

Emulating Quantum-enhanced Long-Baseline Interferometric Telescopy

David Diaz*, Yujie Zhang, Virginia O. Lorenz, and Paul G. Kwiat

Department of Physics, and Illinois Quantum Information Science & Technology Center
University of Illinois Urbana-Champaign, Urbana, IL 61801, USA

*davidd5@illinois.edu

Abstract: We demonstrate the underlying mechanism for quantum-enhanced telescopy, using multiple interconnected Hong-Ou-Mandel interferometers to recover the visibility amplitude and relative phase of the source light into multiple simulated telescopes. © 2021 The Author(s)

1. Introduction

The angular resolution of a telescopic system is limited by the size of the coherent aperture, where a greater size corresponds to a finer angular resolution. In practice, this is accomplished by creating larger telescopes, or alternatively, combining multiple telescopes in an array. The latter allows the user to create a very long baseline between detectors without having a singular massive detection system; telescopic systems using very long baseline interferometry (VLBI) have been able to obtain higher quality images of astronomical objects [1]. However, direct detection VLBI has greater difficulty for photons of higher frequency due to an increase in loss and a decrease in resolution of the photon's phase. A shared quantum state of a terrestrial photon and an astronomical one between two or more separate telescopes can circumvent this by detecting correlations across telescopes, measuring coincidences [2]. In essence, there is a quantum mechanical two-photon interference between the two processes in which the astronomical photon enters one telescope and the terrestrial photon goes to the other, and vice versa. Here, we discuss a design that allows us to recover the visibility \mathcal{V} of an extended source using this method, and present a proof-of-principle demonstration using photons from spontaneous parametric down-conversion (SPDC).

2. Experimental Design

The “terrestrial” and “astronomical” photons in our experiment originate from a beta barium borate (BBO) crystal via type-1, degenerate SPDC pumped with an ultrashort pulsed beam centered at 404 nm. The daughter photons produced are filtered such that they both have equal center wavelengths and bandwidths of 808 nm and 20 nm, respectively. The signal/idler arms represent the astronomical/terrestrial sources, as shown in Figure 1. The beam splitters on the top and bottom create an equal distribution of astronomical and terrestrial photons across each of the telescopes (three shown in Figure 1); the photons are then collected in silicon avalanche photodiodes connected to a single timetagger to measure coincidences between detectors at different telescopes. The added phases ϕ_{1-4} are created using liquid crystals and are used to simulate atmospheric turbulence, along with any controllable phase applied to our terrestrial photons. The coherence between the different telescope modes of an astronomical photon

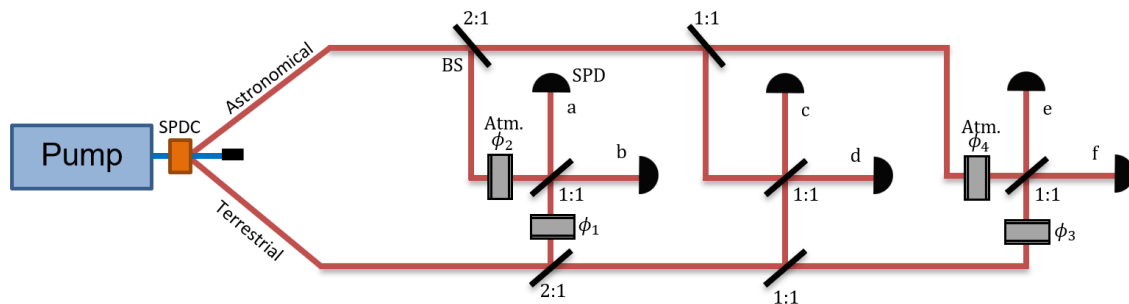


Fig. 1. Three-telescope experimental design. SPDC, spontaneous parametric down-conversion; BS, beam splitter with transmission:reflection ratio; SPD, single-photon detector.

can be simulated by adjusting the arrival times at the beamsplitters – only if the photon arrives *simultaneously* with a terrestrial photon will the underlying processes be indistinguishable and interfere coherently.

We consider how correlations arise by looking at just the first two telescopes and normalizing the counts. If the initial state is $|1\rangle_s |1\rangle_i$, the state after the final beam splitters is

$$|\psi\rangle = \frac{1}{4}(-\sqrt{2}ie^{i(\phi_1+\phi_2)}|2\rangle_a - \sqrt{2}ie^{i(\phi_1+\phi_2)}|2\rangle_b + \sqrt{2}i|2\rangle_c + \sqrt{2}i|2\rangle_d - 2e^{i\gamma}\cos(\delta)|1\rangle_b|1\rangle_d + 2e^{i\gamma}\sin(\delta)|1\rangle_b|1\rangle_c - 2e^{i\gamma}\sin(\delta)|1\rangle_a|1\rangle_d - 2e^{i\gamma}\cos(\delta)|1\rangle_a|1\rangle_c), \quad (1)$$

where $\gamma = \frac{\phi_1+\phi_2}{2}$ and $\delta = \frac{\phi_1-\phi_2}{2}$. This result shows the individual Hong-Ou-Mandel (HOM) interferences within the telescopes (i.e., both photons arriving at the same detector), along with the correlations and anti-correlations between the telescopes, defined by

$$P_{corr} = |\langle 1_a, 1_c | \psi \rangle|^2 = \frac{1}{8}(1 + \mathcal{V} \cos(\phi_1 - \phi_2)), \quad (2)$$

$$P_{acorr} = |\langle 1_a, 1_d | \psi \rangle|^2 = \frac{1}{8}(1 - \mathcal{V} \cos(\phi_1 - \phi_2)), \quad (3)$$

where \mathcal{V} is 1 if the photons are truly indistinguishable and arrive simultaneously at the final beam splitters.

3. Results and Discussion

Each interferometer is arranged to be at the HOM dip (i.e., equal path lengths for the two photons to reach each final beam splitter) to see such interference fringes between them. A change in phase between the telescopes produces fringes in the correlation and anti-correlation coincidences. Figure 2a(b) shows (anti-)correlation fringes between detectors a and c(d), shown in Figure 1, as the phase is allowed to drift in time. We are currently working to minimize this uncontrolled phase drift, so that we can model the atmospheric turbulence (ϕ_2 and ϕ_4) with the liquid crystals. The goal is to optimally recover the amplitude of the visibility and the closure phase between the three telescopes, using discrete terrestrial phase delays (ϕ_1 and ϕ_3) within a coherent turbulence time window.

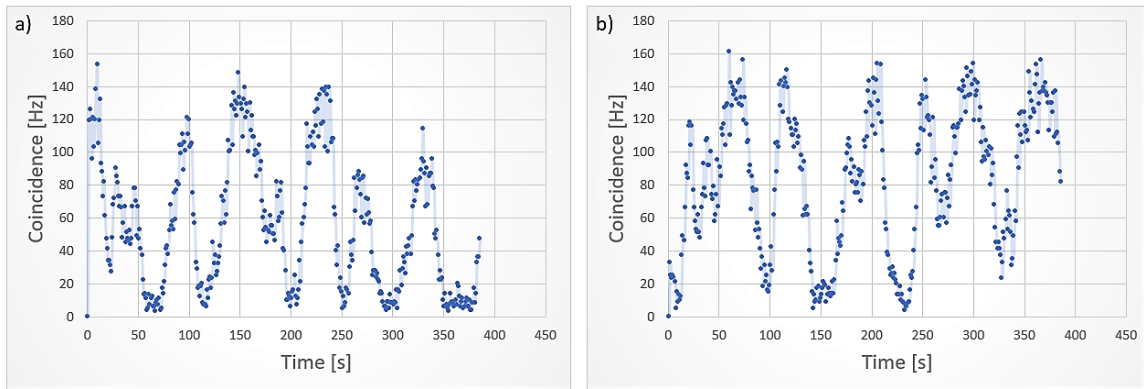


Fig. 2. Coincidence counts between a) Detectors a and c, or b) Detectors a and d, in Figure 1, as the relative phases drift over time. Note that the fringes are π out of phase.

In this proof-of-principle demonstration the astronomical photons were conjugate SPDC partners to the terrestrial ones, greatly solving the issue of spectral-temporal mode-matching; however, this same design can be used to measure a thermal source input to the astronomical arm. Although we can use this to measure a thermal source, this would also greatly increase our required collection time, since we would need to heavily filter the system (the photon bandwidths must be less than the inverse of the detector timing jitter, to observe the desired two-photon interference between photons from independent sources), resulting in a significant decrease in our terrestrial coincidence rates.

References

1. The Event Horizon Telescope Collaboration *et al* 2019 *ApJL* **875** L1.
2. D. Gottesman, T. Jennewein, and S. Croke, Longer-baseline telescopes using quantum repeaters, *Phys. Rev. Lett.* **109**, 070503 (2012).