National Aeronautics and Space Administration

ACCESS Project Presentation to DLR

Exploration & SPACE Communications

More than you ever imagined...

Dr. Harry Shaw
Staff Engineer, Telecommunication and Network Technologies Branch, NASA/GSFC
Advanced Communications Capabilities for Exploration and Science Systems (ACCESS) Project office
September 22, 2023

Introduction

- I lead the technical work in quantum research in the Exploration and Space Communications division, Advanced Communications Capabilities for Exploration and Science Systems (ACCESS) Project office at NASA/GSFC along with Dr. Haleh Safavi
- Our primary focus areas are:
  - Basic and applied research with our partners to support the development of doctorates in quantum-related fields.
    - Some of them will end up within NASA
  - Planning for eventual operations of quantum enabled satellites
  - Improving "quantum literacy" within the American student population with an emphasis on bringing women and underrepresented minorities into the quantum world
    - We have a very robust intern program.
  - We are not full-time researchers. We have "day jobs" operating communications satellites and ground stations

ACCESS Project Quantum Team

rofessional Staff	Degree	Institution	Major
yler Williams	M.S	Capitol Technology University	Cyber Security
lejandro odriguez Perez	Ph.D	University of California Irvine	Materials Physics
eborah Preston	Ph.D	University of California Los Angeles	Chemistry
rika Jones	Ph.D	George Mason University	Computational Sciences and Informatics
aleh Safavi	Ph.D	University of Maryland Baltimore County	Electrical Engineering
arry Shaw	D. Sc.	George Washington University	Electrical Engineering
obert Lafon	Ph.D	SUNY Stonybrook	Physics

octoral Students	Institution	Major	
anon Bart	Tulane University	Physics	
aveed aimipour	University of Illinois Chicago	Electrical Engineering	
ick Savino	Tulane University	Physics	
ost-doctoral	Institution	Major	
an Nodurft	University of Illinois Chicago	Physics	

Dr. Deborah Preston Tyler Williams Dr. Harry Shaw

Dr. Ian Nodurft

Manon Bart

Naveed Naimipour

Dr. Haleh Safavi

Dr. Robert Lafon

Dr. Erika Jones

Nick Savino

Jake Barnes

Dr. Alejandro Rodriguez-Perez

Grants and Subcontracts

New Mexico State (PI Steven Stochai) – Development of an optical communications testbed

Michigan State (PI Virginia Ayres) - Quantum Demonstration Project

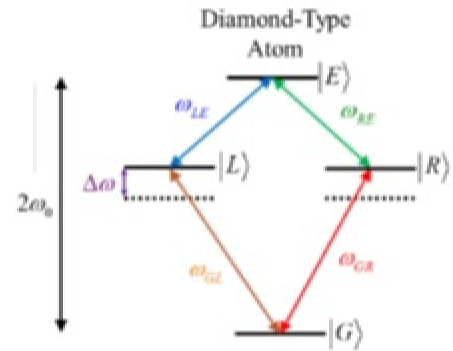
UMBC (PI Sebastian Deffner) – Quantum Thermodynamics

Forced Quantum Entanglement using the quantum Zeno effect

I. C. Nodurft,[1,2,*] B. T. Kirby,[3,4] R. T. Glasser,[4] H. C. Shaw,[5] and T. A. Searles[1,†]

[1]*University of Illinois Chicago, Chicago, IL 60607, USA*
[2]*Peraton, Greenbelt, MD 20770*
[3]*United States Army Research Laboratory, Adelphi, MD 20783, USA*
[4]*Tulane University, New Orleans, Louisiana 70118, USA*
[5]*NASA Goddard Space Flight Center, Greenbelt, MD 20771*

[*]inodurft@peraton.com, [†]tsearles@uic.edu



Abstract: We propose a scheme for generating polarization-entangled photons using the quantum Zeno effect. The observing medium is a series of 4-level atoms coupled to a waveguide device. Bunching is suppressed, yielding polarization entanglement. © 2022 The Author(s)

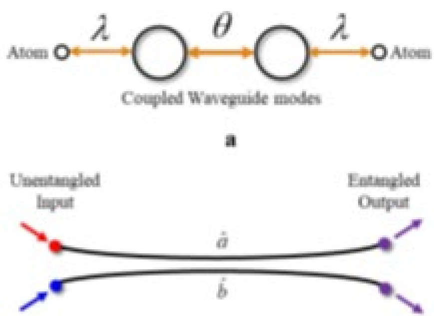


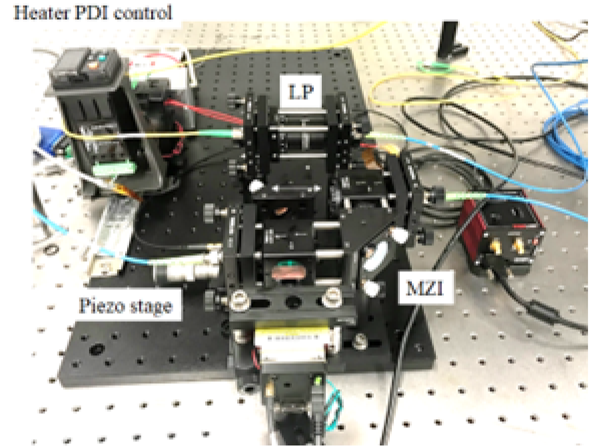
Fig. 2. A 4-level atom in the diamond configuration. Middle levels $|L\rangle$ and $|R\rangle$ are detuned from resonance with a single photon but the excited state $|E\rangle$ is on resonance with a pair of photons. Rubidium satisfies this structure, making it a good choice for building this device [8].

Fig. 1. The basic design and operation of the device. a) A pair of waveguides coupled with strength θ, each separately coupled to an atom with strength λ. b) A pair of unentangled photons enter the coupling region of the waveguide. Suppression of the bunched terms yield an entangled output.

Dr. Nodurft is a former intern, recently completed post-doctoral assignment at University of Illinois Chicago and is now a full-time employee with our group

Quantum thermodynamics – Temperature dependence and materials effects in quantum eraser experiments

- Recent Accomplishments
  - Partnership with the Quantum Thermodynamics group at University of Maryland Baltimore County Physics department. PI is Dr. Sebastian Deffner
  - The quantum eraser provides an excellent test bed for a variety of investigations
  - Nathan Myers, granted Ph.D in 2022, Quantum Engines At The Frontiers Of Physics. Now a post-doc at Virginia Tech



Aifer, Maxwell, Nathan Myers, and Sebastian Deffner. "Thermodynamics of quantum information in noisy polarizers." *arXiv preprint arXiv:2212.00651* (2022).

ACKNOWLEDGMENTS

We would like to thank Todd Pittman, Alejandro Rodriguez Perez, Steve Campbell, and Pat Elden for enlighting discussions. M.A. gratefully acknowledges support from Harry Shaw of NASA Goddard Space Flight Center. N.M.M. acknowledges support from AFOSR (FA2386-21-1-4081, FA9550-19-1-0272, FA9550-23-1-0034) and ARO (W911NF2210247, W911NF2010013). S.D. acknowledges support from the John Templeton Foundation under Grant No. 62422.

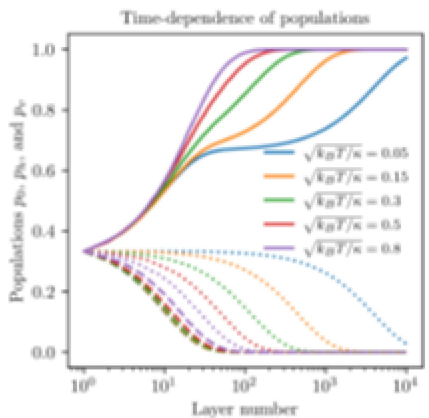
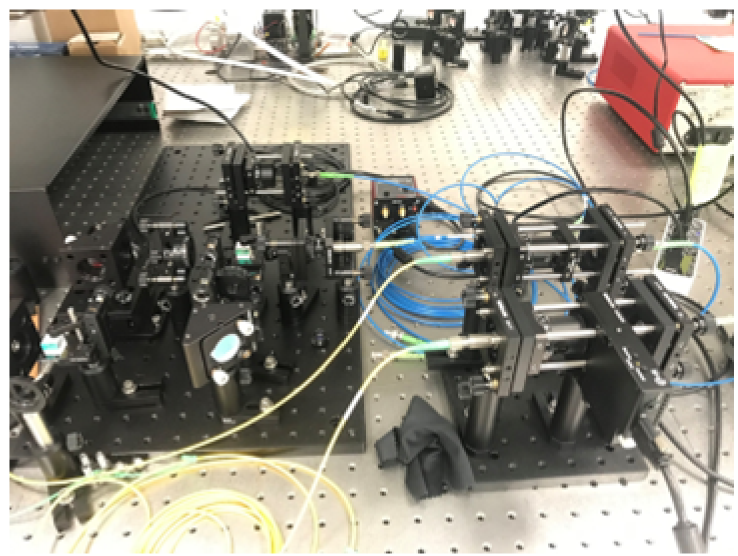


FIG. 7. Populations $p_0 = \rho_{00}$ (solid lines), $p_h = \rho_{11}$ (dotted lines), and $p_v = \rho_{22}$ (dashed lines). The vertical population p_v rapidly decays to zero but the horizontal component takes longer. As a result the vacuum population has a plateau that is flatter at lower temperatures.

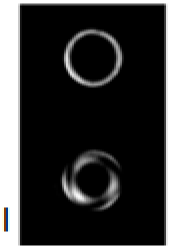


Quantum Communications

Recent Accomplishments:

- Established the first quantum communications laboratory at GSFC
- Baselining quantum entanglement equipment performance of systems at 1550nm and 810 nm
- Conducting experiments in Orbital Angular Momentum for superdense coding
- Investigating novel materials for propagation and storage of quantum states at > LN_2 temperatures

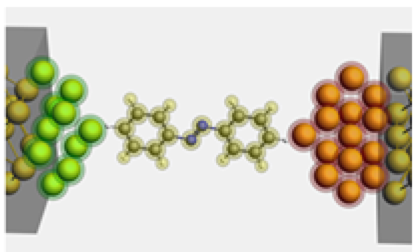
- Photons like other quantum particles contain both spin angular momentum (SAM) and orbital angular momentum (OAM)
  - While SAM is relegated to two-dimensional space, OAM belongs to infinite-dimensional space
- OAM modes are orthogonal
  - Allows multiplexing of Classical information
  - Can implement super-dense coding utilizing OAM modes

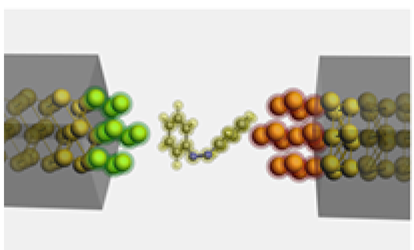


Partner: Tulane University, Ryan Glasser, PI

Harry Shaw, PI

Quantum chemistry simulation of electronic transport through azobenzene. single molecule circuit simulation





2023 NASA Fundamental Physics Workshop May 23-25, Santa Barbara, California.

Partner: Michigan State University, Virginia Ayres, PI

Hybrid State Effects in Quantum Entanglement Experiments

N. Sebasco[1], J. Vetere[1], G. Panda[1], V.M. Ayres[1] and H.C. Shaw[2]
[1] Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA,
[2]Code 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA

Entanglement in Perovskite Quantum Conductive Layers

G. Panda, N. Sebasco, J. Vetere, V. M. Ayres and H. C. Shaw
Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA
Code 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA

Fractalized Quantum Evolutionary Computation

J. Vetere[1], N. Sebasco[1], G. Panda[1], V.M. Ayres[1] and H.C. Shaw[2]
[1] Department of Electrical & Computer Engineering, Michigan State University, East Lansing, MI 48824 USA,
[2]Code 5560, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 USA

Quantum Computing

Recent accomplishments:

- Established access to the AWS Braket Quantum as a Service. This will allow our quantum algorithms to be tested on actual quantum computers.
- Developed and published approach on quantum compressive sensing

Quantum Compressive Sensing Algorithms

- Built upon algorithms work by Kyle Sherbert (Ph.D Physics 2022, U of North Texas, VT post-doc) & Naveed Naimipour
- Bridging compressive sensing algorithms to quantum computing/communication infrastructure
  - Effects of Shot Noise
- Explored Advantages of Quantum Compressive Sensing
- Key Takeaways
  - Basics of quantum computation and circuitry for work on quantum algorithms
    - QISKIT
    - Methods for testing quantum algorithms
  - Built understanding of tomography, noise & quantum noise, compressive sensing techniques

Kyle Sherbert

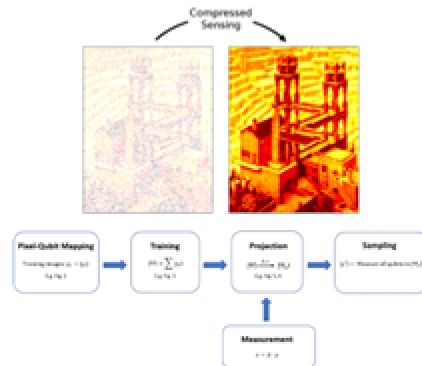
Naveed Naimipour

- Implemented a Projection Method for Quantum Phase Estimation

Sherbert, K. M., Naimipour, N., Safavi, H., Shaw, H. C., & Soltanalian, M. (2022). Quantum Compressive Sensing: Mathematical Machinery, Quantum Algorithms, and Quantum Circuitry. *Applied Sciences*, *12*(15), 7525.

Current and Future Tomography Work

- Exploring post processing areas is integral to the development of quantum tomography
  - Quantum Compressive Sensing
    - Bridging the gap between the quantum and classical worlds of reconstruction
- We present the algorithms and quantum circuits required to implement the training, projection, and sampling steps on a quantum computer
  - We supplement these theoretical results by simulating these circuits with a qualitative model of LIDAR imaging of Earth forests
- Our results indicate that a quantum, data-driven approach to compressive sensing may have significant promise



Amazon Braket Service - Quantum Computing Investigations into Implementing Quantum Compressive Sensing Algorithms

Amazon Braket Features

- "fully managed quantum computing service"
- "build, test, and run quantum algorithms on AWS"
- "access to different types of quantum computers, a unified development environment, a choice of classical circuit simulators, and fully managed execution of hybrid quantum-classical algorithms"

—Amazon Braket Features webpage

NASA Mission Cloud Platform (MCP)

"In collaboration with Amazon Web Services (AWS), MCP provides a consolidated cloud service within NASA, giving mission customers a streamlined process for implementing and using secure, compliant cloud resources."

Provider	Technology	
IonQ	universal gate-based	trapped ion — *chain of ionized ytterbium atoms where internal states of individual* $^{171}Yb^{+}$ *serve as qubits and gate operations are via laser pulses to drive two-photon Raman transitions*
Oxford Quantum Circuits (OQC)	universal gate-based	superconducting — *superconducting qubits in 3D (proprietary "Coaxmon") architecture, i.e., "qubit control electronics perpendicular to the plane of the qubits" [Amazon Braket]*
Rigetti	universal gate-based	superconducting — *"tileable lattices of alternating fixed-frequency and tunable superconducting qubits" [Amazon Braket]*
QuEra	analog Hamiltonian simulation	neutral atom — *arrays of rubidium where internal states of individual Rb atoms serve as qubits, connection of qubits is by Rydberg blockade, and current computational applications target quantum optimization and quantum simulation*

GSFC Quantum Communications Lab Plans

- ➢ **Use cloud service to run algorithms for quantum compressive sensing protocols**
- ➢ Access QC technology type of interest for low-cost setup of QC hardware in house

Other Key Collaborations

- Quantum Eraser Experiments at 1550nm with single photon detectors with UMBC
- Benchtop LCRD quantum capability experiments with UMBC and Michigan State
- Absolute calibration of detectors with entangled photons with ARL, Tulane, GSFC Detectors branch and Science Directorate
- Multiparty quantum clock synchronization with Tulane University
- Forced quantum entanglement University of Illinois Chicago and Tulane

Importance of STEM

- Our main focus is STEM. Through STEM activities and outreach efforts we can achieve great results.
  - Basic and applied research with our partners to support the development of doctorates in quantum-related fields.
  - Some of the STEM interns will end up within NASA
  - Conduct experimental investigations that support US quantum initiatives and needs
  - Planning for eventual operations of quantum enabled satellites
    - Quantum enabled satellites will in turn support terrestrial quantum networks, with flexible geographic diversity and minimal new ground infrastructure
  - Improving “quantum literacy” within the American student population with an emphasis on bringing women and underrepresented minorities into the quantum world
  - We have a very robust intern program.
    - We started with only graduate students and high undergraduates. We are expanding to the high school student level

STEM

Recent Accomplishments:
- Expanded the intern program to include promising undergraduate students
- Expanding subject matter in the quantum areas

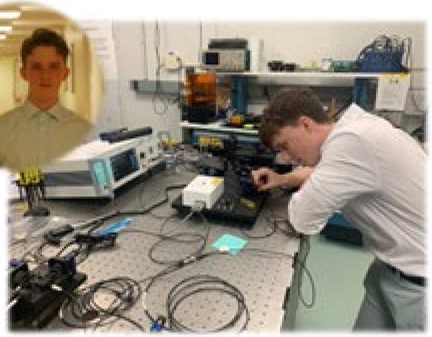
Nishanth Anand

- **University of California, Berkeley**
- ***Bachelor of Arts, Astrophysics / Computer Science, May 2023***

- Performed Experiments
  - QKD with BB84 protocol
  - Quantum Eraser
- Quantum Compressive Sensing Algorithms

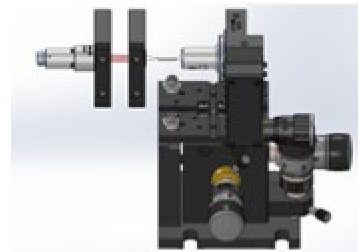
Collin Frink

- **University of Wisconsin, Madison**
- ***Bachelor of Science, AMEP (Applied Math, Engineering, Physics) and Computer Science, December 2022***



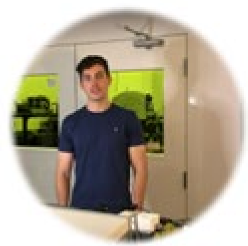
- Trained on low-cost quantum computing tools (Qiskit) and quantum algorithm development
  - Culminated with Shor's algorithm
- Extended previous lab-work in quantum compressive sensing by integrating quantum noise effects

- 2023 NRO Summer Intern Cordell Mazzetti, UT Austin, building a polarization entangled photon source.



Nick Sebasco

- **Developed our Franson Interferometer setup and performed multiple entanglement verification experiments**
- **Michigan State University**
- ***MS, Electrical and Computer Engineering, 2023***



Training, Teaching, Research in Optical Angular Momentum

OAM experiments conducted by Dr. Alejandro Rodriguez Perez

OAM Experimental Setup Activities

Optical Angular Momentum has an infinite orthogonal codeword space

Purpose: To demonstrate our ability to produce and detect OAM modes in addition to distinguishing different modes during simultaneous detection

Set Up:

- Simplest way to produce an OAM wave is to utilize a spiral phase plate (SPP)
- Detection done via diffraction grating implemented on spatial light modulator (SLM)
  - Discrimination of multiple OAM modes simultaneously
  - Advantageous in multiplexing schemes

Undergraduate Student STEM research

Recent Accomplishments:
- Expanded the intern program to include promising undergraduate students
- Expanding subject matter in the quantum areas

Jonas Kolker
- **Columbia University, New York**
- **Bachelor of Science, Applied Physics**

- Trained on IBM software development kit (SDK) Qiskit Explored benchmarking approaches for quantum computing (QC)

Collin Frink
- **University of Wisconsin, Madison**
- ***Bachelor of Science, AMEP (Applied Math, Engineering, Physics) and Computer Science, December 2022***

- Trained on low-cost quantum computing tools (Qiskit) and quantum algorithm development
  - Culminated with Shor's algorithm
- Extended previous lab-work in quantum compressive sensing by integrating quantum noise effects

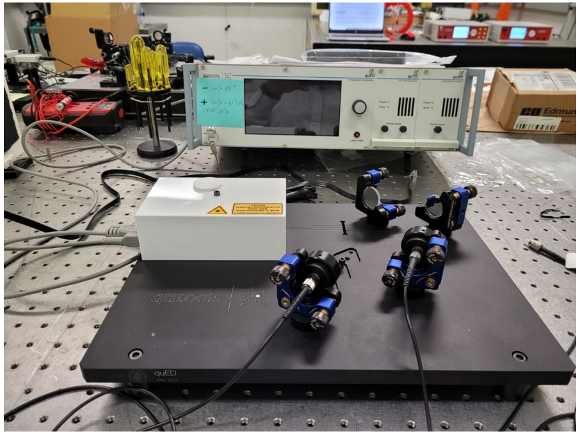
Cordell Mazzetti
- **University of Texas, Austin**
- **Bachelor of Science Electrical and Computer Engineering**

- Identified promising QCS protocols.
- Developed new QCS protocol.
- Built polarization entangled photo source.

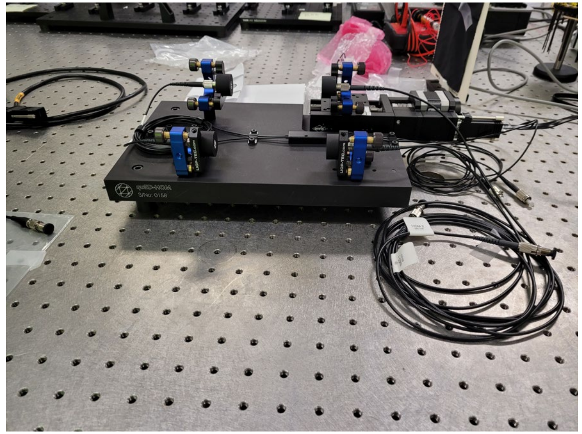
Wade Lamberson
- **Harding University, Searcy**
- **Bachelors of Science in Physics, Mathematics, Software Development, Electrical Engineering**

- Compared SDKs: IBM's Qiskit and Amazon Braket's SDK
- Compared results of jobs submitted to different QC architectures—ion trap and superconducting—available on the QC cloud service Amazon Braket

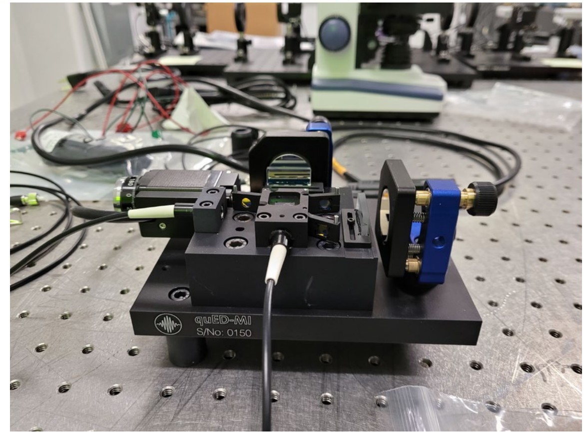
Qutools: This equipment will be used together to perform a variety of experiments



810nm Polarization Entanglement System



Hong-Au-Mandel fixture



Michelson Interferometer

Single Photon Experiments without Interference

Particle Nature of Photons
Quantum Cryptography/QKD: BB84 Protocol
Tomographic Single Photon State Reconstruction
Quantum Random Number Generation

Single Photon Experiments with Interference

Wave Nature of Photons: Single Photon Michelson Interferometer
Quantum Eraser
Wave-Particle Dualism: Michelson + HBT

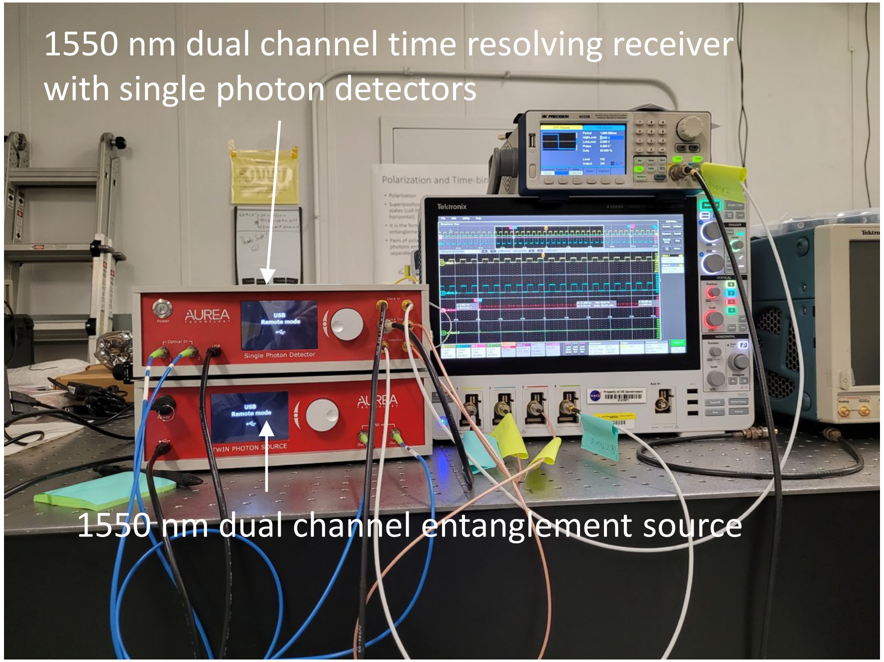
Photon Pair Experiments with Polarisation Entanglement

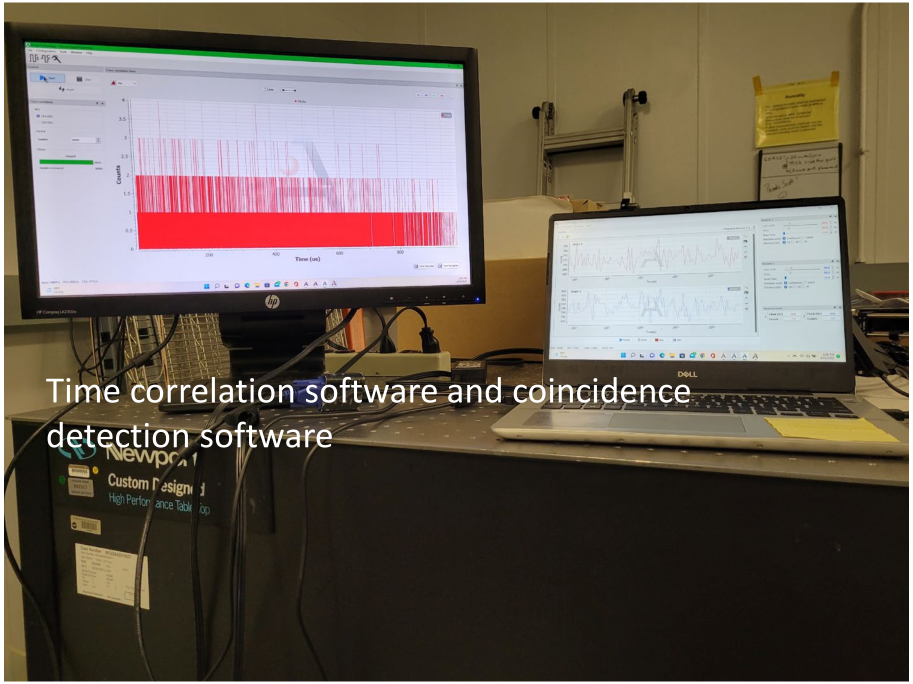
Violation of Bell's Inequality (CHSH)
"Non-Classical" Polarisation Correlations
Tomographic State Reconstruction of an Entangled Photon State
Quantum Cryptography/QKD: BBM Protocol
Quantum Cryptography: Ekert Protocol

Photon Pair Experiments without Polarisation Entanglement

Hong-Ou-Mandel 2-Photon Interference
Hong-Ou-Mandel Interference + Hanbury Brown & Twiss
Franson Interference

Aurea: This equipment will be used as building blocks for experiments with other equipment





Low Cost Optical Ground Terminal (LCOT) at the Goddard Geophysical and Astronomical Observatory (GGAO)

Dr. Haleh Safavi

LCOT Planewave 70 cm Optical Comm Telescope

- 2019 – Received SCaN funding to procure a .7m COTS telescope.
- Selected Planewave Instruments as the telescope vendor.
- Planewave used their experience building low-cost COTS telescopes to develop their first optical comm telescope
- Telescope installed at GGAO
- Next Steps:
  - Adaptive Optics (AO) System that actively corrects distortions from atmospheric turbulence (currently under characterization test)
  - Uplink Telescopes (Building contracts starts Feb. 2023).

LCOT Ground Terminal of the Future