Interferometry-Based Astronomical Imaging Using Nonlocal Interference with Single-Photon States

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Abstract: Recent proposals suggest that a distributed single-photon would outperform weak coherent or thermal states as a phase reference for long-baseline interferometry of dim sources. We demonstrate experimental results toward confirming this prediction.

1. Introduction

Interferometric-based telescope-array imaging has been used in astronomy since the early 1920's, and in 2019 it was used to produce the first image of a black hole in the radio-frequency spectrum. There have been several proposals to increase the sensitivity of optical interferometric telescope arrays by taking advantage of the quantum nature of light including the use of number-resolved detection [1], and local two-photon interference [2]. Recent proposals show that nonlocal quantum states distributed between telescopes can be used to surpass the limits of conventional interferometric-based astronomical imaging methods, which are limited by quantum shot noise, signal loss, or the requirement of bright objects. [3,4] In an initial experiment by our group, photon interference between a nonlocal single-photon state and the thermal-like source to be imaged has been demonstrated to reduce the noise associated with coherent detection, enabling reconstruction of the source spatial distribution with reduced noise – the first instance of quantum-enhanced sensing in this context. The longer-term goal is to discover the optimal quantum-enhanced protocol to achieve ultimate telescope resolution of faint astronomical objects.

The objective of telescope arrays is to determine the complex visibility of interference as a function of telescope separation, as the van Cittert-Zernike theorem states that the Fourier transform of this visibility function is equivalent to the normalized intensity distribution of the source [5]. To measure the visibility given two telescopes, the nonlocal single-photon state is created by splitting the single photon into a superposition of two paths - with a controllable phase difference between them - each traversing to a different telescope as depicted in Fig. 1. The light collected by each telescope is interfered with the corresponding single-photon reference field using 50:50 beam splitters (BS). All the ports of the BSs are monitored. If the state of the light collected by the telescopes is at the single-photon level, then the probability of measuring a coincidence between a pair of detectors - one at each telescope - is

$$P(|v|,\delta,\phi) = \left(1 \pm |v|\cos(\delta-\phi)\right)/4 \tag{1}$$

where $|v|$ is the magnitude of the visibility, δ is the controlled phase, ϕ is the phase of the complex visibility, and the plus or minus is due to the phase gained from transmission or reflection at the BS.

2. Experimental Details

To create the nonlocal single-photon quantum state, a pair of spectrally factorable photons (Schmidt number = 1.003) is generated by frequency doubling a laser pulse centered at 830 nm with 10 nm bandwidth in a BBO crystal and then using type-II parametric down-conversion (PDC) in a KDP crystal. Each pair is split to yield a herald photon with 5 nm bandwidth and an idler with 13 nm bandwidth each centered at 830 nm. Since the state is factorable, detecting the herald leaves the idler photon in a spectrally pure state. Since low average photon number coherent states and thermal states are nearly identical, we can use the unheralded idler photons from the PDC - a thermal state - as a comparison to a classical reference. The idler is then split with equal amplitude along two paths to serve as the nonlocal state at each telescope. In one path, we place a piezoelectric translator (PZT) to modulate the relative phase between the paths using a 600 Hz triangle wave with a maximum deviation of 4π. On the other hand, a faux-star is created by using a pick-off from the initial pulse of the Ti:Sapph laser and illuminating a rotating diffuser with a specific spatial pattern (a Gaussian spot of width 0.24 mm) yielding a spectrally single-mode, Lambertian scatterer with pseudo-thermal statistics ($g^{(2)} \approx 1.929 \pm 0.028$), and average photon number 0.0038. The diffuse light is then collected in two single-mode fibers (Thorlabs PM780-HP) one meter from the diffuser after passing through a 50:50 BS with one fiber in each output port; these operate as mock telescope base stations. By moving one fiber relative to the other, different combinations of positions (baselines) in the detection plane are measured. Each fiber is then combined with one of the idler paths on a 50:50 fiber beam splitter (FBS). The outputs of both FBSs and the herald are then measured using superconducting nanowire single photon detectors (SNSPDs).

It has been shown that averaging the phasors for sinusoidal probability distributions, as we have from Eq. (1), yields the visibility of the interference [6]. Since the initial distribution is symmetric, only the magnitude (not the phase) of the complex visibility is needed to measure the source distribution. To do this, the SNSPD signals and a phase-locked signal from the PZT are then routed to a time-to-digital converter (TDC) with 100 ps resolution. Heralded and non-heralded coincidence times are then measured relative to the PZT triangle driving signal. The phase of that instance can be calculated given the linear ramps of the PZT. The modulus of the averaged phasors for each telescope position is then recorded.

3. Results

Measurements of the visibility were recorded ten times at each of many different baselines for both an unheralded and heralded idler. As shown in Fig. 2, the measured visibility has a Gaussian spatial distribution, and its Fourier transform recovers the width of the source intensity distribution at the diffuser: 0.2 mm for the unheralded data, and 0.19 mm for the heralded data. This closely matches the measured intensity distribution at the diffuser. At the maximum, the visibility of the heralded case is nearly twice the visibility of the unheralded coincidences, yet there are close to seven times the coincidences in the unheralded data (1593 heralded, 10412 unheralded). This shows the advantage of using a single-photon distributed state for spatially resolving very dim sources.

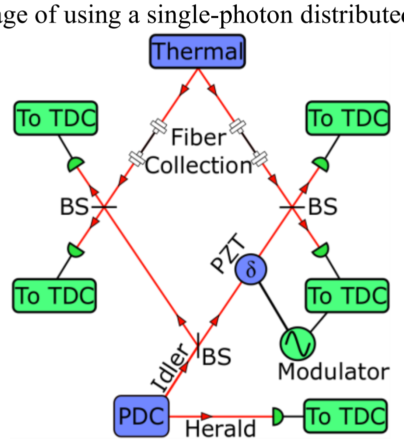

Fig 1: A simplified experimental setup. A PDC crystal creates two spectrally factorable photons. One is used as a herald, while the other is used as the nonlocal single photon. A PZT is modulated to change the phase in one arm of the interferometer. A thermal state is created to be a mock stellar source and fibers collect the light like a pair of telescopes. The collected photons are interfered with the nonlocal state. Detector and modulated PZT signals are routed to a TDC to measure the phase.

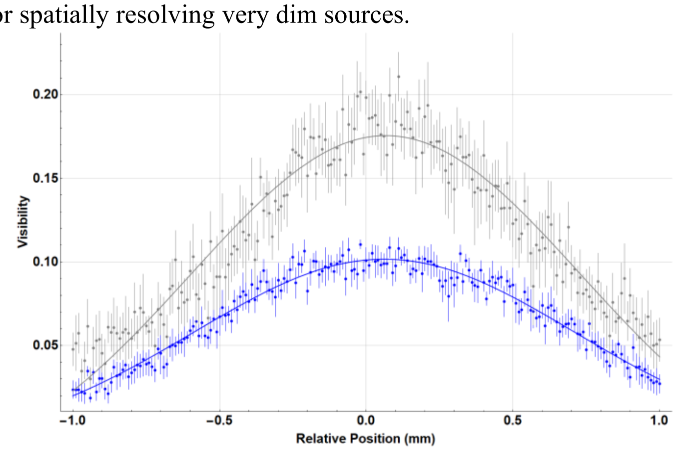

Fig 2: Representative data set, heralded (gray) and unheralded (blue) points are the visibility as a function of the relative position between telescope fibers. The solid line denotes the Gaussian of best fit to the data points. Error bars are found by the standard deviation over 10 measurements.

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