MEASUREMENTS OF THE TURBULENCE MEDIUM CHARACTERISTICS WITH SATURATED LASER SPOT IMAGES

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Abstract

The intensity fluctuations of a laser beam passing through a turbulent medium have been experimentally investigated using saturation of successively registered images of the laser beam cross section. Measurements of the degree of turbulence by estimation of the refractive index structure parameter have been carried out using this approach.

1. INTRODUCTION

When a laser beam propagates through a turbulent medium, in addition to the divergence caused by the diffraction, the beam also spreads by the fluctuations of the refractive index, which results in laser spot intensity variations [1]. One can also possibly obtain a decrease in the spatial and temporal coherence of the beam, and, in some conditions, even a shift of the laser spot intensity medial [2],[3]. Theoretical analysis of the statistical parameters of the intensity fluctuations for plane and spherical waves [4], as well as for spatially limited wave has been developed [5]. The experimental verifications of the theory are carried out by investigation of the statistical parameters of the intensity distribution of alight spot projected from different light sources [6]. The data obtained are used for measuring the refractive index structure parameter of the investigated medium Cn^2. Different approaches have been applied in calculation it using experimental data and analytical formulae. A new technique is reported for the experimental measurement of Cn^2 variations by capturing telescope images of remote light source with video camera [7]. The measurements were provided through obtaining 2-D power spectrum of the image and evaluating correlation area size and corresponding turbulence field coherence length. Two dimensional Fourier transformation is a standard image processing technique that requires a definite time to be implemented. In order to reduce data - handling time and noises of the received signal passed through turbulent medium, measurements of Cn^2 based on estimating image intensity without processing the whole image information is suggested.

2. DESCRIPTION OF THE TECHNIQUE

A new measurement technique utilizing CCD image detector is suggested for obtaining rapidly the state of turbulence of inhomogeneous media. The idea is to provide successive records of the intensity distribution in the cross section of a laser beam passing through a turbulent medium using a saturation of the image detector. Currently available lasers poses sufficient energy to provide the necessary intensity for saturation at long distances, while the commonly used CCD sensors are highly sensitive in respond, so the technique is easy to be implemented.

Instead of the work of the image receiver in saturation can be made limit of the amplitude of the received signal after its registration with the suitable electronic and software methods. In that case is avoid from the overload of the image receiver and from eventual dilution of the signal. In the both case it is used the dependency of the intensity of the registered laser light from the spot radius. Therefore it is possible to make the corresponding processing not over the whole received image, but only over this part of the image, which has provoked the saturation of the image receiver. The level of the saturation of the image receiver or the value of the limit of the amplitude of the signal can be definite preliminary with the help of hard- and software means, dependent from the used method for determination of the medium turbulence characteristics. In that case the information for the condition of the turbulence of the studied medium can be received via the processing only the area of the saturation of the received signals. This allow us to make an operating control via quick analyze of the fluctuations of the spot intensity by the distribution of the laser light through the turbulence medium.

3. EXPERIMENTAL RESULTS

The experimental setup for investigating the state of turbulence of inhomogeneous media comprises a single mode frequency stabilized He-Ne laser with a collimated beam to provide a minimum divergence. The fluctuations of the refractive index due to a vertical turbulent flow are created by local heating beneath the propagating beam. The intensity distribution in the cross section of the beam is successively recorded by CCD imaging camera with the relevant electronics. The receiving optical system consists of objective, neutral filters for overall intensity attenuation and an interference filter at the laser frequency. The exposure time for a single frame is 20 ms, which fixes the short-duration averaging time of the laser spot intensity. In the condition of sufficiently short exposures it is possible to be registered intensity fluctuations due to interactions of the beam with turbulent eddies smaller then the diameter of the laser beam. The recording of the frame sequence through a selected interval is implemented by a frame grabber board incorporated into a PC, where also further image processing is accomplished.

On figure 1 is shown the intensity distribution of an imaged laser spot causing no saturation on the image detector, as it is usually the case when the detector is operated according to the conventional methods for registration and processing of propagating optical signal through a turbulent medium. On figure 2 is shown the registered optical signal by the described optical system with saturation of the image detector. With this approach while the optical signal is being recorded, the noise in the image saturation area is eliminated and preliminary filtration of the acquired images is not necessary. The recorded images are used afterwards for obtaining the state of turbulence of the investigated medium and the corresponding refractive index structure parameter.

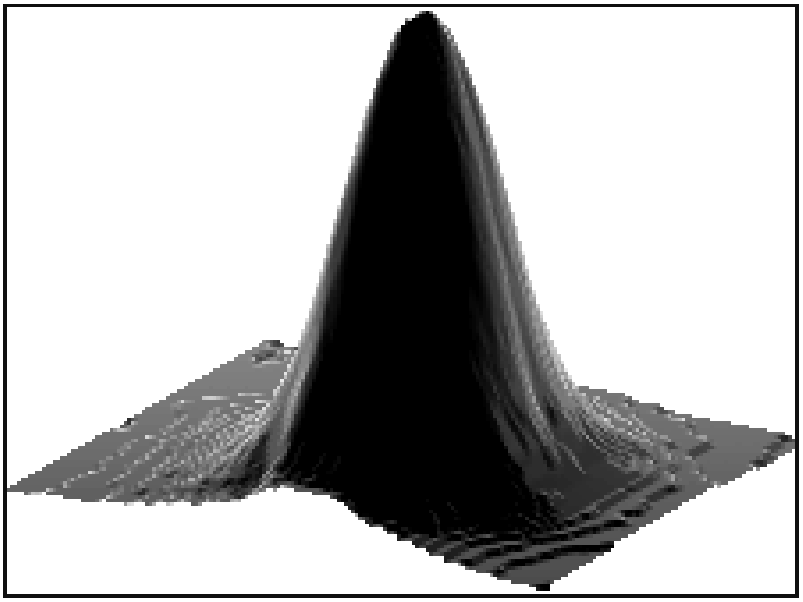

Figure 1. The registered laser spot causing no saturation on the image detector

When laser beam interacts with turbulent eddies larger than the beam diameter, the beam is shifted out of the optical axis, while at interaction with the smaller eddies, it only spreads. That is why when the laser spot is registered by the detector using short exposure, one can obtain the spot spreading, influenced by the small eddies, and the spot centre shifted by the larger eddies. When an image sequence is recorded it is observed a permanent beam shift. The fluctuations of the laser spot radius is possible to be analyzed by calculations the area with saturated intensity from the recorded images. In order to do this, it is only necessary to obtain the number of the image pixels above the level of saturation. The fluctuations of the beam intensity are proportional to the square of the laser spot radius [3]. When saturated images are registered, the fluctuations of the beam intensity could be estimated from the number of pixels above the saturation level from all the registered images.

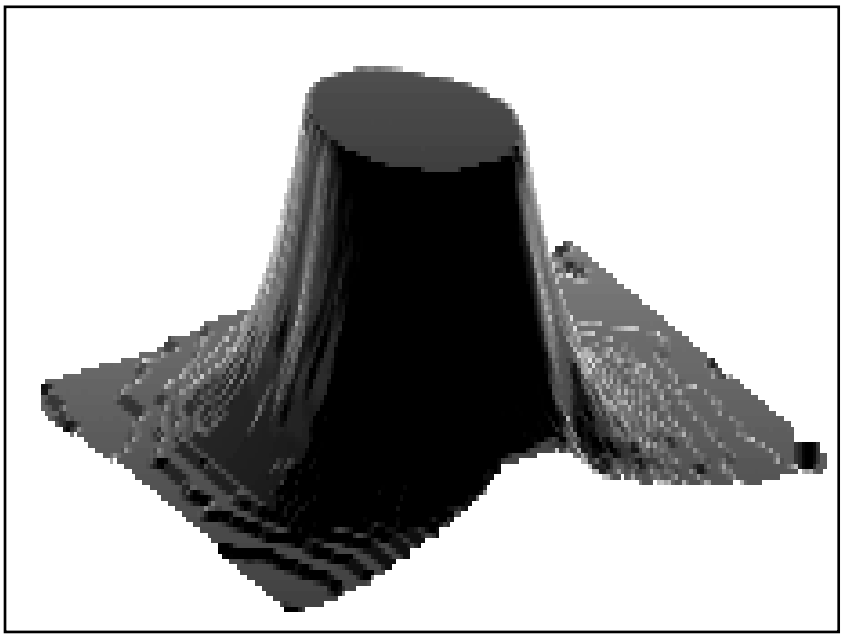

Figure 2. The registered laser spot with image detector saturation

On figure 3 are shown the fluctuations of the saturated area in 100 successively recorded images of the spot of a laser beam, passed through a turbulent medium. In order to compare the results, on the same figure are shown the fluctuations of the saturated area in 50 successively recorded images before the turbulence creation.

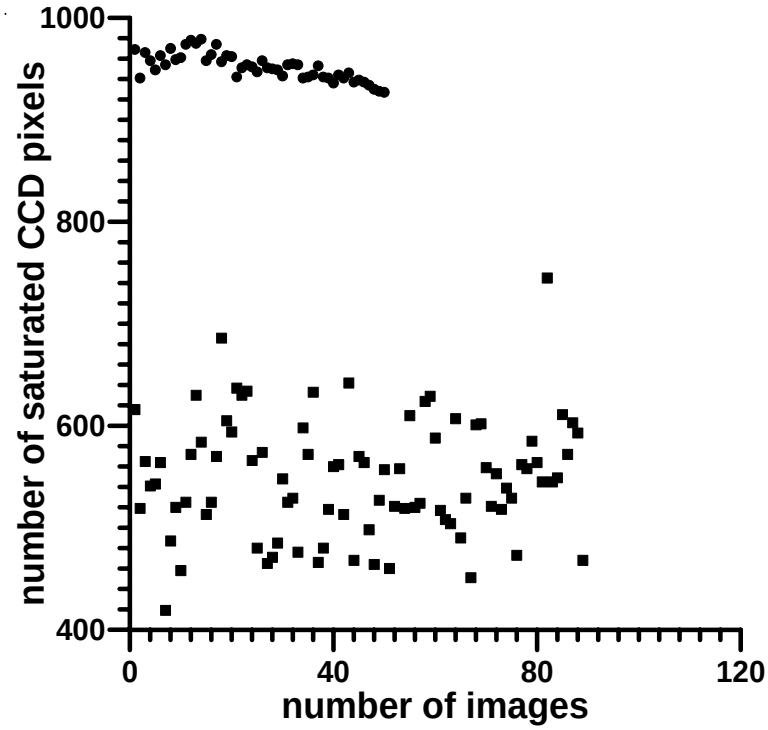

Figure 3. The fluctuations of the saturated area of the imaged laser spot

- before the creation of turbulence
- after the creation of turbulence

The lower average values in turbulent conditions are explained with the intensity decrease of the laser beam when it passes through the turbulent medium [1]. The registered behaviour of the laser beam propagating through a medium where fluctuations of the refractive index occur is typical when the turbulence is weak, and in this case $\sigma_1^2 = 1.23\, k^{7/6}\, x^{11/6} Cn^2 \leq 0.3$.1

In this relation $k = 2\pi/\lambda$ is the wave number, x is the distance between the laser and the image detector, and Cn^2 is the refractive index structure parameter. In a strong turbulence when $\sigma_1^2 > 1$, the intensity medial of the recorded laser spot does not change the position, but the beam splits and several spots are registered. The determination of the state of turbulence could be provided by the analysis of the correlation radius of the intensity fluctuations [5]. It is implemented by calculation of the correlation functions of the laser spot intensity fluctuations. In a case of homogeneous turbulence, when Cn^2 does not depend on x and the turbulence is weak, the correlation radius of the intensity fluctuations is $(\lambda x)^{1/2}$ [5]. By calculation of all correlation functions got from all recorded images, the average radius of correlation is obtained as 10% from the value of the correlation function maximum. On figure 4 is shown the averaged correlation function of the recorded images of the cross section of a laser beam passed through turbulent medium, where the correlation radius is geometrically equal to 55 pixels from the image detector. This value, transformed in centimetres, is close to the value of $(\lambda x)^{1/2}$,which confirms the fact that experiment has been carried out in weak turbulence.

After calculation of all correlation functions, the data obtained could be used for determination the length of coherence Po of the laser beam. In order to do this, the averaged radius of coherence R at level **e**, where **e** is the natural logarithm base, from all correlation functions is achieved. The correlation radius value in the conducted experiments is R= 0,163 cm. According to [8] the coherent length and the radius of correlation are related by $R^2 = 0.5\, Po^2$ and the value for $Po^{5/3}$ is 0.087 $cm^{5/3}$. Than the refractive index structure parameter is obtained by [7]:

$$Cn^2 = (1.09.k^2\, Po^{5/3} x)^{-1} = 2.147.\, 10^{-13}\, cm^{-2/3}\,. \qquad (1)$$

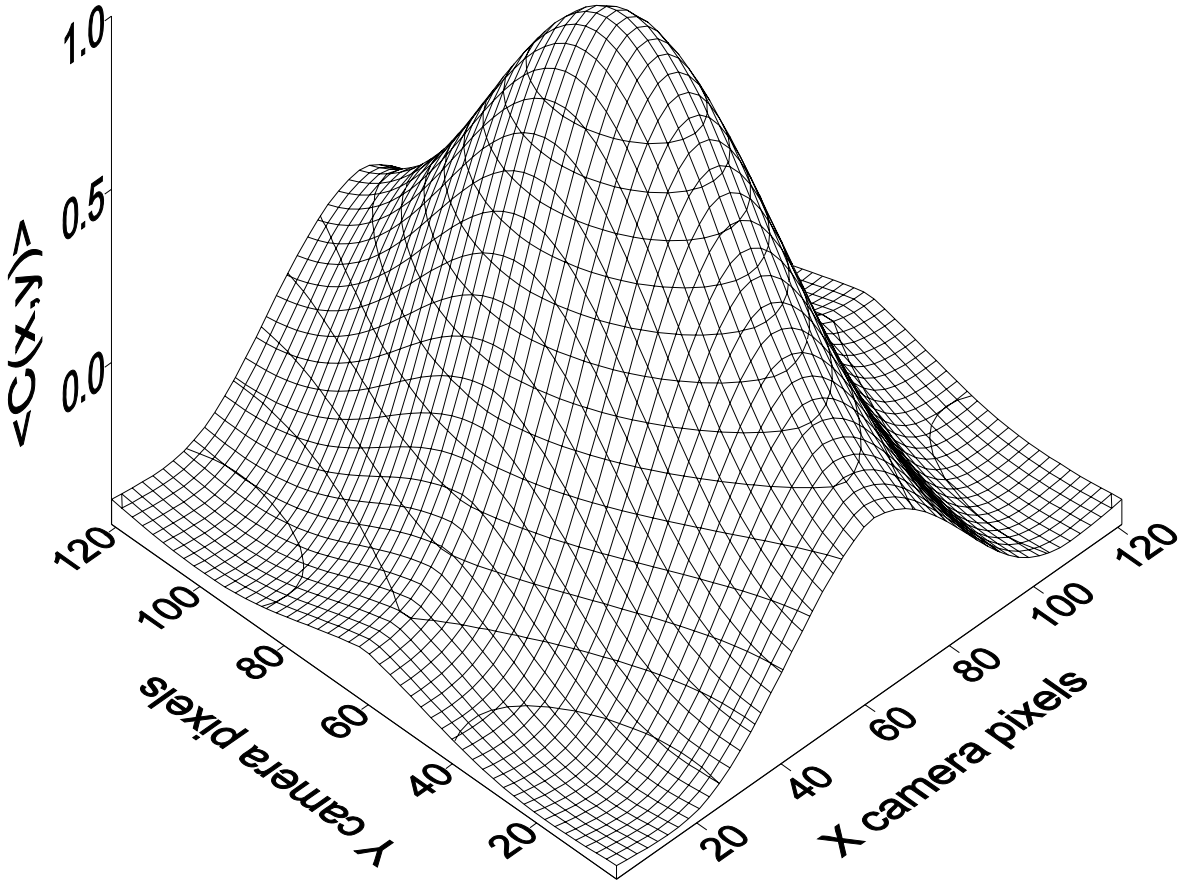

Figure 4. 3-D correlation function <C(x,y)> of the received laser spot passed through turbulen medium

When saturated images are registered, one can easy obtain the dispersion of the laser beam intensity fluctuations σ_I^2 . As it has already been pointed out, the intensity fluctuations are possible to be estimated by calculation of the number of pixels above the saturation level from all recorded images. That is why is reasonable a realization to be composed, which length is equal to the number of recorded images and which elements correspond to the image detector pixels number above the saturation level, as it is shown on figure 3. This realisation is used for calculation the dispersion of the laser beam cross section intensity fluctuations σ_I^2 . The analysis of the medium state of turbulence allows that the refractive index structure parameter is obtained directly from the

condition for weak turbulence $\sigma_1^2 = 1.23\, k^{7/6}\, x^{11/6} Cn^2$. In the conducted experimental measurements the quantities σ_1^2 and σ_I^2 are one and the same as the state of turbulence is determined as low. Than from this relation for Cn^2 is obtained value $2.13.\ 10^{-13}\ cm^{-2/3}$ when $\sigma_I^2 = 1.07$.

The centre of gravity of the recorded laser spot image of the beam passed the area of turbulence is obtained from [1]:

$$R_{x,y} = \frac{\iint d^2 r r I(x,r)}{\iint d^2 r < I(x,r) >} \tag{2}$$

where r is the shift in the image plane and I(x,r) is the laser spot intensity. On figure 5 are shown the fluctuations of x and y coordinates of the centre of gravity of 80 successively recorded images of the beam passed the turbulent area using this method. The dispersion of the fluctuations of the centre of gravity is possible to be applied to the calculation of the refractive index structure parameter according to[1]:

$$< R_{x,y}{}^2 > = \frac{2.97 L^2}{k^2 Po^{5/3} D^{1/3}} \tag{3}$$

This relation is valid for conditions of weak turbulence. In our experiments with collimated laser beam with D = 15 mm and a distance L = 30 m, the dispersion of the centre of gravity fluctuations is 12.6. Then from (1) we obtain $Cn^2 = 2.246.10^{-13} cm^{-2/3}$. The centre of gravity is obtained only by analyze of saturated area of images. This technique enables the use a simple algorithm for calculation. The calculation accuracy is the same as by the use of numerical filter for missing of the noise. In such a way, the use of saturation of images allows us to receive a simplify of the analysis.

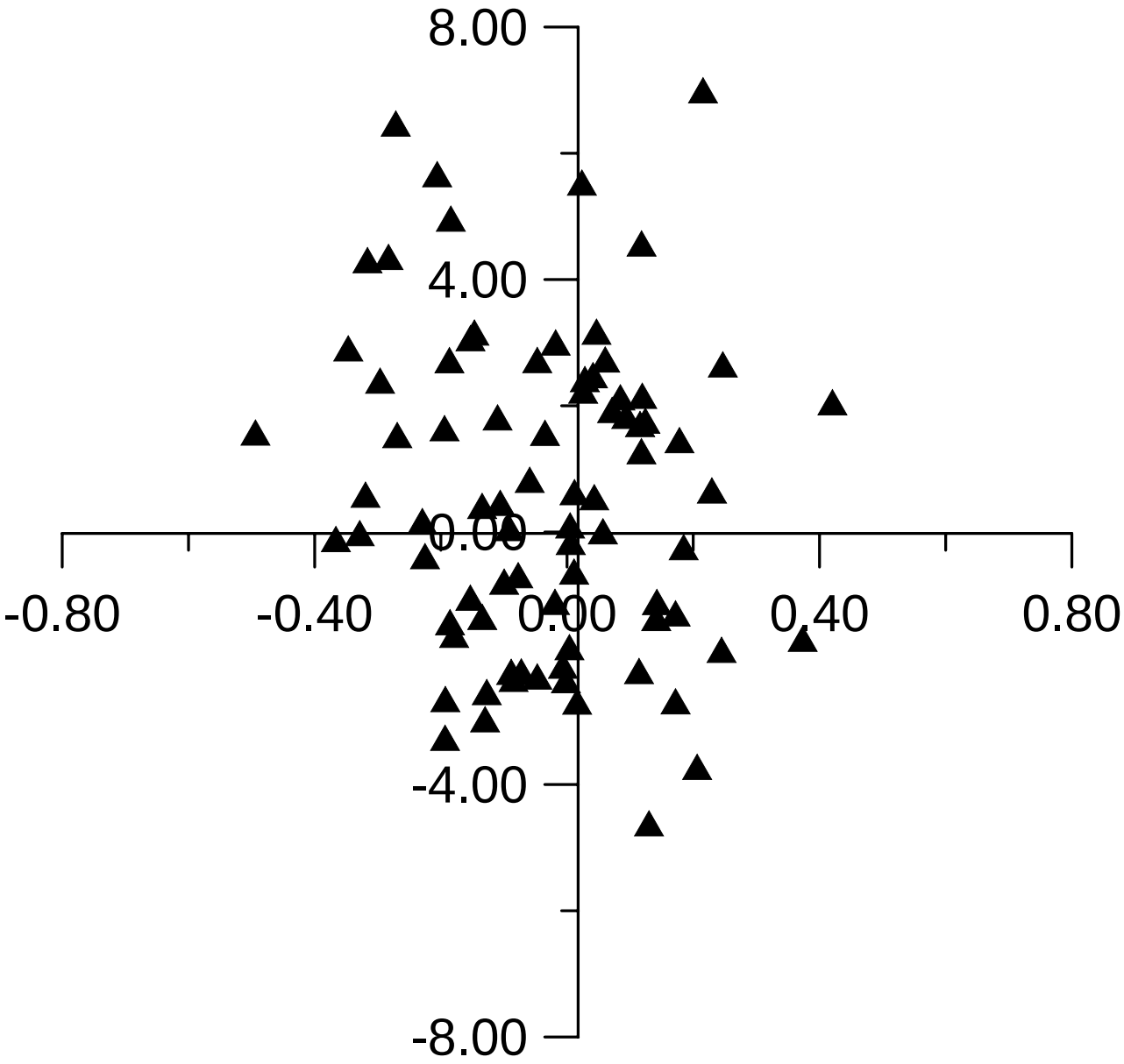

Figure 5. The fluctuations of the centre of gravity of the imaged laser spot

In summary, when the distribution of the laser beam intensity cross section, passed through a turbulent medium, is recorded in saturation mode of the image detector, one can use only two parameters corresponding respectively to the saturated and not saturated imaging areas. It facilitates calculations of the statistical parameters of the recorded signals as well as the determination of the refractive index structure parameter.

ACKNOWLEDGEMENTS

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