



Exploration & **SPACE** Communications

More than you ever imagined...

Trends in classical and quantum optical communications for space. WAMICON 2024



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Advanced Communications Capabilities for Exploration and Science
Systems (ACCESS) Project office
April 16, 2024

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
- (There will be no math in this presentation)

Our main focus is 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

Quantum Space Telecommunication and Algorithms Research (Q-STAR) Laboratory Team



Professional Staff	Degree	Institution	Major
Tyler Williams	M.S	Capitol Technology University	Cyber Security
Alejandro Rodriguez Perez	Ph.D	University of California Irvine	Materials Physics
Deborah Preston	Ph.D	University of California Los Angeles	Chemistry
Erika Jones	Ph.D	George Mason University	Computational Sciences and Informatics
Haleh Safavi	Ph.D	University of Maryland Baltimore County	Electrical Engineering
Alan Hylton	Ph.D	Lehigh University	Mathematics
Harry Shaw	D. Sc.	George Washington University	Electrical Engineering
Robert Lafon	Ph.D	SUNY Stonybrook	Physics
Ian Nodurft	Ph.D	University of Maryland Baltimore County	Physics
Collin Frink	B.S	University of Wisconsin	Applied Math, Engineering, Physics) and Computer Science
Jacob Barnes	B.S.	Kutztown University	Math
Doctoral Students		Institution	Major
Manon Bart		Tulane University	Physics
Naveed Naimipour		University of Illinois Chicago	Electrical Engineering
Nick Savino		Tulane University	Physics
Emily Ferketic		UMBC	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



Collin Frink



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

Grants and Subcontracts



Michigan State (PI Virginia Ayres) - Quantum Demonstration Project



UMBC (PI Sebastian Deffner) – Quantum Thermodynamics



Dr. Alan Hylton

Forced Quantum Entanglement using the quantum Zeno effect



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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)

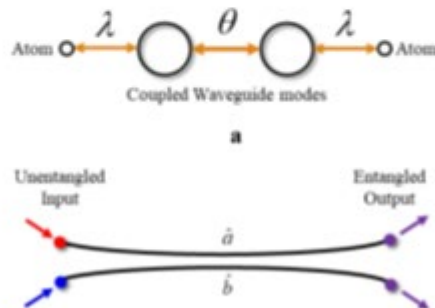


Fig. 1. The basic design and operation of the device. a) A pair of waveguides coupled with strength θ , each separately coupled to an atom with strength λ . b) A pair of unentangled photons enter the coupling region of the waveguide. Suppression of the bunched terms yield an entangled output.

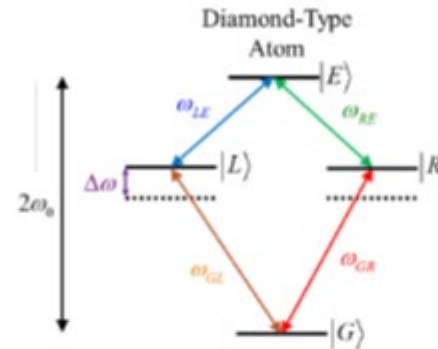


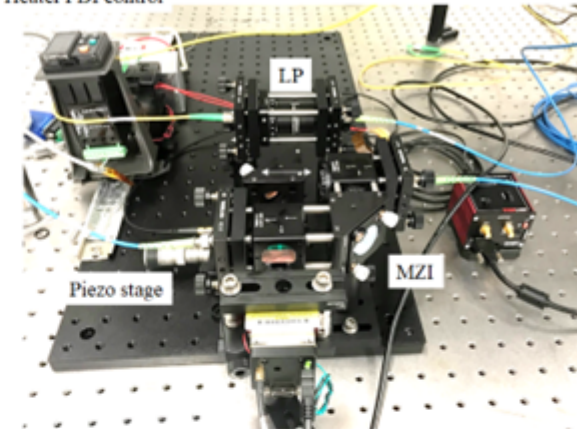
Fig. 2. A 4-level atom in the diamond configuration. Middle levels $|L\rangle$ and $|R\rangle$ are detuned from resonance with a single photon but the excited state $|E\rangle$ is on resonance with a pair of photons. Rubidium satisfies this structure, making it a good choice for building this device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

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



- 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

Heater PDI control



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 enlightening discussions. M.A. gratefully acknowledges support from Harry Shaw of NASA Goddard Space Flight Center. N.M.M. acknowledges support from AFOSR (FA2386-21-1-0081, 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.

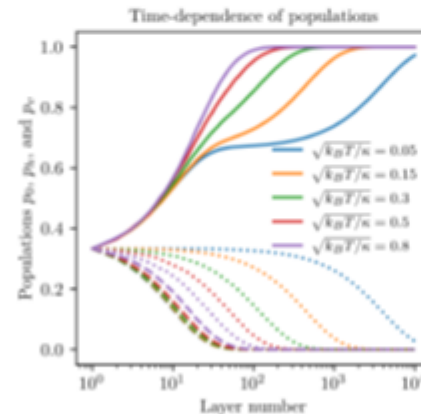
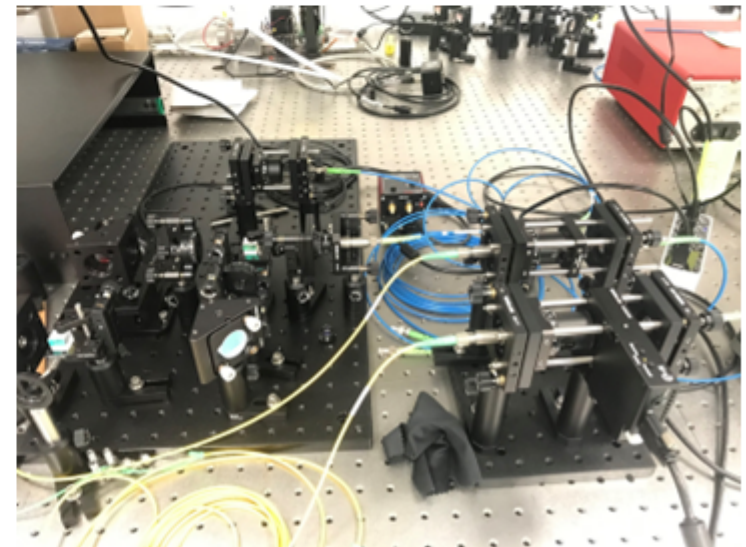


FIG. 7. Populations $p_0 = \rho_{00}$ (solid lines), $p_1 = \rho_{11}$ (dotted lines), and $p_2 = \rho_{22}$ (dashed lines). The vertical population p_2 rapidly decays to zero but the horizontal component takes longer. As a result the vacuum population has a plateau that is flatter at lower temperatures.



Projection Method for Quantum Phase Estimation

- **Rodeo**

- A probabilistic method based on quantum phase estimation originally developed for spectrally identifying eigenvalues of a Hamiltonian operator [1]

- **Decomposition**

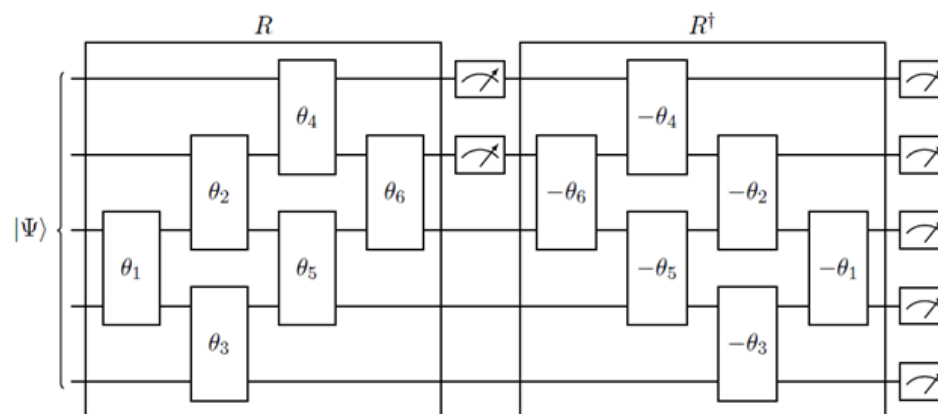
- Based on the decomposition for the sensing matrix A : $A = U\Delta L^\dagger \Pi R$

- **Gaussian**

- We use the methods of Quantum Imaginary Time Evolution (QITE) to implement a unitary operator which *effectively* realizes the same operation

- **Next Steps:**

- Implementation on quantum computer
- Thoroughly explore behavior of techniques with quantum noise



[1] Z. Jiang, K. J. Sung, K. Kechedzhi, V. N. Smelyanskiy, and S. Boixo, "Quantum algorithms to simulate many-body physics of correlated fermions," *Physical Review Applied*, vol. 9, 4 2018.

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).

Classical Optical Communications to Quantum Optical Communications



- Differentiate classical and quantum optical communications based upon quantum entanglement as a part of quantum optical communications
- Classical optical communications continue to grow as a viable option for wideband, high data rate space communications.
- Classical optical communications maturity has passed the point of needing additional 'demonstrations missions'
 - Cost remains an issue.
- Classical optical communications also provides a base for expansion into quantum optical communications.
 - The classical optical communications infrastructure is needed for the space and ground segments for space quantum communication
 - The engineering challenges with classical optical communications are added to additional challenges to performing quantum optical communications

Lunar Laser Communications Demonstration 2013



Space Communications and Navigation (SCaN) developed and tested optical communication technology using lasers through the Lunar Laser Communications Demonstration (LLCD) mission, which transferred data at much higher rates than Radio Frequency (RF) communications systems. SCaN demonstrated the technology with LLCD from October 2013 through April 2014 during the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.

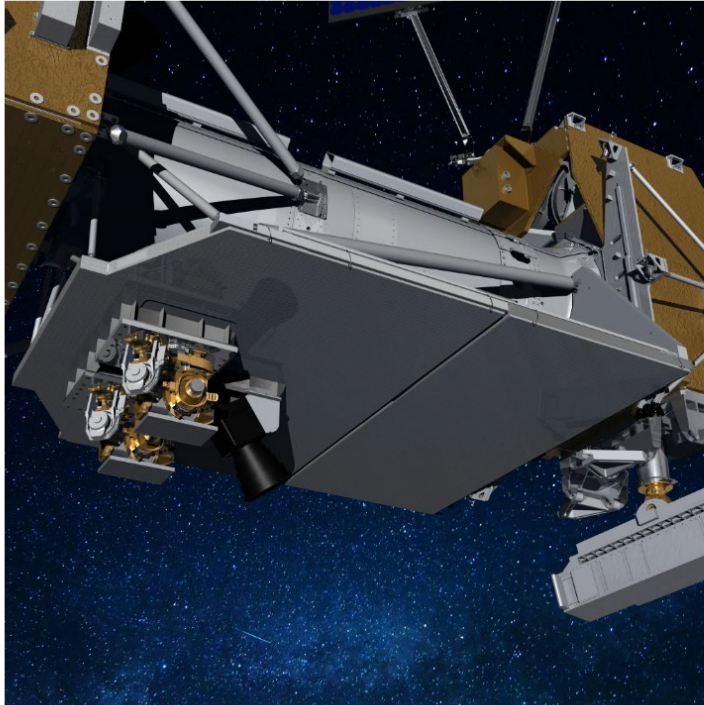


The LLCD demonstration consisted of a space terminal on the LADEE spacecraft and three ground terminals on Earth. Together, they demonstrated that it was possible to transfer up to 622 Mbps of data from the Moon with a space terminal that weighs less, uses less power, and occupies less space than a comparable RF system.

LLCD Project Summary:

- High bandwidth, lunar orbit to Earth optical link
- Downlink: 40-622 Mbps; Uplink: 10-20 Mbps
- Ground stations: White Sands, NM; NASA JPL's Table Mountain, CA; European Space Agency Tenerife, Spain (Canary Islands)
- Flight on LADEE spacecraft: October 2013 – April 2014

Laser Communications Relay Demonstration (LCRD) & (Integrated Laser Communications Relay Demonstration Low Earth Orbit User Modem and Amplifier Terminal) ILLUMA-T



The Laser Communications Relay Demonstration payload is attached to the LCRD Support Assembly Flight (LSAF), which can be seen in this image. The LSAF serves as the backbone for the LCRD components. Attached to the LSAF are the two optical modules, which generate the infrared lasers that transmit data to and from Earth. A star tracker is also attached here. These components are visible on the left side of this image. Other LCRD components, such as the modems that encode data into laser signals, are attached to the back of the LSAF. u003cstrongu003eCredits: NASA's Goddard Space Flight Centeru003c/strongu003e

<https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/laser-communications-relay-demonstration-lcrd-overview/>



The Laser Communications Relay Demonstration (LCRD) launched in December 2021. Together, LCRD and ILLUMA-T will complete NASA's first bi-directional end-to-end laser communications system.

Dave Ryan

<https://www.nasa.gov/technology/space-comms/nasas-first-two-way-end-to-end-laser-communications-system/>



The Deep Space Optical Communications (DSOC) technology demonstration's flight laser transceiver is shown at NASA's Jet Propulsion Laboratory in Southern California in April 2021, before being installed inside its box-like enclosure that was later integrated with NASA's Psyche spacecraft.

NASA/JPL-Caltech

<https://www.nasa.gov/mission/deep-space-optical-communications-dsoc/>

TeraByte InfraRed Delivery (TBIRD)



MIT/Lincoln Labs & NASA. 200 Gbps downlink from LEO



This rendering shows the TBIRD laser communications payload (square box) onboard a small satellite in low Earth orbit establishing an optical link to a ground station in California (circle). Image source: NASA.

<https://www.ll.mit.edu/r-d/projects/terabyte-infrared-delivery-tbird>

Spoogy-1



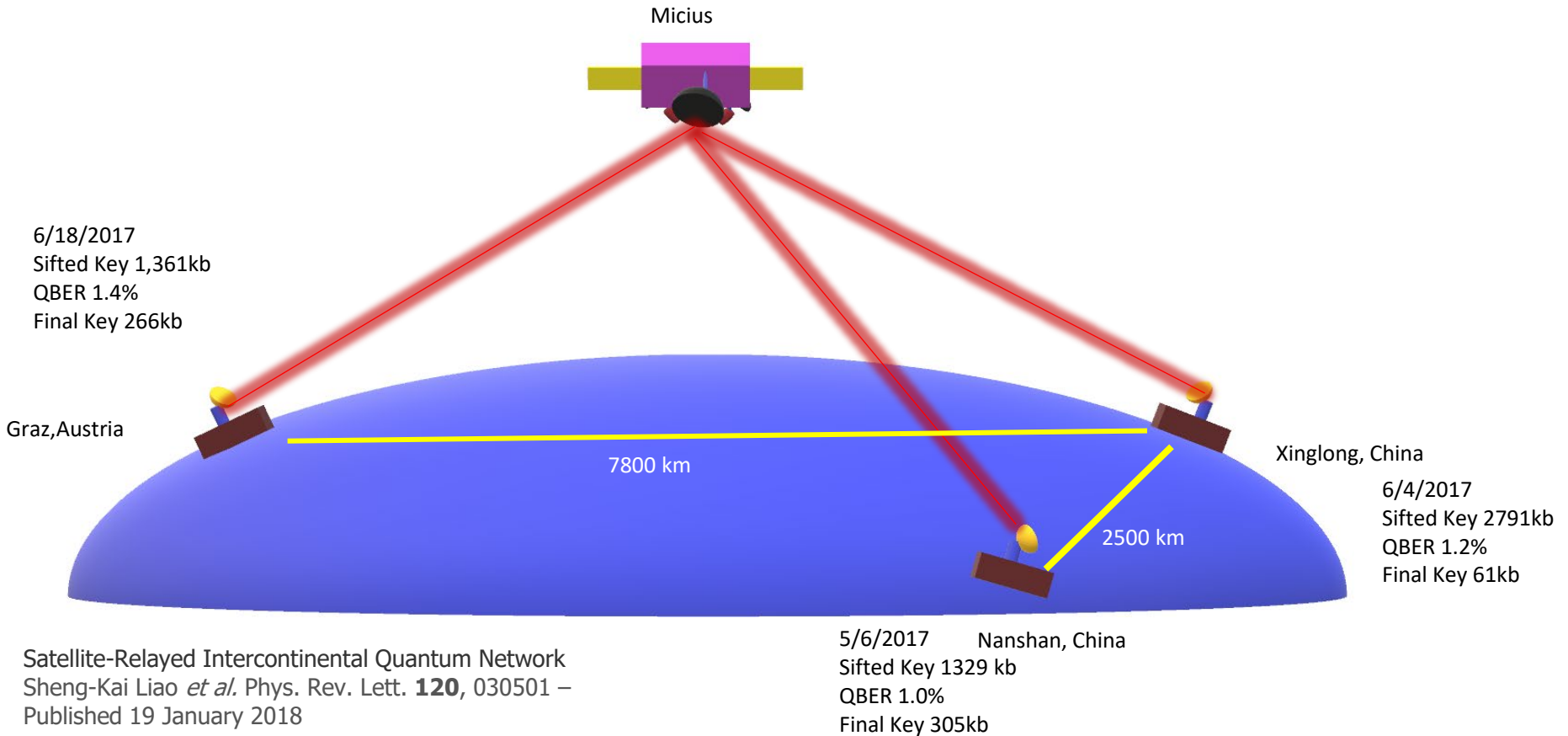
- Demonstrated generation of polarization entangled photon pairs in space on a 6U platform
- Demonstrated their Small Photon Entanglement Quantum System 2
- Investigated aging of their system in space
- Launched from GSFC Wallops Flight Facility June 17 2019 on a Cygnus resupply
- Mission to ISS
- Deployed to 408 km 51.6° orbit
- Two UHF ground stations: National University of Singapore, and Switzerland
- Achieved Clauser-Horne-Shimony-Holt (CHSH) Bell's violation of > 2.6
- No entangled space-to-ground link on this mission
- Long term goal appears to be Quantum Key Distribution (QKD) distribution from Cubesats and eventually spacebased quantum network nodes

China Micius - Important operational details



- Launched August 2016 on a Long March 2D, Jiuquan Satellite Launch Center, China. 500km, Sun-synchronous orbit
- 635kg launch mass
- Micius has a decoy state QKD transmitter at 850nm. BB84 and B92 QKD protocols were used
- Micius also performed a Quantum Entanglement downlink experiment
- Micius has two telescopes, 180mm and 300mm
- Multiple ground stations on Chinese soil including two 1.2 m aperture stations
- Sophisticated Point Ahead and Track, Ground pointing precision, 0.5°
- Uplink and downlink beacons at 532nm, 1.25mrad downlink beacon beam divergence, 0.9 mrad uplink beam divergence. Beacons were also used for time synchronization

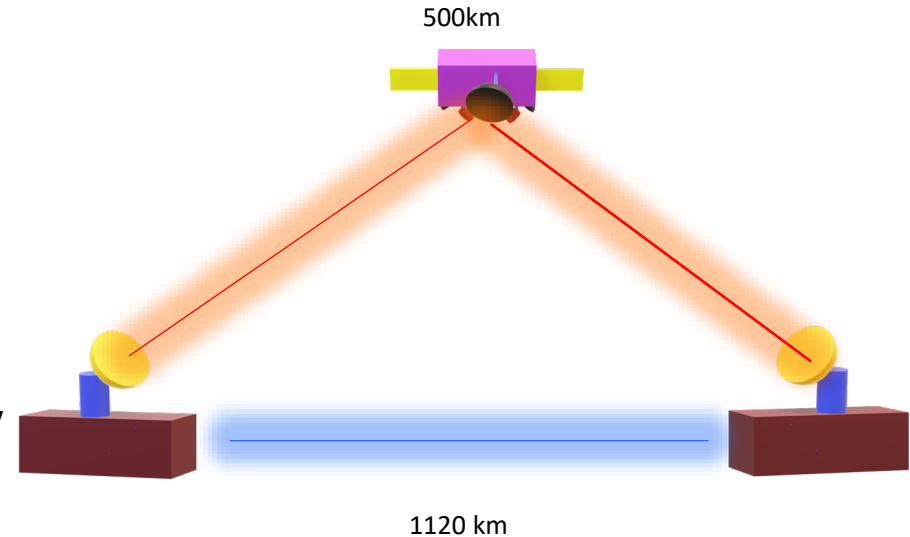
China-Austria QKD example



Micius Entanglement mission



- Conducted completely on Chinese soil
- Three ground stations:
 - Delingha, Qinghai
 - Nanshan Station, Urumqi, Xinjian
 - Gaomeigu Observatory, Linjian
- 5.9×10^6 entangled photon pairs/sec at the source
- Average sifted key rate of 1.1Hz
- QKD rate of 0.12 bits/sec for a 372 bit quantum key
- CHSH-Bell state violation of 2.56 ± 0.07
- Conducted a video conference encrypted with the derived keys



Liao, Sheng-Kai, Wen-Qi Cai, Wei-Yue Liu, Liang Zhang, Yang Li, Ji-Gang Ren, Juan Yin et al. "Satellite-to-ground quantum key distribution." *Nature* 549, no. 7670 (2017): 43-47.

The NASA view on quantum communications



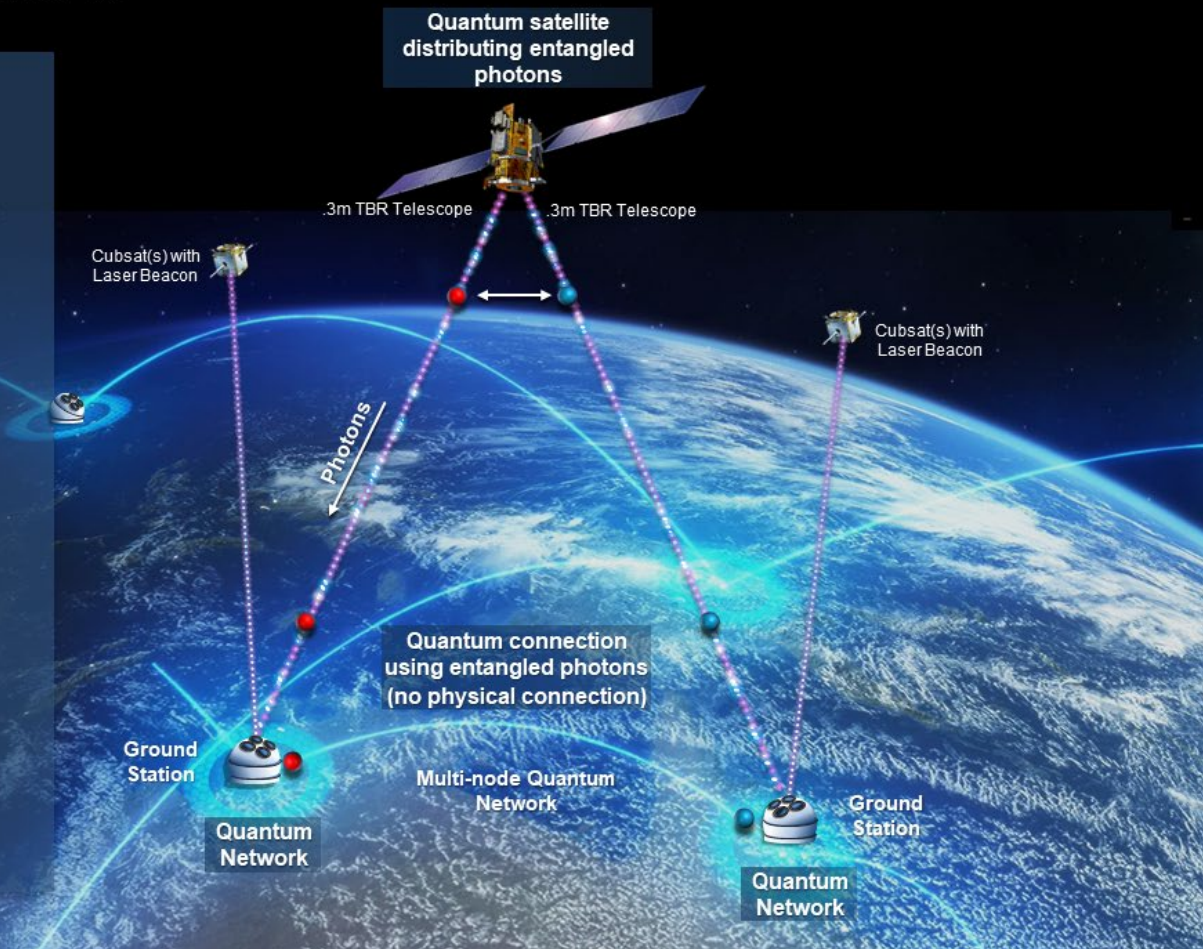
Quantum Communications

Information can now be encoded (represented) by multi-state quantum bits (qubits)

- Entangled photons as qubits can interact with each other at any distance
- By having a satellite distribute entangled photons via optical links to well separated stations on Earth, those stations can “talk” to each other via the entangled photons - without needing to be physically connected

Benefits

- Quantum networks with space links
- Data security
- Improved energy efficiency for optical communications
- Improved bandwidth efficiency for optical communications

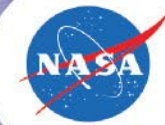


Potential Advantages of Spacebased quantum communications



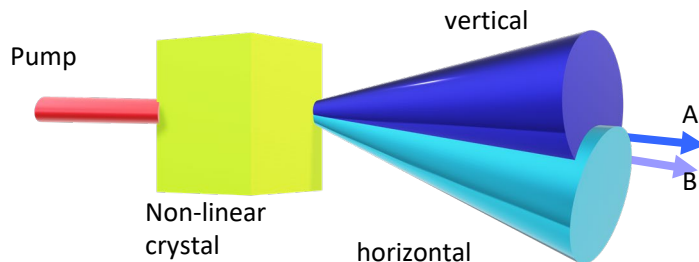
- No fiber infrastructure to be laid
- Eliminates disturbances that optical fibers are regularly subjected to, especially optical fibers that are not buried
- Simplicity of adding nodes to the ground segment
- But –
 - Ground segment nodes have to possess an optical ground station including telescopes, single photon detectors, quantum modems and eventually quantum memories and quantum relays. This puts sites with existing classical optical communications infrastructure at an advantage.
 - The more nodes that are added to the ground segment, the increase in complexity and cost of the space segment (inter-space links, more space based gimballed telescopes, more relay spacecraft in the space segment, more complex concepts of operations, etc.)

Quantum entanglement for space communications

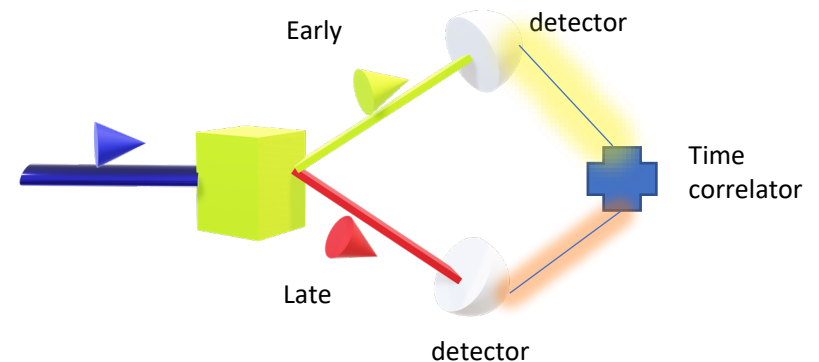


- Forms of Entanglement: Polarization and Time-bin Entanglement are two good possibilities for space-to-ground quantum entanglement work

- Polarization Entanglement
- Superposition of two polarization states call them vertical and horizontal
- It is the form of quantum entanglement most used
- Pairs of polarization entangled photons emerge from two slightly separated wavelengths on a probabilistic basis



- Energy-time Entanglement
- Two pulse-like quasi-orthogonal wave packets. Superposition of two-time states, call them early and late
- Considered to have some advantages of polarization entanglement by some researchers
- Polarization entangled photons can be generated from this source





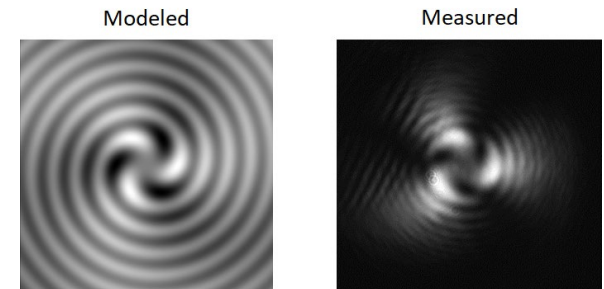
- In a classical channel, only classical information can be sent
- A quantum channel can carry private classical information, entanglement-assisted classical information, quantum information
 - Shannon's theory on channel capacity is of limited value in this domain
 - The classical capacity of a quantum channel is a function of the maximum quantum *mutual* information
 - The quantum channel capacity of transmission of entanglement-assisted classical information can be higher than the classical capacity
 - The quantum capacity of a quantum channel is lower than the classical capacity and is a function of the maximum quantum *coherent* information

Hyperentanglement and Superdense coding



- Hyperentanglement

- In quantum information processing with its high capacity character, defined as the entanglement in multiple degrees of freedom (DOFs) of a quantum system, such as polarization, spatial-mode, orbit-angular-momentum, time-bin and frequency DOFs of photons.
 - Deng, Fu-Guo, Bao-Cang Ren, and Xi-Han Li. "Quantum hyperentanglement and its applications in quantum information processing." *Science bulletin* 62.1 (2017): 46-68.
- Orbital Angular Momentum (OAM)
 - 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 superdense coding utilizing OAM modes



Generated at GSFC in the Q-STAR lab

- Superdense Coding

- Classical communication through quantum channels may be enhanced by sharing entanglement. Superdense coding allows the encoding, and transmission, of up to two classical bits of information in a single qubit.
 - Bowen, Garry. "Classical information capacity of superdense coding." *Physical Review A* 63, no. 2 (2001): 022302.

Quantum Key Distribution will be the technology most used in the short term



1. Quantum Key Distribution without entanglement will be at the base of concepts of operations for most operators in the very near term
 - a. Quantum Cryptography and QKD have commercial value.
 - b. BB84 is relatively straightforward, everyone can do it.
 - c. QKD also has value from operational checkout standpoint.
 - a. If QKD is working, you know your link is good.
 - d. The step from classical optical communications with phase modulated protocols such as DP-QPSK to BB84 QKD is small
 - e. There will have to be integration of operations of both classical channel and QKD channel for practical applications. This will mean single photon detectors at the ground station, most likely with cryostats to cool the detectors.
 - f. High key rates will require high entangled pair generation rates (in the GHz)
2. Operationally, there will be many companies with QKD protocols and algorithms – but no physical infrastructure
3. Companies without the space infrastructure will have to seek out partners or contractors to provide QKD services

QKD can be combined with Chaotic communications to increase security



Approach

◆ Chaotic Systems

- First presented by E. N. Lorenz in 1963
- Display **well defined**, but extremely **complex dynamic behaviors**
 - ◆ Broadband noise-like signals similar to spread-spectrum signals
 - ◆ Multi-path fading resistance
 - ◆ Unpredictability
 - ◆ Sensitivity to initial conditions
- **Difficult for unintentional receivers** to synchronize to the chaotic signal → Security

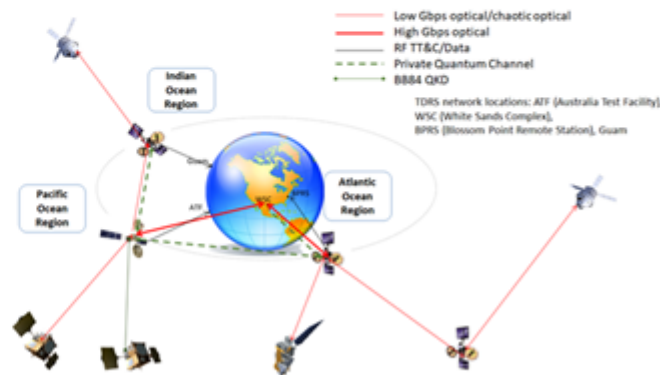
◆ Pyramidal Filtering Structures

- Discrete Wavelet Transformation (DWT)
 - ◆ Minimize **scintillation noise**
 - » Usually found in space-to-ground, near-Earth, and terrestrial communications

◆ FPGAs

- Stringent real-time requirements of FSO communications
 - ◆ Transmission Rates > 1 Gbps
 - ◆ Bit-Error-Ratios (BER) < 10^{-7} (with FEC and modulation)

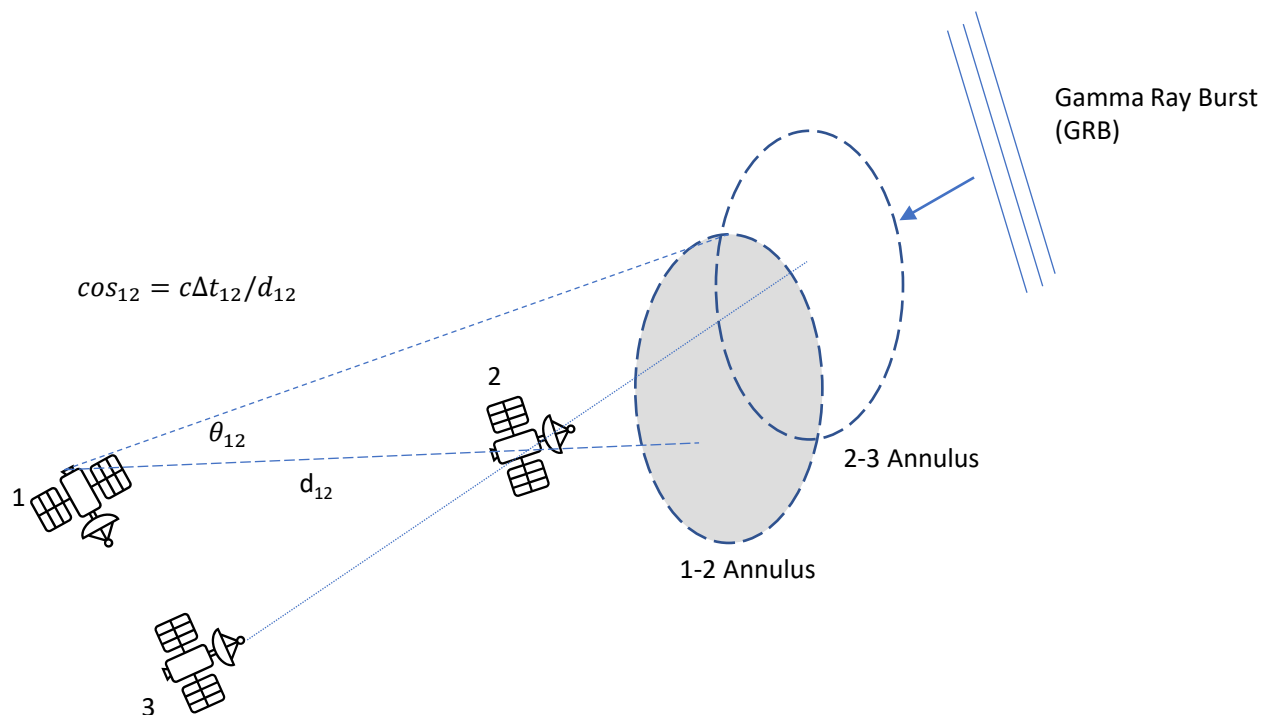
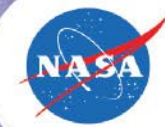
Future Optical Communications missions could include classical optical, chaotic optical, quantum optical over private quantum channels, and RF communications over a satellite constellation



4

Mahmud, Naveed, Esam El-Araby, Harry Shaw, and Lavidia Cooper. "Securing and auto-synchronizing communication over free-space optics using quantum key distribution and chaotic systems." In Quantum communications and quantum imaging XVI, vol. 10771, p. 107710U. International Society for Optics and Photonics, 2018.

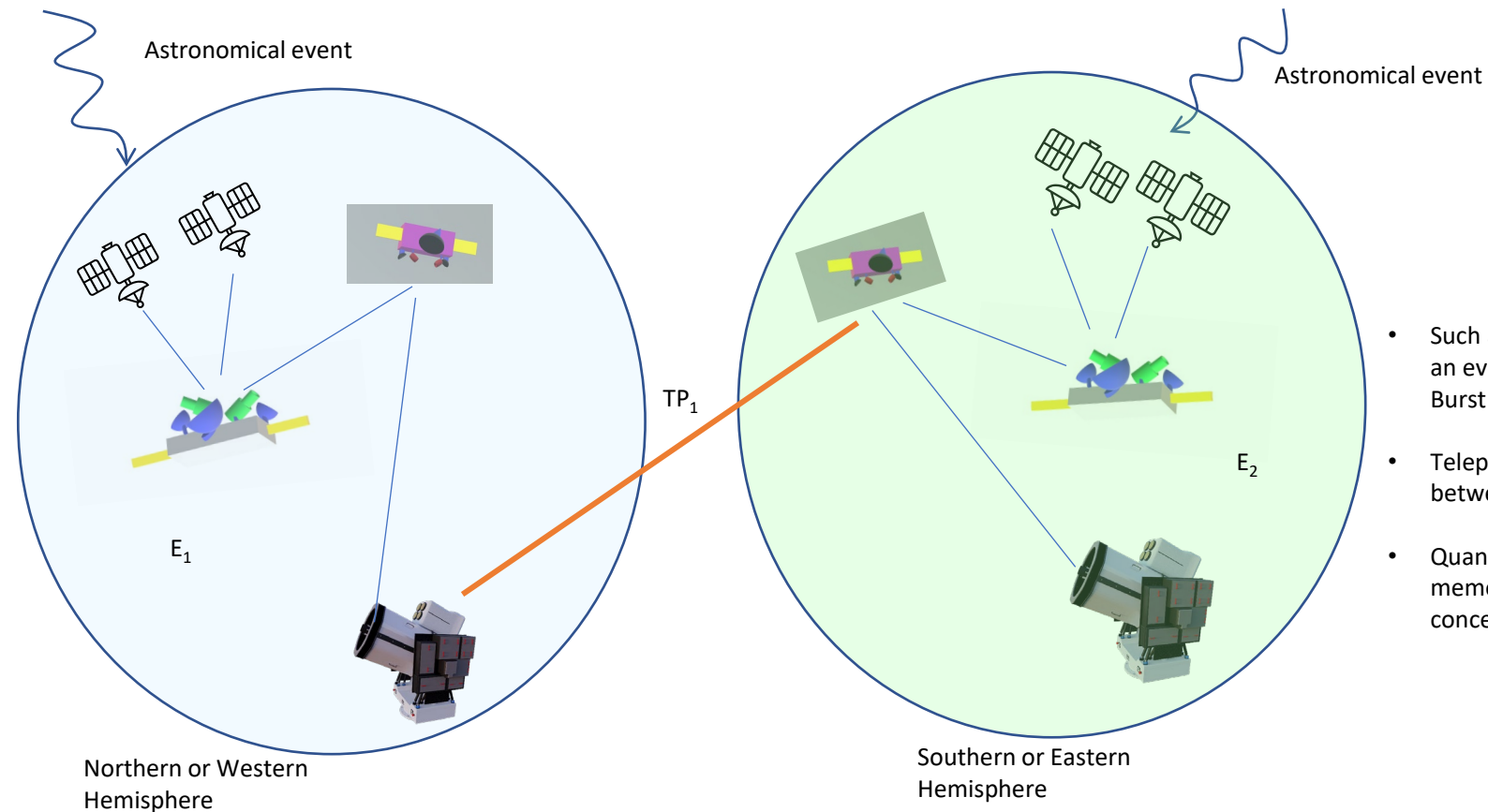
Quantum Clock Synchronization could improve Gamma Ray Burst direction and location estimates



Each independent pair of spacecraft derives an annulus of location for the burst

Hurley, K., V. D. Pal'Shin, R. L. Aptekar, S. V. Golenetskii, D. D. Frederiks, E. P. Mazets, D. S. Svinkin et al.
The interplanetary network supplement to the Fermi GBM Catalog of cosmic Gamma-Ray Bursts.
The Astrophysical Journal Supplement Series 207, no. 2 (2013): 39.

A quantum entangled(E_1 , E_2) Burst Alert Network with a quantum teleportation link TP_1



- Such a network could serve as an evolution of the existing Burst Alarm Network.
- Teleportation could be used between nodes not connected.
- Quantum repeaters and memories would simplify the concept of operations

Other operational concepts of interest for space operations



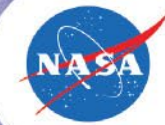
- Networking concepts
 - Blind quantum computing over a space network
 - Quantum leader election
 - Distributed quantum computing
- Agreement protocols
 - Byzantine agreement
 - Coin flipping
 - Device-independent quantum key distribution with random key basis
- Techniques
 - Rapid quantum state reconstruction with machine learning
 - Spacebased Quantum Compressive Sensing
- Security Countermeasures for:
 - Detector blinding
 - Man in the middle attacks

Technology needs (not an exhaustive list)



- High brightness, high efficiency quantum entanglement sources
- Improvements and miniaturization of quantum memories
- Improvements and miniaturization of quantum relays using teleportation
- Significant improvements in efficiency of Geiger mode Avalanche Photodiode single photon detectors
- Miniaturization of cryostats for cooling superconducting nanowire single photon detectors
- Emphasis above the physical layer for implementing quantum networks (The quantum OSI stack)
- Advances in Quantum Machine Learning and Quantum Error Correction Protocols for managing quantum channels

What quantum communications will not achieve



- There is no faster than light communications
 - Eberhard, P.H., Ross, R.R. Quantum field theory cannot provide faster-than-light communication. *Found Phys Lett* 2, 127–149 (1989). <https://doi.org/10.1007/BF00696109>
- There will always be a need for a companion classical channel to exchange measured information about the quantum states
 - R. S. Tessinari *et al.*, "Towards Co-Existence of 100 Gbps Classical Channel Within a WDM Quantum Entanglement Network," *2021 Optical Fiber Communications Conference and Exhibition (OFC)*, San Francisco, CA, USA, 2021, pp. 1-3.

Conclusions



- The transition from only classical optical communications to quantum communications is already happening
- The use of quantum space relays could accelerate development of large geographical quantum networks
- Technology hurdles are being addressed in labs around the world
- There are unexplored possibilities for the utilization of quantum entanglement in quantum communications. Only research can identify and explore these possibilities.

Acronyms



- Advanced Communications Capabilities for Exploration and Science Systems (ACCESS)
- Bennett 92 (B92)
- Bennett and Brassard 84 (BB84)
- Bit Error Ratio (BER)
- Clauser-Horne-Shimony-Holt (CHSH)
- Commercial Off-the Shelf (COTS)
- Discrete Wavelet Transformation (DWT)
- Dual Polarization Quadrature Phase Shift Keying (DP-QPSK)
- Forward Error Correction (FEC)
- Free Space Optical (FSO)
- Gamma Ray Burst (GRB)
- Goddard Space Flight Center (GSFC)
- Low-Cost Optical Terminal (LCOT)
- Lunar Laser Communications Demonstration (LLCD)
- Laser Communications Relay Demonstration (LCRD)
- Open Systems Interconnection model (OSI)
- Orbital Angular Momentum (OAM)
- Quantum Bit Error Rate (QBER)
- Quantum Key Distribution (QKD)
- Quantum Space Telecommunication and Algorithms Research (Q-STAR)
- Spin angular momentum (SAM)
- Science, Technology, Engineering, and Math (STEM)
- Ultra High Frequency (UHF)