Tutorial: Maximum likelihood estimation in the context of an optical measurement

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July 9, 2018

Abstract

The method of maximum likelihood estimation (MLE) is a widely used statistical approach for estimating the values of one or more unknown parameters of a probabilistic model based on observed data. In this tutorial, I briefly review the mathematical foundations of MLE, then reformulate the problem for the measurement of a spatially-varying optical intensity distribution. In this context, the detection of each individual photon is treated as a random event, the outcome being the photon’s location. A typical measurement consists of many detected photons, which accumulate to form a spatial intensity profile. Here, I show a straightforward derivation for the likelihood function and Fisher information matrix (FIM) associated with a measurement of multiple photons incident on a detector comprised of a discrete array of pixels. An estimate for the parameter(s) of interest may then be obtained by maximizing the likelihood function, while the FIM determines the uncertainty of the estimate. To illustrate these concepts, several simple examples are presented for the one- and two-parameter cases, revealing many interesting properties of the MLE formalism, as well as some practical considerations for optical experiments. Throughout these examples, connections are also drawn to optical applications of quantum weak measurements, including off-null ellipsometry and scatterometry.
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1 Introduction

The method of maximum likelihood estimation (MLE) was introduced by R.A. Fisher in the early 20th century as a way to estimate the parameters associated with an observed quantity based on some statistical model [1–3]. This technique has been used in wide-ranging applications in the physical and social sciences [4–7]. Here we focus on its application to the measurement of an optical intensity distribution $I(u; p)$ that depends on some vector of unknown physical parameters $p = (p_1, \ldots, p_N)$. These parameters can take a continuous range of values, and in general they might each have different units. In this context, the goal of MLE is to determine the most likely value of $p$ from a measurement of $I$. The spatial variable $u$ is typically a two-dimensional coordinate in the plane perpendicular to the direction of light propagation. In the treatment that follows, we focus on the information gained from the shape of $I$ (i.e., its dependence on $u$) without regard for the overall intensity (i.e., the total power incident on the detector). One advantage of this approach is that the accuracy of the parameter estimate is not influenced by power fluctuations of the light source, which would otherwise be especially problematic when operating under low-light conditions (as discussed further in Section 5.3).

Useful in-depth tutorials on MLE and the related topic of Fisher information can be found in Refs. [7, 8]. The key concepts are summarized in Section 2 for the case of a discrete random variable that depends on one or more parameters $p_n$. This situation applies directly to most real-world optical measurements, in which the detector is divided into a discrete pixel array, implying that a measurement consisting of a finite number of photon detections has a finite number of possible outcomes. A mathematical description of this scenario is derived explicitly in Section 3. For context and further insight, the results are then compared in Section 4 to the Bayesian statistical approach employed in Ref. [9]. Lastly, Sections 5 and 6 contain a number of simple one- and two-parameter examples illustrating the procedure of MLE for optical measurements, as well as the role of Fisher information in evaluating and optimizing the accuracy of an experiment. The Mathematica code for these calculations is provided in Appendix A. The theory developed in Sections 2 through 4 is presented for the multiple-parameter case (vector-valued $p$), which can trivially be reduced to the single-parameter case when needed (as in Section 5). The main results of this paper are those established in Section 3.
2 Overview of MLE: likelihood, Fisher information, and the Cramér-Rao bound

Before discussing its application to an optical measurement, in this section we review the basic concepts of MLE in a general context. Consider a discrete random variable $X$, and let $P(x|\mathbf{p})$ denote the probability mass function (PMF) specifying the conditional probability of the outcome $X = x$ given some vector of parameters $\mathbf{p}$. The PMF is normalized such that

$$\sum_{x \in \mathcal{X}} P(x|\mathbf{p}) = 1,$$  \hspace{1cm} (1)

where $\mathcal{X}$ is the set of all possible outcomes of $X$. It should be emphasized that the PMF is interpreted as a function of $x$. That is, given a fixed value of $\mathbf{p}$, the function $P(x|\mathbf{p})$ provides the probability of each possible outcome $x$. In a typical measurement, however, we require just the opposite: given an observed value of $x$, we wish to determine the value of $\mathbf{p}$ that is most likely to have produced the measured outcome. This inverse problem is solved by introducing the likelihood function, defined as

$$L(\mathbf{p}|x) = P(x|\mathbf{p}).$$

Although the likelihood function and the PMF appear to be mathematically identical (and indeed they are in their unevaluated symbolic forms), they actually have quite different meanings. In contrast to the PMF, the likelihood function is regarded as a continuous function of $\mathbf{p}$ for some fixed value of $x$. It is not subject to any normalization condition over $\mathbf{p}$. Given an observation $X = x$, $L(\mathbf{p}|x)$ represents the likelihood (relative probability) of a set of candidate parameter values $\mathbf{p}$. Accordingly, the maximum likelihood estimate (also sometimes abbreviated as MLE) for the unknown parameter values is obtained by determining the value of $\mathbf{p}$ that maximizes $L(\mathbf{p}|x)$. For computational convenience, the log-likelihood function $\ell(\mathbf{p}|x) = \ln L(\mathbf{p}|x)$ is often equivalently maximized instead.

Next we address the related problems of (1) evaluating the uncertainty of a maximum likelihood estimate and (2) designing an experiment for optimal sensitivity. These problems are both related to the Fisher information, which quantifies the amount of information about $\mathbf{p}$ that is contained within a measurement of $X$. For

$^{1}$Often, the likelihood is used to describe of a set of measurements $\mathcal{S} = (x_1, x_2, \ldots)$, in which case it could be denoted as $L(\mathcal{S}|\mathbf{p})$. In this tutorial, we use the notation $L(\mathbf{p}|x)$ with the understanding that $x$ could represent either a single measurement or an ensemble of measurements (e.g., an optical intensity distribution, which is a collection of many individual photon detection events).
the case of $N$ parameters, the Fisher information matrix (FIM) $\mathbb{J}(p)$ is defined as the $N \times N$ symmetric, positive semi-definite matrix with elements

$$
[\mathbb{J}(p)]_{mn} = E \left[ \left( \frac{\partial}{\partial p_m} \ell(p|x) \right) \left( \frac{\partial}{\partial p_n} \ell(p|x) \right) \right] \quad (2a)
$$

$$
= \sum_{x \in \mathcal{X}} \left( \frac{\partial}{\partial p_m} \ell(p|x) \right) \left( \frac{\partial}{\partial p_n} \ell(p|x) \right) L(p|x), \quad (2b)
$$

where $E$ denotes the expectation value over $\mathcal{X}$. Under mild regularity conditions [10], the FIM is equivalently defined as$^2$

$$
[\mathbb{J}(p)]_{mn} = -E \left[ \frac{\partial^2}{\partial p_m \partial p_n} \ell(p|x) \right] \quad (3a)
$$

$$
= -\sum_{x \in \mathcal{X}} \left( \frac{\partial^2}{\partial p_m \partial p_n} \ell(p|x) \right) L(p|x). \quad (3b)
$$

Since $\mathbb{J}(p)$ represents the information contained in a single observation of the random variable $X$, it is sometimes called the unit Fisher information. If the measurement is repeated for $T$ independent trials, it can be shown that the total information is $T \mathbb{J}(p)$. Note that while the Fisher information is a function of the true parameter values $p$, it is independent of $x$. This indicates that $\mathbb{J}(p)$ is not a property of an individual measurement, but rather of the measurement scheme (and its expected outcome). For this reason, $\mathbb{J}(p)$ is often referred to as the expected Fisher information. Some texts also define the observed Fisher information $\mathbb{J}^{\text{obs}}(p; x)$ associated with a particular measured outcome $x$ by dropping the expectation values from Eqs. (2a) and (3a) and evaluating at the maximum likelihood estimate for $p$. There has been debate regarding the conditions under which it is more appropriate to use the observed or expected Fisher information [11, 12]. In the asymptotic limit of a large number of observations, it can be shown that the two definitions are equivalent [13].

The statistical significance of the FIM is that its inverse $\mathbb{J}^{-1}(p)$ places a lower limit on the covariance matrix $\mathbb{C}(p)$ for a maximum likelihood estimate of $p$. More

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$^2$To prove this result, one can expand the derivatives in Eq. (3b) using the chain rule and product rule. This produces the RHS of Eq. (2b) plus an additional term $-\sum_{x \in \mathcal{X}} \frac{\partial^2}{\partial p_m \partial p_n} L(p|x) = -\frac{\partial^2}{\partial p_m \partial p_n} \sum_{x \in \mathcal{X}} L(p|x)$. By Eq. (1), the sum over $L(p|x)$ is equal to 1, so its derivative is zero. The “regularity conditions” for this proof essentially require that $L(p|x)$ is twice differentiable and that the order of summation and differentiation can be swapped. In practice, these conditions are met in all but the most pathological cases.
precisely, for any unbiased estimator\(^3\), the Cramér-Rao bound \([4]\) states that the matrix \(C - J^{-1}\) must be positive semi-definite, i.e., for any vector \(p\),

\[
p^T C p \geq p^T J^{-1} p. \tag{4}
\]

The diagonal elements \([J^{-1}]_{nn}\) provide the minimum variance of each parameter \(p_n\), while the off-diagonal elements \([J^{-1}]_{mn}\) (where \(m \neq n\)) represent the expected covariances between parameters \(p_m\) and \(p_n\). The uncertainty of the measurement can be visualized as an ellipsoid in \(N\)-dimensional parameter space (centered at the MLE) representing the standard deviation confidence interval. The principal axis orientations of the ellipsoid are given by the eigenvectors of \(J^{-1}\), and the semi-axis lengths are the square roots of the corresponding eigenvalues \([15]\). Four examples are illustrated in Table 1 for the case of a two-parameter measurement in which the true parameter values for \(p_1\) and \(p_2\) are both zero. Since \(J^{-1}\) is a function of \(p\), in general the size and shape of the error ellipsoid also vary over the parameter space. This dependence can be visualized for the two-parameter case (or a 2D slice of a higher-dimensional parameter space) by plotting a grid of ellipses over a selection of parameter values, as will be seen in Section 6.

In summary, the accuracy of a maximum likelihood estimate can be assessed by calculating the inverse of the expected Fisher information matrix for the measurement. In a similar manner, the FIM can be used to predict and optimize the accuracy of an experiment before any measurements are taken. This is done by minimizing a suitable merit function (chosen based on the desired relative accuracies of each parameter) over the range of interest of \(p\). It is often convenient to reparametrize \(p\) to be dimensionless, such that the intervals \(-1 \leq p_n \leq 1\) (for \(n = 1, \ldots, N\)) correspond to each physical parameter’s range of interest.\(^4\) Then one reasonable choice for the merit function would be the product of the eigenvalues of \(J\), which is inversely proportional to the square root of the area (for two parameters) or volume/hypervolume (for three or more parameters) of the error ellipsoid. Another option is the root mean square (RMS) of the eigenvalues of \(J^{-1}\), which is the inverse of half the diagonal length of the rectangle/box containing the ellipse/ellipsoid. This second merit function is often

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\(^3\)In general, the MLE can be biased. However, it is asymptotically unbiased for a sufficiently large sample size \([14]\). The form of the Cramér-Rao bound given in Eq. (4) only applies when the MLE is unbiased.

\(^4\)One of the advantages of MLE is that it is invariant to the choice of parametrization \([4]\).
| $\mathbb{J}^{-1}$ | Eigenvalues | Eigenvectors | Error ellipse |
|------------------|-------------|--------------|--------------|
| $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ | 1, 1       | $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ |               |
| $\begin{bmatrix} 1 & 0 \\ 0 & 0.2 \end{bmatrix}$ | 1, 0.2     | $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ |               |
| $\begin{bmatrix} 1 & 0.5 \\ 0.5 & 1 \end{bmatrix}$ | 1.5, 0.5   | $\begin{bmatrix} 0.71 \\ 0.71 \end{bmatrix}$, $\begin{bmatrix} -0.71 \\ -0.71 \end{bmatrix}$ |               |
| $\begin{bmatrix} 0.2 & -0.5 \\ -0.5 & 2 \end{bmatrix}$ | 2.13, 0.07 | $\begin{bmatrix} -0.25 \\ 0.97 \end{bmatrix}$, $\begin{bmatrix} 0.97 \\ 0.25 \end{bmatrix}$ |               |

Table 1: Plots of the error ellipses associated with four different $2 \times 2$ Fisher information matrices. The square roots of the eigenvalues of $\mathbb{J}^{-1}$ determine the semi-axis lengths of the ellipse, i.e., the dimensions of the bounding rectangle. The eigenvectors of $\mathbb{J}^{-1}$ determine the orientation. The blue points in each plot represent the estimated parameters from 250 observations of the random variable $X$ (assuming a bivariate normal distribution) given true parameter values $p_1 = p_2 = 0$. In these examples, $p_1$ and $p_2$ are taken to be dimensionless, and they are plotted over the range $-3 \leq p_1, p_2 \leq 3$. 

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a better choice than the first, since it has a lower tendency to heavily prioritize the
accuracy of one parameter at the expense of another.

3 MLE formalism for an optical measurement

We now apply the MLE formalism to the optical measurement described previously,
in which one or more parameters \( p \) are to be estimated from a measurement of an
intensity distribution \( I(u; p) \). The functional form of \( I(u; p) \) (not to be confused with
the measured intensity \( \tilde{I} \) defined below) is generally obtained from either a theoretical
model, simulated data, experimental calibration data, or some combination thereof.
Suppose that the detector is discretized into a finite number of pixels \( i \) centered at
coordinates \( u_i \), and assume the pixels are sufficiently small so that \( I(u; p) \) is nearly
constant over the area of one pixel. Then, given some vector of true parameter values
\( p \), the probability that a single incident photon will hit the detector at pixel \( i \) is
prescribed by the normalized intensity distribution:

\[
P(i|p) = \frac{I(u_i; p)}{\sum_i I(u_i; p)}, \tag{5}
\]

where the sum is taken over all pixels.\(^5\) This equation represents the PMF for a
single detected photon. For a classical measurement, each photon detection can be
considered as an independent event, so the probability of \( M \) photons hitting pixels
\( i_1, \ldots, i_M \) is given by the product

\[
P(i_1 \cap \cdots \cap i_M | p) = \prod_{m=1}^M P(i_m | p). \tag{6}
\]

Now consider a measured intensity \( \tilde{I} = (\tilde{I}_1, \tilde{I}_2, \ldots) \), where \( \tilde{I}_i \) is the number of
photons detected at pixel \( i \). Since the detector is indifferent to the order in which
photons arrive (i.e., photons are indistinguishable), the probability of obtaining this

---

\(^5\) This approximation for small pixels is acceptable for most applications involving sensors with
dense pixel arrays. For sparse arrays, however, one should instead use the exact expression
\( P(i|p) = \langle I \rangle_i / \sum_i \langle I \rangle_i \), where \( \langle I \rangle_i \) is the integral of \( I(u; p) \) over the area of pixel \( i \). For experiments in which
the expected intensity distribution is obtained from a set of calibration images (which themselves
are discretized), Eq. (5) is an exact result.
distribution is given by

\[ P(\tilde{I}|p) = P_0 \prod_i P(i|p)^{\tilde{I}_i}, \]  

(7)

where the leading factor \( P_0 = (\sum_i \tilde{I}_i)! / \prod_i \tilde{I}_i! \) accounts for all possible permutations.

When regarded as a function of \( p \), the right-hand side of Eq. (7) represents the likelihood function \( L(p|\tilde{I}) \). The log-likelihood is therefore given by

\[ \ell(p|\tilde{I}) = \ln P_0 + \sum_i \tilde{I}_i \ln P(i|p). \]  

(8)

Since \( P_0 \) is a constant, the maximum likelihood estimate for \( p \) is obtained by maximizing the sum appearing in this expression. As described in Section 2, the inverse of the Fisher information matrix places a lower bound on the covariance matrix for this estimate. The expected FIM for a single photon can be calculated using Eq. (2) or (3), with \( x \) replaced by the pixel index \( i \) specifying the photon’s location. For a measurement of \( N \) photons, the total information is

\[ \mathcal{N}[J(p)]_{mn} = \mathcal{N} \sum_i P(i|p) \left( \frac{\partial}{\partial p_m} \ln P(i|p) \right) \left( \frac{\partial}{\partial p_n} \ln P(i|p) \right) \]  

(9a)

\[ = -\mathcal{N} \sum_i P(i|p) \frac{\partial^2}{\partial p_n \partial p_m} \ln P(i|p). \]  

(9b)

On the other hand, the observed FIM associated with a particular measurement \( \tilde{I} \) is obtained by summing the derivatives of \( \ell(p|\tilde{I}) \) over all detected photons:

\[ [J^{(obs)}(p;\tilde{I})]_{mn} = \sum_i \tilde{I}_i \left( \frac{\partial}{\partial p_m} \ln P(i|p) \right) \left( \frac{\partial}{\partial p_n} \ln P(i|p) \right) \]  

(10a)

\[ = -\sum_i \tilde{I}_i \frac{\partial^2}{\partial p_n \partial p_m} \ln P(i|p). \]  

(10b)

Since \( \tilde{I}_i \approx \mathcal{N} P(i|p) \) for large \( \mathcal{N} \), the expected and observed information converge in the limit as \( \mathcal{N} \to \infty \). In practice, they should yield nearly identical results in most applications, with the possible exception of extreme low-light measurements using single-photon detectors.

Here the FIM is written in terms of the PMF \( P(i|p) \) to emphasize the dependence on the normalized intensity distribution, but we could just as easily have used the likelihood function \( L(p|i) \) associated with pixel \( i \), which has the same functional form.
In the above analysis, we have implicitly assumed that the detector is capable of measuring any arbitrary number of photons incident on a pixel, i.e., that it can resolve individual photons. However, most real detectors have a finite bit depth, meaning that they can only resolve some finite number of distinct intensity levels. For example, in an 8-bit sensor, each pixel has an integer readout value between 0 and 255. This discretization of pixel values is analogous to the discreteness of photons; therefore, in this situation, Eqs. (7) through (10) can be used with \( \tilde{I}_i \) interpreted as the readout value of pixel \( i \). In the absence of thermal noise or other sources of error, the equivalent “photon count” of the signal from a sensor with finite bit depth must be less than or equal to \( N \), the actual number of photons incident on the detector. If required, the effective bit depth of the sensor can be increased by averaging the output signal over multiple exposures. This time-averaging has the added benefit of reducing the impact of electronic shot noise.

## 4 Comparison to Bayesian statistics

The method of MLE is considered a “frequentist” approach in the sense that it does not assign a probability distribution to the unknown parameter \( p \), but rather it estimates the value of \( p \) that is most consistent with the observed data. A popular alternative is the Bayesian approach, which is predicated on the calculation of a posterior probability density function (PDF) \( P(p|\tilde{I}) \) describing the probability of every possible value of \( p \) given an observed intensity \( \tilde{I} \). In general, \( P(p|\tilde{I}) \) depends on a prior distribution \( P(p) \) as well as the observed intensity. The prior distribution \( P(p) \) may be uniformly distributed (i.e., constant), or it may be used to introduce known (or assumed) information about \( p \) before the measurement takes place. For example, in the polarimetry experiment discussed in Ref. [9] (with \( p = (p_1, p_2, p_3) \) representing the normalized Stokes parameters), \( P(p) \) could be used to incorporate prior knowledge about the source’s polarization. Another example is the focused beam scatterometry experiment discussed in Ref. [16], in which it might be possible in some cases to assign a prior distribution \( P(p) \) based on the fabrication process of the sample under test.
Using Bayes’ theorem, the posterior PDF can be written as

\[ P(p|\tilde{I}) = \frac{P(p)}{P(\tilde{I})} P(\tilde{I}|p), \quad (11) \]

where the constant term in the denominator, given by

\[ P(\tilde{I}) = \int P(p)P(\tilde{I}|p)\,dp, \quad (12) \]

ensures the normalization condition \( \int P(p|\tilde{I})\,dp = 1 \). Substituting Eq. (7) into Eq. (11), one obtains

\[ P(p|\tilde{I}) = \frac{P(p)}{P(\tilde{I})} P_0 \prod_i P(i|p)^{\tilde{I}_i} \]

\[ = \frac{P(p)}{P(\tilde{I})} P_0 \exp \left[ \sum_i \tilde{I}_i \ln P(i|p) \right]. \quad (13a) \]

Notice that \( P(p|\tilde{I}) \) is proportional to the prior distribution times the likelihood. If no prior information is assumed about \( p \), then \( P(p) \) is constant and the peak of \( P(p|\tilde{I}) \) coincides with the maximum likelihood estimate for \( p \). More generally, if \( P(p) \) is nonuniform, the two values converge in the limit as \( N \to \infty \), assuming that \( P(p) \) is smooth and nonzero near the true value of \( p \).

As discussed in Ref. [9], if the measurement is limited by photon noise (as opposed to other noise mechanisms or experimental error) and \( N \) is large, then \( P(p|\tilde{I}) \) is approximately a narrow, generally anisotropic Gaussian distribution that is maximized by the true parameter values \( p_0 \):

\[ P(p|\tilde{I}) \propto \exp \left[ -\frac{1}{2} (p - p_0)^T \Sigma^{-1} (p - p_0) \right]. \quad (14) \]

The covariance matrix \( \Sigma \) determines the shape and width of the distribution, and its inverse \( \Sigma^{-1} \) is the Hessian matrix of second derivatives of \( \ln P(\tilde{I}|p) \) evaluated at \( p_0 \). Recalling the results of the previous sections, one can see that if \( P(p) \) is constant, then \( \Sigma^{-1} \) is equal to the observed FIM \( \mathcal{J}^{(obs)}(p_0) \), and its expected value (taken over all possible outcomes for \( \tilde{I} \)) is the expected FIM \( \mathcal{J}(p_0) \). Intuitively, a measurement with high information content, for which the FIM is large and nearly diagonal, will result in a narrow posterior distribution \( P(p|\tilde{I}) \), enabling a precise estimate of \( p \). Thus, even in
a Bayesian framework, the maximum likelihood estimate and the Fisher information matrix can both be shown to have clear statistical meanings.

5 One-parameter optical MLE examples

In this section we conduct a series of four simple thought experiments involving one-dimensional intensity distributions $I_j(u; p_1)$ (where $j = 1, 2, 3, 4$) that depend on a single parameter $p_1$. Without loss of generality, we assume that $p_1$ is dimensionless and that its range of interest is $-1 \leq p_1 \leq 1$. (As noted earlier, any physical parameter can be reparameterized in this way.) The one-dimensional pupil coordinate $u$ is also taken to be dimensionless. Let us introduce the pupil function

$$\Lambda(u) = \begin{cases} I_0, & -1 \leq u \leq 1, \\ 0, & \text{otherwise}, \end{cases}$$

where $I_0$ represents some reference intensity level. This function will be used for normalization and to introduce a hard aperture with unit radius. In the examples that follow, each intensity distribution is normalized such that it reaches a maximum value of $I_0$ over the range of interest of $p_1$. Note, however, that this does not preclude the possibility of intensities greater than $I_0$ when $|p_1| > 1$.

For simplicity, suppose that the detector consists of a one-dimensional array of 9 pixels, with pixel $i$ centered at coordinate $u_i = (i - 5)/4$, so that

$$(u_1, \ldots, u_9) = (-1, -0.75, -0.5, -0.25, 0, 0.25, 0.5, 0.75, 1).$$

According to Eq. (5), the probability of an incident photon hitting pixel $i$ is given by

$$P_j(i | p_1) = \frac{I_j(u_i; p_1)}{\sum_i I_j(u_i; p_1)}.$$ 

As mentioned earlier, for such a sparse array of pixels, this is a relatively poor approximation since the intensity may vary significantly over the width of each pixel. However, since the approximation is reasonable for most real applications, we use it here for instructive purposes. If desired, the exact expression for $P_j(i | p_1)$ (which is provided in footnote 5 following Eq. (5)) could be substituted into the analysis with
5.1 Linear dependence on \( p_1 \)

For our first example, we consider the intensity distribution

\[
I_1(u; p_1) = \Lambda(u)(0.5 + 0.5 p_1 u).
\]  

(18)

The distribution is only valid when \(-1 \leq p_1 \leq 1\) since larger parameter values would result in negative intensity values, which are not allowed. This is an extreme case of minimal modifications required. Similarly, while the concepts of Fisher information and the Cramér-Rao bound are usually applied to measurements consisting of many observations (photons), the calculations will be demonstrated for measurements of just a few photons and then extended to larger sample sizes. Also note that while the following examples all involve intensity distributions over a 1D pupil coordinate, the more general two-dimensional case can be treated in the same manner by rearranging the numerical output of the detector’s 2D pixel array into a 1D array during signal processing.

The intensity distributions considered in each of the following sections are summarized in Table 2. In Section 5.1, we perform an in-depth analysis of a simple intensity distribution that depends linearly on \( p_1 \). In Section 5.2, we compare these results to those obtained from a similar distribution with a weaker linear dependence on \( p_1 \). Next, the commonly-used experimental configurations of null and off-null measurements are explored in Section 5.3. Finally, in Section 5.4, we examine the case of an intensity that may be far from null, comparing the results to the near-null case.

| Section | Intensity distribution |
|---------|------------------------|
| 5.1     | \( I_1(u; p_1) = \Lambda(u)(0.5 + 0.5 p_1 u) \) |
| 5.2     | \( I_2(u; p_1) = \Lambda(u)(0.9 + 0.1 p_1 u) \) |
| 5.3     | \( I_3(u; p_1) = \Lambda(u)\frac{1}{(|c| + 1)^2} (p_1 - cu)^2 \), where \( c = \text{constant} \) |
| 5.4     | \( I_4(u; p_1) = \Lambda(u)\frac{1}{(|d| + 2)^2} (p - u - d)^2 \), where \( d = \text{constant} \) |

Table 2: Intensity distributions for each example considered in Section 5.
a common real-world scenario in which an approximation is made for the intensity that is only valid over some range of parameter values (for example, the quadratic approximation used in Ref. [16]). In practice, for reliable parameter estimation, the range of interest of \( p \) should be smaller than the region where the approximation is valid (within some prescribed accuracy).

Using Eq. (17), it is straightforward to calculate the PMF for a detected photon:

\[
P_1(i|p_1) = \frac{1}{9} \left( 1 + \frac{i - 5}{4} p_1 \right).
\]

The continuous intensity distribution \( I_1(u; p_1) \) and discrete PMF \( P_1(i; p_1) \) are plotted in Figs. 1(a) and 1(b) for the case that \( p_1 = 0.63 \). To visualize the relationship between the intensity and PMF, it is useful to combine the two plots with appropriately chosen scales, as seen in Fig. 1(c). The dependence of each quantity on \( p_1 \) is illustrated in Fig. 2, which contains plots of \( I_1(u; p_1) \) and \( P_1(i|p_1) \) for five different parameter values over the range of interest.

As discussed previously, the likelihood function \( L_1(p_1|i) \) has the same algebraic form as \( P_1(i|p_1) \), but it is regarded as a continuous function of \( p_1 \). The likelihood functions associated with individual photons detected at each pixel \( i = 1, \ldots, 9 \) are plotted in Fig. 3. To illustrate the procedure of calculating the MLE from the likelihood function, let us now consider a simulated measurement of the intensity for which the true parameter value is \( p_1 = 0.63 \). The simulated intensity \( \tilde{I} \) is constructed by randomly selecting individual photons according to the probability distribution \( P(i|p_1 = 0.63) \) that was plotted previously in Fig. 2(b). For demonstrative purposes, we will assume that the sensor is capable of detecting individual photons, even though this is typically not the case in real experiments where many photons accumulate within the sensor’s exposure time. This will allow us to examine the influence of each photon on the likelihood and the MLE, as well as the evolution of the MLE as photons accumulate.

Suppose that the first simulated photon hits the detector at pixel 1. From Eq. (19), the likelihood of this event is found to be \( L_1(p_1|i = 1) = \frac{1}{9} (1 - p_1) \). The MLE based on this single photon is obtained by maximizing the likelihood with respect to \( p_1 \). This example illustrates the fact that the MLE is not guaranteed to exist in general, since \( L_1(p_1|i = 1) \) would be unbounded if \( p_1 \) were allowed to take any real value. A sufficient condition for the existence of an MLE is that the parameter space is compact \([17, 18]\), such as the closed interval \( p_1 \in [-1, 1] \). Within this interval, the
Figure 1: (a) Linear intensity distribution $I_1(u; p_1)$ and (b) the corresponding PMF for each pixel $i$, both shown for the case that $p_1 = 0.63$. The two plots are shown together in part (c). For practical reasons, the axis labels for $i$ are excluded from the combined plot. In subsequent plots, the vertical axis labels will also be omitted to reduce clutter.

Figure 2: Plots of $I_1(u; p_1)$ (left axis) and $P_1(i|p_1)$ (right axis) for several values of $p_1$.

Figure 3: Likelihood functions $L_1(i|p_1)$ associated with each pixel $i$ in a measurement with theoretical intensity distribution $I_1(p_1)$. 
likelihood function is maximized by \( p_1 = -1 \).\(^7\) Notice from Fig. 3 that a single photon detected at pixel 2, 3, or 4 also would have produced the same MLE, albeit with lower confidence.

Now suppose that a second photon is detected at pixel 7, so that the measured intensity becomes \( \bar{I} = (1, 0, 0, 0, 0, 1, 0, 0) \). The likelihood function associated with this second photon is \( L_1(p_1|i = 7) = \frac{1}{9} (1 - \frac{1}{2} p_1) \). Using Eq. (7) (and remembering that the probability and likelihood are algebraically equivalent), the likelihood of measuring this two-photon intensity distribution is

\[
L_1(p_1|\bar{I}) = \frac{2!}{1! \cdot 1!} L_1(p_1|i = 1) L_1(p_1|i = 7) = \frac{1}{81} (-p_1^2 - p_1 + 2).
\]

(20)

It is easy to show that this function is maximized when \( p_1 = -0.5 \), which becomes the new MLE. Similarly, suppose that a third photon is detected, also at pixel 7, so that the measured intensity becomes \( \bar{I} = (1, 0, 0, 0, 0, 2, 0, 0) \). The likelihood of measuring this intensity distribution is

\[
L_1(p_1|\bar{I}) = \frac{3!}{1! \cdot 2!} L_1(p_1|i = 1) L_1(p_1|i = 7)^2 = \frac{1}{972} (-p_1^3 - 3p_1^2 + 4),
\]

(21)

which is maximized when \( p_1 = 0 \).

The likelihood functions for individual photons at pixels 1 and 7 are plotted in Fig. 4(a), as well as the likelihoods of the two- and three-photon intensity distributions from above. The latter two functions are also plotted separately in Fig. 4(b,c). From these plots one can see the effect of each photon: as photons are detected at pixel 1, then pixel 7, then pixel 7 again, the peak of the likelihood function shifts from \( p_1 = -1 \) to \( p_1 = -0.5 \) to \( p_1 = 0 \). Additionally, the distribution becomes more sharply peaked with each accumulated photon, reducing the uncertainty in the MLE.

This uncertainty can be quantified by using Eq. (10) to calculate the observed Fisher information, which is a 1 \( \times \) 1 “matrix” (i.e., a scalar) in the one-parameter case. For

\(^7\)Note that the condition of compactness is sufficient but not necessary. For the scatterometry application considered in Ref. [16], there is no need to restrict the parameters to a finite range when calculating the MLE. In fact, even in the present example, the restriction quickly becomes unnecessary as soon as multiple photons are detected at different pixels. On the other hand, for the polarimetry application in Ref. [9], the Stokes parameters are restricted to the interval \([-1, 1]\) by definition, guaranteeing the existence of an MLE.
Figure 4: (a) Likelihood functions (based on intensity distribution $I_1$) for detected photons at pixels $i = 1$ and $i = 7$ and for intensity measurements consisting of one photon at pixel 1 and one or two photons at pixel 7. The two- and three-photon likelihoods are also plotted on independent scales in (b) and (c).

For example, for the three-photon measurement $\bar{I} = (1, 0, 0, 0, 0, 0, 2, 0, 0)$, Eq. (10a) yields

$$J_1^{(\text{obs})}(p_1; \bar{I}) = \sum_i \bar{I}_i \left( \frac{\partial}{\partial p_1} \ln P(i|p_1) \right)^2$$

$$= \frac{(i - 5)}{4 + (i - 5)p_1}_{i=1}^2 + 2\left( \frac{(i - 5)}{4 + (i - 5)p_1}_{i=7} \right)^2$$

$$= \frac{1}{(p_1 - 1)^2} + \frac{2}{(p_1 + 2)^2},$$

which produces $J_1^{(\text{obs})} = 1.5$ when evaluated at the MLE $p_1 = 0$. In the one-parameter case, the eigenvalue of the “matrix” $J_1^{(\text{obs})}$ is just the value of $J_1^{(\text{obs})}$ itself. Therefore, the minimum expected standard deviation uncertainty of the measurement is
Figure 5: Expected unit Fisher information for a measurement of $I_1(u;p_1)$.

$1/\sqrt{1.5} = 0.816$. Considering the fact that only three photons were detected, this large uncertainty (relative to the range of interest) is not surprising.

Alternatively, using Eq. (9a), the expected error for a measurement of $N$ photons (independent of the specific outcome of the measurement) can be quantified by calculating the expected Fisher information

$$\mathcal{N} J_1(p_1) = \frac{N}{36} \sum_{i=1}^{9} \frac{(i-5)^2}{4 + (i-5)p_1}. \quad (23)$$

For example, for a three-photon measurement with MLE $p_1 = 0$, the expected standard deviation error is $(3J_1(0))^{-1/2} = 0.894$. Keep in mind, however, that the expected Fisher information is not necessarily appropriate for a measurement containing very few photons. As seen in Fig. 5, $J_1(p_1)$ grows infinitely large in the limit that $|p_1| \to 1$, implying that the uncertainty approaches zero. Although this is a meaningful limit for the case of large $N$, it would clearly be nonsensical to suggest that a single photon could produce an MLE with zero uncertainty!

To observe these concepts on a larger scale, suppose that we continue the simulation until 100,000 photons have accumulated, monitoring the results along the way. For a single random trial of the experiment, Table 3 contains the measured intensities and corresponding MLEs obtained throughout the simulation for several values of $N$. Notice that the MLE approaches the true parameter value ($p_1 = 0.63$) as $N$ increases. As seen in Fig. 6, the log-likelihood function $\ell_1(p_1|\hat{I})$ becomes increasingly narrow as photons accumulate, and its shape becomes approximately parabolic; therefore, the
The likelihood $L_1(p_1|\tilde{I})$ approaches an exponentiated quadratic, i.e., a Gaussian distribution. Furthermore, as observed above, the location of the peak likelihood (which by definition determines the MLE) approaches the true parameter value. The MLE is plotted against $N$ in Fig. 7, with shaded regions representing the standard deviation confidence intervals based on the expected and observed Fisher information. Notice that as $N$ increases, not only does the MLE approach the true value of $p_1$ with increasing confidence, but the expected and observed information rapidly converge.

Although the above simulation is a representative example of the behavior of the MLE, it is merely a single observation of a random process. To gain a broader view of the statistical behavior of $I_1(u;p_1)$, we conclude this section by performing a Monte Carlo simulation of 50,000 trials of a 100-photon intensity measurement, first for a true parameter value of $p_1 = 0$ and then for $p_1 = 0.63$. The results of the simulations are plotted in Fig. 8(a) and 8(b), which contain histograms showing the distribution of the MLE over all trials. As seen in the upper left corner of each plot, the mean MLE over all trials differs from the true parameter value by less than $10^{-3}$. The standard deviations of the MLEs obtained for the $p_1 = 0$ and $p_1 = 0.63$ cases are

| $N$  | MLE ($p_1$) | $\tilde{I} = (\tilde{I}_1, \ldots, \tilde{I}_9)$ |
|------|-------------|-----------------------------------------------|
| 1    | -1.0000     | (1, 0, 0, 0, 0, 0, 0, 0, 0)                  |
| 2    | -0.5000     | (1, 0, 0, 0, 0, 0, 1, 0, 0)                  |
| 3    | 0.0000      | (1, 0, 0, 0, 0, 2, 0, 0)                     |
| 4    | 0.3187      | (1, 0, 0, 0, 0, 2, 1, 0)                     |
| 5    | 0.5024      | (1, 0, 0, 0, 0, 2, 1, 1)                     |
| 6    | 0.5429      | (1, 0, 0, 0, 1, 2, 1, 1)                     |
| 7    | 0.6187      | (1, 0, 0, 0, 1, 2, 2, 1)                     |
| 8    | 0.6727      | (1, 0, 0, 0, 1, 2, 3, 1)                     |
| 9    | 0.6916      | (1, 0, 0, 0, 2, 2, 3, 1)                     |
| 10   | 0.6646      | (1, 0, 1, 0, 2, 2, 3, 1)                     |
| 100  | 0.7114      | (6, 1, 8, 9, 8, 9, 15, 19, 25)               |
| 1000 | 0.6656      | (41, 56, 64, 91, 112, 121, 166, 160, 189)   |
| 10000| 0.6243      | (413, 583, 784, 956, 1112, 1262, 1446, 1615, 1829) |
| 100000| 0.6329     | (4009, 5847, 7696, 9460, 11151, 12839, 14588, 16160, 18250) |

Table 3: Evolution of the MLE for $p_1$ and the measured intensity distribution $\tilde{I}$ as individual photons accumulate for a simulated measurement of $I_1(u;p_1)$ with true parameter value $p_1 = 0.63$. 
Figure 6: Log-likelihood functions associated with the simulated intensities listed in Table 3.

Figure 7: Evolution of the maximum likelihood estimate and standard deviation confidence interval for $p_1$ as 100,000 photons accumulate for a simulated measurement of $I_1(u; p_1)$ with true parameter value $p_1 = 0.63$. The solid red and dashed blue regions represent the confidence intervals based on the expected and observed Fisher information, respectively.
Figure 8: Histograms of the maximum likelihood estimates obtained from 50,000 trials of a 100-photon simulation of $I_1(u; p_1)$ with true parameter values (a) $p_1 = 0$ and (b) $p_1 = 0.63$. The mean ($\mu_{\text{data}}$) and standard deviation ($\sigma_{\text{data}}$) of each distribution are indicated in the upper left corner of the plot. For comparison, a normal distribution with mean $p_1$ and standard deviation $\sigma = (100J_1(p_1))^{-1/2}$ is overlaid in red; the value of $\sigma$ is indicated alongside each curve.
0.1554 and 0.1303, respectively. In comparison, using Eq. (23), the expected Fisher information for the $p_1 = 0$ case is $100J_1(0) = 41.67$, corresponding to a standard deviation error of 0.1549. Similarly, the expected error for the $p_1 = 0.63$ case is found to be 0.1285. These values closely agree with the results of the simulation. To help visualize this, a normal distribution with the expected standard deviation is overlaid in red on top of each histogram in Fig. 8; notice that each curve almost exactly matches the distribution of MLEs over 50,000 trials.

5.2 Weaker linear dependence on $p_1$

For the next example, we consider the intensity distribution

$$I_2(u; p_1) = \Lambda(u)(0.9 + 0.1p_1 u),$$

which is valid when $-9 \leq p_1 \leq 9$. (However, our range of interest is still $-1 \leq p_1 \leq 1$.) Using Eq. (17), the PMF for a single photon is

$$P_2(i|p_1) = \frac{1}{9} \left(1 + \frac{i - 5}{36} p_1 \right).$$

This distribution is nearly the same as the first example except that the linear $p_1$ term is 9 times smaller. As a result, the variations in intensity, PMF, and likelihood with respect to $p_1$ have much lower contrast over the range of interest, as seen in Figs. 9 and 10. Analogously to Section 5.1, suppose that we simulate a measurement of $I_2(u; p_1)$ and that the first three photons are again detected at pixels 1, 7, and 7. Following the same procedure as in the previous example, it can be shown that the

![Figure 9: Plots of $I_2(u; p_1)$ (left axis) and $P_2(i|p_1)$ (right axis) for several values of $p_1$.](image)
maximum likelihood estimates after each photon detection are $p_1 = -9, -4.5, \text{ and } 0$. The corresponding likelihood functions, shown in Fig. 11, are nearly flat, which is a sign that the MLE has a large uncertainty. Indeed, for $\bar{I} = (1, 0, 0, 0, 0, 2, 0, 0)$, the observed Fisher information is found to be

$$J_2^{(\text{obs})}(p_1; \bar{I}) = \frac{1}{(p_1 - 9)^2} + \frac{2}{(p_1 + 18)^2},$$

which yields $J_1^{(\text{obs})} = 0.0185$ when evaluated at the MLE $p_1 = 0$, corresponding to a standard deviation uncertainty of $1/\sqrt{0.0185} = 7.35$. Similarly, the expected Fisher information

$$\mathcal{N}J_2(p_1) = \frac{\mathcal{N}}{324} \sum_{i=1}^{9} \frac{(i - 5)^2}{36 + (i - 5)p_1}$$

for an $\mathcal{N}$-photon measurement of $I_2$ is significantly smaller than the information contained in a measurement of $I_1$, as shown in Fig. 12. For example, the expected standard deviation error for a three-photon measurement, given by $(3J_2(0))^{-1/2} = 8.05$, is nine times larger than it was in the previous example. The discrepancy grows even larger as $|p_1|$ increases.

Next we present the results of a 100,000 photon simulation of $I_2(u; p_1)$. The intensities and corresponding MLEs obtained throughout the simulation are listed in Table 4, and the MLE and standard deviation confidence interval are plotted as a function of $\mathcal{N}$ in Fig. 14. From these results, one can see that the MLE approaches the true parameter value more slowly than in the previous example, with a much larger uncertainty. (Take note of the increased scale of the plot compared to Fig. 7.)
Figure 11: (a) Likelihood functions (based on intensity distribution $I_2$) for detected photons at pixels $i = 1$ and $i = 7$ and for intensity measurements consisting of one photon at pixel 1 and one or two photons at pixel 7. The two- and three-photon likelihoods are also plotted on independent scales in (b) and (c).

Figure 12: Expected unit Fisher information $J_1(p_1)$ and $J_2(p_1)$ for measurements of $I_1(u; p_1)$ and $I_2(u; p_1)$, respectively, plotted on a logarithmic scale.
\[ \mathcal{N} \quad \text{MLE (} p_1 \text{)} \quad \tilde{I} = (\tilde{I}_1, \ldots, \tilde{I}_9) \]

| \( \mathcal{N} \) | MLE (\( p_1 \)) | \( \tilde{I} = (\tilde{I}_1, \ldots, \tilde{I}_9) \) |
|-----------------|-----------------|------------------------------------------|
| 1               | -9.0000         | (1, 0, 0, 0, 0, 0, 0, 0, 0)             |
| 2               | -4.5000         | (1, 0, 0, 0, 0, 1, 0, 0, 0)             |
| 3               | 0.0000          | (1, 0, 0, 0, 0, 2, 0, 0, 0)             |
| 4               | -3.8285         | (1, 1, 0, 0, 0, 2, 0, 0, 0)             |
| 5               | -3.8285         | (1, 1, 0, 0, 1, 2, 0, 0, 0)             |
| 6               | -2.3629         | (1, 1, 0, 0, 1, 1, 2, 0, 0)             |
| 7               | -5.1192         | (1, 2, 0, 0, 1, 1, 2, 0, 0)             |
| 8               | -5.1192         | (1, 2, 0, 0, 2, 1, 2, 0, 0)             |
| 9               | -6.0605         | (1, 2, 0, 1, 2, 1, 2, 0, 0)             |
| 10              | -4.8152         | (1, 2, 0, 1, 2, 2, 2, 0, 0)             |
| 100             | 2.3159          | (6, 6, 12, 17, 13, 11, 9, 13, 13)       |
| 1000            | 1.8366          | (91, 98, 89, 105, 113, 108, 145, 120, 131) |
| 10000           | 0.7542          | (1000, 1044, 1101, 1077, 1117, 1088, 1204, 1168, 1201) |
| 100000          | 0.6331          | (10278, 10541, 10629, 11026, 11138, 11377, 11438, 11843, 11730) |

Table 4: Evolution of the MLE for \( p_1 \) and the measured intensity distribution \( \tilde{I} \) as individual photons accumulate for a simulated measurement of \( I_2(u; p_1) \) with true parameter value \( p = 0.63 \).

Figure 13: Log-likelihood functions associated with the simulated intensities listed in Table 4.
Figure 14: Evolution of the maximum likelihood estimate and standard deviation confidence interval for $p_1$ as 100,000 photons accumulate for a simulated measurement of $I_2(u;p_1)$ with true parameter value $p_1 = 0.63$. The solid red and dashed blue regions represent the confidence intervals based on the expected and observed Fisher information, respectively.

Finally, recall that in Section 5.1 we ran a Monte Carlo simulation of a 100-photon measurement of $I_1(u;p_1)$. To complete the comparison, we now present the results of 50,000 trials of a 1000-photon measurement of $I_2(u;p_1)$. For true parameter values $p_1 = 0$ and $p_1 = 0.63$, the expected standard deviation errors are 0.4409 and 0.4401, respectively. Histograms of the results of each simulation for 50,000 trials are shown in Fig. 15; as indicated on the plots, the standard deviations of the MLEs obtained for each case are 0.4413 and 0.4394, closely matching expectations. Notice that the errors are larger than they were in the previous example (0.1554 and 0.1303) despite the fact that the measured intensity contains ten times as many photons. This is noteworthy because for any value of $p_1$, the total power incident on the detector (given by the sum of the intensity over all pixels) is 1.8 times larger for $I_2$ than it is for $I_1$, indicating that on average nearly twice as many photons will be measured within a given exposure time. Even so, based on the above results, we can conclude that if measurements of $I_1$ and $I_2$ were conducted with identical exposure times, then the measurement of $I_1$ (for which the output signal would contain fewer photons) would be expected to produce a more accurate parameter estimate. This is an important lesson to keep in mind when designing an experiment: the most informative measurement is not always the one
Figure 15: Histograms of the maximum likelihood estimates obtained from 50,000 trials of a 1000-photon simulation of $I_2(u; p_1)$ with true parameter values (a) $p_1 = 0$ and (b) $p_2 = 0.63$. The mean ($\mu_{\text{data}}$) and standard deviation ($\sigma_{\text{data}}$) of each distribution are indicated in the upper left corner of the plot. For comparison, a normal distribution with mean $p_1$ and standard deviation $\sigma = (1000J_1(p_1))^{-1/2}$ is overlaid in red; the value of $\sigma$ is indicated alongside each curve.
with the strongest signal! On the contrary, it can be beneficial to filter out a large fraction of the light before it reaches the detector (e.g., via polarization selection) in such a way that the measured signal contains only the photons emitted from the source that provide the most information about \( p_1 \). This idea is explored further in the next example.

5.3 Null and off-null measurements

For some optical applications, it is advantageous to design the experiment so that low light levels are observed at the detector plane, resulting in increased parameter sensitivity. One notable example is off-null ellipsometry, in which polarization elements are configured to produce a high extinction ratio over the range of interest of the parameter(s) under test [19]. The focused beam scatterometry experiment in Ref. [16] operates on the same principle but with spatially varying polarization components, resulting in an output intensity of the form

\[
I \propto |\sum_n a_n(u)(p_n - \bar{p}_n(u))|^2,
\]

where the functions \( a_n(u) \) characterize the sample under test and the functions \( \bar{p}_n(u) \) (which determine the required input polarization) can be tailored to optimize the sensitivity to each parameter. As an example of this type of measurement for the one-parameter case, we now consider the intensity distribution

\[
I_3(u; p_1) = \Lambda(u) \frac{1}{(|c| + 1)^2} (p_1 - cu)^2,
\]

(28)

where \( c \) is a real constant. For \( c = 0 \), this represents a null measurement for which the (spatially uniform) intensity vanishes when \( p_1 = 0 \) and increases quadratically with \( p_1 \). For \( c \neq 0 \), the condition on \( p_1 \) for zero intensity (i.e., the departure from perfect nulling) varies linearly with the pupil position \( u \). Using Eq. (17), the PMF for a detected photon is found to be

\[
P_3(i|p_1) = \frac{(4p_1 - (i - 5)c)^2}{144p_1^2 + 60c^2}.
\]

(29)

Let us begin by examining the case of perfect nulling \((c = 0)\), for which the intensity \( I_3(u; p_1) = \Lambda(u)p_1^2 \) and PMF \( P_3(u|p_1) = 1/9 \) are plotted in Fig. 16. In contrast to the previous two examples, these plots illustrate that for a given pupil coordinate, the ratio between the measured intensities at two different parameter
values need not be the same as the ratio between the corresponding PMF values. In fact, in this example the PMF is the same for all values of \( p_1 \) with the exception of \( p_1 = 0 \), for which it is undefined (due to the fact that no photons are detected). Consequently, the likelihood function is completely flat and the Fisher information is zero, implying that it is impossible to determine \( p_1 \) from the shape of the measured intensity distribution.\(^8\) (Of course, this is also obvious from the simple fact that the PMF is independent of \( p_1 \).) In this situation, it would only be possible to deduce the value of \( p_1 \) from the total optical power incident on the detector, which is beyond the scope of the current statistical approach. Even then, it would only be possible to determine the magnitude of \( p_1 \) but not the sign (since \( I_3 \) is an even function of \( p_1 \)), and the measurement would be susceptible to temporal fluctuation errors unless the illumination source power were very stable.

The aforementioned shortcomings of a null measurement can be avoided by designing the experiment to operate under an off-null condition, which corresponds to the choice of some constant \( c \neq 0 \) in the present example. The intensity and PMF are plotted in Fig. 17 for several positive values of \( c \); symmetric behavior is observed when \( c \) is negative. Notice in each plot that the null in intensity (when one exists) is located at the pupil coordinate \( u = p_1/c \). When \( |c| = 1 \), the null shifts across the entire width of the pupil as \( p_1 \) varies from \(-1\) to \(1\), causing the shape of \( P_3(i|p_1) \) to vary substantially over the entire range of interest. When \( |c| \gg 1 \), the null is confined to a narrow region near the center of the pupil, resulting in very little variation in \( P_3(i|p_1) \) with respect to \( p_1 \). On the other hand, when \( |c| \ll 1 \), the null shifts away from the origin very quickly when \( p_1 \) is nonzero. This results in dramatic variations in

\(^8\)In this case, the MLE exists but it is not unique, since all values of \( p_1 \) within the range of interest maximize the likelihood function.
$P_3(i|p_1)$ (and very low intensity levels) when $|p_1|$ is small, but much smaller changes near the edge of the parameter range.

This behavior can also be visualized by plotting the likelihood functions $L_3(i|p_1)$ for each pixel, which are shown in Fig. 18. From the definition of the Fisher information, recall that the magnitude of the local slope of $L_3$ is an indicator of the information content of a measurement of $p_1$. In agreement with the observations made above, for $|c| \ll 1$, the likelihood generally has a very large slope when $|p_1|$ is small (enabling a precise estimate of $p_1$), but it becomes nearly flat for larger parameter values. Meanwhile, for $|c| \gg 1$, the likelihood is relatively flat over the entire range of interest, making parameter estimation difficult. Qualitatively, it is evident that the best balance between these two extremes is achieved when $c$ is on the order of unity, so that $L_3(i|p_1)$ exhibits a similar amount of variation over the full range of interest of $p_1$.

For a measurement containing a large number of photons, the uncertainty of the MLE can be calculated from the expected unit Fisher information; a somewhat lengthy but straightforward calculation shows that

$$J_3(p_1) = \sum_{i=1}^{9} \frac{16c^2[5c + 3(i - 5)p_1^2]^2}{3(12p_1^2 + 5c^2)^3} = \frac{240c^2}{(12p_1^2 + 5c^2)^2}. \quad (30)$$

This function is plotted in Fig. 19 for several values of $c$. Notice that the Fisher information is the same for positive and negative $c$; the $c = 0$ case does not appear on the plot since $J_3(p_1)$ goes to zero. Suppose that we are designing an experiment where the output intensity takes the form of $I_3(u; p_1)$, and we wish to determine the optimal value of $c$ that, on average, will produce the best parameter estimate for any true value of $p_1$ within the range of interest, i.e., the smallest expected error $\sigma(p_1) = J_3(p_1)^{-1/2}$. One approach to do so is by minimizing the integral average of the variance $\sigma(p_1)^2$ over the interval $p_1 \in [-1, 1]$, which is given by

$$\langle \sigma^2 \rangle = \frac{1}{2} \int_{-1}^{1} \sigma(p_1)^2 dp_1$$

$$= \frac{1}{240c^2} \int_{-1}^{1} (12p_1^2 + 5c^2)^2 dp_1$$

$$= \frac{5}{24} c^2 + \frac{6}{25} \frac{1}{c^2} + \frac{1}{3}. \quad (31)$$
Figure 17: Plots of $I_3(u; p_1)$ (left axes) and $P_3(i|p_1)$ (right axes) for several values of $p_1$. Each row of plots corresponds to a different value of $c$, as indicated in the leftmost plot.
Figure 18: Likelihood functions $L_3(i|p_1)$ associated with each pixel $i$ in a measurement with theoretical intensity distribution $I_3(p_1)$, plotted for several values of $c$. For negative values of $d$, each plot is flipped about the vertical $p_1 = 0$ axis.

Figure 19: Expected unit Fisher information $J_3(p_1)$ for a measurement of $I_3(u;p_1)$, plotted on a logarithmic scale for several values of $c$. 
Figure 20: Expected variances (averaged over $p_1$) for parameter estimates based on measurements of $I_3(u; p_1)$ containing one detected photon and one emitted photon, plotted as a function of $c$. For the latter case, the error is scaled by the ratio between $I_0$ and the source power $\Phi_s$, which can be treated as a dimensionless quantity (see footnote 9).

This function is plotted as a solid line in Fig. 20. (The dashed line will be explained shortly). Note that for a multi-photon measurement, the variance scales as $1/N$. The average error $\langle \sigma^2 \rangle$ is minimized when $c = \pm (144/125)^{1/4} \approx \pm 1.036$, in close agreement with our prediction that the optimal value of $c$ is on the order of unity.

In the previous example, we alluded to the fact that all of the statistics and performance metrics discussed thus far have pertained exclusively to photons detected by the sensor. However, the information contained in each detected photon is not the only thing to take into consideration when designing an experiment. In a typical experiment, the light source emits a constant optical power $\Phi_s$, of which some fraction reaches the detector. The power incident on the detector, which is given by

$$
\Phi_d(p_1) = \int_{-1}^{1} I_3(u; p_1) \, du = I_0 \frac{2(3c^2 + p^2)}{3(|c| + 1)^2} \tag{32}
$$

in this example, is usually smaller than $\Phi_s$ by some ratio that may be influenced by the choice of measurement scheme (e.g., an off-null configuration). During the exposure time of the sensor, the number of detected photons is (on average) equal to $N = (\Phi_d/\Phi_s)N_s$, where $N_s$ is the number of photons emitted by the source. If the speed of the measurement is a priority, then it is important to make efficient use of

\footnote{The right-hand side of Eq. (32) implicitly has units of $I_0$ times the dimensionless pupil coordinate $u$ (acquired from the integration), i.e., units of power.}
Figure 21: Expected unit Fisher information $J_3^{(e)}(p_1)$ per emitted photon for a measurement of $I_3(u; p_1)$, scaled by the ratio of source power to $I_0$ and plotted on a logarithmic scale for several values of $c$.

the source, i.e., to maximize the information acquired per emitted photon. To that end, we define the expected unit Fisher information per emitted photon as

$$J^{(e)}(p_1) = \frac{\Phi_d}{\Phi_s} J(p_1), \quad (33)$$

so that the total information acquired in a given time interval is $N J(p_1) = N_s J^{(e)}(p_1)$. (Obviously, this is not to suggest that each photon carries information about $p_1$ at the moment that it is emitted from the source; rather, $J^{(e)}(p_1)$ is the average information acquired at the detector plane per photon emitted by the source.)

For the present example, using Eqs. (30) and (32), the Fisher information per emitted photon is found to be

$$J_3^{(e)}(p_1) = \frac{I_0}{\Phi_s} \cdot \frac{160c^2(3p_1^2 + c^2)}{(12p_1^2 + 5c^2)(|c| + 1)^2}. \quad (34)$$

This result is plotted in Fig. 21 for several values of $c$. In comparison to Fig. 19, notice that the peak in $J_3^{(e)}(p_1)$ when $|c| \ll 1$ is much less pronounced than that of $J_3(p_1)$. This is because as $|c|$ decreases, the amount of information per detected photon increases, but the number of detected photons decreases by nearly the same ratio. From Eq. (34), we can calculate the minimum expected variance $\sigma^{(e)}(p_1)^2 = J_3^{(e)}(p_1)^{-1}$
for a measurement of one emitted photon, averaged over the range of interest of $p_1$:

$$\langle (\sigma^{(e)})^2 \rangle = \frac{1}{2} \int_{-1}^{1} \sigma^{(e)}(p_1)^2 dp_1$$

$$= \frac{\Phi_s (|c| + 1)^2}{I_0} \int_{-1}^{1} \frac{(12p_1^2 + 5c^2)^2}{3p_1^2 + c^2} dp_1$$

$$= \frac{\Phi_s (|c| + 1)^2}{480c^2} \left[ \sqrt{3} c^3 \arctan \left( \frac{\sqrt{3}c}{c} \right) + 72c^2 + 48 \right].$$

(35)

This function is plotted as a dashed line in Fig. 20, shown in comparison to the average variance per detected photon derived earlier. A numerical calculation shows that the expected error per emitted photon is minimized when $c = \pm 0.863$, which is slightly smaller than the optimal value $c = \pm 1.036$ for detected photons. This is due to the fact that for parameter values near $|p_1| = 1$, the power on the detector is up to 10% larger for $|c| = 0.863$ than for $|c| = 1.036$, compensating for the slight reduction in information per detected photon.

Recall that in this example the intensity is normalized to have a peak value of $I_0$ regardless of the value of $c$. This is not particularly realistic, since in an actual off-null experiment, a change in the (spatially varying) off-null condition is likely to be accompanied by a global scaling factor in the measured intensity. In some cases, this could result in a much more dramatic difference between the Fisher information per emitted and detected photon than we observed in this example. On a separate note, in situations where $\sigma(p_1)^2$ and $\sigma^{(e)}(p_1)^2$ cannot be calculated analytically, the integral over $p_1$ could be evaluated numerically. If the numerical integration is too computationally expensive, a simpler merit function could be constructed by summing the variance over some appropriately chosen set of parameter values.

### 5.4 Far-from-null (high intensity) measurement

For our final one-parameter example, we briefly discuss the intensity distribution

$$I_4(u; p_1) = \Lambda(u) \frac{1}{(|d| + 2)^2} (p_1 - u - d)^2,$$

(36)

where the constant $d$ introduces a spatially uniform offset from the off-null condition considered in the previous example. When $d = 0$, the intensity is identical to $I_3(u; p_1)$
with \( c = 1 \), which was plotted previously in Fig. 17(c). In comparison, Fig. 22 contains plots of \( I_4(u; p_1) \) and the corresponding PMF for several positive values of \( d \). (Symmetric results are obtained for negative \( d \).) The likelihood functions \( L_4(i|p_1) \) for each case are plotted in Fig. 23. Observe that when \( d = 1 \), the intensity profile and likelihood function are translated in parameter space so that they are symmetric about \( p_1 = 1 \). As \( d \) increases, the distribution continues to shift farther away from the off-null condition of \( I_3(u; p_1) \), so that the intensity becomes large and uniform over the range of interest of \( p_1 \) and the likelihood function becomes very flat. As seen in Fig. 24, the expected Fisher information per detected photon\(^{10}\) decreases rapidly as \( d \) increases. Following the same procedure as in the previous example, it can be shown that the average estimation error over the parameter range is minimized when \( d = 0 \). (This holds true when optimizing for detected or emitted photons, though as noted before, the latter result is in part due to the choice of normalization of the intensity.)

The takeaway from this example is that it illustrates the statistical advantage of off-null measurements over a “far-from-null” experimental configuration in which the parameter of interest causes a small fractional change in the output intensity. Although the parameter estimation technique outlined in Section 3 is only useful for imaging experiments where the off-null condition (and thus the output intensity) varies with pupil position, by looking at Fig. 22 one can also appreciate the principle of traditional off-null ellipsometry, in which only the total power is measured. In that case, the off-null configuration greatly increases the contrast of the variation in power with respect to \( p_1 \), enabling a more accurate measurement while placing less stringent requirements on the fidelity of the sensor. Note that off-null ellipsometry is just one example of a broader class of optical experiments that are applications of the weak measurement formalism in quantum mechanics [20–22], wherein preselected and postselected states are chosen to enhance the sensitivity to small variations of an unknown parameter. Another such example is the measurement of small shifts upon reflection of beams with finite spatial extent [23, 24].

\(^{10}\)Henceforth, all mentions of the Fisher information refer to the expected information per detected photon unless specified otherwise.
Figure 22: Plots of $I_4(u; p_1)$ (left axes) and $P_4(i|p_1)$ (right axes) for several values of $p_1$. Each row of plots corresponds to a different value of $d$, as indicated in the leftmost plot.
Figure 23: Likelihood functions $L_4(i|p_1)$ associated with each pixel $i$ in a measurement with theoretical intensity distribution $I_4(p_1)$, plotted for several values of $d$. Notice that the effect of $d$ is simply a horizontal translation; when $d \gg 1$, the range of interest $p_1 \in [-1, 1]$ only contains a small portion of the left tail of the distribution.
Figure 24: Expected unit Fisher information $J_4(p_1)$ for a measurement of $I_4(u;p_1)$, plotted on a logarithmic scale for several values of $d$. The $d = 0$ case is identical to $J_3(p_1)$ with $c = 1$ (see Fig. 19). For negative values of $d$, each curve is flipped about the vertical $p_1 = 0$ axis.

6 Two-parameter optical MLE examples

To illustrate the use of MLE in the multiple-parameter case, in this section we consider several intensity distributions that depend on two parameters $\mathbf{p} = (p_1, p_2)$. The procedure for calculating the PMF, Fisher information matrix, and expected error is fundamentally the same as in the one-parameter case, although the algebra is more complicated. Rather than dwelling on the mathematical details, in this section we simply present numerical results. This is representative of most real-world applications, in which MLE techniques are typically implemented numerically.

The intensity distributions discussed in the examples that follow are summarized in Table 5. Similarly to the one-parameter examples, each intensity distribution is normalized so that it attains a maximum value of $I_0$ over the region of interest $-1 \leq p_1, p_2 \leq 1$. The distributions considered in Sections 6.1 and 6.2 each have a $p_1$ term with linear pupil dependence and a $p_2$ term with sinusoidal pupil dependence, serving as simple examples for the two-parameter case. Sections 6.3 and 6.4 contain two thought-provoking (albeit unrealistic) examples that illustrate the mathematical mechanisms that can lead to statistical correlations between the parameter estimates for $p_1$ and $p_2$. Finally, a pair of off-null measurements are discussed in Sections 6.5 and 6.6.
Table 5: Intensity distributions for each example considered in Section 6.

| Section | Intensity distribution |
|---------|------------------------|
| 6.1     | $I_5(u; p) = 0.563\Lambda(u)[2 + p_1u + p_2\sin(\pi u)]$ |
| 6.2     | $I_6(u; p) = 0.250\Lambda(u)[2 + p_1u + p_2\cos(\pi u)]$ |
| 6.3     | $I_7(u; p) = \begin{cases} 
0.5\Lambda(u)(1 + p_1u), & u < 0 \\
0.5\Lambda(u)(1 + p_2u), & u \geq 0 
\end{cases}$ |
| 6.4     | $I_8(u; p) = \begin{cases} 
0.5\Lambda(u)[1 + 2p_1(u + 0.625)], & u < -0.125 \\
0.5\Lambda(u), & -0.125 \leq u < 0.125 \\
0.5\Lambda(u)[1 + 2p_2(u - 0.625)], & u \geq 0.125,
\end{cases}$ |
| 6.5     | $I_9(u; p) = 0.125\Lambda(u)[(p_1 - u)^2 + (p_2 - \cos(\pi u))^2]$ |
| 6.6     | $I_{10}(u; p) = 0.320\Lambda(u)[(p_1 - 0.25u)^2 + (p_2 - 0.25\cos(\pi u))^2]$ |

6.1 Linear and sinusoidal variations (case 1)

For the first two-parameter example, we consider the intensity distribution

$$I_5(u; p) = 0.563\Lambda(u)[2 + p_1u + p_2\sin(\pi u)],$$

which is valid over the region of interest $-1 \leq p_1, p_2 \leq 1$. Similarly to the first example in in Section 5, $I_5(u; p)$ depends linearly on the product of $p_1$ and the pupil coordinate $u$. The dependence on $p_2$ is also linear, but this additional term varies sinusoidally across the pupil. Therefore, variations in $p_1$ and $p_2$ result in distinct changes in the shape of the intensity $I_5(u; p)$ and the PMF $P_5(i|p)$, as shown in Fig. 25. For instance, when $p_2 = 0$ (the third row of plots), the intensity is strictly a linear function of $u$ with slope $p_1$. When $p_1 = 0$ (the third column of plots), it is a sine function with a DC offset. For all other cases, the intensity is a linear combination of the two.

For the two-parameter case, the likelihood $L_5(p|i) = P_5(i|p)$ can be plotted in two dimensions as a function of $p_1$ and $p_2$. The likelihood functions associated with each pixel are shown in Fig. 26, with contour lines drawn as a visual aid to identify paths of constant likelihood. These plots have several interesting features. First, notice
Figure 25: Plots of $I_5(u;p)$ (left axes) and $P_5(i|p)$ (right axes) for several values of $p_1$ and $p_2$. 

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Figure 26: Likelihood functions $L_5(p|i)$ associated with each pixel $i$ for a measurement of $I_5(u;p)$. Contour lines are shown in increments of 0.01.
that $L_5(p|i = 5)$ is constant, meaning that pixel 5 provides no useful information about $p_1$ and $p_2$. (Incidentally, this was also the case for the one-parameter intensity distributions $I_1$ and $I_2$. Since the signal from pixel 5 has no effect on the MLE, it can be ignored.) Secondly, the likelihood functions for pixels 1 and 9 are independent of $p_2$ (as evident from the vertical contour lines) since $\sin(\pi u) = 0$ for $u = \pm 1$. In contrast, the likelihood functions associated with pixels 4 and 6 depend more strongly on $p_2$ than $p_1$ as a consequence of the fact that $\sin(\pi u)$ has a larger slope near the center of the pupil than the linear term $u$. Lastly, note that the paths of constant likelihood generally have negative (or vertical) slopes in parameter space. Roughly speaking, this means that if $p_1$ increases and $p_2$ decreases by a similar amount (or if $p_2$ increases and $p_1$ decreases), the likelihood function will only change slightly, making it difficult to distinguish linear combinations of parameters along this direction. On the other hand, a simultaneous increase (or simultaneous decrease) in $p_1$ and $p_2$ will tend to cause a more significant change in the likelihood function, making it easier to distinguish this type of variation in $p$.

The patterns described above can be quantified by calculating the estimation error based on the $2 \times 2$ expected Fisher information matrix, whose elements may be computed using either form of Eq. (9). For a measurement of $\mathcal{N} = 1000$ photons with true parameter values $p = (0, 0)$, the FIM and its inverse are found to be

$$\mathcal{N}J_5 = \begin{bmatrix} 104.2 & 67.1 \\ 67.1 & 111.1 \end{bmatrix}, \quad (\mathcal{N}J_5)^{-1} = \begin{bmatrix} 0.0157 & -0.0095 \\ -0.0095 & 0.0147 \end{bmatrix}. \quad (38)$$

As discussed in Section 2, $(\mathcal{N}J_5)^{-1}$ places a lower limit on the covariance matrix for a 1000-photon measurement of $p_1$ and $p_2$. Since its off-diagonal elements are fairly large in relation to its diagonal elements, a strong coupling between parameters (i.e., large covariance) is expected. Indeed, the principal axes of the error ellipse are given by the eigenvectors $[0.69; 0.72]$ and $[0.72; -0.69]$, and the axis lengths (the square roots of the corresponding eigenvalues) are 0.076 and 0.157, respectively. Thus, the major axis of the ellipse is oriented at approximately $-45^\circ$ in parameter space, and the standard deviation error is about twice as large along the $-45^\circ$ direction as the $+45^\circ$ direction.\footnote{It is only meaningful to refer to angles in parameter space when $p_1$ and $p_2$ have the same units and are normalized to their respective ranges of interest, as they are in this discussion.} In this example, it turns out that similar results are obtained for all values of $p$ within the region of interest. The error ellipses for a selection of true
parameter values are plotted in Fig. 27.

Given a measured intensity \( \mathbf{I} \), the magnitude and orientation of the uncertainty of the MLE are also manifested in the shape of the likelihood function \( L_5(\mathbf{p}|\mathbf{I}) \) and its logarithm \( \ell_5(\mathbf{p}|\mathbf{I}) \). Fig. 28 contains two examples of the log-likelihood functions obtained for simulated 1000-photon measurements with true parameter values \( \mathbf{p} = (0, 0) \) and \( \mathbf{p} = (0.63, -0.25) \). Again, these plots contain several interesting features. First, notice that the contours of equal likelihood are approximately elliptical. This behavior is characteristic of a bivariate Gaussian distribution \( f(\mathbf{p}) = f_0 \exp(-\frac{1}{2} \mathbf{p}^T \Sigma^{-1} \mathbf{p}) \) with covariance matrix \( \Sigma \), for which the locus of points satisfying \( \mathbf{p}^T \Sigma^{-1} \mathbf{p} = k^2 \) (for some constant \( k \)) trace out an ellipse [15]. Thus, the shape of \( \ell_5(\mathbf{p}|\mathbf{I}) \) supports our earlier claim (see Eq. (14)) that the posterior probability distribution \( P(\mathbf{p}|\mathbf{I}) \), which is a scaled version of the likelihood if no prior distribution is assumed, closely approximates a Gaussian distribution when a large number of photons are measured. Comparing Figs. 27 and 28, one can also see that the likelihood function is elongated along the direction with the largest expected estimation error. In Section 5 it was noted that the estimation error is largest when the likelihood function is nearly flat; for the multiple-parameter case, we can further specify that the error is largest along the direction where the likelihood function is flattest, i.e., the direction perpendicular
Figure 28: Log-likelihood functions $\ell_5(p|\tilde{I})$ for simulated 1000-photon measurements of $I_5(u; p)$ with true parameter values (a) $p = (0, 0)$ and (b) $p = (0.63, -0.25)$. The plots are shaded on a logarithmic scale with solid contour lines drawn at powers of 2, as indicated in the legend. The peak of each distribution is marked with a red dot. The locations of these maxima (i.e., the MLEs for each measurement) are $p = (-0.115, 0.064)$ and $p = (0.673, -0.366)$, respectively. The dashed contour line indicates where the likelihood $L_5(p|\tilde{I})$ drops to $1/\sqrt{e}$ times its peak value, representing the standard deviation confidence interval for the MLE.

to the local gradient of $\ell$ with respect to $p$.

Each plot in Fig. 28 contains a red dot representing the MLE for the measurement, i.e., the location of the peak of $\ell_5(p|\tilde{I})$. The estimated parameter values (which are listed in the figure caption) differ considerably from the true values, with errors as large as $\sim 0.11$ for each parameter. The standard deviation confidence interval for the MLE, which is outlined by a red dashed line, consists of the region where the likelihood $L_5(p|\tilde{I})$ is greater than or equal to $1/\sqrt{e}$ times its peak value.\[12\]

This is equivalent to an additive decrease in the log-likelihood by $\ln(e^{-1/2}) = -0.5$. Notice that this region is elliptical, and its size and shape are virtually identical to the nearest ellipse in Fig. 27. In fact, by evaluating the expected FIM at the MLE with $N = 1000$, an extremely close agreement is found between the predicted covariance matrix $(N\mathbb{J}_5)^{-1}$ and the standard deviation confidence interval of $\ell_5(p|\tilde{I})$. (When plotted together, the ellipses are virtually indistinguishable even when zoomed.

\[12\]For the Gaussian distribution $f(p)$ mentioned above, the $k = 1$ ellipse encloses one standard deviation. Along this contour, the function value drops to $f_0 \exp(-\frac{1}{2}) = f_0/\sqrt{e}$. 

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In general, the correlation between the two grows stronger as the number of photons increases. In this example, 1000 photons are sufficient to obtain a very close agreement; in an experiment with smaller expected error, fewer photons would be required.

Similarly to Sections 5.1 and 5.2, we conclude this example by presenting the results of 50,000 trials of a 1000-photon simulated measurement of $I_5(u; p)$ for which the true parameter values are given by $p = (0, 0)$. A histogram of the maximum likelihood estimates obtained in all trials can be found in Fig. 29(a). An overhead view of the distribution is also shown in Fig. 29(b). The data closely resembles a Gaussian distribution with the same orientation as the expected error ellipse, which is shown in black in the overhead view. The statistical covariance matrix of the data matches the matrix $(\mathcal{N}J_5)^{-1}$ given in Eq. (38) to within three significant digits.

### 6.2 Linear and sinusoidal variations (case 2)

For the second two-parameter example, we consider the intensity distribution

$$I_6(u; p) = 0.250 \Lambda(u)[2 + p_1 u + p_2 \cos(\pi u)],$$

(39)
which is similar to \( I_5(u; p) \) but with the sine term replaced by a cosine. The intensity and PMF are plotted for several parameter values in Fig. 30, and the likelihood functions for each pixel are shown in Fig. 31. In this example, in can be seen that the paths of constant likelihood have different orientations for each pixel. This implies, for instance, that a simultaneous increase in \( p_1 \) and \( p_2 \) will cause a significant change in \( L_6(p|i = 1) \), but very little change in \( L_6(p|i = 9) \); meanwhile, a simultaneous increase in \( p_1 \) and decrease in \( p_2 \) will do just the opposite. The reason for this can be understood by examining the plots of \( u \), \( \sin(\pi u) \), and \( \cos(\pi u) \) shown in Fig. 32. Whereas \( u \) and \( \sin(\pi u) \) always have the same sign, this is not the case for \( u \) and \( \cos(\pi u) \). Therefore, for the intensity distribution \( I_5(u; p) \), an increase in \( p_1 \) can be compensated (to a certain extent) by a decrease in \( p_2 \). The distribution \( I_6(u; p) \) is less prone to this situation since any linear combination of \( p_1 \) and \( p_2 \) produces distinct fluctuations at different pixels. However, correlations can still arise in cases where very few photons are incident on one or more pixels (for example, when \( p_1 = p_2 = 1 \)), since the contributions of each pixel to the likelihood function \( \ell(p|\tilde{I}) \) associated with a measured intensity \( \tilde{I} \) may be imbalanced.

Based on the above observations, one can reasonably expect there to be a smaller correlation between the estimated parameters from a measurement of \( I_6(u; p) \) than in the previous example. As a matter of fact, for \( p = (0, 0) \), the FIM and its inverse are diagonal, indicating that there is zero covariance:

\[
\mathcal{N}\mathcal{J}_6 = \begin{bmatrix} 104.2 & 0 \\ 0 & 135.8 \end{bmatrix}, \quad (\mathcal{N}\mathcal{J}_6)^{-1} = \begin{bmatrix} 0.0096 & 0 \\ 0 & 0.0074 \end{bmatrix}, \quad (40)
\]

where \( \mathcal{N} = 1000 \). The eigenvectors of \((\mathcal{N}\mathcal{J}_6)^{-1}\) are \([1; 0]\) and \([0; 1]\), and the square roots of the corresponding eigenvalues are 0.098 and 0.086, respectively. Thus, the error ellipse is nearly circular, with its principal axes oriented along the \( p_1 \) and \( p_2 \) axes. The error ellipses for a selection of parameter values are shown in Fig. 33. As seen in the plot, the expected error is relatively uniform over the entire parameter range, with the smallest error occurring when \( p_2 \) is close to 1. The covariance between \( p_1 \) and \( p_2 \) is also generally small, with one notable exception: as \( |p_1| \to 1 \) and \( p_2 \to 1 \), the two parameters become highly correlated. At the far upper corners of the region of interest, the error ellipse resembles a straight line, indicating complete correlation between \( p_1 \) and \( p_2 \). (Even so, the magnitude of the uncertainty of each parameter is still smaller than the expected errors for other parameter values.) From the uppermost
Figure 30: Plots of $I_6(u; p)$ (left axes) and $P_6(i|p)$ (right axes) for several values of $p_1$ and $p_2$. 
Figure 31: Likelihood functions $L_6(p|i)$ associated with each pixel $i$ for a measurement of $I_6(u;p)$. Contour lines are shown in increments of 0.01.
Figure 32: Pupil dependences of each term appearing in intensity distributions $I_5(u; p)$ and $I_6(u; p)$.

Figure 33: Ellipses representing the expected standard deviation error of a 1000-photon measurement of $I_6(u; p)$ with true parameter values $p_1$ and $p_2$, sampled over a $9 \times 9$ grid in parameter space.
plots in Fig. 30, it can be seen that this correlation arises when the intensity drops to zero at either edge of the pupil (near pixel 1 or pixel 9). This happens because the intensity distribution and the likelihood functions \( L(p|i) \) are distributed such that the remaining pixels cannot easily distinguish between all possible combinations of \( p_1 \) and \( p_2 \), as alluded to in the previous paragraph.\(^{13}\)

The log-likelihood functions \( \ell_6(p|\tilde{I}) \) for simulated 1000-photon measurements of \( I_6(u;p) \) with true parameter values \( p = (0,0) \) and \( p = (0.63,-0.25) \) are shown in Fig. 34. As in the previous example, the contours of equal likelihood are highly elliptical near the peak, indicating that the likelihood is approximately a Gaussian distribution. The Gaussian approximation weakens away from the peak, with the

\(^{13}\)The astute reader might wonder why the expected error is asymmetric with respect to \( p_2 \) despite the fact that the last term of \( I_6(u;p) \) exhibits symmetry with respect to both \( p_2 \) and the pupil coordinate \( u \). The answer is that the asymmetry is a sampling artifact of the 9-pixel array, since pixels 1 and 9 sample the periodic function \( \cos(\pi u) \) at points that are offset by \( 2\pi \) radians. This causes the total measured intensity to vary with \( p_2 \) despite the fact that \( \int_{-1}^{1} \cos(\pi u)du = 0 \). As is often the case, the error is smallest in this example when the total intensity is minimized, which occurs when \( p_2 = 1 \).
Figure 35: (a) Histogram of the maximum likelihood estimates obtained from 50,000 trials of a simulated 1000-photon measurement of $I_6(u; p)$ with true parameter value $p = (0, 0)$. (b) Overhead view of the distribution shown in plot (a), with the color of each pixel indicating the number of trials for which the MLE was within a given interval. The black ellipse at the center of the plot represents the expected standard deviation error based on the Fisher information matrix.

contours of $\ell_6(p|\tilde{I})$ becoming slightly distorted. Compared to $\ell_5(p|\tilde{I})$, the distribution is much more symmetric due to the small covariance between $p_1$ and $p_2$ (for these particular true parameter values). The standard deviation confidence interval, indicated by the dashed red line, is also highly symmetric and slightly narrower than it was in the previous example, matching the expected error based on the FIM. The uncertainty is also reflected in the distribution of the MLEs obtained from 50,000 trials of a 1000-photon measurement of $I_6(p|\tilde{I})$, as shown in Fig. 35. The diagonal elements of the covariance matrix of the simulated data agree with the matrix $(\mathcal{N}_J^6)^{-1}$ given in Eq. (40) to within two significant digits; the off-diagonal elements of the matrix are very close to zero (approximately 500 times smaller than the diagonal elements).

6.3 Piecewise linear dependence (nonzero covariance)

In the next two examples, we examine intensity distributions for which fluctuations due to $p_1$ and $p_2$ occur in completely separate portions of the pupil. Although this is not a particularly common real-world scenario, some interesting insight can be gained
from the analysis. First we consider the piecewise intensity distribution
\[ I_7(u; p) = \begin{cases} 
0.5 \Lambda(u)(1 + p_1 u), & u < 0 \\
0.5 \Lambda(u)(1 + p_2 u), & u \geq 0,
\end{cases} \] (41)

which is plotted in Fig. 36. This distribution is similar to the one-parameter linear intensity profile \( I_1(u; p_1) \), except that the slopes on the left and right halves of the pupil are proportional to \( p_1 \) and \( p_2 \), respectively. Since the intensities on each half of the pupil only depend on a single parameter, one would expect the parameters to be completely uncoupled, enabling an estimate with zero covariance. However, this turns out not to be the case when applying the MLE approach outlined in Section 3. (Note: the MLE formalism only requires the PMF to be twice differentiable with respect to \( p \), so the discontinuity in the derivative of \( I_7(u; p) \) with respect to \( u \) is not a problem.)

As established previously, this treatment relies on the information contained in the shape of the intensity distribution, that is, the relative intensity or PMF. Clearly, the value of \( p_1 \) impacts the probability \( P_7(i|p) \) of detecting a photon at each pixel on the left half of the pupil \((i = 1, \ldots, 5)\); what is perhaps less obvious, however, is that it also affects the probabilities for pixels 6 through 9. Indeed, within any given row of Fig. 36 (for which \( p_2 \) has a fixed value), the intensity on the right half of the pupil is always the same, yet the PMF changes depending on the value of \( p_1 \). This is possible because the total intensity \( \sum_i I_7(u_i|p) \), which appears in the denominator of \( P_7(i|p) \), varies with \( p_1 \) and \( p_2 \) so that each parameter affects the relative number of photons incident on every pixel \( i \). Therefore, the estimates for \( p_1 \) and \( p_2 \) based on the PMF will generally be correlated to some degree. (In this particular example, the best workaround is to treat the signals from each half of the detector as completely separate measurements — more on this later.)

As usual, these effects can also be visualized by plotting the likelihood functions \( L_7(i|p) \) for each pixel, which are shown in Fig. 37. Notice that the likelihood function for pixel 1 is most heavily influenced by \( p_1 \), while that of pixel 9 is mostly influenced by \( p_2 \). Nevertheless, every pixel contains information about both \( p_1 \) and \( p_2 \), since the partial derivatives of \( \ell_7(i|p) \) with respect to each parameter are nonzero. Interestingly, this even implies that photons measured at pixel 5 (the center of the pupil, where \( I(u_5|p) = 0.5 \) for any \( p \)) provide information about \( p_1 \) and \( p_2 \) when considered in relation to the number of photons measured at the other eight pixels.

The error ellipses for several values of \( p_1 \) and \( p_2 \) are shown in Fig. 38. Unlike the
Figure 36: Plots of $I_7(u; p)$ (left axes) and $P_7(i|p)$ (right axes) for several values of $p_1$ and $p_2$. 
Figure 37: Likelihood functions $L_7(p|i)$ associated with each pixel $i$ for a measurement of $I_7(u;p)$. Contour lines are shown in increments of 0.01.
prior two examples, the expected estimation error for a measurement of $I_7(u; p)$ is strongly dependent on $p$, with the largest error (and substantial covariance between $p_1$ and $p_2$) occurring in the upper left quadrant where $p_1 < 0$ and $p_2 > 0$. The distributions of the log-likelihood functions obtained for two 1000-photon measurements with different true parameter values, shown in Fig. 39, are consistent with this trend. The magnitude of the expected error is inversely proportional to the total intensity $\sum_i I_7(u_i|p)$, which is minimized when $p_1 = 1$ and $p_2 = -1$. Not coincidentally, the errors in $p_1$ and $p_2$ approach zero as $p_1 \to 1$ and $p_2 \to -1$, respectively. (As in Section 5.1, this expectation of zero error is only meaningful in the limit of large $N$.) The dramatic variations in error with respect to $p$ can also be understood by revisiting Fig. 37, in which the contours of equal likelihood for each pixel tend to be most closely spaced in the lower right quadrant (where $p_1 > 0$ and $p_2 < 0$), indicating high information content. Pixel 5 in particular provides extremely useful information in this quadrant, not only due to the large slope of $L_7(p|i = 5)$, but also because the direction of maximum variation (i.e., the gradient with respect to $p$) opposes that of pixels 1 and 9. In contrast, pixel 5 is nearly useless in the upper left quadrant of the parameter space since the likelihood changes very slowly with respect to $p$.

As mentioned before, in practice, the best way to deal with an intensity distribu-
Figure 39: Log-likelihood functions $\ell_7(p | \tilde{I})$ for simulated 1000-photon measurements of $I_7(u; p)$ with true parameter values (a) $p = (0, 0)$ and (b) $p = (0.63, -0.25)$. The plots are shaded on a logarithmic scale with solid contour lines drawn at powers of 2, as indicated in the legend. The peak of each distribution is marked with a red dot. The locations of these maxima (i.e., the MLEs for each measurement) are $p = (-0.067, 0.024)$ and $p = (0.582, -0.232)$, respectively. The dashed contour line indicates where the likelihood $L_7(p | \tilde{I})$ drops to $1/\sqrt{e}$ times its peak value, representing the standard deviation confidence interval for the MLE.

A solution such as $I_7(u; p)$ would be to treat it as two separate measurements: one involving pixels 1 through 5 (for which the intensity only depends on $p_1$), and another involving pixels 5 through 9 (for which the intensity only depends on $p_2$). The MLE approach could then be applied separately to each set of data, producing independent estimates for each parameter. In general, whenever it is possible to set up an experiment such that independent measurements can be made in this manner, it is probably best to do so, at least from a statistical standpoint. However, in cases where one does not have this luxury, the above example illustrates how subtle interactions between parameters (of either a physical or mathematical nature) can affect the accuracy of the measurement. Therefore, extra care should be taken to design the experiment such that the error obtained using the chosen statistical method is minimized.
6.4 Piecewise linear dependence (zero covariance)

In comparison to the previous example, we now consider the intensity distribution

\[ I_8(u; p) = \begin{cases} 
0.5\Lambda(u), & u < -0.125 \\
0.5\Lambda(u) [1 + 2p_1(u + 0.625)], & -0.125 \leq u < 0.125 \\
0.5\Lambda(u) [1 + 2p_2(u - 0.625)], & u \geq 0.125 
\end{cases} \tag{42} \]

which is plotted in Fig. 40. As with \( I_7(u; p) \), this intensity varies linearly with \( p_1 \) or \( p_2 \) in either half of the pupil. The key difference in this example is that \( I_8(u; p) \) is contrived in such a way that the total intensity \( \sum_i I_8(u_i|p) \) is independent of \( p \). As a result, the PMF (relative intensity) \( P_8(i|p) \) only depends on \( p_1 \) on the left half of the pupil and \( p_2 \) on the right half of the pupil. Naturally, the same is true of the likelihood function \( L_8(p|i) \), as seen in Fig. 41. Since the gradient of \( L_8(p|i) \) always points along \( p_1 \) or \( p_2 \) (when it is nonzero), the FIM and its inverse are always diagonal, indicating that there is zero covariance between the parameters. For any value of \( p \), the principal axes of the error ellipse are oriented along the \( p_1 \) and \( p_2 \) axes, as seen in Fig. 42. When \( p = (0, 0) \), the error ellipse is circular, meaning that the expected error is identical for each parameter. For other values of \( p \), the relative errors of the two parameters vary in a symmetric fashion over the region of interest. Fig. 43 contains plots of the log-likelihood functions \( \ell_8(p|\tilde{I}) \) for simulated 1000-photon measurements of \( I_8(u; p) \) with true parameter values \( p = (0, 0) \) and \( p = (0.63, -0.25) \).

In light of the above observations, it should come as no surprise that the distribution is highly symmetric about the MLE in each case.

To recap, the contrast between \( I_7(u; p) \) and \( I_8(u; p) \) illustrates a limitation of the MLE approach described in Section 3, as well as one of its key strengths. The shortcoming is that the sole reliance of the parameter estimate on the relative intensity can introduce correlations between parameters that are not present in the absolute (unnormalized) intensity; furthermore, any additional information contained within the overall scale of the intensity is ignored. On the other hand, the advantage of the method is that with good experimental design, the relative intensity can be tailored for optimal sensitivity and minimal coupling between parameters, so that there is no need to analyze the unnormalized intensity. Conveniently, the MLE formalism includes a straightforward error metric (the FIM) that can be used to predict and optimize the sensitivity of the measurement. As stated earlier, the lack of reliance
Figure 40: Plots of $I_8(u; \mathbf{p})$ (left axes) and $P_8(i|\mathbf{p})$ (right axes) for several values of $p_1$ and $p_2$. 
Figure 41: Likelihood functions $L_8(p| i)$ associated with each pixel $i$ for a measurement of $I_8(u; p)$. Contour lines are shown in increments of 0.01.
Error ellipses for $I_8 (N = 1000)$

Figure 42: Ellipses representing the expected standard deviation error of a 1000-photon measurement of $I_8(u; \mathbf{p})$ with true parameter values $p_1$ and $p_2$, sampled over a $9 \times 9$ grid in parameter space.

on total intensity has the added benefit of reducing or eliminating errors arising from fluctuations of the source power.

### 6.5 Two-parameter off-null measurement

In the final two examples, we consider a pair of off-null measurements involving two parameters, starting with the intensity distribution

$$I_9(u; \mathbf{p}) = 0.125 \Lambda(u) \left[ (p_1 - u)^2 + (p_2 - \cos(\pi u))^2 \right].$$

(43)

This is a slightly simplified example of the distribution considered in Ref. [16], with the contributions from each parameter adding incoherently (i.e., in intensity) rather than coherently (i.e., in electric field). Despite this difference, similar statistical behavior can be observed in either case. Notice that the $p_1$ term of $I_9(u; \mathbf{p})$ is identical to that of the one-parameter example $I_3(u; p_1)$ considered in Section 5.3, with $c = 1$. The $p_2$ term introduces an additional departure from the null condition, which varies sinusoidally over the pupil. These pupil dependences were chosen to allow comparison between $I_9(u; \mathbf{p})$ and the earlier two-parameter example $I_6(u; \mathbf{p})$, for which the terms
Figure 43: Log-likelihood functions $\ell_8(p|\tilde{I})$ for simulated 1000-photon measurements of $I_8(u;p)$ with true parameter values (a) $p = (0, 0)$ and (b) $p = (0.63, -0.25)$. The plots are shaded on a logarithmic scale with solid contour lines drawn at powers of 2, as indicated in the legend. The peak of each distribution is marked with a red dot. The locations of these maxima (i.e., the MLEs for each measurement) are $p = (0.021, -0.029)$ and $p = (0.565, -0.256)$, respectively. The dashed contour line indicates where the likelihood $L_8(p|\tilde{I})$ drops to $1/\sqrt{e}$ times its peak value, representing the standard deviation confidence interval for the MLE.

with $u$ and $\cos(\pi u)$ pupil dependences were linear in $p_1$ and $p_2$, respectively. The intensity and PMF for $I_9(u;p)$ are shown in Fig. 44. Compared to $I_6(u;p)$, observe that the off-null configuration employed in the present example produces more dramatic variations in the shape of the intensity profile with respect to $p_1$ and $p_2$, particularly for parameter values close to zero.

The likelihood functions $L_9(p|i)$ for each pixel, which are plotted in Fig. 45, have a far more complex structure than the ones seen in the previous examples. The contributions of each pixel have similar shapes, consisting of a peaked distribution that rotates clockwise and changes scale as $i$ runs from 1 to 9. The balance between different pixels and the densely spaced contours of constant likelihood suggest that the FIM is likely to be large and diagonal, which would result in a small and diagonal covariance matrix. As indicated by the ellipse map shown in Fig. 46, the expected error is indeed quite small, particularly for parameter values near $p = (0, 0)$, for which the total measured intensity tends to be lowest. This symmetric ellipse pattern, with the error growing as the departure from null increases, is typical for an off-null
Figure 44: Plots of $I_9(u; \mathbf{p})$ (left axes) and $P_9(i|\mathbf{p})$ (right axes) for several values of $p_1$ and $p_2$. 
Figure 45: Likelihood functions $L_9(p|i)$ associated with each pixel $i$ for a measurement of $I_9(u;p)$. Contour lines are shown in increments of 0.01.
measurement. There is a considerable covariance between $p_1$ and $p_2$ near the edge of the parameter range, but in nearly all cases, the error is still smaller (often significantly so) than it would be for a measurement of $I_6(u; \mathbf{p})$ (see Fig. 33 for comparison).

The log-likelihood functions $\ell_9(\mathbf{p}|\vec{I})$ obtained for two simulated measurements of $I_9(u; \mathbf{p})$ with true parameter values $\mathbf{p} = (0, 0)$ and $\mathbf{p} = (0.63, -0.25)$ can be found in Fig. 47. For the $\mathbf{p} = (0, 0)$ case, the likelihood is a sharply peaked distribution, with the location of the peak (the MLE) nearly coinciding with the true value of $\mathbf{p}$. (The numerical results are provided in the figure caption.) The distribution is considerably wider and less symmetric for the $\mathbf{p} = (0.63, -0.25)$ case, but the standard deviation uncertainty is still quite small. These results demonstrate the usefulness of an off-null measurement, which enables the simultaneous estimate of multiple parameters with high precision.
Figure 47: Log-likelihood functions \( \ell_9(\mathbf{p} | \tilde{\mathbf{I}}) \) for simulated 1000-photon measurements of \( I_9(u; \mathbf{p}) \) with true parameter values (a) \( \mathbf{p} = (0, 0) \) and (b) \( \mathbf{p} = (0.63, -0.25) \). The plots are shaded on a logarithmic scale with solid contour lines drawn at powers of 2, as indicated in the legend. (Values smaller than \(-1024\) are shown in black.) The peak of each distribution is marked with a red dot. The locations of these maxima (i.e., the MLEs for each measurement) are \( \mathbf{p} = (0.016, 0.001) \) and \( \mathbf{p} = (0.648, -0.237) \), respectively. The dashed contour line indicates where the likelihood \( L_9(\mathbf{p} | \tilde{\mathbf{I}}) \) drops to \( 1/\sqrt{e} \) times its peak value, representing the standard deviation confidence interval for the MLE. (The dashed contour in plot (a) is too small to be seen.)

6.6 Two-parameter off-null measurement with smaller departure from null

For the final example, we briefly consider the intensity distribution

\[
I_{10}(u; \mathbf{p}) = 0.320 \Lambda(u) \left[ (p_1 - 0.25u)^2 + (p_2 - 0.25 \cos(\pi u))^2 \right].
\]  (44)

Notice that the pupil dependence of \( I_{10}(u; \mathbf{p}) \) is identical to the previous case except that the departure from null associated with each parameter is four times smaller. As seen in the plots of the intensity profile (Fig. 48) and the likelihood functions for each pixel (Fig. 49), the measurement is very sensitive to variations in \( p_1 \) and \( p_2 \) when both parameters are close to zero. However, similarly to the \( c \ll 1 \) case in Section 5.3, this comes at the expense of greatly reduced sensitivity (i.e., slower variations in likelihood) near the edge of the region of interest.

The expected error ellipses based on the FIM are plotted for several parameter
Figure 48: Plots of $I_{10}(u; p)$ (left axes) and $P_{10}(i|p)$ (right axes) for several values of $p_1$ and $p_2$. 
Figure 49: Likelihood functions $L_{10}(p|i)$ associated with each pixel $i$ for a measurement of $I_{10}(u;p)$. Contour lines are shown in increments of 0.01.
values in Fig. 50. The error for a measurement of $I_{10}(u;p)$ exhibits the same pattern as that of $I_9(u;p)$ (see Fig. 46), but with a larger disparity between the magnitudes of the errors near the center and edges of the parameter range. More precisely, for a true parameter value of $p = (0,0)$, the expected error is exactly four times smaller for a measurement of $I_{10}$ as it is for a measurement of $I_9$; conversely, the errors near the far corners of the parameter range (where $|p_1| \approx |p_2| \approx 1$) are about 2 to 3 times larger for $I_{10}$ than for $I_9$.

Finally, the log-likelihood functions $\ell_{10}(p|u)$ for simulated measurements of $I_{10}$ with true parameter values $p = (0,0)$ and $p = (0.63,-0.25)$ are shown in Fig. 51. As expected, the likelihood for the $p = (0,0)$ case is extremely narrowly distributed about its peak, producing an estimate with error on the order of $10^{-3}$. In contrast, the distribution for $p = (0.63,-0.25)$ is substantially wider; for parameter values with magnitudes closer to 1, the width of the distribution would continue to grow.

The practical implication of this example is that an off-null measurement can be tailored for high sensitivity over an arbitrarily small range of parameter values. Therefore, it is possible to design an iterative experiment for which the parameter estimate is refined through a series of successive measurements. For example, in the focused beam scatterometry apparatus described in Ref. [25], a spatial light modulator
(SLM) is used to produce an arbitrary spatially-varying polarization state, which can be chosen differently for each iteration of the measurement.

As an example of this iterative procedure, suppose that we wish to refine the measurement of $I_{10}(u; p)$ with true parameter values $p = (0.63, -0.25)$ obtained in Section 6.5. The plot of the log-likelihood function $\ell_9(p|\tilde{I})$ for this measurement is shown again in Fig. 52(a); the MLE based on this initial measurement is $p = (0.648, -0.237)$. To refine the parameter estimate, the experimental configuration could be altered such that the output intensity follows the distribution

$$I_{10}^{(2)}(u; p) = \Lambda(u)\left[\left(p_1 - 0.648 - 0.5u\right)^2 + \left(p_2 + 0.237 - 0.5\cos(\pi u)\right)^2\right],$$

(45)

where the constant normalization factor in front of $\Lambda(u)$ has been omitted for simplicity.\(^\text{14}\) This distribution is designed so that the departure from null is half as large

\(^{14}\text{In a real experiment, the leading factor (which determines the peak intensity) would typically...}
and centered at the previous MLE. The resulting log-likelihood function $\ell^{(2)}_g(p|\tilde{I})$ for a simulated measurement of 1000 photons, shown in Fig. 52(b), is much more narrowly distributed than $\ell_g(p|\tilde{I})$. The MLE based on the refined measurement is found to be $p = (0.644, -0.255)$. This process can be applied repeatedly to obtain an estimate with arbitrary precision (barring experimental limitations, as discussed in the next paragraph). The intensity distributions and resulting MLEs for the first four iterations of the process, including the two mentioned above, are listed in Table 6, and the log-likelihood functions for simulated measurements of $I^{(3)}_g(u; p)$ and $I^{(4)}_g(u; p)$ are plotted in Fig. 52(c,d). As seen in the table, the MLE gets closer to the true value with each iteration, leading to a final estimate of $p = (0.631, -0.249)$. As this happens, the likelihood function becomes increasingly compact with an exceptionally sharp peak, which is the reason for the improvement in accuracy. However, note that the calculation of the MLE must be performed carefully in this case since the likelihood function may contain local maxima or regions with very small slopes, which can cause problems with the numerical search procedure. These issues can generally be mitigated by using the previous MLE as the starting point for the search.

As mentioned above, from a statistical standpoint, this iterative MLE approach can be employed to obtain a parameter estimate with arbitrary precision. That is, vary under different experimental configurations. Since the MLE approach ignores any information contained in this scaling factor, it is not important for this discussion.

| Intensity distribution | MLE for $p$           |
|------------------------|-----------------------|
| $I^{(2)}_g(u; p)$      | $(0.644, -0.255)$     |
| $I^{(3)}_g(u; p)$      | $(0.628, -0.246)$     |
| $I^{(4)}_g(u; p)$      | $(0.631, -0.249)$     |

Table 6: Intensity distributions used for a simulated four-step iterative measurement with true parameter values $p = (0.63, -0.25)$, along with the MLEs obtained from the simulated intensities at each step. The off-null conditions for iterations 2 through 4 are each centered at the MLE from the previous iteration. The magnitude of the departure from null decreases with each iteration in order to refine the accuracy of the estimate.
Figure 52: Log-likelihood functions for simulated 1000-photon measurements of intensity distributions (a) $I_9(u; \mathbf{p})$, (b) $I_9^{(2)}(u|\mathbf{p})$, (c) $I_9^{(3)}(u|\mathbf{p})$, and (d) $I_9^{(4)}(u|\mathbf{p})$ obtained throughout a four-step iterative measurement with true parameter values $\mathbf{p} = (0.63, -0.25)$. The peaks of each distribution are indicated with a red dot, and their locations are listed in the rightmost column of Table 6. The dashed red contour in plot (a) represents the standard deviation confidence interval; the confidence interval is too small to be seen in plots (b-d).
for any fixed, reasonably large number of detected photons $N$, the experiment can be
designed to make the Cramer-Rao bound arbitrarily small, meaning that there is no
fundamental limit to the sensitivity of the measurement. In practice, the accuracy is
determined by experimental factors, including but not limited to:

- the bit depth and signal-to-noise ratio of the sensor;
- the power of the source (which affects the number of photons detected in a given
time interval);
- the level of precision and temporal stability of the experimental configuration
  (e.g., SLM control in the application discussed above);
- the validity of the theoretical model and any approximations made;
- other sources of random or systematic error (e.g., thermal fluctuations or ghost
  images).

(Note that the second point above can be addressed by optimizing the FIM for emitted
photons, as in Section 5.3.) In any case, the MLE approach is still useful for deter-
mining the best nominal design for an experiment, as well as for obtaining parameter
estimates from measured data based on a theoretical or empirical model.

7 Concluding remarks

We have summarized the fundamental concepts of maximum likelihood estimation
and applied them to the measurement of a spatially-varying optical intensity distri-
bution. In this treatment, one or more parameters are estimated from the shape of the
intensity profile, without regard for the total measured power. However, the power
incident on the detector is not completely irrelevant, since the uncertainty of the pa-
rameter estimate scales as the inverse of the square root of the number of detected
photons. Depending on the needs of a given application, the methods discussed in
this manuscript may be used to optimize the performance of an experiment for min-
imal estimation error per photon detected by the sensor or per photon emitted by
the source. Some sample code for calculating and evaluating the uncertainty of the
maximum likelihood estimate in such an experiment can be found in the appendix.
Acknowledgments

The author would like to thank Miguel A. Alonso and Philippe Réfrégier for helpful discussions and suggestions. This work was supported by funding from the National Science Foundation (NSF) (PHY-1507278).

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Appendix

A Mathematica code

Here we show a simple implementation of the MLE approach described in Section 3 using the Wolfram Mathematica [26] programming language. The code includes functions to calculate the PMF, likelihood function, simulated intensity, Fisher information, and MLE for an optical measurement, as well as functions to plot the expected error ellipse(s) for a two-parameter measurement. For simplicity, the code is written for the one-and-two parameter cases explored in Sections 5 and 6; as necessary, it could readily be extended for higher-dimensional problems. The code also assumes a one-dimensional pupil.

Section A.1 below contains a list of the functions defined in this package and the syntax for their use. The function definitions are provided in Section A.2. Finally, a few example calculations are shown in Section A.3.

A.1 Syntax and usage

The functions defined in this package are detailed in Table 7.
Table 7: Summary of symbols and functions created to perform MLE calculations in Mathematica. When applicable, the relevant equations from the main text are listed in the second column.

| Symbol       | Eq. | Syntax and description                                                                                                                                                                                                 |
|--------------|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| uv           | (16) | One-dimensional array of pupil coordinates $u_i$ of each pixel. Can be modified to simulate different pixel arrays.                                                                                                         |
| Isim         | (18), (37) | $\text{Isim}[j][p_1][u]$ evaluates the one-parameter intensity distribution $I_j(u;p_1)$ at pupil coordinate $u$ and parameter value $p_1$. $\text{Isim}[j][\{p_1,p_2\}][u]$ evaluates the two-parameter intensity distribution $I_j(u;\mathbf{p})$ at pupil coordinate $u$ and parameter values $\mathbf{p} = (p_1,p_2)$. In each function below, the argument $j$ identifies which distribution $I_j$ should be used; the corresponding function Isim should be defined beforehand. See Section A.2 for a few examples. |
| Iphotonsim   | N/A | $\text{Iphotonsim}[j][\mathbf{p},N]$ randomly generates a simulated measurement of $I_j(u;\mathbf{p})$ containing $N$ photons, such as those shown in Tables 3 and 4. The output is an array with the same length as $uv$ containing the number of photons detected at each pixel. |
| P            | (5) | $\text{P}[j][i,\mathbf{p}]$ calculates the PMF $P_j(i|\mathbf{p})$, evaluated at pixel $i$ for true parameter value $\mathbf{p}$, or equivalently the likelihood function $L_j(\mathbf{p}|i)$ at $\mathbf{p}$ associated with pixel $i$. The argument $\mathbf{p}$ should be specified in the form $p_1$ or $\{p_1,p_2\}$ for the one- and two-parameter cases, respectively. |
| PInt         | (7) | $\text{PInt}[j][\tilde{\mathbf{I}},\mathbf{p}]$ calculates the probability $P_j(\tilde{\mathbf{I}}|\mathbf{p})$ of measuring an intensity distribution $\tilde{\mathbf{I}}$ given true parameter value $\mathbf{p}$, or equivalently the likelihood function $L_j(\mathbf{p}|\tilde{\mathbf{I}})$. The argument $\tilde{\mathbf{I}}$ is an array with the same length as $uv$. The argument $\mathbf{p}$ should be specified in the form $p_1$ or $\{p_1,p_2\}$ for the one- and two-parameter cases, respectively. |
| LLIntSum     | (8) | $\text{LLIntSum}[j][\mathbf{p},\tilde{\mathbf{I}}]$ calculates the sum appearing in the log-likelihood function $\ell_j(\mathbf{p}|\tilde{\mathbf{I}})$. The constant term $\ln P_0$ in Eq. (8) is ignored to improve computational efficiency when calculating the MLE. The arguments $\mathbf{p}$ and $\tilde{\mathbf{I}}$ are the same as for PInt above. |
| Symbol      | Eq. | Syntax and description                                                                                                                                 |
|------------|-----|------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Fisher1D** | (9), (10) | Fisher1D[j][p_1] calculates the (scalar) expected unit Fisher information $J_j(p_1)$, evaluated at parameter value $p_1$, for the one-parameter intensity distribution $I_j(u;p_1)$. Fisher1D[j][p_1, I] calculates the (scalar) observed Fisher information $J_j^{(obs)}(p_1; \hat{I})$ for a measured intensity $\hat{I}$, which should be specified as an array with the same length as uv. |
| **Fisher2D** | (9), (10) | Fisher2D[j]{{p_1, p_2}} calculates the $2 \times 2$ expected unit Fisher information matrix $J_j(p)$, evaluated for parameter values $p = (p_1, p_2)$, for the two-parameter intensity distribution $I_j(u;p)$. Fisher2D[j]{{p_1, p_2}, \hat{I}} calculates the $2 \times 2$ observed Fisher information matrix $J_j^{(obs)}(p; \hat{I})$ for a measured intensity $\hat{I}$, which should be specified as an array with the same length as uv. |
| **MLE1D** | N/A | MLE1D[j][\hat{I}, cons] finds the maximum likelihood estimate for $p_1$ based on a measurement $\hat{I}$ of the one-parameter intensity distribution $I_j(u;p_1)$. The optional argument cons may be used to specify a constraint on $p_1$, for example, -1<=p1<=1. |
| **MLE2D** | N/A | MLE2D[j][\hat{I}, cons] finds the maximum likelihood estimate for $p = (p_1, p_2)$ based on a measurement $\hat{I}$ of the one-parameter intensity distribution $I_j(u;p_1)$. The optional argument cons may be used to specify constraints on $p_1$ and/or $p_2$, for example, {-1<=p1<=1,-1<=p2<=1}. |
| **ErrorEllipse** | N/A | ErrorEllipse[J, {p_1, p_2}] produces a graphics primitive for the error ellipse associated with the $2 \times 2$ Fisher information matrix $J$. The ellipse is centered at $p = (p_1, p_2)$. |
| **EllipseGrid** | N/A | EllipseGrid[j][N, M] plots an $M \times M$ grid of error ellipses based on the expected Fisher information matrix for a measurement of $N$ photons based on the two-parameter intensity distribution $I_j(u;p)$. Each ellipse corresponds to a different pair of true parameter values $p = (p_1, p_2)$. The grid is sampled over the region $-1 \leq p_1, p_2 \leq 1$ at $M$ equally spaced points in each dimension. |
A.2 Code

Our first step is to define the pupil coordinates $uv$ and the intensity distribution $I_{sim}$. For demonstration, we use the examples discussed in Sections 5 and 6. The coordinates of the 9-pixel array given in Eq. (16) may be defined as follows:

\[
\text{In[1]} := \text{uv} = \text{Array}[\&_{}, 9, \{-1, 1\}]
\]

\[
\text{Out[1]} = \{-1., -0.75, -0.5, -0.25, 0., 0.25, 0.5, 0.75, 1.\}
\]

(For users familiar with MATLAB, this command is the Mathematica equivalent of \text{\texttt{linspace(-1,1,9)}}.) Next we define the one- and two-parameter intensity distributions $I_1$ through $I_{10}$, which are summarized in Tables 2 and 5 in the main text. Their definitions (with normalization constant $I_0 = 1$) are below.

\[
\text{In[2]} := \begin{align*}
\text{getp1}[p_] & := \text{First}[\text{Flatten}[\{p\}]]; \\
\text{La}[u_] & := \text{UnitBox}[u/2]; \\
\text{Isim}[1][p_][u_] & := \text{La}[u]*(0.5+0.5 \text{getp1}[p]*u); \\
\text{Isim}[2][p_][u_] & := \text{La}[u]*(0.9+0.1 \text{getp1}[p]*u); \\
\text{Isim}[3, c_][p_][u_] & := \text{La}[u]/(\text{Abs}[c]+1)^2*(\text{getp1}[p]-c*u)^2; \\
\text{Isim}[4, d_][p_][u_] & := \text{La}[u]/(\text{Abs}[d]+2)^2*(\text{getp1}[p]-u-d)^2; \\
\text{Isim}[5][p_][u_] & := 0.563 \text{La}[u]*(2+p[[1]]*u+p[[2]]*\text{Sin}[\pi*u]); \\
\text{Isim}[6][p_][u_] & := 0.25 \text{La}[u]*(2+p[[1]]*u+p[[2]]*\text{Cos}[\pi*u]); \\
\text{Isim}[7][p_][u_] & := 0.5 \text{La}[u]*(1+p[[1]]*u*\text{Boole}[u<0]+p[[2]]*u*\text{Boole}[u>0]); \\
\text{Isim}[8][p_][u_] & := 0.5 \text{La}[u]*(1+2p[[1]]*(u+.625)*\text{Boole}[u<-1/8] + 2p[[2]]*(u-.625)*\text{Boole}[u>1/8]); \\
\text{Isim}[9][p_][u_] & := 0.125 \text{La}[u]*((p[[1]]-u)^2+(p[[2]]-\text{Cos}[\pi*u])^2); \\
\text{Isim}[10][p_][u_] & := 0.320 \text{La}[u]*((p[[1]]-0.25u)^2+(p[[2]]-0.25\text{Cos}[\pi*u])^2);
\end{align*}
\]
The remaining functions listed in Table 7 are defined as follows:

\[
\text{In[3]:=} \quad \text{Iphotonsim}[\text{case}_\text{_] }[p_, n\text{photons}_\text{]}]:=
\text{BinCounts[}
\quad \text{RandomChoice}[\{\text{Isim}[\text{case}_\text{][}p_/uv\}]\rightarrow\text{Range}[\text{Length}[uv]], n\text{photons}_,
\quad \{1, \text{Length}[uv]+1\}];
\]

\[
P[\text{case}_\text{]}[i_, p_:]=\text{Isim}[\text{case}_\text{][}p_/uv[[i]]]/\text{Total}[\text{Isim}[\text{case}_\text{][}p_/uv];
\]

\[
\text{PInt[case}_\text{]}[\text{Imeas}_\text{], p_:}=\pr{\text{Factorial}[\text{Total}[\text{Imeas}]]/\text{Apply}[\text{Times}, \{\text{Factorial}/\text{Imeas}\}]*
\quad \text{Product}[\{\text{Imeas}_\text{[}i]\_0,1, \text{P[case}_\text{][}i_, p_]^{\text{Imeas}_\text{[}i]\_0}, \{i, \text{Length}[uv]\}}];
\]

\[
\text{LLIntSum[case}_\text{]}[p_, \text{Imeas}_\text{]}:=
\quad \text{Total}[\text{Imeas} \times \log[\text{P[case}_\text{][}#, p_\text{]} & /@ \text{Range}[\text{Length}[uv]]] ];
\]

(*Use the following function to avoid errors from 0*Log[0]*)

\[
\text{prod[xv}_\text{, yv}_\text{]}:=\text{MapThread[If[#1\_0,0,#1*#2]&, \{xv,yv\}}];
\]

\[
\text{Fisher1D[case}_\text{]}[p_, \text{Imeas}_\text{]}:=0]:=
\quad \text{Module}[\{\text{pvar}, \text{Pv}, \text{PorI}\},
\quad \text{Pv}=\text{Table}[\text{P[case}_\text{][}i_, \text{pvar}], \{i, \text{Length}[uv]\}];
\quad \text{PorI}=\text{If}[\text{Imeas}=0, \text{Pv}, \text{Imeas}];
\quad \text{Total}[\text{prod}[\text{PorI}, \text{D[Log[\text{Pv}], pvar]}^2/.\text{pvar}->p]];\]

\[
\text{Fisher2D[case}_\text{]}[p_, \text{Imeas}_\text{]}:=0]:=
\quad \text{Module}[\{\text{Pv}, \text{PorI}, \text{p1var}, \text{p2var}, \text{J11}, \text{J12}, \text{J22}\},
\quad \text{Pv}=\text{Table}[\text{P[case}_\text{][}i_, \{\text{p1var}, \text{p2var}\}], \{i, \text{Length}[uv]\}];
\quad \text{PorI}=\text{If}[\text{Imeas}=0, \text{Pv}, \text{Imeas}];
\quad \text{J11}=\text{Total}[\text{prod}[\text{PorI}, \text{D[Log[\text{Pv}], p1var]}^2]];\]
\quad \text{J12}=\text{Total}[\text{prod}[\text{PorI}, \text{D[Log[\text{Pv}], p1var]} \times \text{D[Log[\text{Pv}], p2var]]}];\]
\quad \text{J22}=\text{Total}[\text{prod}[\text{PorI}, \text{D[Log[\text{Pv}], p2var]}^2]];\]
\quad \{\{\text{J11}, \text{J12}\}, \{\text{J12}, \text{J22}\}\}/.\{\text{p1var}->p[[1]], \text{p2var}->p[[2]]\}];
\]

\[
\text{MLE1D[case}_\text{]}[\text{Imeas}_\text{], cons}_\text{]}:=
\quad \text{p1}/.\text{Last@Maximize}[\{\text{LLIntSum[case}_\text{][}p1, \text{Imeas}], \text{cons}\}] ;\]

\[
\text{MLE2D[case}_\text{]}[\text{Imeas}_\text{], cons}_\text{]}:=
\quad \{\text{p1}, \text{p2}\}/.\text{Last@Maximize}[\{\text{LLIntSum[case}_\text{][}p1, p2, \text{Imeas}], \text{cons}\}] ;\]

\[
\text{ErrorEllipse[J}_\text{, p}_\text{]}:=
\quad \text{Rotate[Circle[p, Sqrt[#[{1}]]], ArcTan@#[{2,1}]} & @
\quad \text{Eigensystem[Inverse[J]]}];
\]

\[
\text{EllipseGrid[case}_\text{]}[\text{nphotons}_\text{, numpts}_\text{]}:=
\quad \text{Module}[\{\text{pvals, eig, ellipses}\},
\quad \text{pvals}=\text{Array}[\text{Identity}, \text{numpts}, {-1,1}];
\quad \text{ellipses}=\text{Table[}
\quad \text{ErrorEllipse[\text{nphotons}*\text{Fisher2D[case}_\text{][}pp1, pp2\}], pp1, pp2, pvals];
\quad \text{Graphics[}\{\text{Black, Thick, ellipses}\}, \text{Frame->True}\}];
\];
\]
A.3 Examples

The following examples demonstrate some calculations for the one- and two-parameter intensity distributions $I_1(u; p_1)$ and $I_9(u; p)$ from Sections 5.1 and 6.5, respectively.

```
In[4]:= (*Simulate an intensity distribution with 1000 photons, given true parameter values $p_1=0.63$ and $p_2=-0.25$*)
Imeas1=Iphotonsim[1][.63,1000]
Imeas9=Iphotonsim[9][{.63,-.25},1000]
Out[4]= {45,56,71,98,99,109,161,177,184}
Out[5]= {255,160,124,131,155,88,7,14,66}

In[6]:= (*Find the maximum likelihood estimates based on each simulated intensity from above. For the one-parameter example, constrain $p_1$ to the range over which $I_1$ is valid*)
MLE1=MLE1D[1][Imeas1,{-1<=p1<=1}]
MLE9=MLE2D[9][Imeas9]
Out[6]= 0.638811
Out[7]= {0.618961, -0.257141}

In[8]:= (*Calculate the expected and observed Fisher information for the one-parameter measurement of $I_1$. Then invert and take the square root to calculate the standard deviation error for each case*)
J1=1000*Fisher1D[1][.63];
J1obs=Fisher1D[1][.63,Imeas1];
Sqrt[1/J1]
Sqrt[1/J1obs]
Out[8]= 0.0406453
Out[9]= 0.0397809

In[10]:= (*Calculate the expected and observed Fisher information matrices for the two-parameter measurement of $I_9$. Then invert the matrices to obtain the covariance matrices for each case*)
J9=1000*Fisher2D[9][{.63,-.25}];
J9obs=Fisher2D[9][{.63,-.25},Imeas9];
Inverse[J9]
Inverse[J9obs]
Out[10]= {{0.00299494, 0.000763432}, {0.000763432, 0.000823367}}
Out[11]= {{0.00283021, 0.000765918}, {0.000765918, 0.000839408}}
```
In[12]:= (*Plot the error ellipse for the measurement of I9, centered at the MLE*)
Graphics[{Thick, ErrorEllipse[J9, MLE9]}, Frame -> True]

Out[12]=

In[13]:= (*The following command reproduces Fig. 46 (sans formatting), which
contains a grid of error ellipses representing the expected error for
a measurement of I9.*)
EllipseGrid[9][1000, 9]