

Photon-transmission-loss-independent quantum-enhanced interferometer

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A quantum-enhanced telescope (interferometer) can have significant advantages in precisely measuring the angular position of remote objects through sending out ancillary quantum entanglement pairs alongside the large baselines of telescopes. In principle, the larger the baseline, the higher the expected measurement resolution. However, the well-known major problem of photon transmission loss would drastically undermine the practical application of all quantum-enhanced telescopes and optical interferometers that transmit photons along the baseline, especially for the large baselines required for high angular resolution. Here, we propose a photon-transmission-loss-independent quantum-enhanced interferometer that is robust to the transmission loss and keeps its advantages unchanged given whatever large baseline. This removes the well-known barrier to the practical application of quantum-enhanced telescopes. Moreover, in contrast to the previous results of quantum-entanglement-enhanced telescopes requesting sophisticated resources—perfect single-photon entanglement, photon-number-resolving detectors, or quantum memories—our method requires only threshold detectors and tunable coherent-state or two-mode squeezed-state sources, which are mature technologies nowadays, and it does not need any quantum memory. We demonstrate the high performance of our method using Fisher information. For the phase difference of weak light from a remote star, the high-quality result of Fisher information remains constant under arbitrarily large transmission loss, and hence all the advantageous results and the performance of our method are actually independent of transmission loss.

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I. INTRODUCTION

The optical interferometer is a fundamental technique for detecting distant astronomical objects with ultrahigh precision. Traditional optical interferometers rely on transmitting stellar photons through baselines of two telescopes to achieve (postselected) single-photon interference. In principle, the longer the baseline length, the higher the precision of the measurement result of interference. However, implementing such single-photon interference with a long baseline is highly challenging, especially because of the inherent difficulties in manipulating photons from stars, which exhibit unstable frequencies, random arrival times, and other unpredictable characteristics. An important breakthrough [1] is to introduce auxiliary single-photon entanglement to enhance the observation, i.e., quantum-enhanced telescope. These schemes no longer require controlling and transmitting the incoming stellar photons; instead, they only need to manipulate single photons generated by controllable sources. This greatly reduces experimental complexity and enables baseline lengths far exceeding those of existing traditional methods. However, the well-known major problem of photon transmission loss

would drastically undermine the practical application of all quantum-enhanced telescopes and optical interferometers that transmit photons along the baseline, especially for the large baselines required for high angular resolution. Consequently, the maximum baseline length of existing quantum-enhanced interferometers is severely constrained. While quantum repeaters and quantum memories [2] can in principle extend the distance, they require challenging technologies.

Here, we propose a photon-transmission-loss-independent quantum-enhanced interferometer that is robust to the transmission loss and keeps its advantages unchanged for any large baseline. Using the measure of Fisher information to demonstrate the high performance of our method, we find that the high-quality result of Fisher information of the phase difference of weak light from a remote star remains constant under arbitrarily large transmission loss; hence, all advantageous results including highly precise observation of angular position and the performance of our method are actually independent of transmission loss. Our loss-independent method does not require quantum repeaters, quantum memories, or ideal single-photon entangled sources. Moreover, it needs yes/no detectors only, rather than photon-number-resolving detectors. This makes it practically feasible when we use methods with multi-inputs of auxiliary quantum states [3]. Our method uses practical auxiliary photon sources, and we tune the intensity of these photon sources according to channel transmittance for a given baseline length. The auxiliary state can be controlled through tuning parameters in the initial physical state. Numerical simulations show that our method remains efficient against loss for arbitrarily long baselines.

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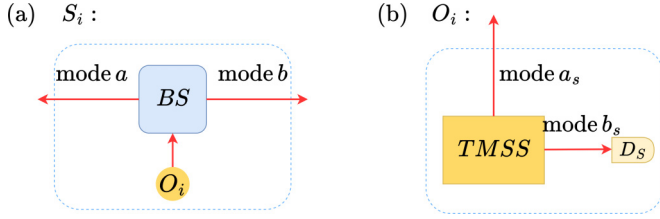


FIG. 1. Schematic setup of (a) the auxiliary source S_i and (b) the original source O_i . The original source O_i can be either a coherent-state source or a TMSS source with threshold detector D_S . BS denotes a 50:50 beam splitter.

Actually, the Fisher information keeps a satisfactory constant for whatever large baselines.

II. AUXILIARY QUANTUM STATES

As shown in Fig. 1(a), we define the combination of the original physical source O_i and the 50:50 beam splitter (BS) as the auxiliary source S_i , and the resulting two-mode state of the beams arriving at the telescopes as the auxiliary state. The input beam of the BS comes from the original source O_i , which may be a simple single-mode source or a heralded two-mode source—e.g., a two-mode squeezed state (TMSS) with heralding [Fig. 1(b)]. In the heralded case, heralding of mode b_s by clicking on detector D_S postselects mode a_s as the auxiliary input. Our auxiliary photon source is photon-transmission-loss-independent: by optimizing the intensity of the physical source in O_i under any channel transmittance η , the probability of the single-photon entangled state in the transmitted mixed state remains constant.

A. Coherent state of source O_i

We can generate the two-mode auxiliary state by directly using a coherent photon source:

$$|\sqrt{\mu}e^{i\delta}\rangle = \sum_n e^{-\frac{\mu}{2}} \frac{\mu^{\frac{n}{2}} e^{in\delta}}{\sqrt{n!}} |n\rangle. \quad (1)$$

Since our method is supposed to use simple and mature techniques only, we do not take control or manipulations to the global phase δ here, and hence the value δ may drift randomly. We use the following mixed state for coherent states:

$$\rho_C = \sum_{n=0}^{\infty} e^{-\mu} \frac{\mu^n}{n!} |n\rangle\langle n|. \quad (2)$$

Suppose the channel transmittance from BS to a telescope is η (this means the channel transmittance for beam a or b is η). In arriving at telescopes, our auxiliary quantum state is

$$\rho_{ab} = \sum_{m=0}^{\infty} \mathcal{P}_m |\psi_m\rangle\langle\psi_m|, \quad (3)$$

where

$$\mathcal{P}_m = e^{-\eta\mu} \frac{(\eta\mu)^m}{m!} \quad (4)$$

and

$$|\psi_m\rangle = \frac{(a_i^\dagger + b_i^\dagger)^m}{\sqrt{2^m m!}} |\text{vac}\rangle, \quad (5)$$

for example, $|\psi_0\rangle = |0\rangle|0\rangle$ and $|\psi_1\rangle = \frac{|0\rangle|1\rangle + |1\rangle|0\rangle}{\sqrt{2}}$. As shown later in Sec. III, the final result of our quantum-enhanced interferometer is almost independent of transmission loss if we use the optimized source parameters according to the specific channel transmittance.

Remark: We do not worry about whether the global phase δ in Eq. (1) is perfectly random. As shown later, our major result is simply independent of the value of the global phase δ , no matter whether it is random or not random, or taking whatever time-dependent values.

B. Heralded source O_i from TMSS

We can generate the auxiliary quantum state through using a two-mode initial state with heralding as shown in Fig. 1(b): we choose mode a_s conditional on the heralding of mode b_s , i.e., clicking of detector D_S . The state of the TMSS is

$$|\Psi\rangle_H = \sqrt{1-r^2} \sum_n r^n |n\rangle|n\rangle = \sum_n \sqrt{p_n} |n\rangle|n\rangle, \quad (6)$$

where $p_n = (1-r^2)r^{2n} = \frac{\mu^n}{(1+\mu)^{n+1}}$ and

$$\mu = \frac{r^2}{1-r^2} \quad (7)$$

denotes the mean photon number of the source. Given the ideal detector D_S , the auxiliary quantum state is

$$\rho_{ab} = \sum_{m=0}^{\infty} \mathcal{P}_m |\psi_m\rangle\langle\psi_m|, \quad (8)$$

with

$$\mathcal{P}_0 = \frac{1-\eta}{1+\eta\mu},$$

$$\mathcal{P}_m = \frac{1+\mu}{\mu} \frac{(\mu\eta)^m}{(1+\mu\eta)^{m+1}}. \quad (9)$$

According to Eq. (7), here μ is determined by the tunable parameter r of the initial physical source.

III. PHOTON-TRANSMISSION-LOSS-INDEPENDENT INTERFEROMETER OVER LARGE BASELINE

We propose the setup of our photon-transmission-loss-independent quantum-enhanced interferometer with a single auxiliary source and multiauxiliary sources in Figs. 2 and 3, respectively. Each auxiliary source is connected to the linear optical circuits at the two telescope stations via a pair of equal-length optical fibers. Note that, different from the prior works [1,3], here in our setup, we have proposed to replace the perfect single-photon sources with practical sources, which rely solely on matured technologies and whose intensities are tunable. This makes the base of our loss-independent quantum-enhanced telescope: by choosing the intensity value according to the baseline loss, our setup can work efficiently with arbitrarily large transmission loss of the baseline. Under the framework of Refs. [1,3], we also use linear

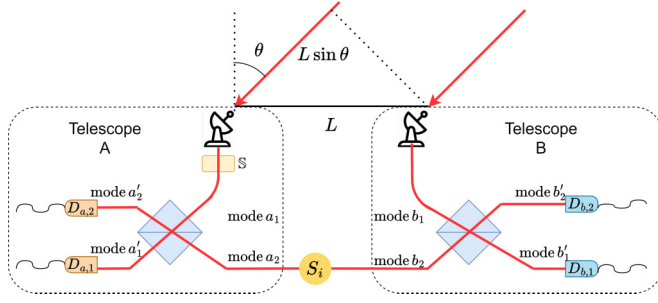


FIG. 2. Schematic setup of the loss-independent quantum-enhanced interferometer method with one auxiliary photon source: The two telescopes are separated by a distance L , with each telescope independently equipped with a 50:50 beam splitter and two threshold detectors. The auxiliary photon source is deployed at the midpoint between the two telescopes.

optical circuits for our method. In the method with multi-auxiliary photon sources, each telescope is equipped with an $N \times N$ linear optical circuit consisting of beam splitters and phase shifters only and N threshold detectors. $N - 1$ auxiliary sources are placed at the midpoint of the baseline between the two telescopes.

A. Received quantum states of telescopes from star

For the target source at angular position θ in Fig. 3, the emitted light attenuates into a mixture of vacuum state and single-photon entangled state by the time it reaches the telescopes:

$$|\varphi_1\rangle = \frac{e^{i\phi}\hat{a}_1^\dagger + \hat{b}_1^\dagger}{\sqrt{2}}|\text{vac}\rangle, \quad \phi \equiv \frac{2\pi L \sin \theta}{\lambda}, \quad (10)$$

where λ is the wavelength, and a_1 and b_1 are the modes of telescopes A and B, respectively. The two telescopes are separated by a distance L (the baseline length). We denote the mean photon number of the starlight received by the telescopes as ϵ . Consequently, in a fraction ϵ of the time windows, the two telescopes share the single-photon entangled state $|\varphi_1\rangle$ defined in Eq. (10); in the remaining windows, both telescopes receive the vacuum state.

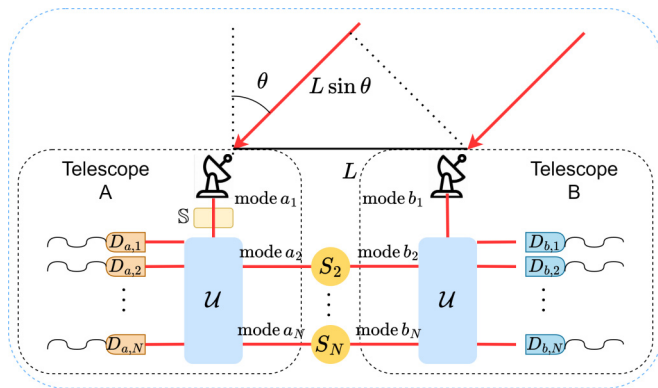


FIG. 3. Schematic setup of our method with multiauxiliary photon sources. Each telescope is equipped with a linear optical network U and N threshold detectors.

B. The method with single auxiliary photon source

Here, we demonstrate how the loss-independent method with one auxiliary photon source determines the value of ϕ defined in Eq. (10), and compare the Fisher Information between our loss-independent method and the method with auxiliary single-photon source [1].

1. Our method

The setup of the method with one auxiliary heralded photon source is shown in Fig. 2. We use threshold detectors and we count the frequency of each kind of events defined by the joint click of the detectors $\{D_{a,1}, D_{a,2}, D_{b,1}, D_{b,2}\}$. In particular, we denote the events of click outcomes by $\vec{m} = (b_{a,1}, b_{a,2}, b_{b,1}, b_{b,2})$, where $b_{x,i} = \text{bool}(n_{x,i})$ ($x \in \{a, b\}$, $i \in \{1, 2\}$) means $b_{x,i} = Y$ when the threshold detector $D_{x,i}$ clicks and $b_{x,i} = N$ when the threshold detector $D_{x,i}$ is silent.

Since we choose optimized parameter values for the source according to the transmission loss of each channel distance, the performance of our method is photon-transmission-loss-independent. Moreover, we need some other values to complete the calculation of phase difference ϕ and Fisher Information. We need the probability of different types of events $\{\vec{m}\}$. In a real experiment, we also need to record the number of each kind of events $\{\vec{m}\}$ through observing those threshold detectors. Based on this, we have the constraints for values ϕ and $P(\vec{m}|\phi)$. Given these constraints, we can calculate the ϕ value through maximum likelihood estimation (MLE). However, in the calculation of Fisher Information alone, we only need the theoretical value of $P(\vec{m}|\phi)$, which can be calculated by Eqs. (16) and (17) directly, and we do not need the (simulation of) experimentally observed data though the simulation is needed in calculating ϕ by MLE. Below, we derive these constraints. The actual starlight is often very weak, so it is a mixture of lots of vacuum and single-photon states as shown by Eq. (10). Mathematically, the density operator of starlight is

$$\rho_S = (1 - \epsilon)|\text{vac}\rangle\langle\text{vac}| + \epsilon|\varphi_1\rangle\langle\varphi_1|, \quad (11)$$

where ϵ is a small positive number and $|\varphi_1\rangle$ is defined by Eq. (10).

Given the interference of the starlight and the auxiliary light, we can compute the probability $P(\vec{m}|\phi)$. Asymptotically,

$$P(\vec{m}|\phi) = \sum_{\{\vec{d}|\vec{d} \in S_{\vec{m}}\}} \epsilon(\mathcal{A}_{\vec{d}} + \mathcal{B}_{\vec{d}} \cos \phi) + \mathcal{C}_{\vec{d}}. \quad (12)$$

We will present the detailed derivation of Eq. (12) in Sec. III B 3.

2. Fisher information

We quantify the performance of methods with different auxiliary sources by comparing their Fisher information. The Fisher information is defined as

$$\mathcal{F}(\phi) = \sum_{\vec{m}} \left(\frac{\partial P(\vec{m}|\phi)}{\partial \phi} \right)^2 \frac{1}{P(\vec{m}|\phi)}. \quad (13)$$

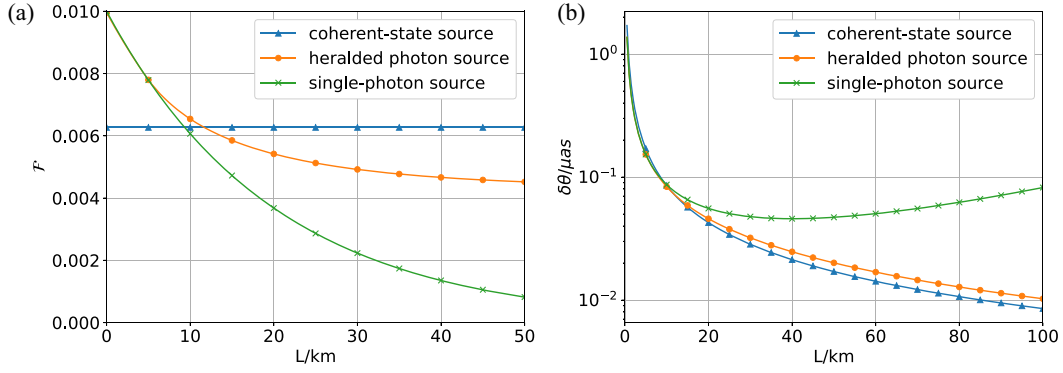


FIG. 4. Performance comparison of different methods using (a) Fisher information and (b) the angular uncertainty under different baseline lengths. We take $N_t = 10^5$ independent measurements in panel (b). The comparison is conducted under a fixed starlight intensity of $\epsilon = 0.02$. We have taken the optimized value μ in the initial physics source for the calculation of each distance point, as shown in Fig. 6.

The variance of our method, $(\delta\phi)^2$, is proportional to the inverse of the Fisher information:

$$(\delta\phi)^2 \geq \frac{1}{N_t F(\phi)}, \quad (14)$$

where N_t is the number of independent experiments. The corresponding angular uncertainty $\delta\theta$ is

$$\delta\theta = \frac{\lambda \delta\phi}{2\pi L} \geq \frac{\lambda}{2\pi L} \frac{1}{\sqrt{N_t F(\phi)}}. \quad (15)$$

3. Value of $P(\vec{m}|\phi)$

To calculate the Fisher Information above, we need the value of $P(\vec{m}|\phi)$ as defined around Eq. (12). In our calculation of the Fisher Information, we only need the asymptotic value of $P(\vec{m}|\phi)$. For presentation convenience, we introduce a virtual setup where we use photon-number-resolving detectors, say, what would happen if we had photon-number-resolving detectors. We represent events in this imaginary setup by $\vec{d} = (n_{a,1}, n_{a,2}, n_{b,1}, n_{b,2})$, where $n_{x,i}$ is the number of photons received by detector $D_{x,i}$. For example, notation $\vec{d} = (1, 0, 1, 0)$ represents the state that one photon arrives at detector $D_{a,1}$ and one photon arrives at detector $D_{b,1}$, while detectors $D_{a,2}$ and $D_{b,2}$ receive no photon. We use definition $\vec{d}$ for the purpose of notational simplicity only. We emphasize that our method does not use any photon-number-resolving detector as actual detection is performed using yes/no detectors.

Theoretically, the value of phase difference ϕ is determined by $P(\vec{m}|\phi)$, the probability of finding each event $\vec{m}$ in the real setup:

$$P(\vec{m}|\phi) = \sum_{\{\vec{d}|\vec{d} \in S_{\vec{m}}\}} P(\vec{d}). \quad (16)$$

With this formula, to complete the calculation formulas of Fisher Information, we only need the calculation formula $P(\vec{d})$ as shown below:

$$P(\vec{d}) = \epsilon(\mathcal{A}_{\vec{d}} + \mathcal{B}_{\vec{d}} \cos \phi) + \mathcal{C}_{\vec{d}}. \quad (17)$$

The calculation of the coefficients $\mathcal{A}_{\vec{d}}$, $\mathcal{B}_{\vec{d}}$, and $\mathcal{C}_{\vec{d}}$ can be seen in Eqs. (S8)–(S11) of the Supplemental Material [4].

4. Numerical results of Fisher information

Using Eq. (13) together with Eqs. (16) and (17), the Fisher Information of our method is numerically calculated. Figure 4(a) shows the optimal Fisher information of methods using a heralded or a coherent photon source at various baseline lengths L . These methods are compared with the existing single-photon source method [1]. By tuning the source intensity to maximize $\mathcal{P}_1$, both the heralded and coherent source methods maintain nearly constant Fisher information under low channel transmittance, demonstrating the photon-transmission-loss-independent nature of the approach. Figure 4(b) further compares the optimal angular uncertainties of different methods for $N_t = 10^5$ independent experiments, based on the Fisher information shown in Fig. 4(a). While the method using a single-photon source reaches its resolution limit at a baseline length of 40 km, our methods continue to improve in angular resolution as the baseline length increases.

5. Advantages of heralded source

(1) Value of ϵ in the density operator of starlight. In the calculation above, we assumed a known value for ϵ . However, determination of this value itself is not so trivial. The starlight can be very weak, and its state does not have to be stable. Therefore, it is not convincing to simply take an additional experiment to find the value ϵ before or after the interference experiment with auxiliary quantum states because the (average) value $\langle \epsilon \rangle$ can be different for the above two experiments done at different times. To convincingly estimate the value ϵ in an experiment, we can randomly choose some time windows to send out vacuum auxiliary states. If we use this method, the way of using a heralded auxiliary source seems to be more convenient: it does not need any active operation because it can simply use those nonheralded states of the beam a_s .

(2) Higher performance with multi-input auxiliary heralded photon sources. As has been shown numerically already, the coherent state auxiliary source has a higher Fisher Information than that of the heralded photon source if we only use one auxiliary photon source. However, the result of the coherent auxiliary source has no improvement even if we use multi-inputs, while the result is significantly improved if we use multi-input auxiliary heralded photon sources, as shown in Sec. III C.

6. Results of MLE

Although Fisher Information represents the theoretically achievable result of our method, in a real experiment, we can only compute the value ϕ by a specific numerical method such as MLE. Experimentally, we record the counts of different outcomes $\vec{m}$, denoted by $\hat{N}_{\vec{m}}$. We set the phase shifter $\mathbb{S}$ in Fig. 3 to two different values, $\mathbb{S} = 0$ and $\mathbb{S} = \pi/2$, and for each phase-shifter configuration, we take N_t independent experiments. The experimentally observed counts of events $\{\vec{m}\}$ with probabilities $\{P(\vec{m}|\phi)\}$ (zero phase shift on $\mathbb{S}$) are denoted as $\{\hat{N}_{\vec{m}}\}$, and the counts of events with probabilities $\{P(\vec{m}|\phi + \pi/2)\}$ ($\pi/2$ phase shift on $\mathbb{S}$) are denoted as $\{\hat{N}'_{\vec{m}}\}$. The negative log-likelihood function is defined as

$$\mathcal{L}(\phi) = - \sum_{\{\vec{m}\}} (\hat{N}_{\vec{m}} \log(P(\vec{m}|\phi)) + \hat{N}'_{\vec{m}} \log(P(\vec{m}|\phi + \pi/2))). \quad (18)$$

The estimated value $\tilde{\phi}$ is

$$\tilde{\phi} = \arg \min_{\phi} [\mathcal{L}(\phi)]. \quad (19)$$

The estimated angle value $\tilde{\theta}$ is then

$$\tilde{\theta} = \arcsin \left(\frac{\lambda \tilde{\phi}}{2\pi L} \right). \quad (20)$$

We have also numerically simulated the average angular uncertainty of the MLE result, as shown in Fig. 7. The result is in agreement with the Fisher Information very well. In our calculation in both Fisher Information as shown by Fig. 4 and MLE method as shown in Fig. 7, we have never used the individual values of $P(\vec{d})$, though we have used the total probability of $\vec{m}$, which can be observed directly by threshold detectors. Therefore, our method reported here does not need any photon-number-resolving detectors.

C. Our method with multiauxiliary photon sources

As shown by Marchese and Kok [3], the performance of a quantum-enhanced interferometer can be improved using multi-inputs of single-photon entanglement sources. Here, we use multi-inputs of heralded photon sources to improve the Fisher Information of our method. Different from the prior artwork [3], our method requires neither single-photon sources nor photon-number-resolving detectors.

Recall the setup in Fig. 3; each telescope is attached with an $N \times N$ linear optical circuit U , whose matrix elements are $U_{i,j} = \frac{\exp[i(i-1)(j-1)\pi/N]}{\sqrt{N}}$. The U circuit can be implemented with a linear optical circuit containing at most $\frac{N(N-1)}{2}$ beam splitters and phase shifters [5,6], and hence has no significant challenges under current technologies.

The N output modes of the linear optical circuit U are each measured by one threshold detector. We denote the outcomes of detectors $\{D_{a,1}, \dots, D_{a,n}, D_{b,1}, \dots, D_{b,n}\}$ by the vector $\vec{m} = (b_{a,1}, \dots, b_{a,N}, b_{b,1}, \dots, b_{b,N})$. The probability of each outcome $\vec{m}$ is

$$P(\vec{m}|\phi) = \sum_{\{\vec{d}|\vec{d} \in S_{\vec{m}}\}} \epsilon(\mathcal{A}'_{\vec{d}} + \mathcal{B}'_{\vec{d}} \cos \phi) + \mathcal{C}'_{\vec{d}}, \quad (21)$$

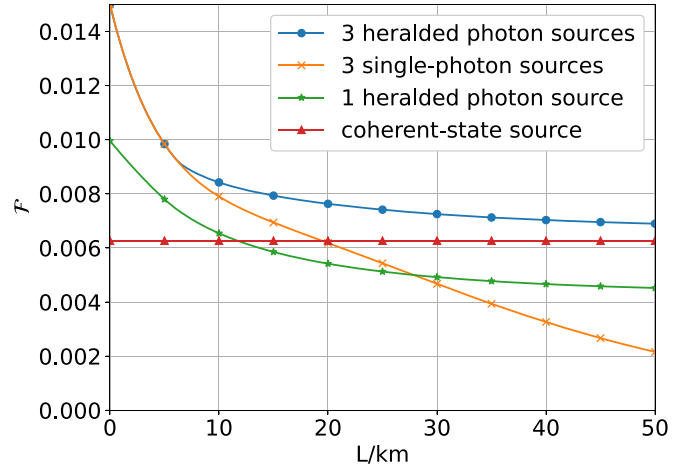


FIG. 5. Performance comparison of different methods using Fisher information. The comparison is conducted under a fixed starlight intensity of $\epsilon = 0.02$.

which is in the same form as Eq. (12), where $S_{\vec{m}}$ is the set for all events $\{\vec{d}\}$ of the virtual method that can cause the measurement outcome of $\vec{m}$. Given Eq. (21), we can quantify the performance of our method with the Fisher information $\mathcal{F}(\phi)$ defined in Eq. (13).

Numerical results. We have also compared the Fisher Information of our method with three auxiliary heralded sources and the existing method with three ideal single-photon sources under different baseline lengths; the results are shown in Fig. 5. Evidently, the performance of our method with multiple auxiliary heralded sources behaves better than the method with a single auxiliary coherent source and the existing method with three ideal single-photon sources [3] under low transmittance.

IV. CONCLUSION

We demonstrate the photon-transmission-loss-independent quantum-enhanced interferometer method and show its advantage over existing quantum-enhanced results [1–3,7–21]. Our loss-independent quantum-enhanced interferometer is experimentally feasible, requiring only threshold detectors, coherent-state sources or two-mode squeezed photon sources, beam splitters, and phase shifters. By tuning the intensity of the initial physical sources, the baseline can be made arbitrarily long while the Fisher information remains almost constant.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and

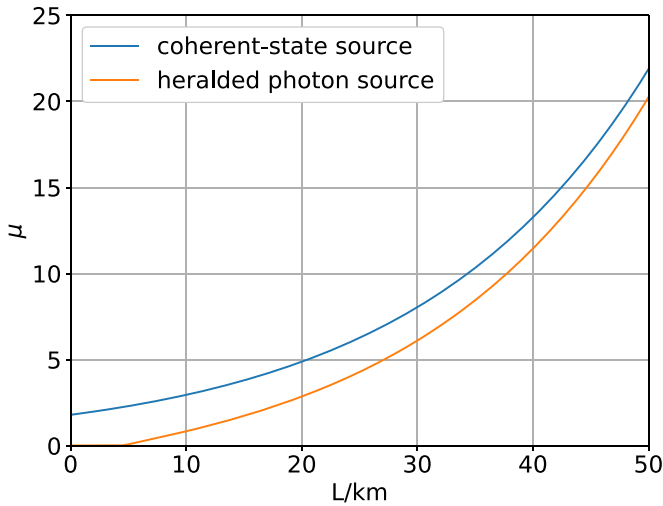


FIG. 6. The optimized parameter values μ of the initial physical sources in the calculation of Fisher Information in Fig. 4.

hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: THE OPTIMIZED PARAMETER VALUES OF THE INITIAL PHYSICAL SOURCE

Our auxiliary source has the photon-transmission-loss-independent property since we can choose optimized parameter values of the initial physical source under any channel transmittance η . As shown in Sec. III, the final result of our quantum-enhanced interferometer is almost independent of transmission loss if we use the optimized source parameters according to the specific channel transmittance. The optimized parameter values of methods with single auxiliary sources are shown in Fig. 6.

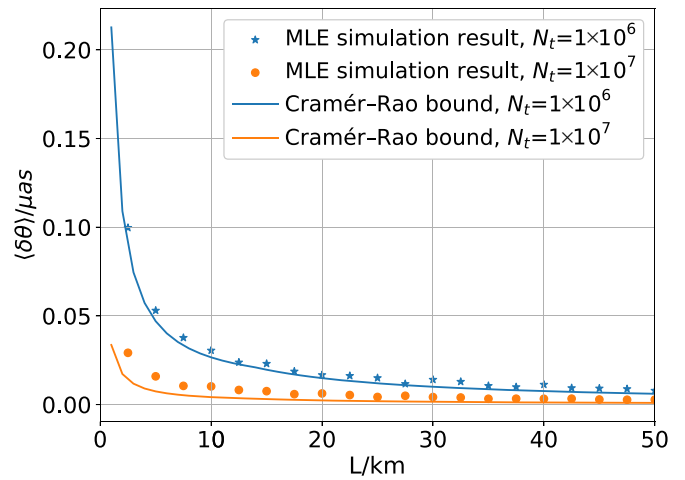


FIG. 7. Angular uncertainty of our method and the Cramér-Rao bound. N_t denotes the number of effective time windows for each phase shift on $\mathbb{S}$. For each simulation data point, hundreds of random angle values θ uniformly distributed in $[0, \lambda/L]$ are generated, and all possible measurement outcomes are simulated to compute the average deviation between the estimated and true angle values.

APPENDIX B: NUMERICAL SIMULATION RESULTS OF MLE

We numerically simulate the average angular uncertainty $\langle\delta\theta\rangle$ between the exact value θ and the estimated value $\hat{\theta}$ for the method with a single heralded source. The numerical results are shown in Fig. 7. The simulation result is close to the Cramér-Rao bound predicted by the Fisher Information of the system, indicating that our method with MLE maintains high precision under high transmission losses.

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