AN ACCOUNT OF THE DEAD TIME OF THE COUNTING DEVICE IN EXPERIMENTAL STUDY OF LASER BEAM PROPAGATION THROUGH THE TURBULENT ATMOSPHERE

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Received June 3, 1988

Theoretical results ' with experimental confirmation of the influence of the counter dead time on the photoncount statistics of laser radiation transmitted through the turbulent atmosphere are presented. The discrepancy between the calculated photoncount probability distribution and the experimental one is revealed at large irradiances. The derived approximate analytical expressions permit a correction of the photoncount probability distribution which allows for the influence of the "dead" time for high burdens.

The photoncount probability distribution (PPD) at the output of a photodetector with "dead" time of some type, irradiated by amplitude-stabilized (AS) laser radiation propagated through the atmosphere, differs from the Poisson law. The change in the PPD due to the deadtime effect has been studied both theoretically[1] and experimentally[2]. The influence of atmospheric scattering on the PPD has been investigated[3] both with deadtime and without it when the sampling time T was much greater, than the autocorrelation time τ_c of a signal in the atmosphere. The effect of atmospheric turbulence was analyzed[4] for deadtime not taken into account and $T \ll \tau_c$. The aim of the present article is to fill the gaps in both theory and experiment in this important case of the turbulent atmosphere for $T \ll \tau_k$, taking the deadtime of the counter into account. As was shown in Ref. 1, the photoncount probability distribution of the detector with deadtime of a non-prolonging type, irradiated by AS radiation, can be written[1] as follows

$$P_1(n;N,\varepsilon)=\begin{cases} \sum\limits_{k=0}^{n} P_0(k;N(1-n\varepsilon)) - \sum\limits_{k=0}^{n-1} P_0(k;N[1-(n-1)\varepsilon]), & n < \frac{1}{\varepsilon}, \\ 1-\sum\limits_{k=0}^{n-1} P_0(k;N[1-(n-1)\varepsilon]), & \frac{1}{\varepsilon} \le n < \frac{1}{\varepsilon}+1, \\ 0, & n \ge \frac{1}{\varepsilon}+1, \end{cases} \tag{1}$$

where $\varepsilon = \tau/T$ (τ is the counter "dead" time), $P_0(k;\ z)$ is the Poisson distribution with parameter z (Ref. 3), $N = \eta IT$ is the mean number of photoelectrons, I is the irradiance, and η is the quantum efficiency of the PMT. To allow for atmosphere turbulence it is necessary to average Eq. (1) over the ensemble of I-fluctuations:

$$P_2(n;N',\varepsilon) = \langle P_1(n;N,\varepsilon)\rangle_I,$$

where $N' = \eta\langle I\rangle T$ is the mean number of photocounts produced by the radiation transmitted through the turbulent atmosphere. The propagation of radiation in the atmosphere is characterized by the variance ($\sigma^2 = \langle y^2\rangle - \langle y\rangle^2$) of the logarithm of the relative intensity, where $y = \ln(I/I_0)$ and I_0 is the intensity not taking atmospheric turbulence into account.

Using the lognormal distribution of the intensity[4] and averaging Eq. (1) one obtains

$$P_2(n;N',\varepsilon)=\begin{cases} F_n(N'(1-n\varepsilon);\varepsilon)-F_{n-1}(N'[1-(n-1)\varepsilon]; & n<\frac{1}{\varepsilon} \\ 1-F_{n-1}(N'[1-(n-1)\varepsilon]; & \frac{1}{\varepsilon} \le n < \frac{1}{\varepsilon}+1 \\ 0, & n \le \frac{1}{\varepsilon}+1 \end{cases} \tag{2}$$

where

$$F_n(N'(1-n\varepsilon);\varepsilon)=\frac{1}{\sqrt{2\pi\sigma}}\sum_{k=0}^{n}\frac{|N'(1-n\varepsilon)|^k}{k!}\times$$

$$\times\int_{-\infty}^{\infty}\exp\left\{ky-N'(1-n\varepsilon)\exp(y)-\frac{1}{2\sigma^2}\left[y+\frac{\sigma^2}{2}\right]^2\right\}dy.$$

Figure 1 shows the dependences of $P_2(n;\ N;\ \varepsilon)$ on the number of photoncount n both with atmospheric turbulence ($\sigma = 0.5$) and without it ($\sigma = 0$) for different values of ε from 0 to 0.1. As can be seen from the figure, as the counter deadtime increases, the PPD curves narrow down and shift towards smaller values of n.

In the comparison of the PPD calculated according to Eq. (2) with the experimentally obtained PPD, the parameter σ often remains unknown. It can be determined when the variance σ_n^2 and the mean number of photoncounts at $\varepsilon = 0$ are known:

$$\sigma = \sqrt{\ln\left[1 + \frac{\sigma_n^2 - \langle n\rangle}{\langle n\rangle^2}\right]} \qquad (3)$$

Thus, when $\langle n\rangle$ and $\langle n^2\rangle$ are experimentally measured over a given interval of time T the value σ can be estimated by Eq. (3).

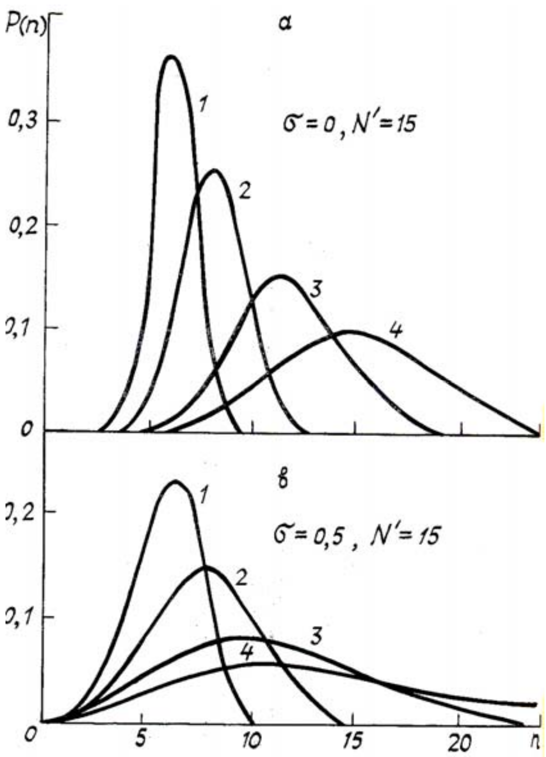

FIG. 1. The PPD versus the number of photoncounts (a) without ($\sigma = 0$) and (b) with ($\sigma = 0.5$) the turbulent atmosphere at ε =: 1 — 0.1; 2 — 0.06; 3 — 0.02; 4 — 0.0.

DESCRIPTION OF THE EXPERIMENTAL SETUP

The purpose of the experiment is to measure the PPD .of laser radiation which has passed through the atmosphere over paths with reflection lengths of $2I$ = 100, 1000 and 2000 m. The scheme of the experimental setup is shown in Fig. 2. A beam from the amplitude-stabilized laser1 which has passed through the telescope3 and the atmosphere 4, is incident upon the mirror 5. A photomultiplier 8 operating in the photon counting regime was used as the photodetector. Electrical pulses from the PMT are standardized by the forming device 9 on the basis of their amplitudes and durations, and are read by the photon counter 10. The experimental data are fed through an interface 11 into the microcomputer "Electronika D3-28". To control the experiment and to process the data, a routine In BASIC and two subroutines in machine language were written. The statistic analysis is carried out over the 100000 point array, with the maximum rate (40000 data points/second). The data collection time can be set at as 1, 2, 4, 2^3, ..., 2^7 μs. built up from the received data. The PPD histogram is on a display screen, and average values of $\langle n\rangle$ and $\langle n^2\rangle$ are computed and the variance of the photocount numbers and the parameter cr are also calculated. The collection time during the experiment was 2^3 μs.

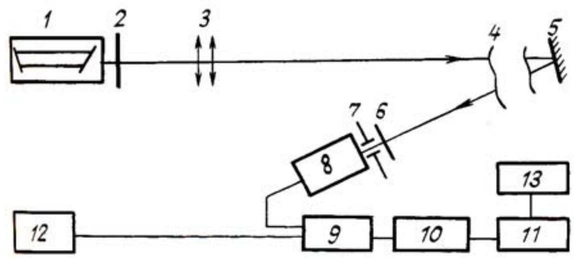

FIG. 2. Experimental setup: 1) laser, 2) neutral filter, 3) telescope, 4) atmosphere, 5) mirror, 6) interferent filter, 7) diaphragm, 8) photomultiplier, 9) former, 10) counter, 11) interface, 12) frequency meter, and 13) computer.

DISCUSSION OF EXPERIMENTAL RESULTS

Measurements were carried out in the Tien-Shan mountains at an altitude of 1500 m above sea-level along the fixed paths with reflection. The atmosphere was such that the values of σ varied over the range 0.169—1.269. The measured counter deadtime was 24 ns. The dependence of the PPD on pathlength for different mean levels of signal radiation was measured. In practice, for example, the study of the dependence of the photoncount statistics on the received radiation level plays a very significant role in the detection of laser signals. Figure 3 shows the experimental PPD of laser radiation at different $\langle n\rangle$ on the short path. As follows from the Figure, the calculated and experimental data are in agreement up to $\langle n\rangle$—10. The disagreement of the calculated and experimental results at <*n*> ≥ 10 is due to the influence of the counter deadtime on the photoelectron statistics at large <*N′*> (see Fig. 1).

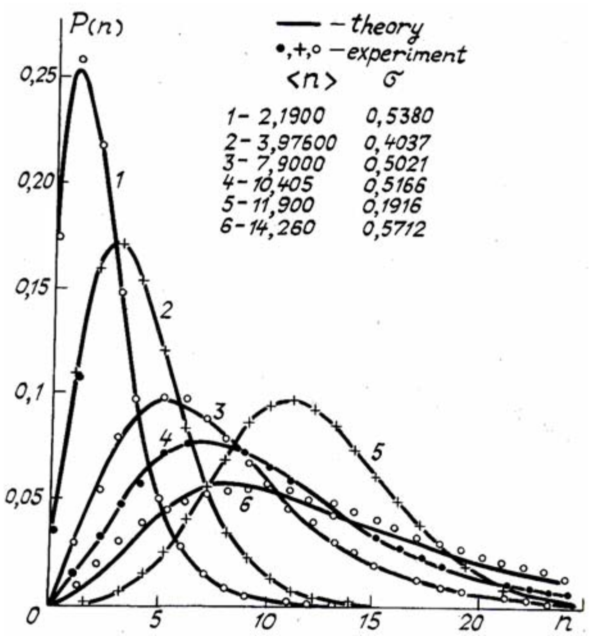

FIG. 3. PPD curves for laser radiation along an atmospheric path with length 2l = 100 m at different radiation levels and degree of turbulence: solid curves theory, points-experiment: theory; points experiment: <n>=2.19 and σ = 0.538 (1), 3.976 and 0.4037 (2), 7.9 and 0.5021 (3), 10.405 and 0.5166 (4), 11.9 and 0.1916 (5), and 14.26 and 0.5712 (6), respectively.

To compare the measured PPD with theory taking into account *DT* at an arbitrary load, it is necessary to know the input N' and σ in Eq. (2). They are often unknown a priori. Without they can be found from the experimental PPD. In this case N'=<*n*>, and σ is determined by Eq. (3). With deadtime we have <*n*> <*N′*>. Equation (3) gives a lower value of σ since σ(ε) < σ(0). To determine N' and σ from the experimental data a study was made of the calculated dependence of $P_2(n;\ N',\varepsilon)$ on N, σ, and ε. Calculations were carried out with the following values: N = 5–25, σ = 0.1–0.5, and ε = 0.002–0.06. Using the dependences given above for different ε, the unknown values of N' and σ were found by a trial and error technique.

Figure 4 shows a comparison of the theoretical and the experimental results for N' and σ found by this technique (curve 3), the experimental values being <*n*> = 23.0 and σ(ε) = 0.221 and the calculated ones for ε = 0.003 being N' = 25.2 and σ(0) = 0.285. For comparison, the PPD computed at N' = 23.0 and σ = 0.447 is also shown without deadtime (curve 2) and with it: N' = 23.0; σ = 0.447, ε = 0.003 (curve 1). As can be seen from the figure, curve 3 is in much better agreement with the experimental data.

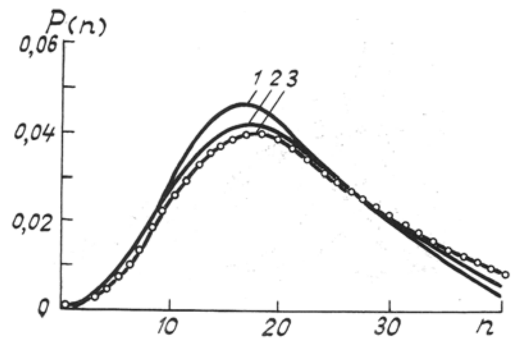

FIG. 4. Comparison of the dependence of the PPD on the number of photoncounts for the input and found values of the parameters: 1) ε = 0.003, N′ = 23.2; 2) ε = 0, N′ = 23, and 3) ε = 0.003, N′ = 25.2; the points represent the experimental results at ε = 0.003, <n> = 23 and σ = 0.45.

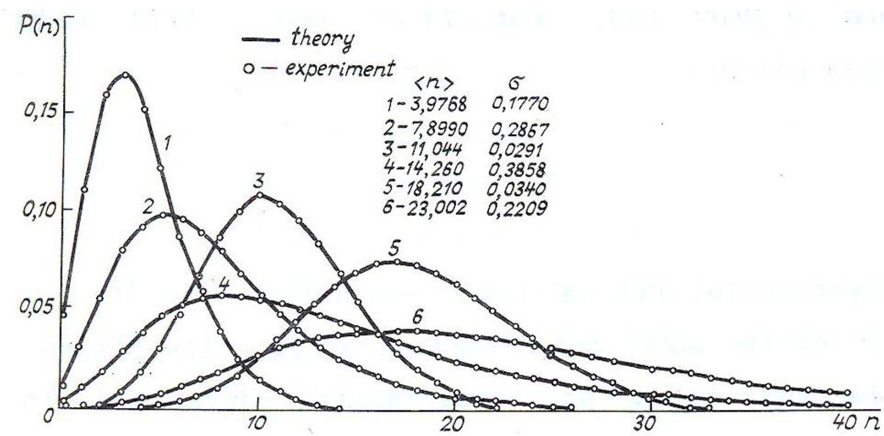

FIG. 5. The experimental and theoretical PPD versus the number of photoncounts n for different radiation levels and degrees of turbulence along an optical path with length 2l = 100 m: solid curve-theory, the points-experiment: <n> = 3.98 and σ = 0.18 (1), 7.9 and 0.29 (2), 11.044 and 0.03 (3), 14.26 and 0.39 (4), 18.21 and 0.034 (5), and 23 and 0.221 (6).

PPD for different $<n>$ and σ along an optical path with reflection with length $2l$ = 100 m is shorn in Fig. 5. Here solid curves represent calculations based on Eq. (2) at values of N' and σ' found using the above-described method. As follows from the Figure, the calculated curves agree with the experimental results rather exactly.

The local error of reconstruction of the PPD in the experiment was estimated by the formula

$$\delta(n) = \sqrt{\frac{1-P(n)}{P(n)N_0}} ,$$

which is valid for statistically independent measurements, where δ is the local relative standard deviation of the PPD for measured $P(n)$, and N_0 is the total number of measurements. In our case the value of σ for the most probable n never exceeded 1% for N_0 = 150000.

Thus, the difference between the theoretical PPD without deadtime[4] and experiment has been demonstrated experimentally at large levels of the received signal, and the deadtime correction was introduced by means of Eq. (2) under conditions of moderate intensity fluctuations of the radiation in the atmosphere $\sigma \le 0.5$.

The results of this work will be useful in; the interpretation of optical spectral measurements in the photon counting regime in the atmosphere.

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