter aperture and lens socket. Modelling of the diffraction of a generally elliptical optical beam on the circular aperture is described in detail in chapter 3.

Other effects which might be from the testing of FSO links point of view regarded as non-standard and thus causing cross-sensitivity issues in TFSO links are:

- frost at the transceiver windows,
- rain drops and snow flakes at the transceiver windows,
- dewy transceiver windows,
- action of transverse forces on the transceivers and their mounting brackets,
- diffraction of the transmitted beam at the transmitter aperture.

To decrease the degree of influence of the non-standard effect is possible by various means, however all of them must be taken into account be the FSO link availability estimation. The situation at the transceiver location and its condition are shown in Fig.6.



(a) (b)

Figure 6. (a) Frost at the transceiver; (b) Raindrops at the transceiver window.

The influence of the frost and dew on the transceiver windows can be significantly reduced by a heating of the window or by simultaneous heating with a fan inside the transceiver body. Detection of the raindrops and snowflakes at the windows can be carried out be means of a dedicated capacitance rain sensor as is nowadays common at some modern automobiles. Optimised shape of the transceiver housing, cover and brackets may also significantly reduce the influence of the wind on the transceiver, vibrations and deviation of the transmitted beam from the RXA.

4. INFLUENCE OF ELLITPICALLY SYMMETRICAL BEAMS ON THE LINK BUDGET

The general representation of the Gaussian beam is the elliptically symmetrical Gaussian beam with beam half-widths w_x and w_y. Its intensity distribution $I(x,y,z)$ in the plane perpendicular to the beam propagation is described by the expression (4) and shown in Fig.7.

$$I(x,y,z) = I(0,0,z)\cdot \exp\left\{-2\left[\frac{x^2}{w_x^2(z)}+\frac{y^2}{w_y^2(z)}\right]\right\}, \tag{4}$$

where $I(0,0,z)$ is the value of axial intensity in the distance z.

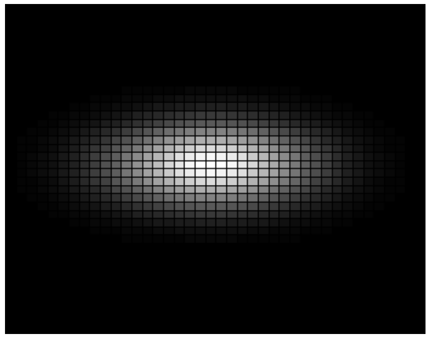


Figure 7. Intensity distribution of an elliptically symmetrical optical beam.

The total optical power of the beam depends on the optical intensity and for the elliptically symmetrical beam we write

$$P = I(0,0,z)\int_{-\infty}^{\infty}\exp\left[-\left(\frac{2x^2}{w_x^2(z)}\right)\right]\mathrm{d}x\int_{-\infty}^{\infty}\exp\left[-\left(\frac{2y^2}{w_y^2(z)}\right)\right]\mathrm{d}y = I(0,0,z)\frac{\pi}{2}w_x(z)w_y(z). \tag{5}$$

Partial restriction of the beam by a circular aperture with a radius ρ_0 causes additional attenuation and the optical power of the beam behind the aperture is smaller. This effect occurs mainly in the transmitters where part of the beam is restricted by the circular socket of a collimating lens or in the receiver where the receiver aperture is smaller than the beam or when the active surface of a photodiode is smaller than a spot created by the receiver lens. These facts have in general practical meaning, however, one must take into account the effects that occur in such cases.

The part of the optical power transmitted to the free space is then given by the integral in equation (6). In this case we don't integrate over the whole plane x-y as in (5), but only over the part restricted by the transparent part of the lens socket. Moreover, the integral in (5) is transformed from Cartesian coordinates into polar coordinates (ρ,φ) and solved in two steps. At first we integrate by radial coordinate ρ

$$\begin{aligned} P &= I(0,0,z)\int_{x^2+y^2\le\rho_0^2}\exp\left\{-2\left[\frac{x^2}{w_x^2(z)}+\frac{y^2}{w_y^2(z)}\right]\right\}\mathrm{d}x\,\mathrm{d}y = \\ &= I(0,0,z)\cdot\frac{\pi}{2}w_xw_y\left\{1-\frac{2}{\pi}\frac{w_xw_y}{w_x^2+w_y^2}\exp\left[-\frac{w_x^2+w_y^2}{w_x^2w_y^2}\rho_0^2\right]I'(\rho_0)\right\}, \end{aligned} \tag{6}$$

where the term $I'(\rho_0^2)$ is given by

$$I'\left(\rho_0^2\right) = \int_0^{\pi}\frac{\exp\left[\rho_0^2\,\dfrac{w_x^2-w_y^2}{w_x^2w_y^2}\cos\varphi\right]}{1-\dfrac{w_x^2-w_y^2}{w_x^2+w_y^2}\cos\varphi}\,\mathrm{d}\varphi\,. \tag{7}$$

The integral in (7) must be in the next step solved numerically.

Alternatively one may first integrate by the axial coordinate φ

$$\begin{aligned} P &= I(0,0,z)\int\limits_{x^2+y^2\le\rho_0^2}\exp\left\{-2\left[\frac{x^2}{w_x^2(z)}+\frac{y^2}{w_y^2(z)}\right]\right\}\mathrm{d}x\,\mathrm{d}y = \\ &= I(0,0,z)\cdot 2\int_0^{\rho_0}\exp\left(-\rho^2\frac{w_x^2+w_y^2}{w_x^2w_y^2}\right)\cdot\int_0^{\pi}\exp\left(\rho^2\frac{w_x^2-w_y^2}{w_x^2w_y^2}\cos\varphi\right)\mathrm{d}\varphi\,\rho\,\mathrm{d}\rho \end{aligned} \quad . \tag{8}$$

Using the expression 3.339 [5] followed by a substitution $t = (\rho/\rho_0)^2$ yields to

$$\begin{aligned} P &= I(0,0,z)\int\limits_{x^2+y^2\le\rho_0^2}\exp\left\{-2\left[\frac{x^2}{w_x^2(z)}+\frac{y^2}{w_y^2(z)}\right]\right\}\mathrm{d}x\,\mathrm{d}y = \\ &= I(0,0,z)2\pi\int_0^{\rho_0}\exp\left(-\rho^2\frac{w_x^2+w_y^2}{w_x^2w_y^2}\right)I_0\left(\rho^2\frac{w_x^2-w_y^2}{w_x^2w_y^2}\right)\rho\,\mathrm{d}\rho \end{aligned} \quad , \tag{9}$$

where I_0 is a modified Bessel function of the first kind and zero order. Next step is again numerical integration of the integral in (9).

From the point of view of the optical power attenuation calculation are the expressions (6), (8) and (9) equivalent. In Fig.8 is shown an example of the dependency of the transmitted optical power on the radius of the restricting aperture ρ_0

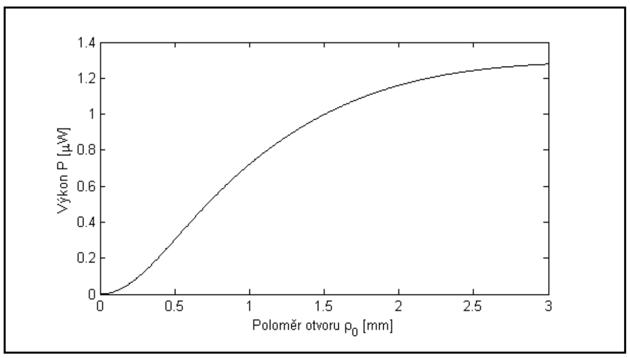


Figure 8. Graph of the dependency of the transmitted optical power P (vertical axis) on the radius ρ_0 of the aperture. w_x = 1.72 mm; w_y = 0.48 mm; $I(0,0,z)$ = 1 W/m^2

This applies when the centre of the optical beam is identical with the optical axis of the link. However, in case of strong winds, which is typical for some urban and mountain areas, the deviation Δ of the optical beam occurs causing additional attenuation. In such case, it was shown [6], that the received optical power P in case of circularly symmetrical beam with a half-width w is

$$\begin{aligned} &P(\Delta,z) = \sqrt{\frac{\pi}{2}}w(z)I(0,z)\cdot \\ &\cdot\int_0^{\rho_0}\left\{\exp\left[\frac{-2x^2}{w^2(z)}\right]\mathrm{erf}\left[\frac{\sqrt{2}}{w(z)}\left(\Delta+\sqrt{\rho_0^2-x^2}\right)\right]-\exp\left[\frac{-2x^2}{w^2(z)}\right]\mathrm{erf}\left[\frac{\sqrt{2}}{w(z)}\left(\Delta-\sqrt{\rho_0^2-x^2}\right)\right]\right\}\mathrm{d}x. \end{aligned} \tag{10}$$

Taking into account results of the equation (10) leads to optimisation of the exploitation of the elliptical symmetry of the optical beam to reduce the influence of wind which mainly occur in the plane parallel to the plane xz of the FSO link. Preferred is then elliptically symmetrical beam with the main axis oriented in the horizontal plane.

5. CONCLUSION

In the paper we have focused on the problem of the modelling, testing and evaluation of FSO links. Complex model of FSO link was shown as a synthesis of the stationary and the statistical approach to FSO link modelling. Stationary model requires knowledge of the key parameters of the FSO link used for a given service. There is no “general” FSO link, but we always deal with an FSO link dedicated to a certain service working in specific conditions. It was shown, that the statistical FSO link model characterising given location must take into account not only standard atmospheric effects which occur in the volume between the two transceivers but also “non-standard” effects such as diffraction of the elliptical beam on the transmitter aperture, frost on the transceivers, dew and raindrops of the windows and the influence of the wind on the vibration and mechanical deformation of console and brackets.

We have stressed out, that the attenuation caused by decreased window transmissivity or by the optical beam deviation from the main optical axis can not be regarded as the attenuation of the atmospheric environment itself. The effect of diffraction is partially caused by the restriction of the transmitted beam in the transmitter not by the atmosphere itself, however, can caused additional attenuation especially during turbulent events (detection of narrow diffraction maxima/minima). The statistical model which doesn’t take these effects into account is incorrect. Non-standard effects can be detected and to some extent eliminated. However, standard atmospheric effects (e.g. attenuation and turbulence) can not be eliminated and problems they cause must be overcome by special techniques (e.g. sufficient system margin). In case, the TFSO link measures and evaluates only the standard atmospheric effects, its measurement error should not be further increased by the “non-standard” effects. Results published based on the measurements influenced by “non-standard” effects are therefore incorrect

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