# THE TURBULENT AREA AND SUBSTITUTIVE TURBULENT FUNCTION OF THE CIRCULAR SYMMETRIC GAUSSIAN BEAM

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## ABSTRACT

For the Gaussian beam in the turbulent atmosphere we can calculate correlation between influenced laser beam and ideal Gaussian beam. Idea of the turbulent area, the turbulent optical intensity envelope and the substitutive function is introduced. Expression of the volume of atmospheric turbulences by turbulent area is presented in this work.

## 1. INTRODUCTION

The requirement for data speed transmission and signal quality continually increases. Optical wireless links fulfill the demand for high transfer rate and desired bit error rate (BER). Free space optical link (FSO) consists of optical transmitter and optical receiver. Scheme of the FSO is depicted at figure 1.

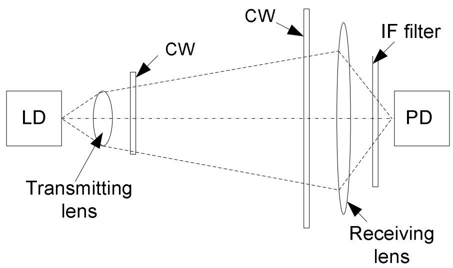


**Figure 1:** Scheme of optical wireless link

Most of the standard used wireless optical links work as dual communication systems. Laser diode (LD), transmitting lens and cover window (CW) are typical components of the transmitter. Usually laser diode with wavelength of 785 nm, 850 nm or 1550 nm is picked. Purpose of transmitting lens is to set divergence of optical beam. Cover window protects transmitting system from hydrometeors and atmospheric dust. Photodetector (PD), interferential filter (IF) which leaks out transmitted wavelength only, cover window and receiving (Fresnel) lens are parts of receiver.

Optical wireless link can be provided at horizontal or vertical direction. Horizontally oriented optical link for distances about (300 – 1000) m are well known and relatively widely applied for high quality and data rate transmission (fig. 2). Thick fog, smog, rain or snow influences optical signal attenuation. Sun shine or increasing temperature of electrical circuits in transceiver debases noise properties of the communication system. The turbulent atmosphere can be issue so there is necessary to avoid it if it is possible or try to eliminate influence of atmospheric turbulences.

Vertical free space optical links (fig. 3) are employed in high altitude platform (HAP) systems. The communication proceeds between HAP which can be located up on high about tens of kilometers and Earth station. Planetary boundary layer with high volume of atmospheric turbulences in troposphere and ozone layer with attenuation on molecules in stratosphere occur as a point.

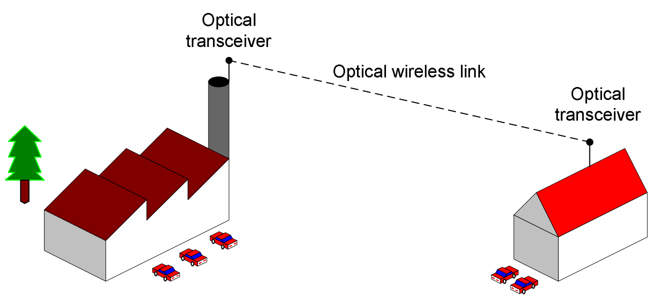


**Figure 2:** Horizontal optical wireless link

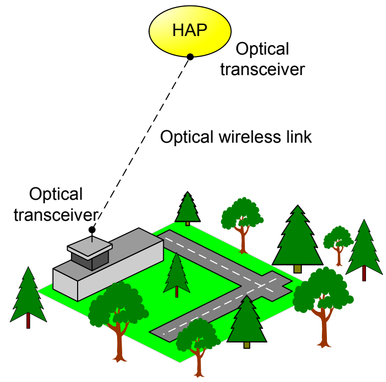


**Figure 3:** Vertical optical wireless link

For both communication systems we consider volume of atmospheric turbulences. In case of high turbulences the optical communication can be debased, or it can be interrupted.

## 2. ATMOSPHERIC TURBULENCES

Atmospheric turbulences, generated by a temperature differential between the Earth's surface and the atmosphere, influence optical waves. During daytime, the Earth is hotter than the air, causing the air nearest the ground to be hotter than that above. This negative temperature gradient causes light rays parallel to the earth to bend upward. If the negative temperature gradient is sufficiently strong, it can result in an inverted image known as a mirage. Temperature gradients are positive during nighttime hours, resulting in downward bending of light rays. In addition, atmospheric turbulence disrupts the coherence of laser radiation and optical wave. [1].

### 2.1. Circular Gaussian laser beam

Optical source as a laser diode or LED emits beam with Gaussian distribution of optical intensity. For circular and symmetric laser beam spot optical intensity $I(r)$ can be expressed

$$I(r) = I_0 e^{-2\left(\frac{r}{w_0}\right)^2}, \tag{1}$$

where $I_0$ [W/m$^2$] is maximum optical intensity, $w_0$ [m] is laser beam halfwidth and $r$ [m] is radial distance from beam axis (fig. 4).

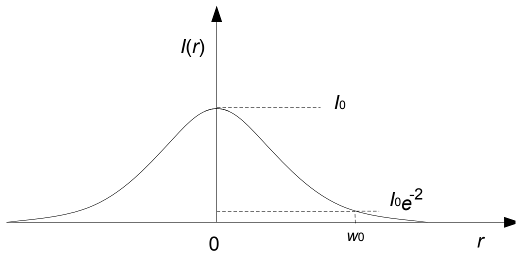


**Figure 4**: Gaussian beam distribution of circular laser beam

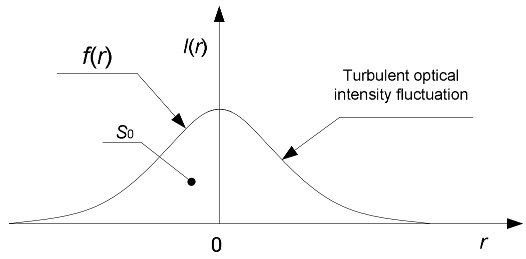


**Figure 5:** Optical intensity distribution in non turbulent atmosphere

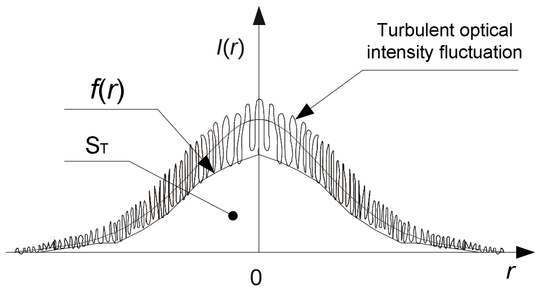


**Figure 6:** Optical intensity distribution in turbulent atmosphere

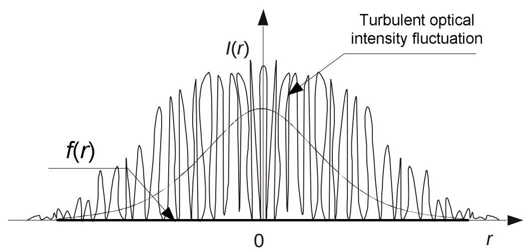


**Figure 7:** Optical intensity distribution in very high turbulent atmosphere

In the non-turbulent atmosphere the optical intensity distribution agrees with Gaussian distribution. We can calculate the turbulent area $S_T$ [W/m] (fig. 6) which represents volume of atmospheric turbulences influence. For atmosphere without the turbulences (fig. 5) the turbulent area $S_T = S_0$ can be evaluated by the expression

$$S_0 = \int_r I_0 e^{-2\left(\frac{r}{w_0}\right)^{-2}} dr \,. \tag{2}$$

With increasing atmospheric turbulences the optical intensity fluctuations rises so the turbulent area $S_T$ [W/m] decreases in comparison with the non-turbulent atmosphere. The turbulent atmosphere causes the optical intensity fluctuation and the turbulent optical intensity envelope is formed (fig. 6, 7). Decreasing correlation between examined laser beam profile and ideal Gaussian beam was identified so for increasing atmospheric turbulences we have to find the substitutive turbulent function instead of Gaussian function to describe the optical intensity distribution.

The substitutive function is limited from below by the turbulent optical intensity envelope and can be generally expressed as $f(r)$, and then the turbulent area $S_T$ is determinate by

$$S_T = \int_r f(r) dr \,. \tag{3}$$

We suppose that for very high atmospheric turbulences (fig. 7) the substitutive function is $f(r) = 0$. This situation arises when the turbulent optical intensity envelope aligns to $x$ – axis, so the turbulent area $S_{T,\max}$ [W/m] can be expressed

$$S_{T,\max} = \int_r 0 dr = 0 \,. \tag{4}$$

Of course there can be higher optical intensity fluctuations, but the atmospheric turbulences determination from the turbulent area $S_T$ has this limit.

From the findings mentioned above we can dedicate that the volume of atmospheric turbulences influenced optical Gaussian beam can be rated by the turbulent area $S_T$. The atmospheric turbulences can vary from very low level, then the turbulent area $S_0$ is evaluated by equation (2), and for very high level the turbulent area $S_{T,max}$ is determinate by equation (4). All atmospheric turbulences states vary between these two values.

The optical sources resistivity on the atmospheric turbulences can be quantify by the turbulent areas $S_T$ comparison.

### 2.2. EXPERIMENT

We obtain information about the laser beam optical intensity distribution influenced by the atmospheric turbulences from the instrument laser beam profiler (LBP). The output of LBP brings us information about the laser beam properties in $x$ – axis, appropriate software which is part of LBP is able to calculate the correlation between ideal Gaussian optical intensity distribution and measured optical intensity distribution influenced by the atmospheric turbulences.

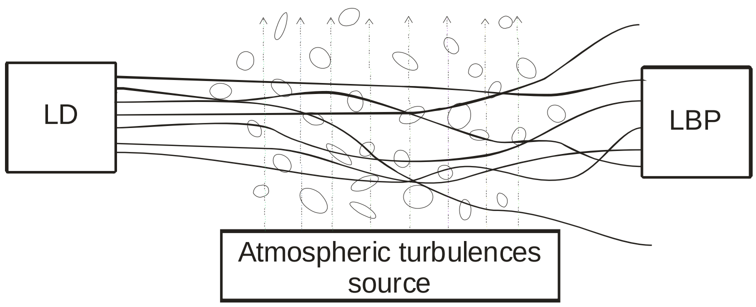


**Figure 8:** Workstation scheme

We investigated the influence of the weak turbulent atmosphere on the laser beam geometry properties. We used laser diode which emits wavelength 670 nm. Laser diode properties in $x$ -axis was scanned, correlation between measured beam and Gaussian beam was examined and $C_n^2$ was calculated. Following table (Tab. 1) presents measured results.

| $C_n^2$ | corr. $x$ | $S_{T,rel}$ |
|---|---|---|
| [$m^{-3/2}$] | [%] | [-] |
| 1,23E-16 | 87,2 | 1 |
| 4,91E-16 | 86,9 | 0,98 |
| 1,12E-15 | 86,4 | 0,95 |
| 9,94E-15 | 85,9 | 0,93 |
| 2,76E-14 | 85,3 | 0,89 |
| 5,94E-14 | 84,5 | 0,87 |

**Table 1:** Measured results of the experiment

$C_n^2$ is calculated structure parameter refractive index and presents the volume of evocated atmospheric turbulences, corr. $x$ presents correlation between the laser beam and Gaussian beam and finally the relative turbulent area $S_{T,rel}$ [-] is calculated, where

$$S_{T,rel} = \frac{S_T}{S_0}. \quad (5)$$

For $C_n^2 = 1{,}23 \cdot 10^{-16}$ (low turbulences) we consider turbulent area as $S_0$, so for this structure parameter refractive index $S_{T,rel}$ is equal to 1.

### 2.3. RESULTS

The results of the laser beam and Gaussian beam correlation comparison are evident at fig. 9. With increasing atmospheric turbulences caused by atmospheric turbulent source the correlation between laser beam and Gaussian beam decreases.

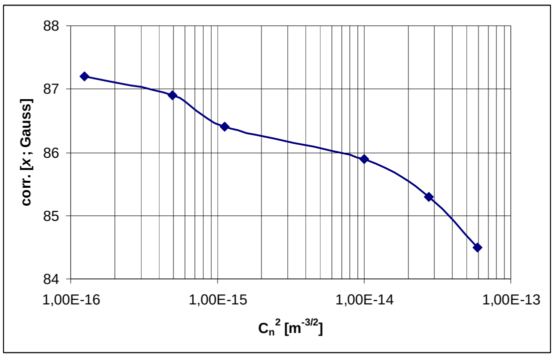


**Figure 9:** Correlation of laser beam and Gaussian beam in turbulent atmosphere

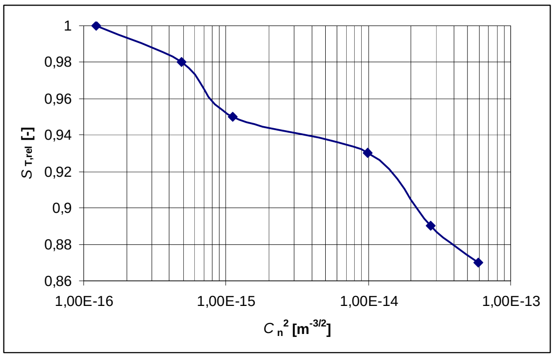


**Figure 10:** Relative turbulent area $S_{T,rel}$ in turbulent atmosphere

With increasing structure parameter refractive index and the volume of atmospheric turbulences, relative turbulent area decreases (fig. 10).

## 3. CONCLUSION

There is a possibility to determine volume of atmospheric turbulences by calculating turbulent area $S_T$, which can be calculated from the substitutive turbulent function $f(r)$ obtained from the turbulent optical intensity envelope of the beam profile. In the experiment we proved that with increasing structure parameter refractive index $C_n^2$ the turbulent area $S_T$ decreases in logarithmic scale. Presently the relation between turbulent area and signal looses isn't determined by formula. The next works will focus on exact formula searching.

## ACKNOWLEDGEMENT

This research has been supported by the Research programs of Brno University of Technology MSM21630513, by the Grant Agency of the Czech Republic under contracts No. 102/08/H027 and by grant FRVS under contract 1574/2008.

## REFERENCES

[1] L. C. ANDREWS, R. L. PHILLIPS, Laser Beam Propagation through Random Media, SPIE – The International Society for Optical Engineering, 1998.