Fast Two-Photon Interferometer Capable of Spectral Binning for Quantum Telescopy

Andrei Nomerotski, BNL

with Paul Stankus, Anze Slosar, Stephen Vintskevich, Raphael Abrahao, Jesse Crawford, Sergei Kulkov, Jakub Jirsa, Steve Bellavia, Michael Keach, Justine Haupt, Edoardo Charbon, Claudio Bruschini, Ermanno Bernasconi, Michal Marčišovský, Aaron Mueninghoff, Brianna Farella, Julian Martinez-Rincon et al
Astronomy picture of the decade

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with $\sim 10000$ km baselines
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 $c$/bandwidth

Need path length stabilized to better than $\lambda$

Accuracy $\sim 1$ mas

Max baselines to $\sim 100$ m
Two-photon techniques
Second photon for quantum assist

Quantum (two-photon) interferometer

- Distribute path entangled photons
- Use photon counting
  - coincidences are sensitive to phase!
  \[
P(c \ g) = P(d \ h) = \frac{1}{8} \left( 1 + \cos(\delta - \phi) \right)\]
  \[
P(c \ h) = P(d \ g) = \frac{1}{8} \left( 1 - \cos(\delta - \phi) \right)\]
- Transfer the photon quantum state \(\rightarrow\) can use quantum networks, this will allow long distances
- Enables long baselines and could improve astrometric precision by orders of magnitude
- Major impact on astrophysics and cosmology

\[\Delta \theta \sim \frac{\lambda}{b}\]
Quantum Astrometry

Idea: use another star as source of coherent states for the interference

- Relative path phase difference $\delta_1 - \delta_2$ can be extracted from the coincidence rates of four single photon counters: c, d, g and h

- Can provide 10 microarcsec resolution for bright stars

- Perfect to start exploring this approach - no quantum sources, no connection between stations, otherwise same instrumentation

$$P(c^2) = P(d^2) = P(g^2) = P(h^2) = \frac{1}{8}$$
$$P(CG) = P(DH) = \frac{1}{8}(1 + \cos(\delta_1 - \delta_2))$$
$$P(CH) = P(DG) = \frac{1}{8}(1 - \cos(\delta_1 - \delta_2))$$

Full QFT calculation

$$N_c(xy) = \eta_1\eta_2A^2\int_0^{T_r} P_{L,R,\tau}^{two\ photons} d\tau =$$

$$A^2\eta_1\eta_2T_r \left[ (I_1 + I_2)^2 + I_1^2 \frac{\tau_c g_{11}}{T_r} + I_2^2 \frac{\tau_c g_{22}}{T_r} \right]$$

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

New oscillatory term!

Hanbury Brown – Twiss
Intensity Interferometry

Our technique can be considered as extension of standard SII HBT with two separated sources

New idea: Coincident pair detections now sensitive to *phases* of incoming photons
Possible impact on astrophysics and cosmology

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder (Dark Energy)
- Proper star motions (Dark Matter)
- Microlensing, see shape changes (Dark Matter)

- Black hole imaging
- Gravitational waves in $\mu$Hz – nHz: coherent motions of stars
- Exoplanets

Requirements for detectors

- Photons must be close enough in frequency and time to interfere → **temporal & spectral binning**: need \( \sim 0.01 \text{ nm} \times 20 \text{ ps} \)

- Fast imaging techniques are the key
  - Several promising technologies: **SPADs** & **SNSPDs**

- Spectral binning: diffraction gratings, echelle spectrometers

- High photon detection efficiency
Bench-top model of two-photon interferometry

- Use 794 nm Ar line
- SPAD and SNSPD readout

$$P(cg) = P(dh) = \frac{1}{8} (1 + \cos(\delta_1 - \delta_2))$$

$$P(ch) = P(dg) = \frac{1}{8} (1 - \cos(\delta_1 - \delta_2))$$
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

Ar Lamp

Out 1

Out 2

Out 3

Out 4

Polarizer and filter

Input fiber coupler

Output fiber coupler

Phase adjustment

50:50 non-polarizing beam splitter

Mirror
Polarized – V H

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

Polarizer and filter

Input fiber coupler

Output fiber coupler

Phase adjustment

50:50 non-polarizing beam splitter

Mirror

Out 1

Out 2

Out 3

Out 4
Phase dependence

Towards Quantum Telescopes: Demonstration of a Two-Photon Interferometer for Quantum-Assisted Astronomy

JESSE CRAWFORD, DENIS DOLZHENKO, MICHAEL KEACH, AARON MUENINGHOFF, RAPHAEL A. ABRAHAO, JULIAN MARTINEZ-RINCON, PAUL STANKUS, STEPHEN VINTSKEVICH, ANDREI NOMEROSKI

arxiv.org/abs/2301.07042

Next:
Replace one Ar lamp with SPDC source

phase oscillations confirmed!
Next step: 50 ps timing resolution
LinoSPAD2 linear SPAD array

SPAD = single photon avalanche device
p-n junction with amplification

- 512 x 1 pixels
- 24 x 24 micron pixels
- Max PDE (with microlenses) ~ 30%
- Fill factor ~ 40%
- DCR ~ 30 Hz /pix @ room T
- Deadtime ~ 100ns
- Asynchronous readout of pixels

Developed by AQUA group in EPFL (Switzerland) E.Charbon et al

SPAD arrays with 50 ps resolution

Two beams from SPDC source

Coincidence of two single photons

86, 87, 88, 222, 223, 224

240k photons per peak

time difference, $\sigma=57$ ps

$\Rightarrow$ 40 ps per photon
HBT peaks in LinoSPAD2

Two beams from Ar lamp + polarizer after beamsplitter

LinoSPAD
512 x 1 pixels – using only half 256
24 x 24 micron pixels

Time difference, $\sigma=110$ ps
Visibility = 50%

Look for HBT = photon bunching, natural coherence time $>$ resolution
Next step: spectral binning
Spectrometer with LinoSPAD2

Used Ar lamp coupled to SM fiber

Achieved 0.04 nm spectral and 40 ps timing resolution

arxiv.org/abs/2304.11999
Wavelength anti-correlation in LinoSPAD2

- Combine signal and idler in single fiber so can use single spectrometer channel
- At 50 mW signal and idler spectra do not overlap

Spectrometer with 0.04 nm and 40 ps resolutions only x10 above Heisenberg hbar/2 limit

arxiv.org/abs/2304.11999
Next step: broadband HBT

• Each spectral line is a separate experiment

• Step 1: interfere neon lines

• Step 2: interfere spectral bins, this is what we need for quantum-assisted astrometry
7.5 ps superSPAD sensor

- Developed in AQUA group in EPFL
- 7.5 ps FWHM time resolution
- Starting tests at BNL

telescopes
On-sky measurements

Experimenting with SM fiber coupling and adaptive optics

Next:

- 2 telescopes
  - demo of SII
- 4 telescopes
  - demo of quantum astrometry
- spectral binning demo
On-sky measurements

Mizar A & B
- 50 ms exposure
- 15 arcsec separation

Jitter of two stars is correlated and could cancel in differential measurement
Optica Quantum 2.0 Conference and Exhibition

Special Programs

- Quantum-Enhanced Telescopy Workshop
- Nobel Symposium: Foundations on Quantum Physics

Quantum-Enhanced Telescopy Workshop

Sunday, 18 June 09:00 - 17:30

Speakers
Summary

• Single-photon interferometry reaches much higher resolutions than single telescopes; but practical issues limit maximum baselines.

• Two-photon interferometry can permit independent stations over longer baselines.

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

• Bench-top demonstration of new ideas for quantum astrometry with temporal and spectral binning.

Broad program in quantum-assisted optical interferometry ahead.
Main publications

- Original idea: https://doi.org/10.21105/astro.2010.09100
- Earth rotation fringe scanning: doi.org/10.1103/PhysRevD.107.023015
- Experimental proof of principle: https://arxiv.org/abs/2301.07042

- See https://www.quantastro.bnl.gov/node/3 for the full list

- Our web site
  www.quantastro.bnl.gov
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Questions?

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