Quantum-Assisted Optical Interferometry

Some forward-looking ideas and works in progress

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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 and detectors
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
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 $k \approx 2\pi B / \lambda$

$|V| = 1.0$  $|V| = 0.5$  $|V| = 0.1$
Can literally record entire waveform, over some band, separately at each receiver station and interfere later offline.

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

Need path length *compensated* to better than $c/bandwidth$.

Need path length *stabilized* to better than $\lambda$. 
How cool is this?

Classical summary

- 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 $\sim 100$ m
Two-photon techniques *(quantum mechanical)*

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

"The birth of quantum optics"

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

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

If \((t_B - L/v) = (t_C - (L + \Delta L)/v) = t_A\)

then \(\text{Rate}^{BC}(t_B, t_C) \propto \| \hat{a}_A(t_A)^2 | \Psi_{Th} \rangle \|^2\)

\[
\| \hat{a}_A(t_A)^2 | \Psi_{Th} \rangle \|^2 = 2 \| \hat{a}_A(t_A) \hat{a}_A(t_A') | \Psi_{Th} \rangle \|^2
\]
In Hanbury Brown & Twiss (HBT) intensity interferometry, the observable is the correlation between photon detections at two separate detectors.

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

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
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?

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

Sky photon  Ground photon

Beam Splitters

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

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

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

\[
\frac{N(cg) + N(dh) - (N(ch) + N(dg))}{N(cg) + N(dh) + N(ch) + N(dg)}
\]

New visibility observable:

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

\[
= \cos\left(\frac{2\pi \sin \theta b}{\lambda} - \delta_{\text{Ground}}\right)
\]

- Same measurement as single-photon interferometry, if ground photons are available
- Can be interpreted as \textit{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:

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

Quantum field theory version; full:

\[
N_c(xy) = \eta_1 \eta_2 A^2 \int_0^{T_r} P_{L,R,\tau}^{\text{two photons}} d\tau = \\
A^2 \eta_1 \eta_2 T_r \left[ (I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \right] \pm \\
2I_1 I_2 \frac{\tau_c g_{12}}{T_r} \cos \left( \frac{\omega_0 B (\sin \theta_1 - \sin \theta_2)}{c} + \frac{\omega_0 \Delta L}{c} \right)
\]
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\]

Quantum field theory version; full:

Base combinatoric pair rate

HBT enhancement

Oscillatory term, fringe passing
Idea: Earth rotation fringe scan

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

This will evolve as the Earth rotates

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

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

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

\[\bar{n} = \text{average pair rate}\]
\[T = \text{total observation time}\]

A modest experiment:

- Bright stars, mag 2
- 1 m\(^2\) collecting area
- \(10^4\) seconds observation
- 0.15 nsec time resolution
- \(10^4\) 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 HIPPACOS (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!
Experiments and Detectors

What are we going to need?
Experiments in progress

Supported at BNL by DOE HEP
QuantISED grant 2020-21

Superconducting Nanowire Single Photon Detector (SNSPD) at BNL
Four channels at ~795nm
Experiments in progress

Supported at BNL by DOE HEP
QuantISED grant 2020-21

Check: We can see HBT coincidence enhancement peak in all channel combinations
Future detector requirement

• 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? Timing, QE, many channels

A. Nomerotski, SPIE (2020)
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

\[ \delta \lambda \star \delta t \approx 5 \text{ ns} \times 0.5 \text{ nm} \]

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.
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Backups
Each fringe observation measures \textit{amplitude} and \textit{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 $\Delta \theta \sim \lambda/B$
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

(Pre-)Preliminary observation of anti-correlation between 1&3+2&4 pairs against 1&4+2&3 pairs, with random length/phase changes.