Longer-Baseline Telescopes Using Quantum Repeaters

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(Received 25 October 2011; revised manuscript received 22 May 2012; published 16 August 2012)

We present an approach to building interferometric telescopes using ideas of quantum information. Current optical interferometers have limited baseline lengths, and thus limited resolution, because of noise and loss of signal due to the transmission of photons between the telescopes. The technology of quantum repeaters has the potential to eliminate this limit, allowing in principle interferometers with arbitrarily long baselines.

DOI: 10.1103/PhysRevLett.109.070503 PACS numbers: 03.67.Pp, 07.60.Ly, 42.50.Ex, 95.55.Br

The two primary goals for a telescope are sensitivity and angular resolution. Interferometry among telescope arrays has become a standard technique in astronomy, allowing greater resolving power than would be available to a single telescope. In today's IR and optical interferometric arrays [1,2], photons arriving at different telescopes must be physically brought together for the interference measurement, limiting baselines to a few hundred meters at most because of phase fluctuations and photon loss in the transmission. Improved resolution would, if accompanied by adequate sensitivity, have many scientific applications, such as detailed observational studies of active galactic nuclei, more sensitive parallax measurements to improve our knowledge of stellar distances, or imaging of extra-solar planets.

The field of quantum information has extensively studied the task of reliably sending quantum states over imperfect communications channels. The technology of quantum repeaters [3] can, in principle, allow the transmission of quantum states over arbitrarily long distances with minimal error. Here we show how to apply quantum repeaters to the task of optical and infrared interferometry to allow telescope arrays with much longer baselines than existing facilities. The traditional intended application for quantum repeaters is to increase the range of quantum key distribution, but the application to interferometric telescopes has more stringent demands in a number of ways. Quantum repeaters are still under development, and our work provides a new goal for research in that area. It sets a new slate of requirements for the technology, but simultaneously broadens the appeal of successfully building quantum repeater networks.

We begin by reviewing the standard approach to optical and infrared interferometry, known as "direct detection", [1,2] but we will treat the arriving light quantum-mechanically. The light is essentially in a weak coherent state, but the average photon number per mode is much less than 1, so two-photon events are negligible. Therefore, we assume the incoming wave consists of a single photon. We consider first an idealized set up with two telescopes and no noise, as in Fig. 1.

Depending on the orientation of the "baseline" (the relative position of the telescopes in the interferometer), the light has a relative phase shift ϕ between the two telescopes L and R, resulting in the state

$$|0\rangle_L|1\rangle_R + e^{i\phi}|1\rangle_L|0\rangle_R, \quad (1)$$

with $|0\rangle$ and $|1\rangle$ indicating 0 and 1-photon states. If we measure ϕ with high precision, that tells us the source's location very precisely. ϕ is proportional to the baseline, so

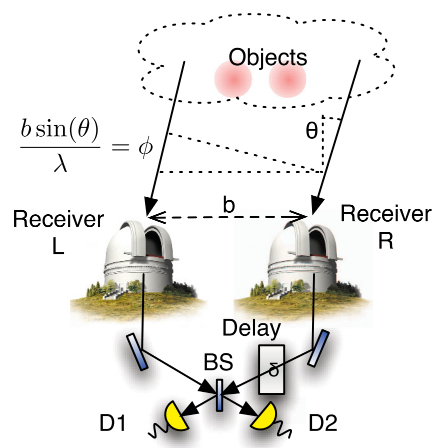

FIG. 1 (color online). Basic setup of a direct-detection interferometer. In the arrangement pictured, light travels an additional distance $b\sin\theta$ to reach telescope L rather than telescope R. For light with wavelength λ, the extra distance imposes a phase shift $\phi = (b\sin\theta)/\lambda$ at telescope L relative to telescope R.

longer baselines produce a more accurate measurement of the source's position.

Often we are interested in sources that have structure on the scale we can resolve with the interferometer. Different locations on an astrophysical source usually emit light incoherently, so the light is in a mixed state, formed by a mixture of photons from different locations on the source. Because different locations give different phase shifts ϕ, the off-diagonal components of the density matrix decrease. We get a density matrix of the form

$$\rho = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & \mathcal{V}^* & 0 \\ 0 & \mathcal{V} & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (2)$$

in the basis $|0\rangle_L|0\rangle_R$, $|0\rangle_L|1\rangle_R$, $|1\rangle_L|0\rangle_R$, $|1\rangle_L|1\rangle_R$. $\mathcal{V}$ is known as the "visibility." $\mathcal{V}(\vec{b})$ is a function of the baseline vector between the telescopes.

The light from the two telescopes is then brought together. The light from telescope R is subjected to an additional delay relative to the light from L so that when the photons are combined in the interferometer, the path travelled by an L photon differs from the path of an R photon by less than the coherence length of the incoming light. The delay line is adjustable, producing a known phase δ for the light from telescope R. In Fig. 1, the light then enters a beam splitter. We see the photon in output port 1 with probability $[1 + \mathrm{Re}(\mathcal{V}e^{-i\delta})]/2$, and in output port 2 with probability $[1 - \mathrm{Re}(\mathcal{V}e^{-i\delta})]/2$. By sweeping through different values of δ, we can measure both the amplitude and the phase of $\mathcal{V}$.

A single pair of telescopes with a fixed baseline does not produce enough information to reconstruct the original source brightness distribution, but an array of telescopes with many different baselines acquires much more information. The van Cittert–Zernike theorem [4] states that the visibility (as a function of baseline) is the Fourier transform of the source distribution. Thus, if we could measure the visibility for all baselines, we could completely image the source. With only a limited number of baselines, the discrete Fourier transform may nonetheless give a good approximation of the source brightness distribution.

There are two major difficulties involved in implementing the setup described in Fig. 1. First, if the telescopes are ground based, density fluctuations in the atmosphere modify the relative phase shift between the telescopes. The phase noise is large enough to completely swamp the signal. Our proposal suffers from this problem just as do direct-detection interferometers, and the same solutions to it apply. For instance, one can use space-based telescopes, perform phase referencing to recover the original phase information, or, in an array of many telescopes, calculate closure phases, which combine the interference results from different pairs of telescopes to cancel out telescope-specific phase shifts due to atmospheric fluctuations or other causes [1].

The second problem is that it is difficult to transport single photons over long distances without incurring loss of photons and additional uncontrolled phase shifts. For instance, slight variations in path length due to vibrations or small misalignments of the optical elements both produce reduced interference fringes. The signal we wish to measure is the amount of interference—for instance, a point source should have complete constructive and destructive interference, while a uniformly bright field of view should have no interference at all. Since many different error mechanisms also cause a reduction in the interference visibility, this is a serious problem. Loss of photons can present a severe limitation on the array's sensitivity to faint sources. In practice, these problems limit the baseline size of interferometers using direct detection. Today's best optical and infrared interferometers use baselines of only a few hundred meters at most. This is the problem we wish to address.

The task of transporting quantum states reliably has been intensively studied in the field of quantum information. For the specific task of interferometry, we suggest using a "quantum repeater" [3,5]: Instead of sending a valuable quantum state directly over a noisy quantum communications channel, instead create a maximally entangled state [6] such as $|01\rangle + |10\rangle$, and distribute that over the channel. The entangled state is known and replaceable, so we can check to see that it has arrived correctly. If it has, then we transmit the original quantum state using a technique known as "quantum teleportation" [7].

For an interferometric telescope, it is not necessary to perform the teleportation explicitly; we can use the entangled pair directly to measure the visibility, as in Fig. 2. We now have two separate interference measurements, one at each telescope. We postselect on the measurement results, considering only the case where we see one photon at telescope L and one photon at telescope R. One of these photons has come from the astronomical source, and one has come from the entangled pair, but we have no way of knowing which is which. We refer to them as the "astronomical" photon and the "lab" photon, respectively. On

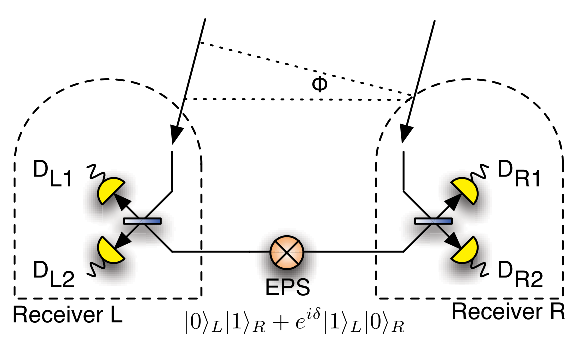

FIG. 2 (color online). Performing an interference measurement between two telescopes using an entangled state emitted from a central entangled photon source (EPS).

each side, there are two detectors, and the probability of seeing a photon at the two detectors is equal. The signal we wish to measure is contained not in the number of photons seen at any given detector, but in the correlation between which L detector clicks and which R detector clicks.

Again, we assume the state of the astronomical photon is given by Eq. (2). The variable delay line is now applied to the entangled state when the photon is sent to L, producing the entangled state $|0\rangle_L|1\rangle_R + e^{i\delta}|1\rangle_L|0\rangle_R$. Note that the interference measurement at detector L occurs slightly later than the interference measurement at R. When we postselect, we insist that the observed photons be displaced by precisely this time delay, with an uncertainty given by the coherence length of the photons.

Half the time, both photons arrive on the same side. We discard those cases. We lump together pairs of outcomes where there is one photon on each side. The total probability of seeing a correlation ($L1$, $R1$ or $L2$, $R2$), conditioned on having one click at each telescope, is $[1 + \mathrm{Re}(\mathcal{V}e^{-i\delta})]/2$, and the total probability of seeing an anticorrelation ($L1$, $R2$ or $L2$, $R1$) is $[1 - \mathrm{Re}(\mathcal{V}e^{-i\delta})]/2$. The measurement of correlation vs anticorrelation thus provides the same information as the two outputs of the beam splitter in a direct-detection experiment.

Figure 2 can be interpreted as a postselected teleportation at R followed by an interference experiment at L. The beam splitter and photo-detectors at R implement a measurement with projectors $|0\rangle_A|1\rangle_E \pm |1\rangle_A|0\rangle_E$, where the subscript A denotes an astronomical photon mode and E denotes a mode of the entangled photon. When 0 or 2 photons arrive at R, the teleportation fails and we discard the state, but when 1 photon is detected at R, we succeed in teleporting the arriving A state to L, where it is interfered with the A mode arriving at L. Of course, the diagram is completely symmetric, so we can equally well consider it as teleporting the state from L to R.

In principle, the sensitivity of an entangled-state interferometric telescope can be similar to that of a direct-detection interferometer, but there are a number of significant technological barriers to achieving the same level of sensitivity, even without a quantum repeater. We need a high-rate true single-photon source [8,9] which puts out exactly one photon per field mode to produce the entangled states, and very fast detectors to allow a large bandwidth. Furthermore, 50% of the light will be lost in the scheme of Fig. 2, corresponding to cases where the astronomical photon and entangled photon arrive at the same telescope. The loss can be reduced to $1/n$ for an array of n telescopes by using a "W" state as the entangled state, consisting of a single photon split coherently between the n telescopes. These and other issues relating to implementation of the scheme are discussed in more detail in the supplemental material [10].

Our scheme's advantage is that it allows extending the baseline of interferometers well beyond what is currently possible. There is a substantial body of research investigating how to create entangled states shared by faraway sites [3], and our scheme allows us to apply those techniques to the problem of creating long-baseline interferometers.

A quantum repeater can help us establish an entangled state at the two telescope locations by reducing two common types of noise. The first challenge is phase noise, often due to path length variation in the interferometer. Active stabilization of path lengths can substantially reduce phase noise [11]. Another solution to phase noise is entanglement distillation [12], a protocol which takes a number of noisy entangled states as input and outputs a smaller number of less-noisy entangled states. Active stabilization can be applied equally to direct-detection or entangled-state interferometry, but entanglement distillation is only available for entangled-state interferometry. The second challenge is loss of photons, under which only a fraction of the entangled states that are sent are received. One well-known scheme to reduce loss is due to Duan *et al.* [13]. In that scheme, two atomic clouds are entangled in a "heralded" way, meaning we have a measurement that tells us when the entanglement has succeeded despite the loss during transmission. We continually attempt to generate entanglement between the atomic clouds, and once we succeed, we can store it until it is needed. We discuss repeater protocols further in the supplemental material [10].

Building on the basic quantum repeater protocols, one could build a network of quantum repeaters to create entangled states shared between arbitrarily distant points [5]. Repeater stations are positioned at a modest distance from each other, so that transmission errors and loss between neighboring stations are correctable via the repeater protocols described above. We can create entangled pairs shared between neighboring repeaters, then join together multiple entangled states as in Fig. 3, using entanglement swapping [14] to create an entangled state between any pair of nodes in the network.

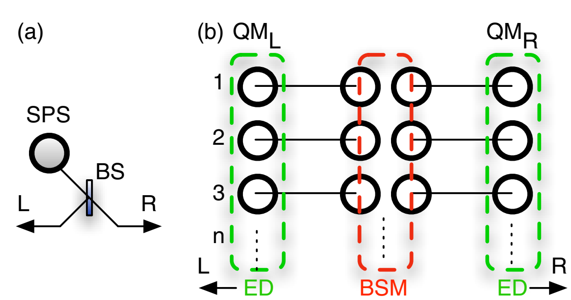

FIG. 3 (color online). Creating shared entanglement. (a) shows the simplest scenario: pass one single photon through a beam splitter and send the resulting entangled modes to the receivers. (b) In a quantum repeater, a series of quantum relays entangles several entangled photon pairs via a Bell-state measurement (BSM), and uses entanglement distillation (ED) to extract high-quality entanglement between distant receivers.

Our protocol is a very demanding application of quantum repeater networks. In order to get a sense for the required photon rates and the sensitivity, we define a figure of merit $s = rp\Delta\lambda$. r is the rate of entangled states output by the repeater network, measured in entangled states per spatiotemporal mode ($0 \leq r \leq 1$). $\Delta\lambda$ is the optical bandwidth for the system, which requires the repeaters to produce entangled states of bandwidth $\Delta\lambda$, and constrains the speed of the detectors, which must distinguish between photons arriving at that bandwidth. p is the optical transmission and detection efficiency in the components of the system, not counting the 50% inherent transmission due to postselection. The rate of detected signal events (involving one astronomical photon and one lab photon) is equal to $s/2$ times the rate of astronomical photons per unit bandwidth hitting the telescopes, which is derived from the wavelength λ, the aperture size, and the magnitude of the star being observed.

We need to have more signal photons than dark counts, and enough photons arriving in an atmospheric fluctuation time (around 10 ms [1]) to measure the visibility. Assuming 1 m receiver apertures, $r = p = 0.5$ and $\Delta\lambda = 0.1$ nm at $\lambda = 800$ nm (corresponding to 1.5×10^{11} entangled photons per polarization per second), we have $s = 0.025$ nm. Then the system is sensitive to stars with apparent magnitude around 7.5. This is comparable to the sensitivity of today's CHARA interferometer array [15], which also uses 1 m telescopes. Today's repeater protocols are nowhere near capable of working at this bandwidth, nor can they achieve this rate of entangled-state production. Achieving this sensitivity with 30 km-long baselines (a hundredfold improvement over CHARA) would produce a very useful astronomical observatory. Even a somewhat lower sensitivity with baselines of this size would in some respects be an improvement over existing instruments, with better angular resolution but lower sensitivity.

We also want the quantum repeater output to have a high fidelity to the correct entangled state. In particular, if the quantum repeater occasionally produces two entangled states in the same mode, this leads to spurious detection events where the photons at L and R are both entangled photons. The effect is much the same as having dark counts, so the rate of double entangled-state production should be comparable to the rate of dark counts (say about 100 per second).

Let us compare our scheme to other interferometric techniques. Both intensity interferometry [16] and heterodyne interferometry [17,18] can achieve much longer baselines than direct-detection interferometry, and they are technically much easier than entangled-state interferometry. However, neither is sensitive enough to be generally applicable for interferometry in optical wavelengths except for the brightest sources, whereas entangled-state interferometry could be, if the technical hurdles we have discussed can be overcome. Both schemes are related to entangled-state interferometry, and we discuss the connections in the supplemental material [10].

In this Letter, we have primarily considered how distributed quantum entanglement can improve optical interferometry. For radio frequencies, interferometry can be performed robustly today even between telescopes spread across the planet. At optical frequencies, many fewer photons arrive per mode, making interferometry much more difficult. In telescope design, the arriving light is usually treated classically, but when the number of photons arriving is small, the quantum state of the light may become important. Thus, the field of quantum information is well-suited to provide advances.

Quantum repeaters have until now been under development primarily for use in quantum communications, so interferometry offers an interesting new venue for the application of quantum information techniques. As we have shown, quantum repeaters can completely lift the upper limit on distance over which it is possible to do interferometry, but a number of technical hurdles need to be overcome first. In particular, we need quantum repeater protocols capable of producing an extremely high rate of broadband entangled photons, as well as high efficiency photodetectors with fast time resolution. One additional requirement we have is that we would like to perform astronomy at a variety of optical frequencies; either the repeater protocols need to work at those frequencies or we need a way to shift the frequencies [19] of either the arriving light or the entangled photons.

Quantum information technology may offer even further significant applications to help improve astronomical observation, even beyond direct quantum detection techniques [20]. For instance, it may be advantageous to coherently store arriving photons using a quantum memory and then perform the quantum Fourier transform, rather than measuring and performing the classical Fourier transform. The quantum Fourier transform works reasonably well even with a small number of photons, whereas if we measure first, we need enough photons to get a reliable measurement of each phase.

We would like to thank Andy Boden, Latham Boyle, Avery Broderick, Jean-Philippe Bourgoin, Ignacio Cirac, Alexey Gorshkov, Liang Jiang, Jeff Kimble, Evan Meyer-Scott, Barry Sanders, and Cristoph Simon for helpful conversations. All authors acknowledge support by NSERC, by the Government of Canada through Industry Canada, and by the Province of Ontario through the Ministry of Research & Innovation. D. G. and T. J. are supported by CIFAR, and T. J. is supported by the Canadian Space Agency.

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