Proof-of-Principle Laboratory Demonstration of Long-Baseline Interferometric Imaging Using Distributed Single-Photons

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Abstract: We report results of very-long-baseline interferometric imaging using distributed single photons. We demonstrate source autocorrelation reconstruction, and increased signal-to-noise ratio per detected coincidence compared to using classical states as phase reference.

1. Introduction

Quantum networks offer many promising applications: secure communication [1], distributed quantum computing [2], and distributed clocks [3]. Recently, applications of quantum networks in distributed astronomical imaging have been of considerable interest [4-6]. In their original proposal, Gottesman et al. (GJC) suggested that distribution of quantum resources—a single path-entangled photon—between telescopes will increase both the distance between telescopes for visible spectrum imaging, and the sensitivity for low-flux measurements compared to classical methods [4].

Particularly the idea of very-long-baseline interferometry (VLBI) is the application of two principles: the van Cittert-Zernike theorem (the Fourier transform of the normalized intensity distribution of a light source is equal to the mutual coherence function in the far field) and aperture synthesis (using coherent detection, one can create an effective telescope using multiple smaller telescopes with resolution proportional to the distance between the telescopes). In the radio regime, aperture synthesis is achieved by direct detection of the electromagnetic field. However, in the visible spectrum, no such detectors exist; so, one must resort to using interferometers that interrogate the mutual coherence between different paths of the light, equating the visibility parameterized by the baseline to the mutual coherence function. This becomes infeasible for dim sources as 1 km of fiber already results in 50% loss of the incoming light in the visible spectrum. Exploring the benefits of the two schemes, Tsang showed that the GJC scheme has half the useful detection rate compared to direct interference of each telescope on a beam splitter (BS) [6]. Nevertheless, by using quantum repeaters, a single photon can be transported over long distances with considerably less loss than in a direct fiber link, creating a strict advantage when dealing with long baselines. Further, the single photon acting as a non-local phase reference is not shot-noise limited like classical states, eliminating the need for traditional local oscillators.

2. Experimental Details

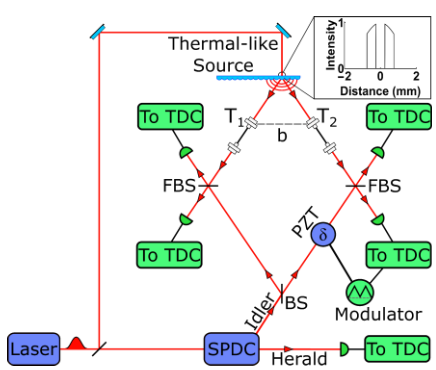

Fig. 1: A pulsed laser pumps both an SPDC and a thermal-like source which are used for laboratory long-baseline imaging as proposed by GJC.

GJC proposed splitting a single-photon reference state along two individual paths (one with a controllable phase, represented by δ) to each telescope. Each telescope collects light from a stellar source and interferes it with the non-local photon at a 50:50 beam splitter (BS) [4]. To generate a single-photon state we use type-II, spontaneous parametric down conversion (SPDC) to produce pairs of spectrally separable photons in a potassium di-hydrogen phosphate (KDP) crystal (see Fig. 1) [7]. The photons are separated using a polarizing BS and coupled into single-mode fibers. Detection of one photon is used to herald its twin, which is sent to a 50:50 BS to produce the single-photon path-entangled reference state. To create a time-dependent controllable phase, one path contains a piezoelectric translator (PZT) which changes the relative lengths of the two paths. The PZT is driven with a triangle wave at a frequency of 600 Hz and has an amplitude corresponding to 4π of phase. A square pulse is sent to a time-to-digital converter (TDC) at the start of each period. Each path is guided to separate fiber beam splitters (FBS).

To simulate a star in the laboratory, part of the pump laser pulse is propagated with a known transverse intensity profile to a rotating diffuser followed by a linear polarizer to create a thermal-like state ($g^{(2)}(0)$=1.93±0.03) with a near-Lambertian angular scattering distribution. The diffuse light propagates for 1 m to a 50:50 BS, with each output monitored with a bare, single-mode fiber that forms the telescope. One fiber is translated across the wavefront, sampling over a 6.2-mm range in 0.01-mm steps, while the other fiber remains at a fixed position. Each fiber (T1 and T2 in Fig. 1) receives an average of 0.0038 photons per pulse and connects to the remaining input port of one FBS. The outputs of the FBSs and the fiber collecting the herald photon are monitored with superconducting nanowire single-photon detectors and a TDC. To ensure temporal overlap, Hong-Ou-Mandel interference is found by monitoring the coincidences of each FBS while changing the relative delays of each input [8].

The collected coincidences are filtered so that only coincidences (these can be either heralded or unheralded) between different paths are considered. The probability of such a coincidence is given by

$$P(|\mathrm{v}|, \delta, \phi) = (1 \pm |\mathrm{v}| \cos(\delta - \phi))/2, \tag{1}$$

where |v| and ϕ are the magnitude and phase of the complex visibility at a given baseline respectively, and phase gained from transmission or reflection at the beam splitters determines the sign. Finally, the phase (δ_j) applied for each coincidence count can be measured given the relative timing to the PZT position. The phasor ($e^{i\,\delta_j}$) is averaged over many events to retrieve the visibility [9].

3. Data & Results

A double slit source was created using two 0.5 mm-wide slits separated by 1 mm. For each baseline position, the absolute value of the visibility was measured ten times. The average of each measurement is shown in Fig. 2a) for unheralded and heralded data and their fit to theory. Note that the visibility is much higher for the heralded case where the single-photon nature of the local oscillator does not include shot noise. A reconstruction of the source intensity distribution autocorrelation via Fourier transform of the visibility squared is shown in Fig. 2b). Here the separation of the side peaks from the main peak shows the separation of the slits, while the half width of the side peak shows the width of an individual slit. In Fig. 2c), the signal-to-noise ratio per coincidence event is shown for each baseline value, confirming that more information was gathered per event in the heralded case compared to unheralded. In summary, we have shown reconstruction of the source intensity distribution autocorrelation, a strict advantage of a non-local oscillator over a classical local oscillator scheme, and an important application of a future quantum network allowing for longer baselines in visible wavelength VLBI.

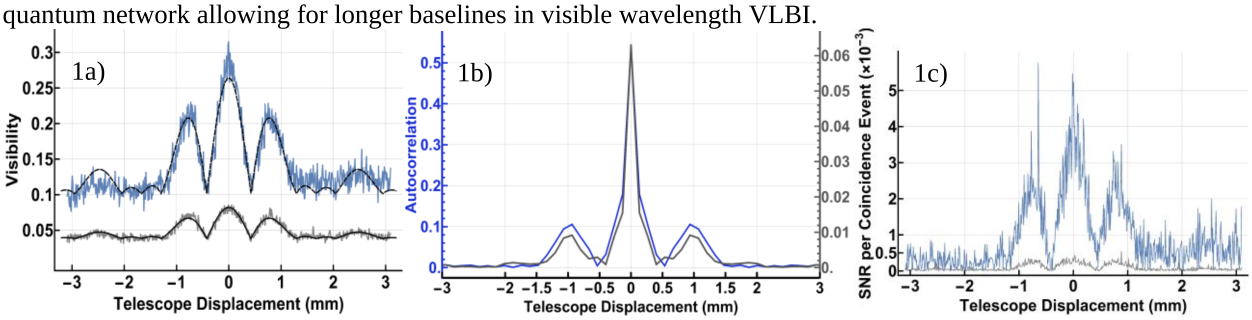

Fig. 2: a) visibility vs baseline, b) source distribution autocorrelation, and c) SNR per coincidence event. Blue(grey) is (un)heralded; black represents fitted theory curves.

[1] Thalacker, C., et al. “Anonymous and secret communication in quantum networks.” New J. Phys. 23, 083026 (2021)
[2] Broadbent, A; Fitzsimons, J; Kashefi, E. “Universal Blind Quantum Computation.” 50th Annual IEEE Symposium on Foundations of Computer Science, 517–526 (2009).
[3] Kómár, P. et al. "A quantum network of clocks." Nature Physics. 10, 582–587 (2014).
[4] Gottesman, D.; Jennewein, T.; and Croke, S., “Longer-baseline telescopes using quantum repeaters.” Phys. Rev. Lett. 109, 070503 (2012)
[5] Khabiboulline, E. T. et al, “Quantum-assisted telescope arrays.” Phys. Rev. A 100, 022316 (2019).
[6] Tsang, M. “Quantum nonlocality in weak-thermal-light interferometry.” Phys. Rev. Lett. 107(27), 270402 (2011).
[7] Mosely, P. J., et al. “Heralded Generation of Ultrafast Single Photons in Pure Quantum States.” Phys. Rev. Lett. 100, 133601 (2008)
[8] C. K. Hong, Z. Y. Ou, and L. Mandel, “Measurement of subpicosecond time intervals between two photons by interference,” Phys. Rev. Lett. 59, 2044–2046 (1987).
[9] Tamimi, A., et al., “Fluorescence-detected Fourier transform electronic spectroscopy by phase-tagged photon counting.” Opt. Exp. 28, 25194-25214 (2020).