Fast Imaging of Single Photons for Astronomical Applications

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Idea: employ quantum entanglement to improve astrometrical precision of optical interferometers

Two-photon amplitude interferometry for precision astrometry
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Will also discuss experimental implications: temporal and spectral resolutions required for implementation

Astronomy picture of the decade

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines
In the optical

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

Different sources yield shifted fringes
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.
Optical interferometry examples

Dynamic convection on Antares (VLTI, ESO)


Nova in progress (CHARA)
Two-photon techniques
• Measure photon wave function phase difference performing Bell State Measurement at one station so teleporting the sky photon to the other station
• Enables long baselines and could improve astrometric precision by orders of magnitude

Quantum (two-photon) interferometer

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

Idea: use another star as source of entangled 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 f

Different from Hanbury Brown Twiss intensity interferometry, can produce both negative and positive rate oscillations \(\rightarrow\) amplitude interferometry
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

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

A modest experiment:

- Bright stars, mag 2
- 1 m² collecting area
- 10⁴ seconds observation
- 0.15 nsec time resolution
- 10⁴ spectral channels
- 200 m baseline

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

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

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

State of art: 7 \(\mu\)as GAIA (2013 - )
Possible impact on astrophysics and cosmology

So far a blue-sky research offers orders of magnitude better astrometry

- Parallax: improved distance ladder $\rightarrow$ SN science $\rightarrow$ Dark Energy
- Proper motions: local Dark Matter patterns
- Microlensing, see motions and shape changes, Dark Matter hunting
- Gravitational waves, coherent motions of stars
- Exoplanets
- etc

Requirements for detectors

- Photons must be close enough in frequency and time to interfere → temporal & spectral binning: need ~ 0.01 ns * 0.2 nm for 800 nm

- Fast imaging techniques are the key
  - Several promising technologies: CMOS pixels+MCP, SPADs, SNSPDs, streaking
  - Target 1-100 ps resolution

- Spectral binning: diffraction gratings, Echelle spectrometers
  - Fringe rate resolution doesn’t depend on bin width - wider spectral binning gives lower visibility but same statistical precision
  → what’s important is # of spectral channels

- Photon detection efficiency: high
Timepix3 Camera \(\rightarrow\) 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

Intensified camera is single photon sensitive

Image intensifier (Photonis PP0360EG)

Quantum efficiency ~ 30%
Each photon is a cluster of pixels
→ 3D (x,y,t) centroiding

Time resolution: 2 ns / photon
Spectroscopic binning

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

Pump photon wavelength vs time difference

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


MCP Timing Performance

- Micro-channel plate (MCP) is fast
  - Demonstrated resolution < 30 ps
- MCP readout for Tpx3 camera
  - 50 ps, not for single photons yet

Possible technologies: SNSPD

- Superconducting nanowires
  - Used Single Quantum SNSPD
  - 100 ps resolution for single photons using SPDC photon pair source
  - 3 ps devices reported

Possible technologies: Streaking

- Streaking: use a spatial coordinate for time measurement
  - Deflect photoelectrons by oscillating field
  - 1 ps resolution possible

Possible technologies: SPADs

- Starting characterization of 50 ps SPADs
Experiments in progress

Bench-top model of two-photon interferometry
Ar vapor lamps with ultra-narrow band filters
Superconducting nanowire single-photon detectors

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Summary

- Two-photon amplitude interference can be used to improve astrometrical precision by orders of magnitude
  - Application of quantum entanglement and teleportation techniques to astronomy with great potential
- Not far from practical implementation with existing technologies
  - Motivates new technologies for fast single photon detection with sub-ns resolution
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