Comparing Weak References For Quantum Long-Baseline Telescopy

Matthew Brown[1], **Markus Allgaier**[2], **Michael Raymer**[1], **and Brian Smith**[1]
[1]Department of Physics, University of Oregon, Eugene, Oregon 97403, United States
[2]Department of Physics and Astrophysics, University of North Dakota, Grand Forks, North Dakota 58202, United States
mbrown9@uoregon.edu

Abstract: We compare the signal-to-noise ratio for different measurements that could be used for stellar interferometry. We find that single-photon sources with number-resolved detection outperform other weak local oscillator states.

1. Introduction

Since 1921, telescope arrays have been used to increase resolution beyond that of a single aperture [1]. This utilizes the van Cittert-Zernike theorem (where spatially incoherent light becomes partially coherent after propagation) along with several spatially separated apertures, which allow for the measurement of the partial coherence as a function of aperture separation [2]. From the measured coherence, one can recreate an image of the original source where the ultimate resolution is proportional to the inverse of the longest aperture separation. In the radio regime, the coherence is measured by using strong, synchronized local oscillators (LOs) to perform homo- or heterodyne detection at each aperture (as in Fig. 1b)); however, due to the low average photon number collected in the optical part of the spectrum, the intrinsic shot noise of the LOs would overwhelm the signal [3]. Hence, to measure in the optical portion of the spectrum, it is typical to collect the stellar fields and transport them to a central location where the fields are interfered (e.g., on a beam splitter) as in Fig. 1a).

We recently carried out the first proof-of-principle experiment using a path-entangled single photon (i.e., a photon that is split into two path modes using a beam splitter) as a LO [4]. Using single-photon detectors and coincidence correlations across telescopes (see Fig. 1c)), it is possible to measure the coherence of the collected fields [5]. This largely removes the shot-noise issue and can, hypothetically, remove any loss the stellar fields incur as they propagate to the central interference location by employing a quantum network. However, there is nothing obviously special about a single-photon state and any state with low average photon number could be used as the LO, if one can tolerate the increased noise. In this article, we discuss a way to systematically compare various LOs with coincidence detection.

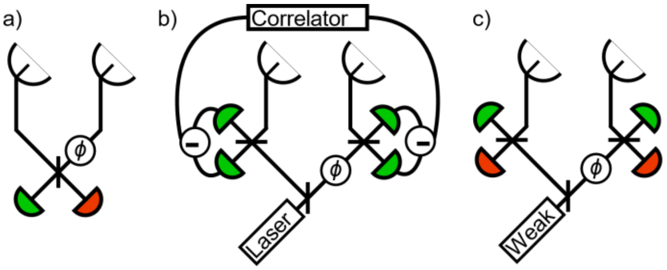

Fig 1. Measurement Types a) Michelson stellar interferometry, b) Balanced homodyne and c) coincidence detection with weak/single photon local oscillators depicted in [4, 5].

2. Theory

To compare the many possible LOs theoretically, we need a standard. We will assume that the controllable phase, ϕ, is applied to one of the LO path-modes (seen in Fig. 1) and linearly ramps in time with a known period. A total of 800,000 LO pulses are simulated, which is the number of pulses that could be created from a typical 80 MHz repetition rate pulsed laser system within an atmospheric fluctuation window of 10 ms. We assume that 1) the average photon number of the LO and collected fields is known; 2) only photons from the astronomical source are collected by the telescopes; 3) the fields collected by each telescope have the same average photon number; 4) the complex degree of coherence is 1, which is achievable when two apertures are close together; 5) the detectors have unit efficiency without dark counts; and 6) both the LO and stellar fields occupy the same spatial-temporal-spectral mode.

Following [4], the probability of a coincidence detection event and the measured visibility for single-photon measurements can be generalized to any weak LO since the visibility can be shown to be independent of the coherence between different Fock-state layers, but depends on the probability of each diagonal component of the density matrix in the number basis. The general form for the probability of a coincidence event can be expressed as

$$P(\bar{n}_s, \bar{n}_{LO}, v)[1 \pm V(\bar{n}_s, \bar{n}_{LO}, v)\cos(\Delta\phi)], \tag{1}$$

where $P(\bar{n}_s, \bar{n}_{LO}, v)$ is the probability per pulse, averaged over phase, that a coincidence event will occur, V is the estimated visibility, $\bar{n}_s$ and $\bar{n}_{LO}$ are the average photon number per pulse collected by the telescopes and in the LO respectively, v is the complex degree of coherence between the fields collected by the telescopes, $\Delta\phi$ is the difference between arg (v) and ϕ, and $\pm$ is from the different phases added by the beam splitters for the different detector combinations. It should be noted that the explicit form for P and V also depend on the probability distribution of both the thermal source and the photon probability distribution of the LO.

To estimate the visibility, V, and its variance, σ^2, for our measurement, we employ a technique called phase tagging wherein coincidence events are distributed randomly in time based on the ramping of the applied phase [6]. From the time of an event, the phase applied, ϕ_j, can be inferred and, hence, the phasor $\exp(i\phi_j)$. Twice the average of the collected phasors equals the complex visibility [6, 7]. Due to properties of the distribution, the Cramer-Rao lower bound for this measurement cannot be achieved; so, we must sample numerically to find the variance [7]. First, we sample the raised cosine distribution $((1 + V\cos(\psi - \phi))/2\pi)$ with a total number of samples that is binomially distributed, as every pulse has a probability to yield a coincidence event given by $P(\bar{n}_s, \bar{n}_{LO}, v)$, and a total number of trials given by $4\times 800{,}000$ (the factor 4 is due to the four possible detector combinations). Utilizing phase tagging, we calculate the visibility from the samples, and then repeat 10^5 times. By the central limit theorem, the complex visibility is normally distributed with a mean value V and a variance σ^2, which we then calculate from the 10^5 visibilities.

3. Data & Results

Using the techniques described in the previous section, we plot V/σ (taking inspiration from the signal-to-noise ratio) as a function of $\bar{n}_{LO}$ and $\bar{n}_s$ for different states of the LO field (coherent, thermal and single-mode squeezed vacuum states as well as heralded single-photon states from parametric down conversion (PDC) with and without photon-number-resolving detection for heralding) to compare them (see Fig. 2). We see that there is a significant advantage to having a single-photon-like state as well as photon-number-resolving (PNR) detection, as indicated by the performance of PDC with PNR heralding compared to all other approaches. The improvement arises from the reduction in multiphoton events from both the astronomical source and the LO, which do not carry information about the visibility. Further, the use of a single-photon state removes the probability that the LO is in the vacuum state, ensuring that useful information is obtained whenever a photon is collected by the telescopes. These results show that at low flux from the stellar source, PNR detection and non-classical states of light used as a reference field provide advantages for interferometric imaging.

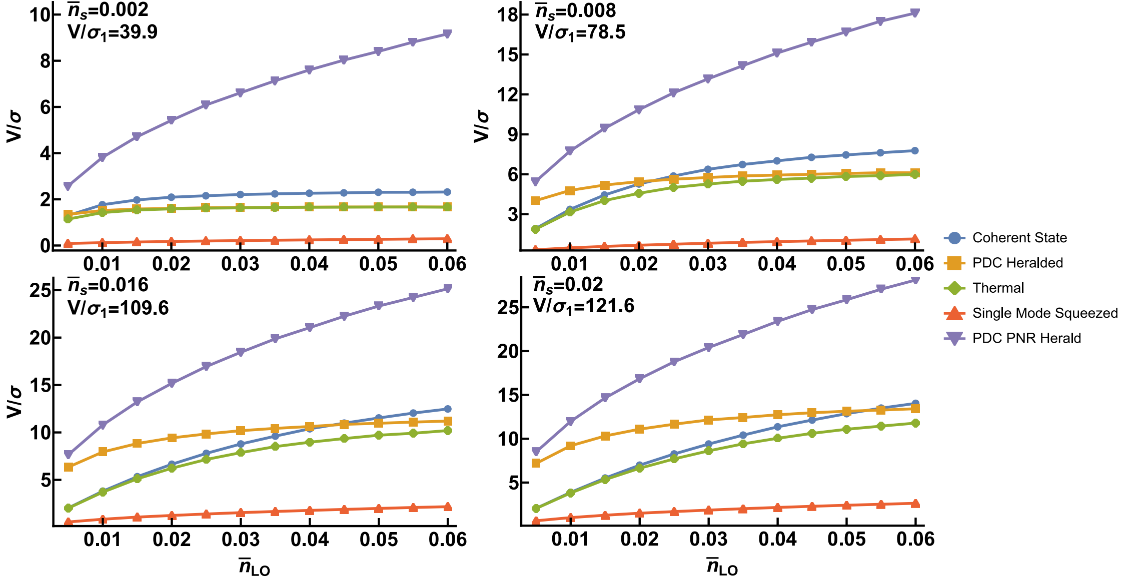

Fig. 2. V/σ vs $\bar{n}_{LO}$. Inset indicates $\bar{n}_s$ and V/σ for an ideal single-photon source with PNR detection.

[1] Michelson , A. A. and Pease, F. G.; "Measurement of the diameter of Alpha-Orionis by the interferometer," Proc. Natl. Acad. Sci. U.S.A. 7, 143 (1921).
[2] Mandel, L. and Wolf, E.; "Optical Coherence and Quantum Optics," (Cambridge University Press, Cambridge, England, 1995).
[3] C. H. Townes, in "Principles of Long Baseline Stellar Interferometry," edited by Peter Lawson (JPL, Pasadena, California, 2000), pp. 59–70.
[4] Brown, M.R., et al., "Interferometric Imaging Using Shared Quantum Entanglement," Phys. Rev. Lett. 131, 210801 (2023)
[5] Gottesman, D.; Jennewein, T. and Croke, S.; "Longer-baseline telescopes using quantum repeaters," Phys. Rev. Lett. 109, 070503 (2012)
[6] Tamimi, A., et al., "Fluorescence-detected Fourier transform electronic spectroscopy by phase-tagged photon counting," Opt. Express 28, 25194-25214 (2020).
[7] K.V. Mardia; "Statistics of Directional Data," (Academic Press, London, England, 1972).