Quantum-Assisted Optical Interferometry for Astrometry and Precision Imaging

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Interferometry: Imaging and Astrometry

High-resolution imaging is the most well-known use for long-baseline interferometry.

Interferometry can also be used for precision astrometry, measurement of the positions of objects on the sky.

Fig. 11.—Apparent interferometric orbit of Mizar A with NPOI measurements. The dotted line is the orbit published by H95 based on Mark III observations, which did not cover the northwest quadrant.
Idea 0

**Originally:** Gottesman, Jennewein, Croke 2012

**Demonstrated:** Oregon & Illinois 2022

**Matthew Brown,** Valerian Thiel, Markus Allgaier, Michael Raymer, Brian Smith, Paul Kwiat, and John Monnier "Long-baseline interferometry using single photon states as a non-local oscillator", Proc. SPIE 12015, Quantum Computing, Communication, and Simulation II, 120150E (1 March 2022);
Idea 1: Use two sky photons

Sensitive to difference in path length differences \( \theta \) opening angle!

Basis for precision astrometry; could achieve \( \sim 10 \) microarcsec for bright objects

Does not require live optical link between stations; can use arbitrary baseline, similar advantage as HBT.

Does require coincidence of sky photons, similar drawback as HBT
Idea 1: Use two sky photons

Bench analog
Reminder: HBT effect

"The birth of quantum optics"

Thermal Source
Polarizer
Narrow band filter

Coherence time and detector resolution

Superconducting Nanowire Single Photon Detector (SNSPD) at BNL
Four channels at ~795nm
Polarized – V V

Correlated Hits (APs Removed) Chs1&2 all data

Correlated Hits (APs Removed) Chs1&3 all data

Correlated Hits (APs Removed) Chs1&4 all data

Correlated Hits (APs Removed) Chs2&3 all data

Correlated Hits (APs Removed) Chs2&4 all data

Correlated Hits (APs Removed) Chs3&4 all data

Input fiber coupler

Output fiber coupler

Polarizer and filter

Phase adjustment

50:50 non-polarizing beam splitter

Mirror

Ar Lamp

Out 1

Out 2

Out 3

Out 4

1&2

1&3

1&4

2&3

2&4

3&4
Polarized – V H

1&2

1&3

1&4

2&3

2&4

3&4

Correlated Hits (APs Removed) Chs1&2 all data

Correlated Hits (APs Removed) Chs1&3 all data

Correlated Hits (APs Removed) Chs1&4 all data

Correlated Hits (APs Removed) Chs2&3 all data

Correlated Hits (APs Removed) Chs2&4 all data

Correlated Hits (APs Removed) Chs3&4 all data

Ar Lamp

Out 4

Out 1

Out 3

Out 2

Input fiber coupler

Output fiber coupler

Phase adjustment

50:50 non-polarizing beam splitter

Mirror
Input fiber coupler

Output fiber coupler

50:50 non-polarizing beam splitter

Phase adjustment

Ar Lamp

Polarizer and filter

Out 1

Out 2

Out 3

Out 4

Oscillatory behavior confirmed

Pair Yield

Phase Shifting

Unpolarized

Oscillatory behavior confirmed

Pair Yield

Phase Shifting

Unpolarized

Oscillatory behavior confirmed

Pair Yield

Phase Shifting

Unpolarized

Oscillatory behavior confirmed

Pair Yield

Phase Shifting

Unpolarized
Idea 2: “Switched” config for astrometry

Does not require a coincidence from two sky objects; great improvement for faint sources.

Stable against (slow) ground path changes.
Idea 3: Very large arrays

GJC; see also
Khabiboulline,
Borregaard, De Greve,
Quantum Advantage! Each coincidence between $i$ and $j$ reflects interferometric visibility on baseline $\vec{B}_i - \vec{B}_j$; achieve an $N$-aperture interferometer with only $N$ beam combiners, rather than $O(N^2)$ that would be required classically.
Shopping list

• Field-deployable single photon detectors with ~nanosecond resolution
• Arrays of nanosecond SPD’s with spectrographic separation
• Telescopes able to focus stably into single mode (e.g. SM fiber)
• High-rate source of energy-entangled photon pairs

Not a dream but realistic IMO: everything either available now or can be soon.

We can build an on-sky experiment with demonstrated quantum advantage for astronomy in the next few years.
Testing point source to fiber coupling through small telescope in the lab.
Next step: outdoors.
Spectrographic fast pixels

Single-mode fiber-fed twin spectrograph onto fast Si pixel array camera (256x256, ~nsec)

Spread of Ar spectral lines near 795nm

Anticorrelation between wavelengths of SPDC pairs
Impacts for cosmology and astrophysics

Qualitatively better astrometric precision can yield:
• Improved parallax-based distance measurements; $H_0$ tension
• Mapping orbits of binaries; independent distance measurements
• Improved proper motions, relevant to galactic dark matter

Astrometry and imaging on faint objects:
• Parallax with galaxies
• Microlensing in real time

And more:
• Gravitational wave detection through coherent stellar motion
• Exoplanet spectra through precision nulling
Summary

• Long-baseline, high-resolution optical interferometry has great scientific -- and possibly also commercial? – value

• Long baseline interferometers can gain quantum advantage from (i) single photon generation, (ii) long-distance entanglement preparation/teleportation, (iii) quantum memory storage

• Two–photon technique of GJC now extended to use two sky photons for quantum-assisted astrometry science application; bench demonstrations shown, on sky soon

• Very promising development path immediately ahead: switching, energy entangled pairs, $W$ state distribution, very large arrays

BNL effort supported by DOE HEP QuantiSED grant; see our work at https://www.quantastro.bnl.gov
Backup
HBT with two, separated sources

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

Original motivation: gravitational waves
Can now run $10^3$-10$^4$ experiments at once (!), each in a spectral bin of width $\Delta \nu \sim 1/\tau_{\text{Detector}}$. 

Idea 0.5