Stability of solutions to the inverse problem of photocount statistics obtained by the inverse Bernoulli transform

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Abstract

A general criterion for evaluating the photocount distributions $Q_m$ in the case of few-photon light, which makes it possible to establish whether the solution to the inverse problem of photocount statistics by inverse Bernoulli transform method is stable for $\eta < 0.5$, is found. As an example of application of the obtained criterion, the critical quantum efficiency $\eta_{cr}$ is found for compound Poisson distribution, below which the solution of the inverse problem of photocount statistics becomes unstable. It is also shown that the normalization of $Q_m$ is not sufficient to obtain a correct solution using the inverse Bernoulli transform.

1 Introduction

One of the most widely used methods for determining the energy characteristics of light is based on measuring the photocount distribution [1], that is, the statistics of electrons emitted from the photocathode irradiated by the light beam. This method is based on detecting the optical radiation by single-photon counters [2]. To date, the photon counting method, which has a long history [3], is widely used in both applied [4, 5, 6, 7, 8] and fundamental research [9, 10, 11, 12]. Nowadays, it is one of the key experimental methods used in quantum optics.

1.1 Semi-classical inverse problem of photocount statistics

Already at the initial stage of application of the photon counting method, in addition to the direct problem — finding the photocount distribution from the known light state, interest was aroused by the inverse problem — determination of the light properties from the known photocount statistics. One of the most important properties of light is energy distribution. For the first time, the problem of reconstructing the energy distribution from the photocount one was considered in [13]; later, various approaches were developed to solve this problem [14, 15, 16]. These studies were based on Mandel’s semi-classical formula for the photocount distribution $Q_m$ [17], which is mathematically the averaged Poisson distribution over the energy distribution of the detected radiation (Poisson transformation of the energy distribution):

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\[ Q_m = \int_0^\infty \frac{(\eta \mathcal{E})^m}{m!} \exp(-\eta \mathcal{E}) w(\mathcal{E}) d\mathcal{E}, \]  

(1)

where \( \mathcal{E} = \mathcal{E}(T) = \int_t^{t+T} \int_S I(\vec{r},t) d^2r dt \) is the light energy falling onto the detector area \( S \) during time \( T \); \( \eta \) is the quantum efficiency of detection; \( I(\vec{r},t) \) is the light intensity; \( w(\mathcal{E}) \) is the probability density of the fluctuating parameter \( \mathcal{E} \); \( m \) is a number of photoelectrons, emitted during time \( T \).

Within the framework of the semi-classical model, the inverse problem of photocount statistics [18] is the reconstruction of the distribution \( w(\mathcal{E}) \) from measured distribution \( Q_m \). The problem of reconstructing the intensity distribution has been solved more than once. Thus, in [13], the Poisson transform was inverted using the Fourier transform and the apparatus of characteristic functions. In [14], an expansion of the intensity distribution in terms of Laguerre polynomials was applied. The authors of [15] used Padé approximants to inverse the Poisson transform, and in [16], cubic B-splines are used for the same purpose.

1.2 Quantum inverse problem of photocount statistics

For a correct description of the photodetection process, especially when applied to few-photon light, the field itself should also be considered as a quantum object. A consistent theory of such a process gives the following result [19]:

\[ Q_m = \left\langle : \frac{1}{m!} \left[ \eta \hat{\mathcal{E}} \right]^m \exp \left[ -\eta \hat{\mathcal{E}} \right] : \right\rangle. \]  

(2)

Here \( \hat{\mathcal{E}} = \hat{\mathcal{E}}(T) = \int_t^{t+T} \int_S \hat{E}^-(\vec{r},t) \hat{E}^+(\vec{r},t) d^2r dt \); \( \hat{E}^- (\hat{E}^+) \) is the negative- (positive-) frequency field operator, \( \langle : :) \) is the normally ordered averaging. As shown in [19], the expression (2) can be rewritten in the Fock basis as

\[ Q_m = \sum_{n=m}^{\infty} C^m_n \eta^m (1-\eta)^{n-m} P_n, \]  

(3)

where \( P_n = \langle : \frac{1}{n!} \hat{\mathcal{E}}^n \exp \left[ -\hat{\mathcal{E}} \right] : \rangle \) is the photon-number distribution, or the probability that \( n \) photons hits a detector during a time \( T \), and \( C^m_n = n!/[m!(n-m)!] \) is the binomial coefficient. The formula (3) is commonly called the Bernoulli transformation [20, 21, 22]. The distribution (3) allows us to give a clear physical interpretation. Since \( \eta \) is the probability of registering one photon during the measurement interval, then \( \eta^m \) is the probability of registering \( m \) photons, and \( (1-\eta)^{n-m} \) is the probability of not registering \( (n-m) \) photons when \( n \) photons arrive at the detector. The coefficient \( C^m_n \) takes into account the possible number of combinations of occurrence of \( m \) photoelectrons.

Thus, in the quantum approach, the photocount distribution is given by the convolution of the photon-number distribution with the Bernoulli one (3) and differs from the semi-classical Mandel formula (1). Therefore, at a low-intensity (few-photon light fields) level, for a correct description of the photodetection process, one must proceed from the Bernoulli transformation (3).

Thus, the inverse problem of the photocount statistics in few-photon mode is the finding \( P_n \) from the known distribution \( Q_m \) which are associated by the relation (3). The importance of this problem lies, in particular, in the fact that currently, few-photon light...
sources are of significant interest in quantum technologies [23, 2, 24]. Photon-number distribution for few-photon radiation is an analog of the intensity for bright radiation; therefore, it can be considered as one of the most important characteristics of a light source. Experimentally, the photon counting method is apparently the simplest and cheapest method to get data about the photon-number distribution. If we had an ideal photon counter with $\eta = 1$ there wouldn’t be any problem with obtaining these data, as distributions $Q_m$ and $P_n$ coincide. However, the quantum efficiency of existing photon counters is typically less than 1, for example, for modern SiPM detectors $\eta \leq 65\%$ [25]. This, as will be shown below, causes significant difficulties in inverting the formula (3).

Two analytical methods are known for solving the inverse problem for few-photon light, which takes into account the losses in photodetection due to $\eta < 1$. One of them is based on the direct inversion of the Bernoulli transformation [20, 21] and the second one is the method of generating functions [22, 26, 27]. In [21], the authors, following the idea of the first method, managed to get an expression of statistical uncertainty for $P_n$ values and made the first base research of the solution convergence. They showed that for any finite $Q_m$ the solutions are stable for arbitrary $\eta$. However, for infinite $Q_m$, the solutions are stable only if $\eta > 0.5$, and in the case of $\eta < 0.5$, one can find counterexamples when the solution turns out to be unstable. As an example, they gave the thermal distribution, for which the stable reconstruction is impossible below some critical quantum efficiency.

In this paper, we take the next step in studying the convergence of solutions obtained using the inverse Bernoulli transform. We do not restrict ourselves to thermal statistics but consider arbitrary photocount distributions. The goal of our work is to find a general criterion for evaluating the distributions $Q_m$, which makes it possible to establish whether the inverse problem solution of photocount statistics by the inverse Bernoulli transform method is stable for $\eta < 0.5$.

## 2 Inverse Bernoulli transform method

The inverse Bernoulli transform method is based on the fact that the formula (3) can be reversed [20]. The easiest way to see this is to represent this formula in matrix form $Q = \hat{T}P$. In the case of a finite $P_n$, when the number of members in the distribution is limited to $N$, the matrix representation of the formula (3) has the form:

$$
\begin{pmatrix}
Q_0 \\
Q_1 \\
\vdots \\
Q_{N-1} \\
Q_N
\end{pmatrix}
= 
\begin{pmatrix}
1 & (1-\eta) & (1-\eta)^2 & \cdots & (1-\eta)^N \\
0 & \eta & 2\eta(1-\eta) & \cdots & N\eta(1-\eta)^{N-1} \\
0 & 0 & \eta^2 & \cdots & \cdot \\
\vdots & \vdots & \vdots & \ddots & \cdot \\
0 & 0 & \cdot & \cdot & \eta^{N-1} \\
0 & 0 & \cdot & \cdot & \eta^N
\end{pmatrix}
\begin{pmatrix}
P_0 \\
P_1 \\
\vdots \\
P_{N-1} \\
P_N
\end{pmatrix},
$$

or simply $Q = \hat{T}P$, where $Q$ and $P$ are the $N$-dimensional vectors. This matrix equation is easy to solve: $P = \hat{T}^{-1}Q$, where $\hat{T}^{-1}$ is an inverse matrix to $\hat{T}$.

Calculating the inverse matrix and passing back to analytical form, it is possible to show [20] that the solution to the inverse problem of photocount statistics can be represented as
As seen from the formula (5), the inverse matrix is triangular, like the original matrix \( \hat{T} \). If the distribution \( Q_m \) is finite-dimensional and no restrictions are imposed on it, then no problems with the stability of solutions to the inverse problem arise for any \( \eta \) [21]. However, in our consideration, the vectors \( P \) and \( Q \) are the probability distributions, hence \( P_n \geq 0 \) for all \( n \) and \( Q_m \geq 0 \) for all \( m \). Moreover, the normalization conditions must be met, i.e. \( \sum_{n=0}^{N} P_n = 1 \) and \( \sum_{m=0}^{N} Q_m = 1 \). The listed restrictions imposed on \( P_n \) and \( Q_m \) lead to the important feature of the solution (5), namely that the transformation \( \hat{T} \) turns out to be contracting.

If to interpret \( P_n \) and \( Q_m \) as projections of unit vectors to coordinate axes in \( N \)-dimensional space, it is convenient to illustrate a contraction action of \( \hat{T} \) by depicting the ranges of possible values for \( P_n \) and \( Q_m \) in such space. To illustrate this, refer to Fig. 1, which shows the ranges of valid values of \( P_m \) and \( Q_m \) for 3-dimensional distributions. In Fig. 1 the distributions \( P_n \) and \( Q_m \) are interpreted as projections of unit vectors on the coordinate axes in 3-dimensional space.

The domains of possible values of \( P_n \) and \( Q_m \) lie in the same plane, which intersects the coordinate axes at the points \( A = \{1, 0, 0\}, B = \{0, 1, 0\}, C = \{0, 0, 1\} \). However, the sizes of these domains are different. Thus, the possible values of \( P_n \) fill the equilateral triangle \( ABC \), while the possible values of \( Q_m \) lie inside the triangle \( ADE \) or \( AD'E' \) of a smaller areas depending on \( \eta \). Note that the coordinates \( D \) and \( E \) of the vertices of this triangle coincide with the columns of the matrix \( \hat{T} \), and, therefore, depend on the \( \eta \): \( D = \{1 - \eta, \eta, 0\}, E = \{(1 - \eta)^2, 2\eta(1 - \eta), \eta^2\} \). If \( \eta = 1 \) then P- and Q-triangles coincide. In the case of \( N \) dimensions the reasoning is similar, but instead of triangles...
one should use multi-dimensional generalization of a triangle — simplex.

This specified property of the transformation $\hat{T}$ causes potential incorrectness in the $P_n$ reconstruction from experimentally obtained $Q_m$ according to the formula (5). Indeed, in the case of a contraction mapping, normalization of the $Q$ distribution does not guarantee the correctness of reconstruction, since although the normalization guarantees that the end of the vector $Q$ falls on the $ABC$ plane, it does not guarantee that it falls inside the $Q$-simplex. As a result, the reconstructed $P_n$ distribution may be outside of $P$-simplex and you can get, in principle, arbitrary values of $P_n$, both greater than 1 and even negative.

To illustrate this conclusion, consider an example of incorrect recovery of $P_n$ from a pre-normalized 3-dimensional $Q_m$. Let us assume that $Q = \{0, 0, 1\}$, then according to formula (5) the elements of the reconstructed distribution $P_n$ will have the form: $P_0 = (1 - \frac{1}{\eta})^2$, $P_1 = 2\eta^{-1}(1 - \frac{1}{\eta})$, $P_2 = \eta^{-2}$. For example, if $\eta = 0.5$ then $P = \{1, -4, 4\}$. Note that despite the obtained negative value of $P_1$, the normalization of the distribution $P_n$ remains.

This feature of the solution (5) becomes critical in the processing of experimental data and, no doubt, requires the development of special methods which would not allow the experimental values to go beyond the boundaries of the $Q$-simplex. However, this problem is beyond the scope of the questions discussed in this article, and we will not touch on this issue further.

3 Stability of the inverse Bernoulli transform method for infinite distributions

Another feature of the solution (5) arises with the transition to infinite distributions. In general, when $N$ is infinite, the stability of the solutions to the inverse problem in the form (5) is not guaranteed. An unsolved problem in studying the stability of the inverse Bernoulli transform method is the question of the stability of solutions for $\eta < 0.5$. Our goal is to find the criterion for the stability of the solution (5).

From a mathematical point of view, the solution (5) can be viewed as a countable set of series. Therefore, the solution will be stable if all series (5) converge for any $n$. Let’s choose an arbitrary series with number $n$ and rewrite it in the equivalent form

$$P_n = (\eta - 1)^{-n} \sum_{m=n}^{\infty} (-1)^m \left(\frac{1}{\eta} - 1\right)^m C_m^n Q_m,$$

whence it can be seen that it is an alternating series. Denoting $a_{nm} = \left(\frac{1}{\eta} - 1\right)^m C_m^n Q_m$, we can write it in a more compact form:

$$P_n = (\eta - 1)^{-n} \sum_{m=n}^{\infty} (-1)^m a_{nm}.$$

An interesting feature of the solution (6) is the presence of a critical value of the quantum detection efficiency $\eta_c = 0.5$. You can see this by looking at the structure of the sequence $a_{nm}$, which can be considered as the product of two sequences $a_{nm}^{(1)} = \left(\frac{1}{\eta} - 1\right)^m C_m^n$ and $a_{nm}^{(2)} = Q_m$. Because the series $\sum_{m=0}^{\infty} Q_m$ converges for any distributions $Q_m$ due to the normalization condition, then by Abel convergence criterion it is sufficient for the convergence of the series (6) that the sequence $a_{nm}^{(1)}$ was monotone and limited. The sequence $a_{nm}^{(1)}$ starting from some number $m$ is monotone, therefore, for its boundedness
it is sufficient that it converges to 0. As follows from the explicit form of \( a_{nm}^{(1)} \), for \( \eta > 0.5 \) \( \lim_{m \to \infty} a_{nm}^{(1)} = 0 \), and for \( \eta < 0.5 \) \( \lim_{m \to \infty} a_{nm}^{(1)} = \infty \). This implies that for \( \eta > 0.5 \) the series (6) converges for any distribution \( Q_m \), and for \( \eta < 0.5 \) the convergence of the series (6) depends on the type of distribution \( Q_m \).

Now we can find the criterion that the distribution \( Q_m \) must satisfy to ensure the convergence of the series (6) for \( \eta < 0.5 \). The series (6) will converge if the Leibniz criterion is fulfilled, i.e. the sequence \( a_{nm} \) monotonically tends to zero as \( m \to \infty \).

Because the sequence \( a_{nm} \) is non-negative, it is sufficient to satisfy the monotonicity condition \( a_{n,m+1} < a_{nm} \) starting from some number \( M \). Noticing that

\[
 a_{n,m+1} = a_{nm} \cdot \frac{m+1}{m} \cdot \frac{1}{m} \cdot \frac{1}{\eta} \cdot \frac{Q_{m+1}}{Q_m},
\]

we obtain the condition of monotonicity for the sequence \( a_{nm} \) in the form:

\[
 Q_{m+1} < Q_m \cdot \left( 1 - \frac{n}{m+1} \right) \frac{\eta}{1 - \eta}.
\] (8)

The relation (8) can be regarded as a criterion for the convergence of the series (5) for an arbitrary \( n \). In relation to the stability of the inverse problem solution, this criterion should be understood as follows. If for all \( n \) for a given \( \eta \) it is possible to find a finite \( m = M_n \), starting from which the condition (8) is satisfied, then the solution to the inverse problem is stable. Note that the obtained stability criterion implies that the distribution \( Q_m \) stable for some \( \eta \) may become unstable for smaller \( \eta \). Let’s call the minimal \( \eta \) for which the solution is stable \( \eta_{cr} \).

### 4 Examples of application of the stability criterion

#### 4.1 Poisson distribution

Let \( Q_m \) be the Poisson distribution:

\[
 Q_m = \frac{(\bar{m})^m}{m!} \cdot e^{-\bar{m}},
\] (9)

where \( \bar{m} \) is the mean number of photocounts.

The stability criterion (8) for the distribution (9) is written as:

\[
 \frac{(\bar{m})^{m+1}}{(m+1)!} \cdot e^{-\bar{m}} < \left( 1 - \frac{n}{m+1} \right) \frac{\eta}{1 - \eta} \frac{(\bar{m})^m}{m!} \cdot e^{-\bar{m}}.
\] (10)

From the relation (10) it follows that the inequality is satisfied if \( m > M_n = n - 1 + (1 - \eta) \eta^{-1} \bar{m} \). Hence it follows that for any given \( n \) and \( \eta \) there exists \( M_n \), starting from which the stability criterion is fulfilled. It means that in the case of the Poisson distribution the solution obtained by inverse Bernoulli transform is stable for arbitrary \( \eta \).

#### 4.2 Compound Poisson distribution

Let \( Q_m \) be the compound Poisson distribution:

\[
 Q_m = \frac{\Gamma(a + m)}{m! \Gamma(a)} \left( \frac{\bar{m}}{a} \right)^m \frac{1}{(1 + \bar{m}/a)^{a+m}}.
\] (11)
where $\bar{m}$ is the mean number of photocounts, $a$ is a clusterization (or bunching) parameter. Using (11) we can describe a wide class of photocount distributions [28]. As shown from Fig. 2, this distribution strongly depends on the $a$ value. If $a \to \infty$ it goes to the Poisson distribution, if $a = 1$ it coincides with the thermal one. Also, it has a physical meaning if $0 < a < 1$ and for negative integers if $\bar{m} \leq -a$. But for negative $a$ the distribution becomes finite and as shown above all series (5) converge. So, problems of convergence can arise only for $a > 0$.

Writing down the stability criterion (8) for the distribution (11) and taking into account that $\Gamma(a + m + 1) = (a + m) \Gamma(a + m)$, we arrive to inequality

$$m \left( \frac{\eta}{1 - \eta} - \frac{\bar{m}}{a + \bar{m}} \right) > \frac{\eta(n - 1)}{1 - \eta} + \frac{\bar{m}a}{a + \bar{m}}. \quad (12)$$

Further transformation of inequality (12) depends on the sign of $\xi = \eta(1 - \eta)^{-1} - \frac{\bar{m}}{a + \bar{m}}^{-1}$.

If $\xi > 0$, then the inequality (12) can be written as

$$m > M_n = \left( \frac{\eta(n - 1)}{1 - \eta} + \frac{\bar{m}a}{a + \bar{m}} \right) \times \left( \frac{\eta}{1 - \eta} - \frac{\bar{m}}{a + \bar{m}} \right)^{-1}. \quad (13)$$

Note that for $n = 0$ the right-hand side of the inequality (13) for small $a$ can be negative, but it will hold for any $m$ and we can put $M_n = 0$.

If $\xi < 0$, then the inequality (12) leads to an upper constraint of $m$, which means that $M_n$ does not exist.

Figure 2: Compound Poisson distributions with $\bar{m} = 4$, $a = 0.2, 1, 50$. 

![Figure 2: Compound Poisson distributions with $\bar{m} = 4$, $a = 0.2, 1, 50$.](image-url)
Thus, the condition for the existence of $M_n$ is the fulfillment of the condition $\xi > 0$, from which it immediately follows that

$$\eta_{cr} = \left(\frac{a}{m} + 2\right)^{-1}. \quad (14)$$

As is known, the compound Poisson distribution transforms into the usual Poisson distribution for $a \to \infty$. With this $a$ the critical quantum efficiency $\eta_{cr} = 0$, i.e. the solution turns out to be stable for any $\eta$, which coincides with the conclusion obtained above when analyzing the usual Poisson distribution.

The expression (14) also generalizes the special case of the thermal distribution given in [21] as an example of the possibility of the existence of unstable solutions. The compound Poisson distribution transforms into a thermal distribution at $a = 1$. Substituting this value into (14) we get $\eta_{cr} = (m^{-1} + 2)^{-1}$, which coincides with the value obtained in [21] from fundamentally different considerations.

The obtained coincidences are an additional confirmation of the correctness of the stability criterion obtained in this paper.

5 Conclusions

As shown above, non-ideal quantum efficiency $\eta < 1$ leads to a number of problems when trying to reconstruct photon-number distribution $P_n$ from the measured photocount distribution $Q_m$. These problems must be taken into account in practical implementation of the recovery procedure. In the present paper, to our knowledge, we did the first detailed stability analysis of the solutions obtained by inverse Bernoulli transform for infinite $Q_m$ distributions. We found the criterion that allows us to estimate the stability of the solution for arbitrary types of infinite photocount distributions for any $\eta \in [0, 1]$. According to the obtained criterion, it become possible for each $Q_m$ to determine the minimum possible $\eta = \eta_{cr}$, below which the reconstruction of the infinite $P_n$ distribution becomes impossible.

The results for finite distributions also seems to us rather important since it can positively influence the development of numerical methods for solving the inverse problem of photocount statistics. The obtained results show that normalization of the experimentally obtained distribution of photocounts is insufficient to obtain the correct solution using the inverse Bernoulli transform. It is necessary to additionally ensure that probabilities $Q_m$ lie inside the $Q$-simplex. This condition indicates a new way of developing algorithms for solving the inverse problem of photocount statistics.

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