Emulating Turbulence Free Quantum-enhanced Interferometric Telescopy

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Abstract: We demonstrate the underlying mechanism for one version of quantum-enhanced telescopy, using multiple interconnected Hong-Ou-Mandel interferometers to recover the visibility amplitude of the source of light in the presence of arbitrary turbulence.

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. This can be accomplished by creating larger telescopes, or alternatively, simulating a larger telescope by combining multiple 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. However, direct detection VLBI has greater difficulty for photons of higher frequency, e.g., visible photons, due to increased transmission losses in optical fibers at these wavelengths, and the inability to directly record the electric field at optical frequencies (in contrast with radio telescopes, whose signals can be recorded electronically and subsequently 'interfered', as with the Event Horizon Telescope [1]). Gottesman, Jennewein and Croke proposed to circumvent this limitation by detecting correlations across telescopes, each fed by a superposition of an astronomical photon and a terrestrial one (with a controllable relative phase between the telescopes) [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. The variation in the interference visibility as a function of telescope baseline separation determines the mutual coherence of the source at the two telescopes, which in turn, via the Van Cittert-Zernike theorem, allows one to determine the intensity distribution of the light source [3]. Here we present a proof-of-principle demonstration using photons from spontaneous parametric down-conversion (SPDC).

2. Experimental Model

The "terrestrial" and "astronomical" photons in our experiment originate from a 0.6-mm-long beta barium borate (BBO) crystal via type-I phase-matched SPDC into an opening angle of $\sim 3^\circ$. The crystal is pumped by a TiSa

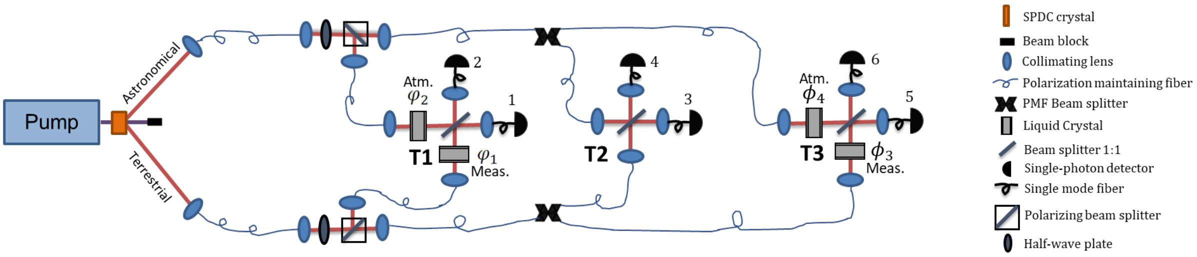

Fig. 1. Three-telescope experimental design. The pump consists of a TiSa pulsed laser centered at a wavelength of 810 nm doubled to 405 nm. This pumps a beta barium borate (BBO) crystal for SPDC with type-I phasematching. The photons from each path are collected into polarization maintaining fiber (PMF) and distributed to three "telescopes" via half-wave plates, polarization beam splitters and fiber beam splitters. Two of the telescopes contain liquid crystals to simulate atmospheric turbulence and apply the measurement scheme via induced phases $\{\phi_1, \phi_2, \phi_3, \phi_4\}$, where the last telescope is set as a reference phase.

laser centered at 810 nm with a repetition rate of 80 MHz and a 62-fs pulse width, doubled to 405 nm using a 0.6-mm-long bismuth borate (BiBO) crystal. The signal/idler arms represent the astronomical/terrestrial sources. The photons are collected into polarization maintaining fibers; a combination of half-wave plates, polarizing beam splitters and fiber beam splitters is then used to direct the photons to the various ”telescopes” (see Fig. 1). The photons are then subjected to a phase change via liquid crystals as they arrive to the telescopes. The astronomical arm has liquid crystals in its path to simulate turbulence, whereas the terrestrial path’s liquid crystals are used to impose discrete phase settings, optimized to recover the visibility amplitude of the source. This should allow us to obtain data to the same level of accuracy as continuously scanning over a fringe, for a set amount of N data points.

The longitudinal coherence between the different telescope modes of an astronomical photon 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. Our experiment thus requires us to equalize the paths for a given telescope, in order to see the desired interference effects. We can understand how correlations arise by considering just the first two telescopes. If the initial state is composed of one photon from the “astronomical” source and one photon from the “terrestrial” source $|1\rangle_a |1\rangle_t$, the state after the final beam splitters and at detectors $\{1,2,3,4\}$ is

$$\begin{aligned} |\psi\rangle \quad = \quad & \frac{1}{4}(-\sqrt{2}ie^{i(\phi_1+\phi_2)}|2\rangle_1 - \sqrt{2}ie^{i(\phi_1+\phi_2)}|2\rangle_2 + \sqrt{2}i|2\rangle_3 + \sqrt{2}i|2\rangle_4 \\ & -2e^{i\gamma}\cos(\delta)|1\rangle_1|1\rangle_3 + 2e^{i\gamma}\sin(\delta)|1\rangle_1|1\rangle_4 - 2e^{i\gamma}\sin(\delta)|1\rangle_2|1\rangle_3 - 2e^{i\gamma}\cos(\delta)|1\rangle_2|1\rangle_4), \end{aligned} \tag{1}$$

where $\gamma \equiv \frac{\phi_1+\phi_2}{2}$ and $\delta \equiv \frac{\phi_1-\phi_2}{2}$. This result shows the individual Hong-Ou-Mandel (HOM) interference within each telescope (i.e., both photons arriving at the same detector, top line in Eq. (1)), along with the correlations and anti-correlations between the telescopes, e.g.,

$$P_{corr} \quad = \quad |\langle 1_2, 1_4|\psi\rangle|^2 = \frac{1}{8}\left(1 + \mathscr{V}\cos(\phi_1 - \phi_2)\right), \tag{2}$$

$$P_{acorr} \quad = \quad |\langle 1_2, 1_3|\psi\rangle|^2 = \frac{1}{8}\left(1 - \mathscr{V}\cos(\phi_1 - \phi_2)\right). \tag{3}$$

Here, $\mathscr{V} = 1$ if the photons are truly indistinguishable (i.e., if the modes entering the telescopes are coherent with each other). As each interferometer is arranged to have equal path lengths for the two photons to reach each final beam splitter, a change in phase between the telescopes produces fringes in the correlation and anti-correlation coincidences.

3. Discussion

For this proof-of-principle experiment our “astronomical” photons were generated to be coincident with and identical to our terrestrial photons. However, the same quantum mechanical interference would occur if the astronomical photons had instead been generated by a weak thermal light source with the same bandwidth. Our testbed also allows us to explore other methods relevant to the quantum telescopy problem. For example, the measured fringe visibility will be reduced if there is different coupling into the telescopes; using the waveplate and polarizing beamsplitter, we can match this imbalance on the terrestrial photon, recovering full interference visibility (up to the coherence of the telescope input modes). We can also investigate the use of > 2 telescopes to implement “closure phase” methods, which allow one to extract not only the magnitude of the mutual coherence (the interference visibility) but also the *phase* information as well.

References

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