Quantum-Assisted Optical Interferometry

Some forward-looking ideas and works in progress

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https://www.quantastro.bnl.gov

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⟨BNL|â†|QIST⟩
Agenda

• The glories of interferometry
• Single-photon methods (classical)
• Two-photon methods (quantum mechanical)
• Quantum assist; futuristic ideas
• New: two-photon interference for precision astrometry
• Astrophysical applications
• Experiments in progress
Astronomy pictures of the day year decade

Radio source Cygnus A imaged at 6cm

Center of M87 imaged at 1.3mm
Single-photon techniques (classical)
In classical times

Michelson Stellar Interferometer at Mt. Wilson c. 1920, after original idea by Michelson & Fizeau c. 1890

Different sources yield *shifted* fringes
Each source \( i \) at sky position \( \theta_i \) produces a fringe shifted by phase amount \( \Delta \phi = 2\pi B \sin \theta_i / \lambda \).

Intensity pattern is sum over all sources \( \Leftrightarrow \) Fourier moment!

Fringe contrast (visibility) measures amplitude of Fourier moment at wavenumber \( k \approx 2\pi B / \lambda \).

\[
|V| = 1.0 \quad |V| = 0.5 \quad |V| = 0.1
\]
Each fringe observation measures *amplitude* and *phase* of Fourier moment along baseline vector at specific wavenumber.

Repeat for many different baselines/wavenumbers and invert to reconstruct original image.

(Note Earth rotation synthesis)

**Measurement at baseline** $B$

**sensitive to source features with angular size** $\Delta \theta \sim \lambda/B$
Radio $\bar{n} \gg 1$

Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline.

Optical $\bar{n} \ll 1$

One photon at a time! Need to bring paths to common point in real time.

Need path length *compensated* to better than $c/\text{bandwidth}$.

Need path length *stabilized* to better than $\lambda$. 

\[ D \cos \theta \]
\[ D \sin \theta \]
\[ \theta \]
\[ \Delta L \]
\[ B \]
\[ B \sin \theta \]
How cool is this?

Classical summary

All very well-known at Caltech/JPL! Owens Valley, Keck, etc.

- EM waves interfere with themselves; single photons do same
- Interferometer sensitive to features on angular scale $\Delta \theta \sim \frac{\lambda}{B}$
- Drawbacks in \textit{optical}:
  - Need live optical link between stations
  - Need path length control precision on order $\lambda^2/\Delta \lambda$
  - Atmospheric effects enter at $O(1)$
  - Need to control polarization during transport
  - Practical limit on baselines $\sim 100\text{m}$
Two-photon techniques *(quantum mechanical)*

**Prelude:** Two-photon Intensity Interferometry
The curious HBT effect

"The birth of quantum optics"

Glauber theory of photodetection, c. 1963

\[
\text{Rate}^{BC}(t_B, t_C) \propto \| \hat{a}_B(t_B) \hat{a}_C(t_C) \langle \Psi \rangle \|^2
\]

\[
\propto \| \hat{a}_A(t_B - L/v) \hat{a}_A(t_C - (L + \Delta L)/v) \langle \Psi \rangle \|^2
\]

If \( (t_B - L/v) = (t_C - (L + \Delta L)/v) = t_A \) then \( \text{Rate}^{BC}(t_B, t_C) \propto \| \hat{a}_A(t_A)^2 \langle \Psi_{Th} \rangle \|^2 \)

\[
\| \hat{a}_A(t_A)^2 \langle \Psi_{Th} \rangle \|^2 = 2 \| \hat{a}_A(t_A) \hat{a}_A(t_A') \langle \Psi_{Th} \rangle \|^2
\]

Coherence time and detector resolution

SNSPD at BNL
HBT and stellar sizes

In Hanbury Brown & Twiss (HBT) intensity interferometry, the observable is the correlation between photon detections at two separate detectors:

\[
\frac{(Pairs)}{(Singles)(Singles)} = \frac{\|\hat{a}_{k1}\hat{a}_{k2}|\Psi\rangle\|^2}{\|\hat{a}_{k1}|\Psi\rangle\|^2 \|\hat{a}_{k2}|\Psi\rangle\|^2} = \begin{cases} 1 & k_1 \neq k_2 \\ 2 & k_1 = k_2 \end{cases}
\]

Glauber theory of photodetection, c. 1963

(It works for other bosons, too.)
High ride of HBT, 1956-1974 ...and beyond?

Stellar intensity interferometer at Narrabri, Australia, 1968

Fig. 3. Examples of the observed variation of correlation with baseline for three stars. (a) β Cru (1965); (b) α Eri (1965); (c) α Car (1965).
HBT track record

• Advantages:
  • Separate stations with only classical connection
  • Arbitrary baselines, set by desired angular scale
  • No path-length corrections needed
  • Immune to atmospheric effects (at leading order)

•Drawbacks:
  • Low rates! Need to see coincident photon pairs, only pairs with $\Delta \nu \Delta t < 1$ will show effect; but more & finer spectral bins will help
  • Sensitive to square of image Fourier moment, washes out fine details
  • Used (thus far) mainly for gross features of bright objects
Two-photon techniques (quantum mechanical)

New: Two-Photon Amplitude Interferometry
Improved single photon interference?

\[ \Psi_{\text{Initial}} = \psi_1 \psi_2 = \frac{1}{2} (\hat{a}^\dagger + e^{i\delta_1} \hat{c}^\dagger)(\hat{b}^\dagger + e^{i\delta_2} \hat{f}^\dagger) \]

Sky photon  Ground photon

Beam Splitters

\[ \hat{a}^\dagger \rightarrow (\hat{c}^\dagger + \hat{d}^\dagger)/\sqrt{2} \quad \hat{b}^\dagger \rightarrow (\hat{c}^\dagger - \hat{d}^\dagger)/\sqrt{2} \]
\[ \hat{c}^\dagger \rightarrow (\hat{g}^\dagger + \hat{h}^\dagger)/\sqrt{2} \quad \hat{f}^\dagger \rightarrow (\hat{g}^\dagger - \hat{h}^\dagger)/\sqrt{2} \]

Output state:

\[ \Psi_{\text{Output}} = (1/4)(\hat{c}^\dagger \hat{c}^\dagger - \hat{d}^\dagger \hat{d}^\dagger + e^{i(\delta_1 + \delta_2)}(\hat{g}^\dagger \hat{g}^\dagger - \hat{h}^\dagger \hat{h}^\dagger) + (e^{i\delta_1} + e^{i\delta_2})(\hat{c}^\dagger \hat{g}^\dagger - \hat{d}^\dagger \hat{h}^\dagger) + (e^{i\delta_1} - e^{i\delta_2})(\hat{c}^\dagger \hat{h}^\dagger + \hat{d}^\dagger \hat{g}^\dagger)) \]

Probability:

\[ P(c^2) = P(d^2) = P(g^2) = P(h^2) = 1/8 \]
\[ P(cg) = P(dh) = (1/8)(1 + \cos(\delta_1 - \delta_2)) \]
\[ P(ch) = P(dg) = (1/8)(1 - \cos(\delta_1 - \delta_2)) \]
Two-photon amplitude interferometry

\[
\frac{N(cg) + N(dh) - (N(ch) + N(dg))}{N(cg) + N(dh) + N(ch) + N(dg)} = \cos(\delta_1 - \delta_2)
\]

New visibility observable:

\[
\frac{N(cg) + N(dh) - (N(ch) + N(dg))}{N(cg) + N(dh) + N(ch) + N(dg)} = \cos\left(\frac{2\pi \sin \theta b}{\lambda} - \delta_{\text{Ground}}\right)
\]

- Same measurement as single-photon interferometry, if ground photons are available
- Can be interpreted as quantum teleportation of sky photon from one station to the other
Let slip the quantum technology!

**Idea:** Capture and store sky photons in quantum memories, then teleport and measure as needed.

**Idea:** Efficient time-bin encoding of photon arrivals.

**Idea:** Use quantum Fourier transform (QFT) to directly invert pattern from array.
Two-photon spin-off technique

New: Two-Photon Amplitude Interferometry for Astrometry*

* Astrometry = measurement of positions of objects on the sky
HBT with two sources?

New idea: Coincident pair detections now sensitive to *phases* of incoming photons

Original motivation: gravitational waves
Idea: two photons from two sky sources

Topology is equivalent to GJC(2012) but now with both photons from the sky, and from different objects.

Sensitive to *difference* in path length differences opening angle!

Does *not* require live optical link between stations; can use arbitrary baseline.
Observable is the number/rate of coincidences $xy = \{cg, dh\}$ or $\{ch, dg\}$ at different stations. (Can do many spectral bins in parallel.)

Quantum mechanics (Fock state) version; quickie:

$$\langle N(xy) \rangle = \frac{k(S_1 + S_2)^2}{8} \left[ 1 \pm V_{2\text{PS}} \cos \left( \frac{2\pi B}{\lambda} (\sin \theta_1 - \sin \theta_2) + \frac{2\pi \Delta L}{\lambda} \right) \right]$$

Quantum field theory version; full:

$$N_{c}(xy) = \eta_1 \eta_2 A^2 \int_{0}^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau =$$

$$A^2 \eta_1 \eta_2 T_r \left[ (I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \pm \right.$$

$$\left. 2I_1I_2 \frac{\tau_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B(\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right) \right]$$
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\]

Quantum field theory version; full:

Base combinatoric pair rate

HBT enhancement

Oscillatory term (New!)

\[
\begin{align*}
N_c(xy) &= \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau = \\
&= A^2 \eta_1 \eta_2 T_r \left[ (I_1 + I_2)^2 + \frac{I_1^2 \tau_{c} g_{11}}{T_r} + \frac{I_2^2 \tau_{c} g_{22}}{T_r} \right] \\
&\pm 2I_1I_2 \frac{\tau_{c} g_{12}}{T_r} \cos \left( \frac{\omega_0 B (\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right)
\end{align*}
\]
Idea: Earth rotation fringe scan

\[ \langle N(xy) \rangle = \frac{k(S_1 + S_2)^2}{8} \left[ 1 \pm V_{2PS} \cos \left( \frac{2\pi B}{\lambda} (\sin \theta_1 - \sin \theta_2) + \frac{2\pi \Delta L}{\lambda} \right) \right] \]

This will evolve as the Earth rotates

\[ \langle N_{xy}(t) \rangle = \bar{N}_{xy} \left[ 1 \pm V \cos (\omega_f t + \Phi) \right] \]

Coincidence rates oscillate

\[ \omega_f = \frac{2\pi B \Omega_{\oplus} \sin \theta_0}{\lambda} \Delta \theta \]

Fringe oscillation rate is a direct measure of sources' opening angle!
Can measure with high precision
World-competitive precision

\[
\sigma[\Delta \theta] = \sqrt{\frac{6}{\pi^2 \kappa} \frac{1}{V} \frac{\lambda}{B} \frac{1}{T \Omega_\oplus \sin \theta_0} \frac{1}{\sqrt{\bar{n} T}}}
\]

\(\bar{n}\) = average pair rate
\(T\) = total observation time

A modest experiment:
- Bright stars, mag 2
- 1 m² collecting area
- 10⁴ seconds observation
- 0.15 nsec time resolution
- 10⁴ spectral channels

\(\sigma[\Delta \theta] \sim 10 \mu\text{as} \ (\sim 10^{-11} \text{ rad})\)

Idea: Dynamic Astrometry

Track day-over-day changes in \(\Delta \theta\) to observe parallax, proper motion, orbital motion, gravitational lensing

1 mas HIPPARCOS (1989-1993)
7 \(\mu\)as GAIA (2013-?)
Astrophysics topics in dynamic astrometry

• Parallax: improved distance ladder
• **Proper motions**: local dark matter patterns
• **Microlensing**, see motions and shape changes
• **Gravitational waves** at mid-frequency
• **Quantum applications**, e.g. quantum key distribution

Further ideas are encouraged!
Check: We can see HBT coincidence enhancement peak in all channel combinations.
Future detector requirements

• Two essential figures of merit:
  • Number of detectors/spectroscopic channels (more pairs)
  • Detector time resolution (wider spectroscopic bins, more pairs per detector)

• Fast pixel array (Timepix) + dispersive spectrograph (Echele?)
• Very fast single photon detectors – improved SNSPD?
Intensified camera is single photon sensitive

Quantum efficiency ~ 30%

A.Nomerotski, Imaging and time stamping of photons with nanosecond resolution in Timepix based optical cameras, NIM A 937 (2019) 26
Spectroscopic binning already demonstrated

In collaboration with NRC (Ottawa) D. England, Y. Zhang et al

\[ \delta \lambda \ast \delta t \sim 5 \text{ ns} \ast 0.5 \text{ nm} \]

Pump photon wavelength vs time difference


Just the beginning! A broad future program

- Observations with >2 receivers and >2 objects; phase closure?
- More complicated quantum states (GHZ, etc.)
- New kinds of entanglement distribution (polarization qubits, e.g.)
- Involvement of quantum memories to enhance pair rates; local expertise (SBU) with $^{87}$Rb vapor room-temp QM’s
- Atmospheric effect compensation
- On-sky experiments possible soon!
Points to take home

• Classical, single-photon interferometry reaches much higher resolutions, order milli-arcsec, than single telescopes; but practical issues limit maximum baselines

• Two-photon interferometry can permit independent stations over longer baselines; historical HBT is one example

• Two-photon techniques are in general quantum mechanical; new ideas suggest quantum technology can enhance interferometry

• One specific two-photon technique addresses dynamic astrometry, which will have interesting astrophysics applications

• There is a potentially broad program in quantum-assisted optical interferometry ahead
Backups
Hybrid pixel detectors

Have roots in R&D for LEP/LHC vertex detectors

- Decouple readout chip and sensor
- Optimize technologies for chip and sensor separately

Use different sensors with same readout, versatile approach for x-rays (Si, CZT)

→ we will use OPTICAL sensors
Timepix3 Camera → Tpx3Cam

Camera = sensor + ASIC + readout

Optical sensor with high QE developed at BNL
  • Sensor is bump-bonded to chip Timepix3

Timepix3 ASIC:
256 x 256 array, 55 x 55 micron pixel
  • 1.56 ns timing resolution
  • data-driven readout, 80 Mpix/sec, no deadtime