Reference frames in astronomical interferometry

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Abstract: We connect the reference frame problem in astronomical interferometry to the concept of decoherence-free subspaces in quantum information. Inspired by this connection, a new scheme that does not rely on reference frame is proposed.

In astronomical interferometry based on the van Cittert-Zernike theorem, photons from astronomical sources are collected by telescopes separated by long baselines and interfered to determine the degree of coherence between the telescopes [1]. One obvious difficulty in its implementation in the optical domain is transmission loss in combining the light from the distant telescopes, which has motivated measurement proposals that do not require direct interference. However, performing a measurement at two distant locations raises an important difficulty: the requirement of a shared phase reference frame. In this work we study the phase reference problem in astronomical interferometry in detail and present a new scheme that does not rely on reference frame.

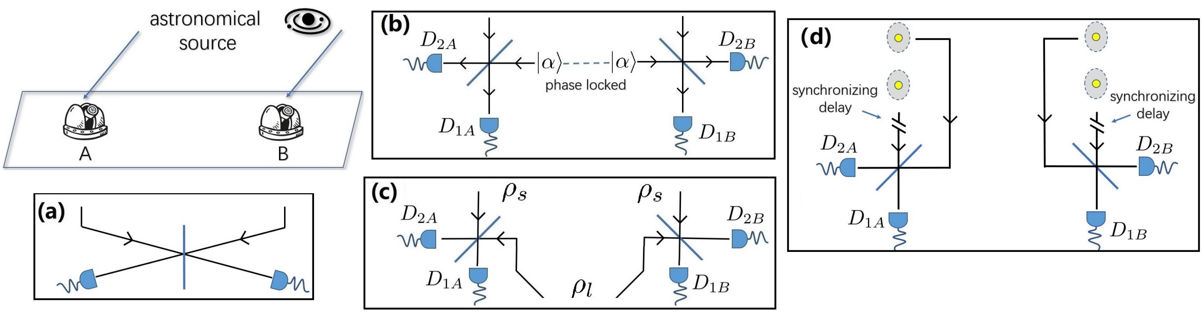

Fig. 1. Setups for different measurements in astronomical interferometry. (a) Directly combine the light from two telescopes to do interference. (b) Local measurement with shared phase reference frame. The dash line indicates the LOs in the two telescopes should be phase locked. The measurement is done by combining light from the astronomical source with a coherent state $|\alpha\rangle$ locally at each telescope on a beam splitter. (c) Measurement with a nonlocal resource. Distributing a lab photon ρ_l to two telescopes and combine with the state received from astronomical source ρ_s, where δ is a controllable phase delay. (d) Joint measurement to avoid requirement of a shared phase reference. The states received at two temporal modes $\rho_{s1,s2}$ are combined locally at each telescope on a beam splitter. Unlike intensity interferometry, temporal correlation is not required. So, the two photons come from different temporal modes.

We adopt the theoretical perspective related to reference frame reviewed in Ref. [2]. Consider the case in which each telescope has a local phase reference, where telescope B's phase reference frame differs from A's frame by a constant ϕ. In B's reference frame, any operation or state preparation performed at A will be transformed by operator $\hat{U}_\phi = e^{i\phi\hat{n}}$, where $\hat{n}$ is the total photon number operator. If the telescopes do not have a shared reference frame, then ϕ is unknown. The operation is then described as a mixture with all possible ϕ, which is mathematically equivalent to decoherence of bases with different photon number. To solve this problem, the phase reference system must be modified to extend the Hilbert space such that each term of the composite system has the same photon number, which is the internalization of reference frame. We discuss the role of reference frame in several existing proposals, shown in Fig. 1: (a) Combine the light from the two telescopes on a beam-splitter; the measurement is the projection onto state $|0_A 1_B\rangle + e^{i\delta}|1_A 0_B\rangle$ for the two modes at the two telescopes, where δ is an added phase delay. Since each term has the same photon number, no shared phase reference is required to do this measurement. (b) Project onto states $\hat{U}_{\delta_A}|\pm\rangle_A \otimes \hat{U}_{\delta_B}|\pm\rangle_B$, where $|\pm\rangle_{A,B} = (|0\rangle \pm |1\rangle)/\sqrt{2}$ is the superposition of vacuum and single photon states, through interference with a coherent state. Here, phase-locked lasers are used as a phase reference but require an optical feedback system that limits the baseline length [3]. (c) The proposed scheme of Ref. [4]: combine a lab photon in entangled state $\rho_l = \frac{1}{2}(|01\rangle + e^{i\delta}|10\rangle)(\langle 01| + e^{-i\delta}\langle 10|)$ with the state from the astronomical source ρ_s on beam-splitters. The distributed lab photon serves as a phase reference used in the two telescopes. The scheme of Ref. [5, 6] builds on this method by exploiting quantum memories to significantly reduce the required entanglement resources between two distant telescopes – this scheme implicitly assumes a shared phase reference, which requires additional resources.

The shared phase reference frames in the protocols above help to retrieve information from a decoherence-free subspace [7, 8]. However, if we use two source photons instead of just one, the information can be encoded in a decoherence-free subspace spanned by $\{|0_1 1_2\rangle, |1_1 0_2\rangle\}$ from the beginning, where subscripts 1,2 denote two different modes. The coherence between the two bases can thus be maintained without a shared phase reference frame [2]. To work in a decoherence-free subspace spanned by $\{|0_1 1_2\rangle, |1_1 0_2\rangle\}$, we can perform joint measurements on two temporal modes from the source, $\rho_{s1} \otimes \rho_{s2}$, where both ρ_{s1} and ρ_{s2} are the same state ρ_s received from the astronomical source, where $1, 2$ label the time at which they arrive at the telescope. We emphasize that this is different from Ref. [4], where one of the modes is a distributed state from the lab. This method is also different from intensity interferometry [9, 10], where the two modes are temporally correlated; here the different temporal modes have no temporal correlation. Quantum memories can be used to store the temporal modes so they can be synchronized and measurements can be performed on the two copies of the state at the same time. Local projective measurements at telescopes A and B can then be performed: $M = |\psi\rangle\langle\psi|$, $|\psi\rangle = \frac{1}{2}(|0_1 1_2\rangle_A + |1_1 0_2\rangle_A) \otimes (|0_1 1_2\rangle_B + |1_1 0_2\rangle_B)$. Notice each term of $|\psi\rangle$ has exactly one photon at telescope A and one at B. The measurement is hence not affected by the lack of knowledge of ϕ and no phase reference is required. This measurement can be implemented as shown in Fig. 1(d) by simply combining the two temporal modes on a beam-splitter. We find that the sensitivity of this method is the same as that of intensity interferometry by directly calculating the probability distribution of measurement outcomes. We emphasize that, when observing weak thermal sources commonly encountered at optical wavelengths, local schemes such as the one proposed above are not able to perform as well as a schemes that directly combine the source light or exploit entanglement resources as in Fig. 1(a,c), as pointed out in Ref. [11]. When the amplitude of the coherence function is small, our proposed scheme will also perform worse than local schemes with a shared phase reference as in Fig. 1(b), which is the cost of avoiding using a shared phase reference.

The above measurement only allows us to learn the amplitude of the coherence function. To further measure the phase information without a shared phase reference, we can similarly construct a measurement $M = |\varphi\rangle\langle\varphi|$ that uses three telescopes and three copies of the state, $\rho_s^{\otimes 3}$, where $|\varphi\rangle = \frac{1}{2^{3/2}}(|0_1 0_2 1_3\rangle_A + |0_1 1_2 0_3\rangle_A) \otimes (|0_1 1_2 0_3\rangle_B + |1_1 0_2 0_3\rangle_B) \otimes (|1_1 0_2 0_3\rangle_C + |0_1 0_2 1_3\rangle_C)$. This measurement allows us to obtain information about the closure phase $\theta_1 - \theta_2 + \theta_3$, where $\theta_{1,2,3}$ are the phases of the coherence functions between the three pairs of telescopes.

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