Quantum-Assisted Optical Telescopes

Andrei Nomerotski, Brookhaven National Lab

28 September 2021

In collaboration with: Paul Stankus, Stephen Vintskevich, Anze Slosar, Ning Bao, Zhi Chen, Jonathan Schiff, Alex Parsells, Duncan England, Yingwen Zhang et al

Sensing with Quantum Light
SQL21

WE-Heraeus-Seminar, 26 Sep - 29 Sep 2021

Physikzentrum Bad Honnef, Germany
Astronomy picture of the decade

Black hole in the center of M87 imaged at 1.3mm

Achieved by radio interferometry with ~10000 km baselines

53M light years away
\[ \delta \sim 10 \mu \text{as} \ (\sim 10^{-11} \text{ rad}) \]

\[ \Delta \theta \sim \frac{\lambda}{b} \]
Radio

Can literally record entire waveform, separately at each receiver station and interfere later offline

Optical

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

Need path length stabilized to better than $\lambda$

Accuracy $\sim 1$ mas (milliarcsecond)
Max baselines $\sim 100$ m
Optical interferometry examples

Dynamic convection on Antares
(VLTI, ESO)


Nova in progress (CHARA)
Two-photon techniques
Quantum-assisted telescopes

Quantum (two-photon) interferometer

- 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
- Observables: measure coincidence rates of four single photon counters

\[ \Delta \theta \sim \frac{\lambda}{b} \]
Possible impact on astrophysics and cosmology

offers orders of magnitude better astrometry with major impact

- Parallax: improved distance ladder
- Proper star motions
- Microlensing, see shape changes
- Gravitational waves, coherent motions of stars
- Exoplanets
- etc

More recent developments

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

Optical Interferometry with Quantum Networks

E. T. Khabibouline, J. Borregaard, K. De Greve, and M. D. Lukin

1Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen Ø, Denmark

(Received 17 September 2018; published 15 August 2019)

Quantum-assisted telescope arrays

E. T. Khabibouline, J. Borregaard, K. De Greve, and M. D. Lukin

1Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
2QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen Ø, Denmark

Idea: Efficient time-bin encoding of photon arrivals
More futuristic ideas

Quantum hard drives!

Quantum Astronomy Could Create Telescopes Hundreds of Kilometers Wide

Astronomers hope to use innovations from large arrays

By Anil Anar

Astronomers Want to Design Quantum Telescopes That Span the Globe

By Ryan Whitwam on April 26, 2021 at 7:30 am

Quantum memories and the double-slit experiment: implications for astronomical interferometry

JOSS BLAND-HAWTHORN\textsuperscript{1,2,3}, MATTHEW J. SELLARS\textsuperscript{4}, and JOHN G. BARTHOLOMEW\textsuperscript{1,5,6}

\textsuperscript{1}School of Physics, University of Sydney, NSW 2006, Australia
\textsuperscript{2}Sydney Astrophotonic Instrumentation Labs (SAIL), School of Physics, University of Sydney, NSW 2006, Australia
\textsuperscript{3}Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
\textsuperscript{4}Centre for Quantum Computation and Communication Technology, Research School of Physics and Engineering, The Australian National University, Canberra 2600, Australia
\textsuperscript{5}Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia
\textsuperscript{6}The University of Sydney Nano Institute, The University of Sydney, NSW 2006, Australia

Corresponding author: jbh@physics.usyd.edu.au
Quantum Astrometry

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

Comparison to Hanbury Brown – Twiss Intensity Interferometry

Standard HBT

Source

Detectors

Photon bunching if path difference is within coherence time

Quantum astrometry

Source 1

Half mirrors

Common spatial mode

Detectors

Source 2

Coincident pair detection sensitive to phase difference of two photons
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

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

Coincidence rates oscillate

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

Fringe oscillation rate is a direct measure of sources’ opening angle!

world competitive precision with a modest experiment (for bright stars)

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

• Spectral binning: diffraction gratings, Echelle spectrometers
  – Need large number of bins

Intensified Timepix3 Camera

time-stamps single photons with ns resolution

Camera = intensifier + sensor + ASIC + readout
– 256 x 256 array
– 1.6 ns time bin, data-driven readout


arxiv.org/abs/1902.01357
Spectral binning

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

Δλ*Δt ~ 5 ns * 0.5 nm

Pump photon wavelength vs time difference


Fast timing technologies

• Superconducting nanowires (SNSPD)
  – In our measurements: 100 ps resolution for single photons, high QE
  – 3 ps SNSPD devices reported

Other technologies under evaluation

• Single Photon Avalanche Device (SPAD)
  – 10 ps resolution possible
  – Scalable: 1D and 2D matrices

• Streaking cameras
  – Use spatial information for time measurement
  – 1 ps resolution possible

Experiments in progress

Bench-top model of two-photon interferometry

Ar vapor lamps (794 nm line) with narrow band filters
Superconducting nanowire single-photon detectors
(Single Quantum)

Supported by DOE HEP QuantISED grant
First results

- Effect can be seen in coincidence correlations between pairs of SNSPD channels
  - Technique is less sensitive to phase instability (~ 10 sec)
- Results agree with predictions, correlations ~ 0.1-0.2 @ > 3 $\sigma$

[Graph showing coincidence pairs]

[arxiv.org/abs/2107.09229]
Next steps
Preparations for on-sky experiments

- Star pair selection for fringe scans
  - Used catalog of bright stars visible from BNL site
- Modeled reconstruction of fringes to evaluate experimental errors
- Paper in preparation

Earth rotation fringe evolution

\[ \delta_{\text{RA}} \sim 0.3 \text{ deg} \]
\[ \delta_{\text{DEC}} \sim 0.06 \text{ deg} \]
Developing the quantum

Geometry: 2 stars + A,B,C telescope stations + source of entangled photon states + detectors

Use multi-partite entanglement (ex W or GHZ states) distributed between multiple stations and quantum protocol to process information in noisy environment

- Density operators $\rho$
- Multi-partite entanglement is distributed over multiple stations
- Quantum protocol evaluates experimental observables
- Paper in preparation
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

- Planning on-sky measurements
- Developing theoretical framework, looking for new observables

www.quantastro.bnl.gov
spares
In the optical

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

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

\(\bar{n}\) = average pair rate
\(T\) = 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
- 200 m baseline

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

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

state of art: 7 \(\mu\text{as}\) GAIA (2013 - )
Intensified Timepix3 Camera

time-stamps single photons with ~ ns resolution

Camera = intensifier + sensor + ASIC + readout

• Optical sensor with high QE @ BNL
  – Sensor is bump-bonded to chip Timepix3

• Timepix3 ASIC @ CERN
  – 256 x 256 array, 55 x 55 micron pixel
  – 1.6 ns timing resolution, data-driven readout

• 10 Gbs readout SPIDR @ Amsterdam Scientific Instruments

• Intensifier with GaAs photocathode @ Photonis
  QE ~ 30%


Zhao et al, Coincidence velocity map imaging using Tpx3Cam, a time stamping optical camera with 1.5 ns timing resolution, Review of Scientific Instruments 88 (11) (2017) 113104.
Each photon is a cluster of pixels  
→ 3D (x,y,t) centroiding

Time resolution:  2 ns / photon

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: Streaking

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