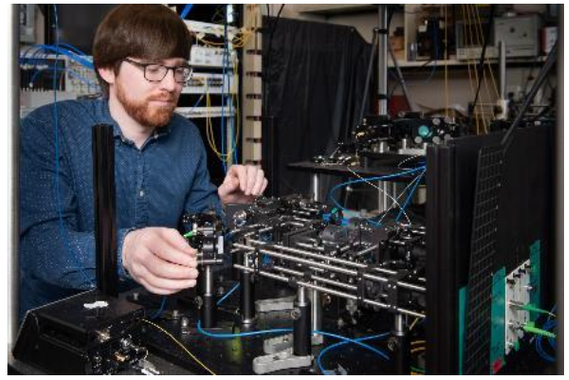
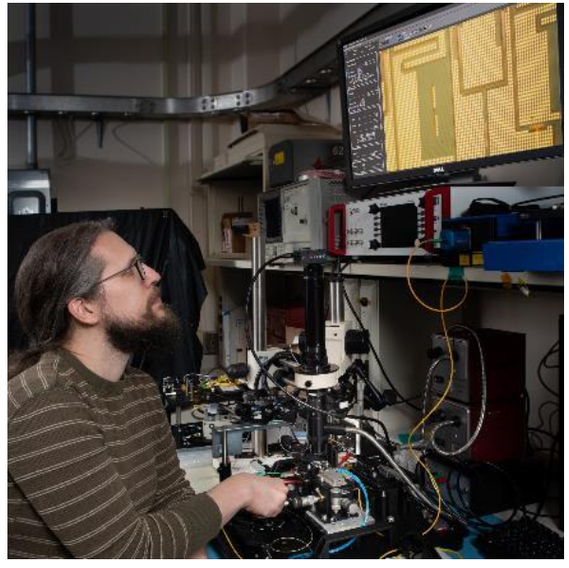
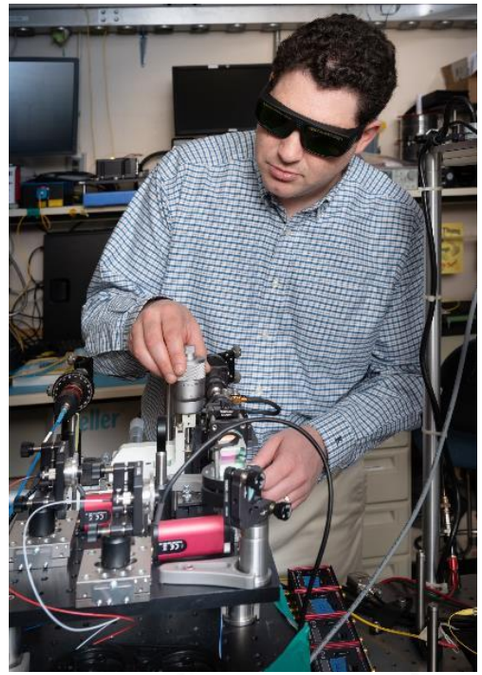
Quantum Information Systems at NASA Glenn Research Center

Nathan Wilson, Brian Vyhnalek, Ian Nemitz, Evan Katz, Adam Fallon, Yousef Chahine,
John Lekki
NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH, USA 44135

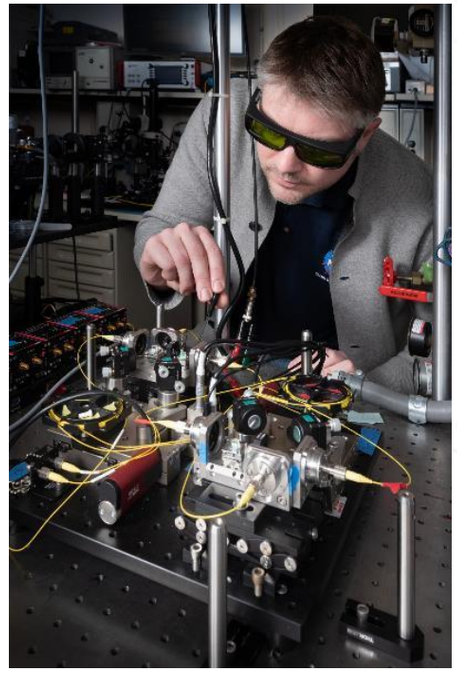
NASA GRC Quantum Communications Research Team



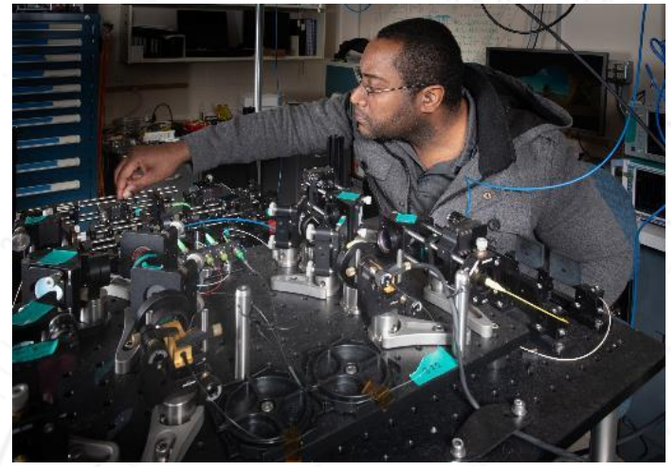


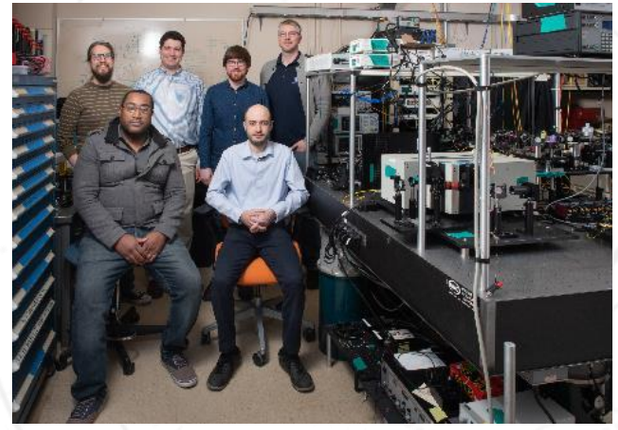


Dr. Yousef Chahine
Dr. Adam Fallon
Dr. Dan Hart
Dr. Evan Katz



Dr. Ian Nemitz
Mr. Brian Vyhnalek
Dr. Nathaniel Wilson





Overview

- Potential NASA applications of Quantum Information Systems
- The NASA Quantum Metrology Laboratory
- The NASA Quantum Communications Analysis Suite
- Quantum Communications to Aircraft Testbed
- Connecting testbed, metrology and modeling
- Path Forward – Very Long Baseline Telescopy Example

Study Results

Independent Panel Report for Technical Assessment of NASA and External Quantum Sensing Capabilities

1. Optical clocks for tests of fundamental physics, gravitational wave detection, and precise positioning of spacecraft
2. Transition edge sensors for X-ray detection with enhanced energy resolution for Heliophysics
3. Compact magnetometers for multi-satellite Earth and planetary science
4. Rydberg atoms for RF communication
5. Colloidal quantum dots for spectrometry
6. Atom interferometry for Earth science and hydrology
7. Solid-state quantum sensors for magnetic analysis and imaging of extraterrestrial rocks and minerals
8. Passive quantum imaging for low-light star tracking and passive navigation

Kitching, John, et al. *Independent Panel Report for Technical Assessment of NASA and External Quantum Sensing Capabilities*. No. NASA/TM-20230018123. National Aeronautics and Space Administration, 2023.

Study Results

Workshop on Space Quantum Communications and Networks

Quantum Computing Network

- Blind (private) quantum computing
- Distributed quantum computing

Quantum Enhanced Sensor Arrays

- Entangled Optical telescopes (Long Baseline Interferometry)
- Entangled atomic clocks
- Entangled atomic vapor cells

Enhanced Communication Capability

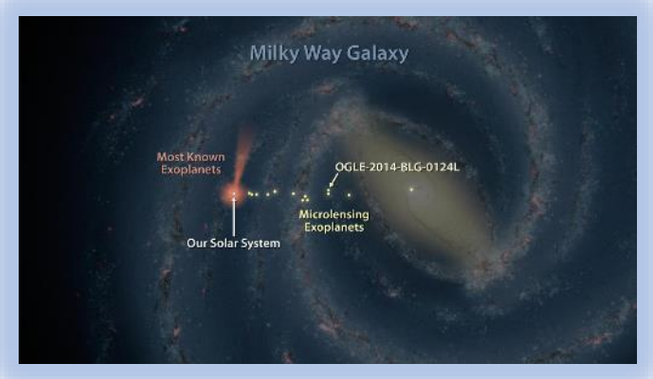
- Secure quantum communication links
- Synthetic optical communication transmitter / receiver arrays

Barghouty, Abdulnasser F., et al. "Workshop on Space Quantum Communications and Networks." *Developing a Roadmap to Quantum Communications in Space*. National Aeronautics and Space Administration, 2020.

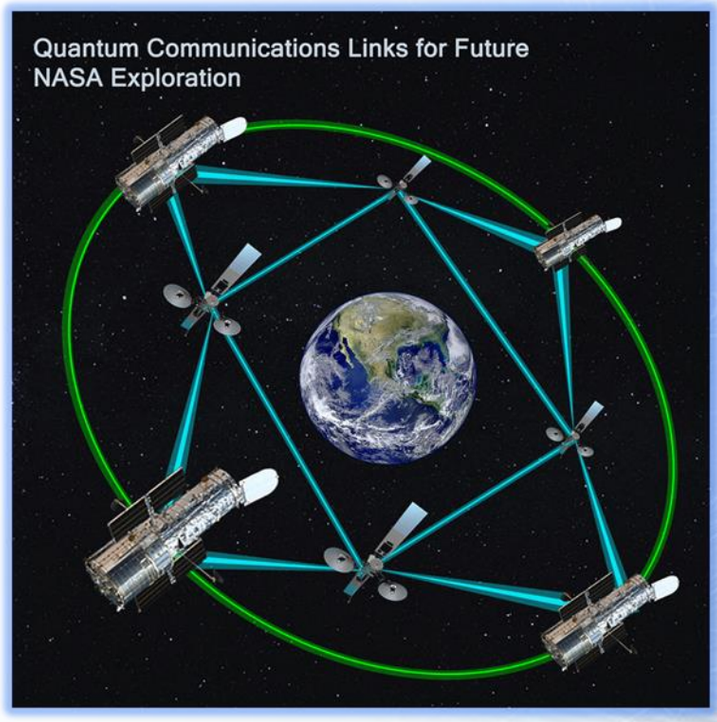
Science applications where increased precision is critical

Long Baseline Interferometry

Benefits: High resolution exo-solar imaging of never-before-seen celestial bodies and surfaces

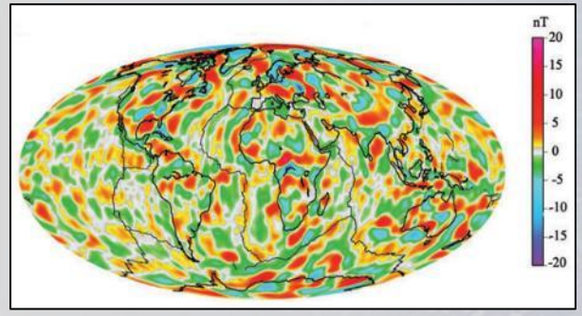


Map of Exoplanets found in our Galaxy – artist concept
Credit: NASA/JPL-Caltech.



Atomic Vapor Cells

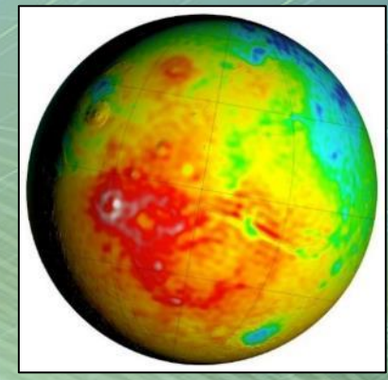
Benefits: High resolution imaging of sun/planet/moon magnetic fields



Credit: Terrence Sabaka et al./NASA GSFC.

Atomic Clocks

Benefits: High accuracy global timing system. High resolution imaging of celestial gravitation fields. Location of gravimetric sources, such as underground caverns.



Variations in thickness of Mars Crust from gravitational pull on orbiters
Credit: NASA/GSFC/Scientific Visualization Studio.

Future Quantum Networks

$$$

Monetary transfers between financial institutions secured by Quantum Comm

Image credit: NASA TDRS





Researchers access the research power of centralized quantum computers and maintain confidentiality

New Materials

Image credit: NASA/Marshall Space Flight Center

Quantum Network

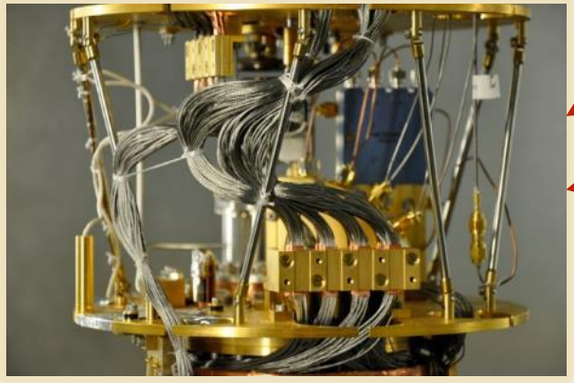


Image Credit: NASA Ames / John Hardman



Breakthroughs in Medicine



Image credit: NASA TDRS

Quantum Sensor arrays may be used to monitor local aquifers

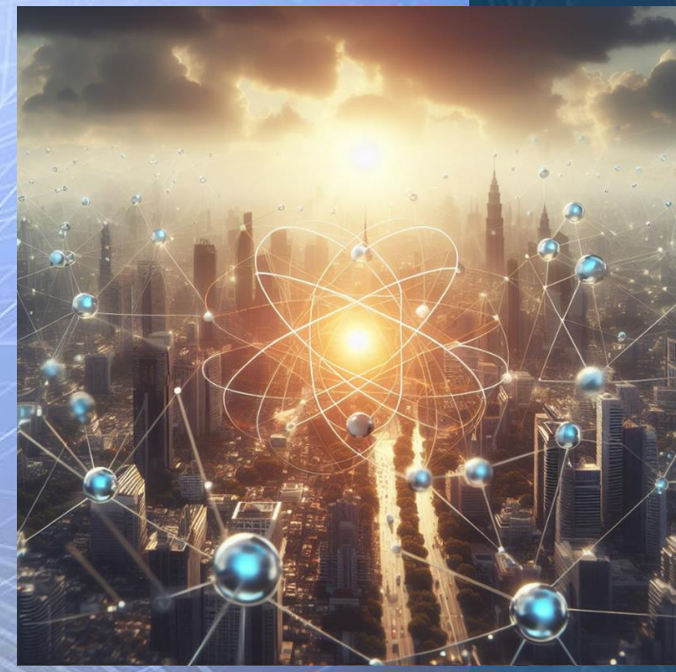
$$$

Airbridge to nationwide quantum connectivity

Opportunity:

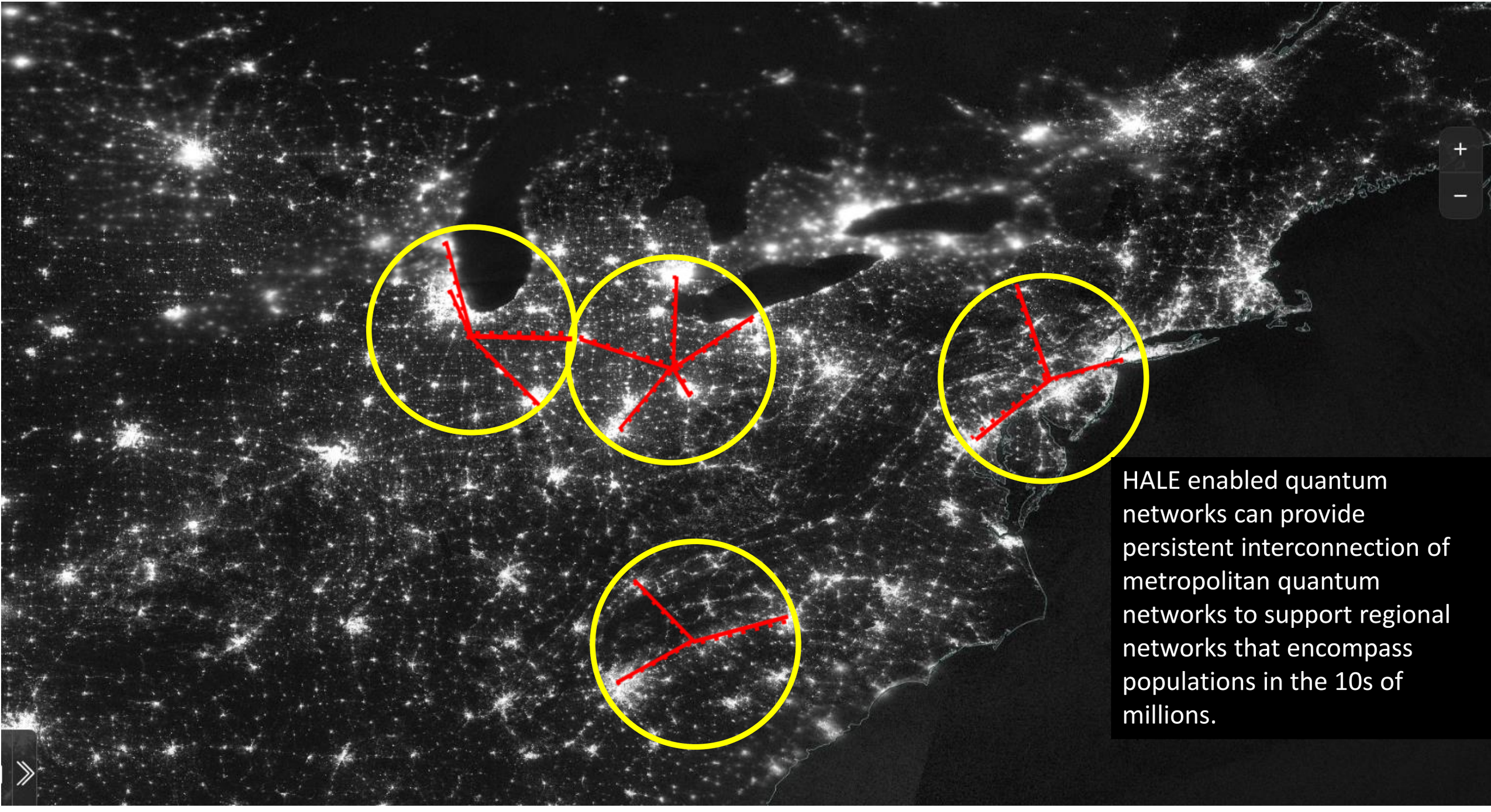
How might NASA Aeronautics contribute to, and utilize, quantum connectivity for the expansion of national benefits from quantum computation and sensing technologies?

- The development of groundbreaking quantum technology is a national (and world wide) priority
- Quantum entanglement is a key resource for quantum information processing, from quantum communication, to quantum computing, to quantum sensing
- To fully realize these benefits, researchers and businesses must be able to widely utilize delegated quantum computation.
- Connecting quantum devices at the quantum level provides inherent security that is maintained through the transmission, processing, and retrieval of computational results, enabling blind delegated quantum computation where the computation can be done without risking loss of intellectual property.



Idea:

Develop a quantum networking capability that can be flown on a high altitude aero platform that can provide long distance connectivity between local quantum networks and thereby increase the impact of quantum technology.


HALE enabled quantum networks can provide persistent interconnection of metropolitan quantum networks to support regional networks that encompass populations in the 10s of millions.

The quantum metrology need for networks

- Quantum network technologies are still relativity low TRL. Quantum metrology is needed to support iterative technology and requirement development.

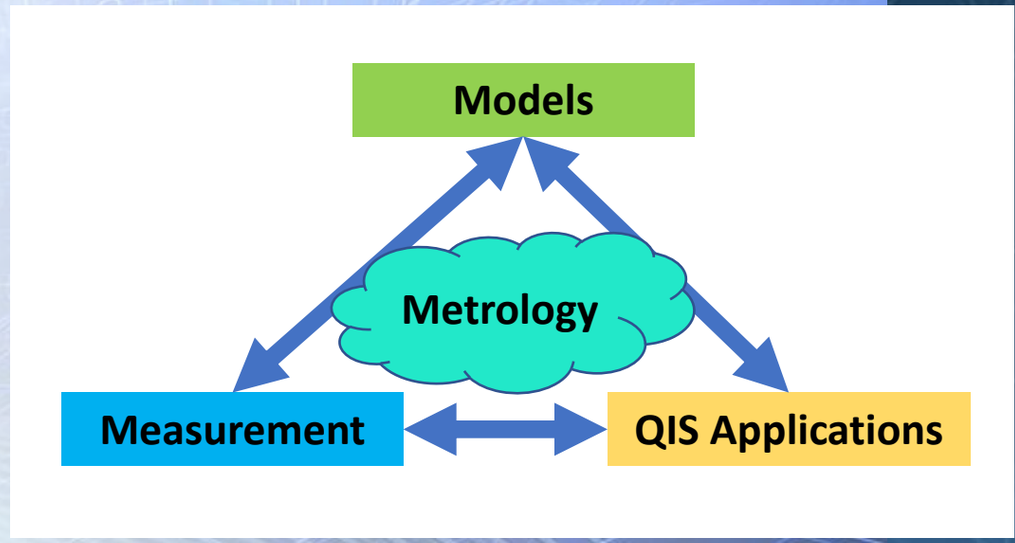
- *Quantum networks consist of complex engineering challenges. Quantum metrology is needed to evaluate quantum networks with realistic environmental conditions and with real hardware and testbed information.*

Researchers at NASA Glenn Research Center utilize an integrated measurement and modeling approach to perform their quantum metrology. The integrated approach serves as an evaluation method and as a method for moving technologies up in Technology Readiness Level

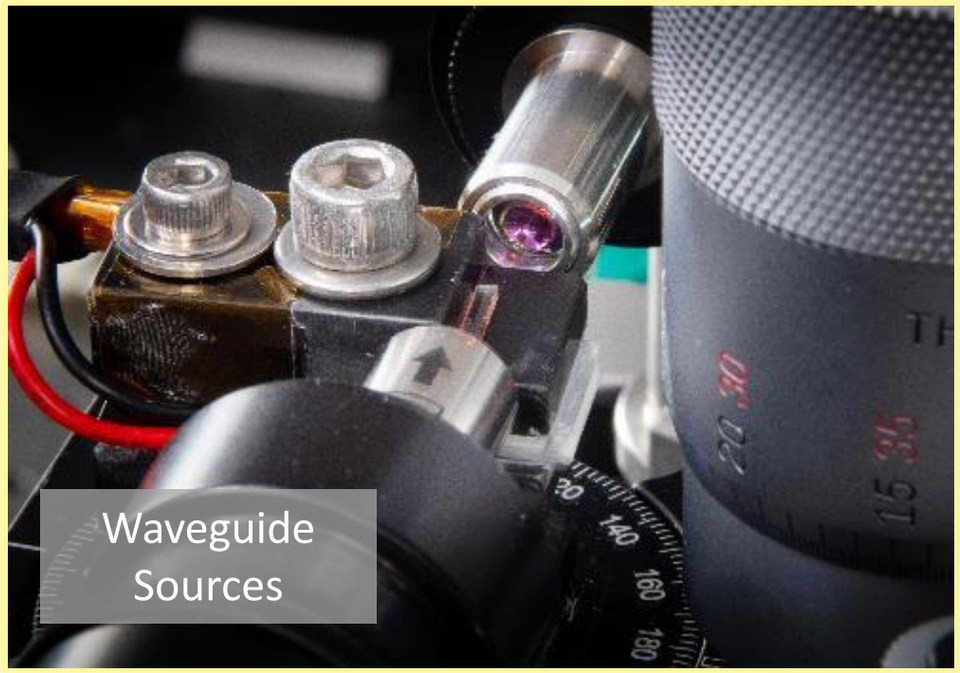
Benefits of an Integrated Measurement *and* Modeling approach

Measurement and modeling enables:

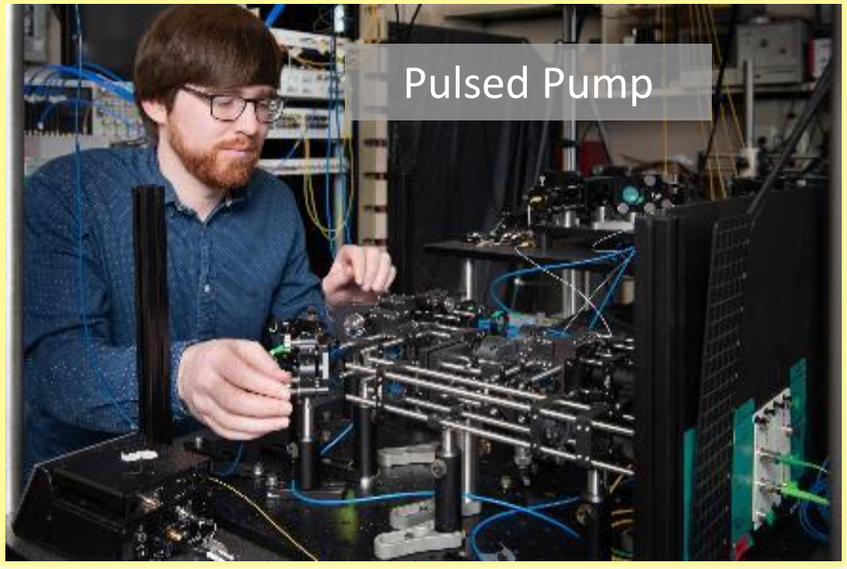
- Architectural feasibility and trade studies
- Evaluation of component performance against requirements
- Modeling of system performance based on measured component characteristics
- Identification of technology gaps within desired architectures
- Development of architectures based on specific components

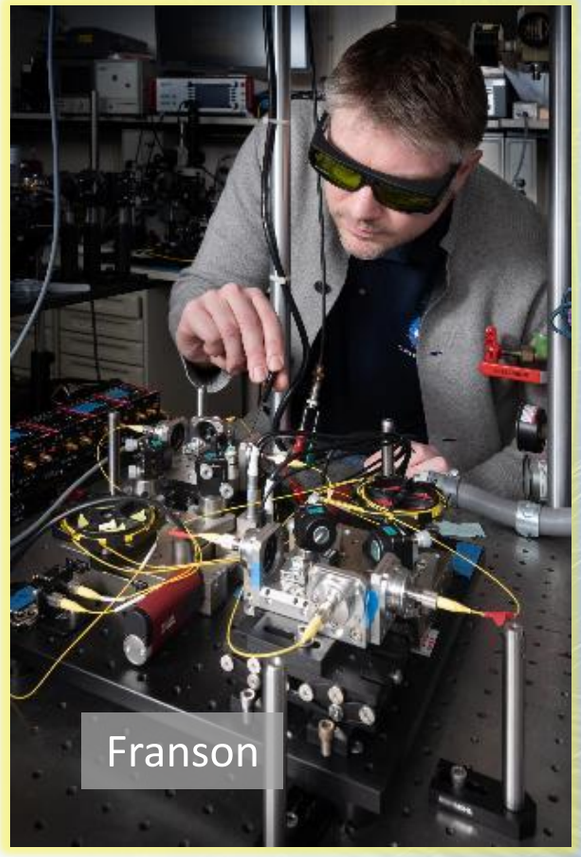


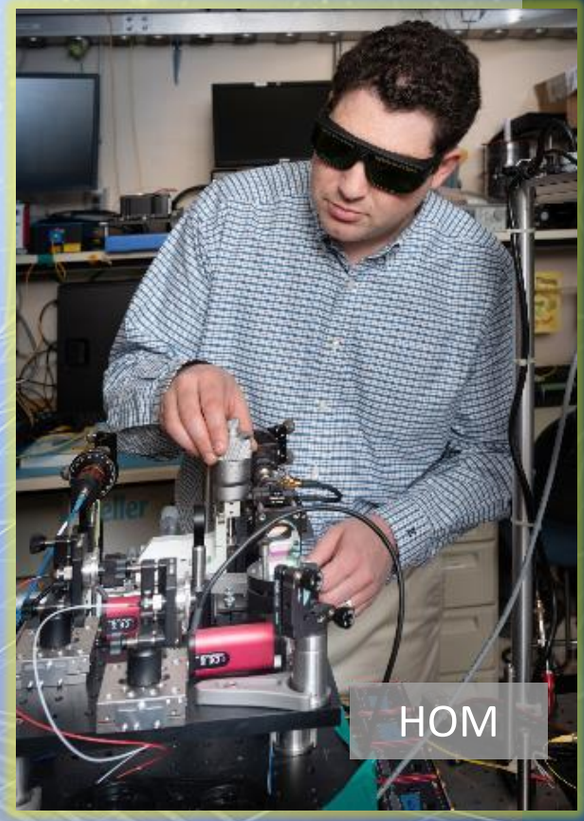
Measurement: The NASA Quantum Metrology Laboratory (NQML)



Credit to NASA GRC for all pictures







- Non-degenerate and degenerate waveguide sources
- Superconducting Nanowire Single Photon Detectors
- DLCZ Quantum Memory
- Monochromator
- Joint Spectral Intensity
- And more…

Modeling: NASA Quantum Communications Analysis Suite (NQCAS)

Develop baseline dynamic performance estimations

- Identify limits of quantum links to guide mission design
- Anchor rate / fidelity analysis based on key fundamental parameters

Verification and Validation performed through:

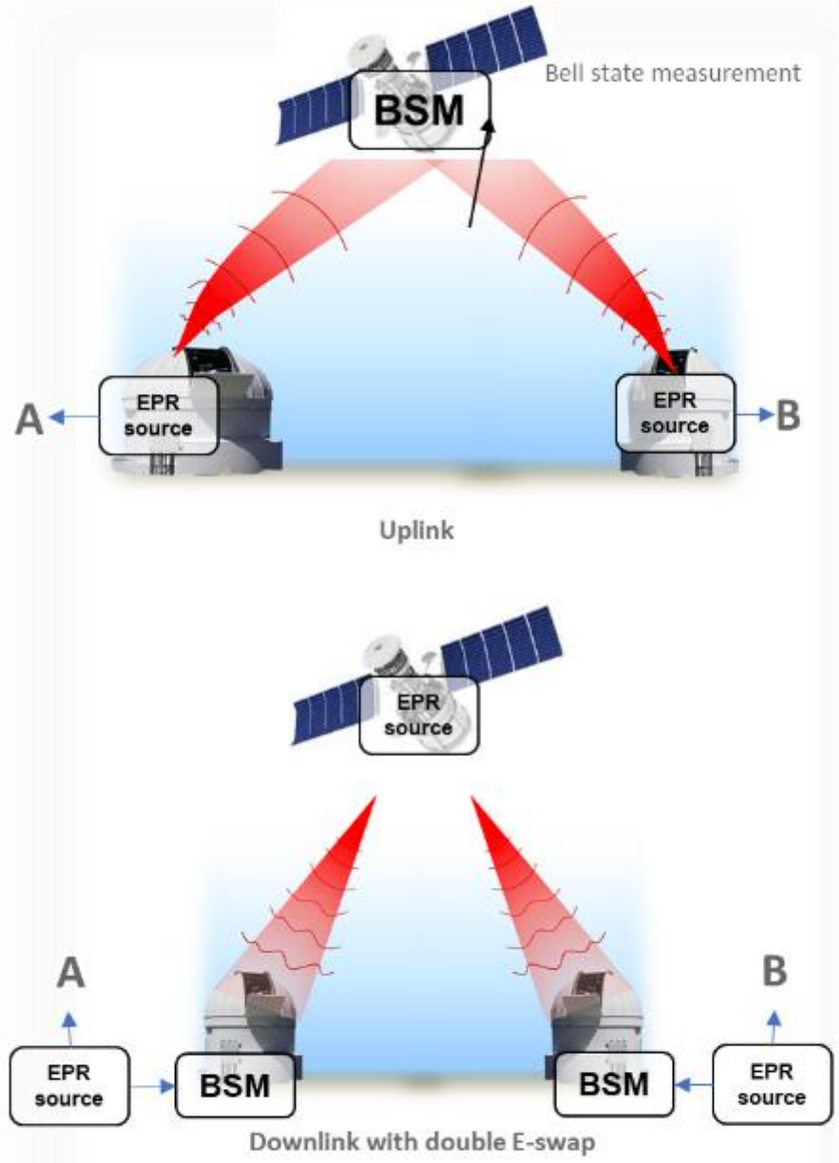
- ***NQML component characterization***
  - > ***Utilize results to inform NQML studies***
- State propagation / LOS vs. ISS

Statistical or user defined dynamic variable input

- Creation/propagation of communication assets, with relevant sources of noise, loss, and state changes

Focus of simulations is on systems operating within limitations set by current technology.

- All-photonic systems



Credit to NASA GRC

Sources

- User models photon flux / double pair generation (SPDC sources)
- Fully quantum models

Free Space Effects

- Photon time of flight variation
- Atmospheric depolarization / decoherence
- Background irradiance / optical filtering
- Adaptive optics.

Detectors

- Jitter
- Deadtime / Detector Paralysis
- PNR / Detector arrays

Quantum Memory (in progress)

- Duan Kimble / Barret & Kok
- NV centers / Rubidium cold atom

Decomposing Rate and Fidelity into Metrology Capabilities

Key measures:

The **rate** R at which quantum states can be transmitted

- A higher rate allows for higher system bandwidth

The **fidelity** F of the quantum state transmission

- A higher fidelity improves measurement SNR

Rate = $f\left(\underbrace{R_s, p_s, g_s^{(2)}}_{\text{Sources}}, \underbrace{\eta_c, p_c, \mathcal{I}_c}_{\text{Channels}}, \underbrace{\eta_d, \nu_d, \rho_d}_{\text{Detectors}}, \underbrace{R_m, p_m, \eta_m, \nu_m, \tau_m}_{\text{Memory}}\right)$

Fidelity = $F\left(p_s, g_s^{(2)}, \eta_c, p_c, \mathcal{I}_c, \eta_d, \nu_d, \rho_d, p_m, \eta_m, \nu_m, \tau_m\right)$

R_s = *source repetition rate*
p_s = *photon source generation probability*
$g_s^{(2)}$ = *source second-order correlation (multi-photon noise)*

η_c = *channel transmission efficiency*
p_c = *qubit decoherence*
$\mathcal{I}_c$ = *photon indistinguishability (Bell state measurement)*

η_d = *quantum detection efficiency*
ν_d = *noise count probability*
ρ_d = *photon number resolving power*

R_m = *memory repetition rate*
p_m = *photon generation probability*
η_m = *quantum memory storage efficiency*
ν_m = *noise added probability*
τ_m = *memory coherence time*

Joint Spectral Intensity to Assess System Level Requirements

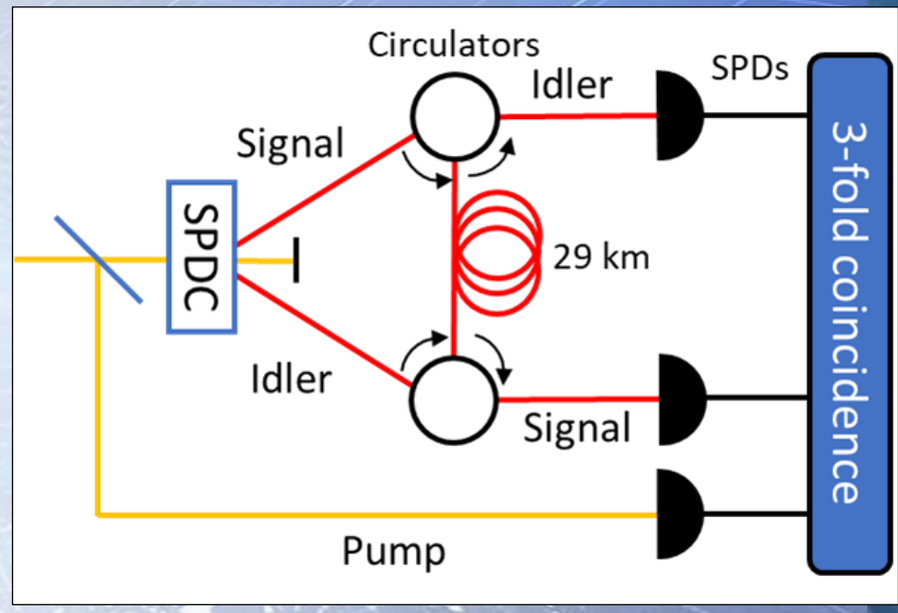
- **<u>Goal:</u> Highlight a metrology performed within the NQML with subsequent parameter application into NQCAS.**

- **<u>Device characterized</u>: Time-energy Spontaneous Parametric Down Conversion (SPDC) entanglement source**
  - Periodically poled potassium titanyl phosphate (pp-KTP) waveguide.
  - Degenerate at 1550 nm

- **<u>Metrology</u>: Dispersive fiber method**
  - Optical fiber of length L_{IR} = 29 km (SMF-28e+)
  - Dispersion of α_{IR} = 16 ps/(nm·km)
  - Total dispersions of α_{IRLIR} = 467 ps/nm.
  - **Expected spectral resolution of 110 pm**



Credit to NASA GRC



Example: Assessing components to system requirements

Component Selection
SPDC + 1.8nm Filter

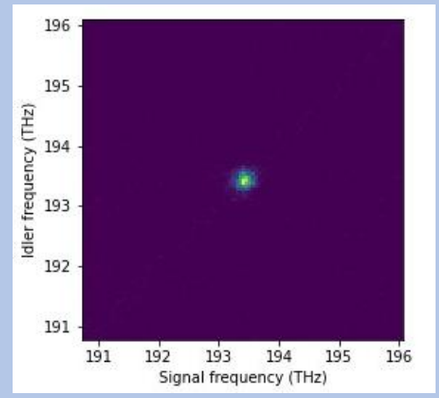


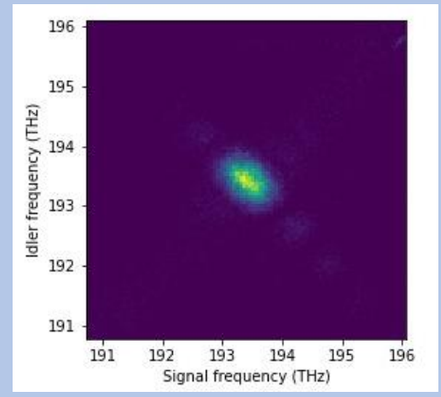
+ 1.8nm Bandpass



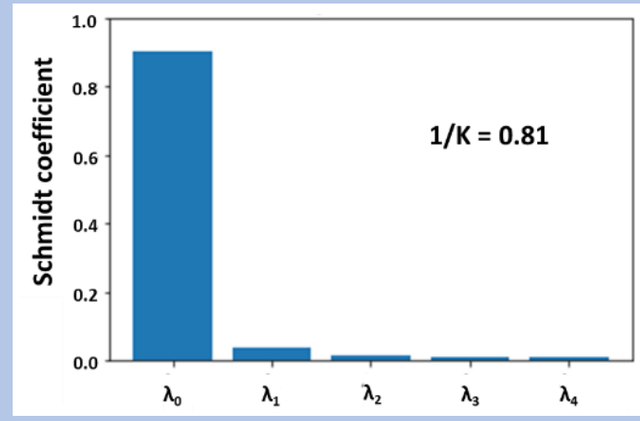
No Filter

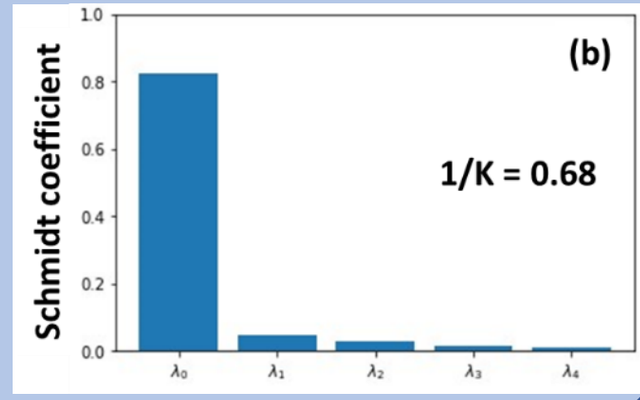
Quantum Metrology
Joint Spectral Intensity





Analysis
Purity values

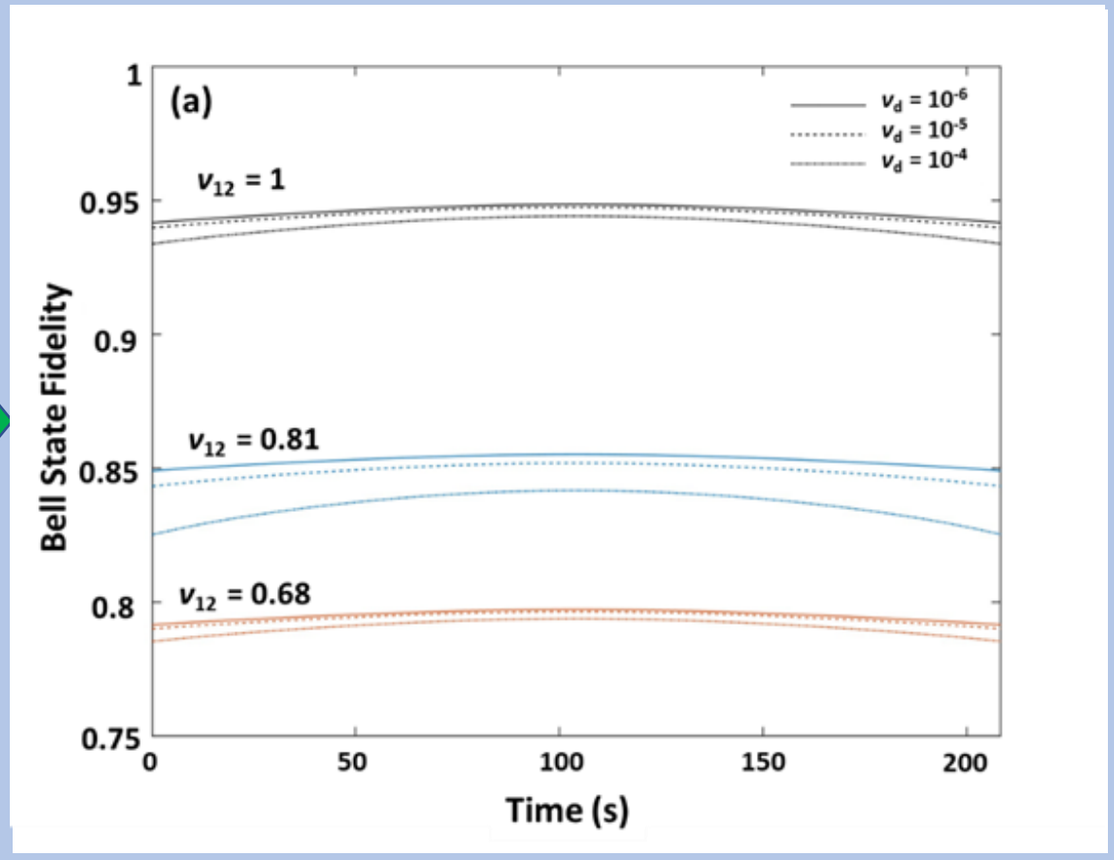


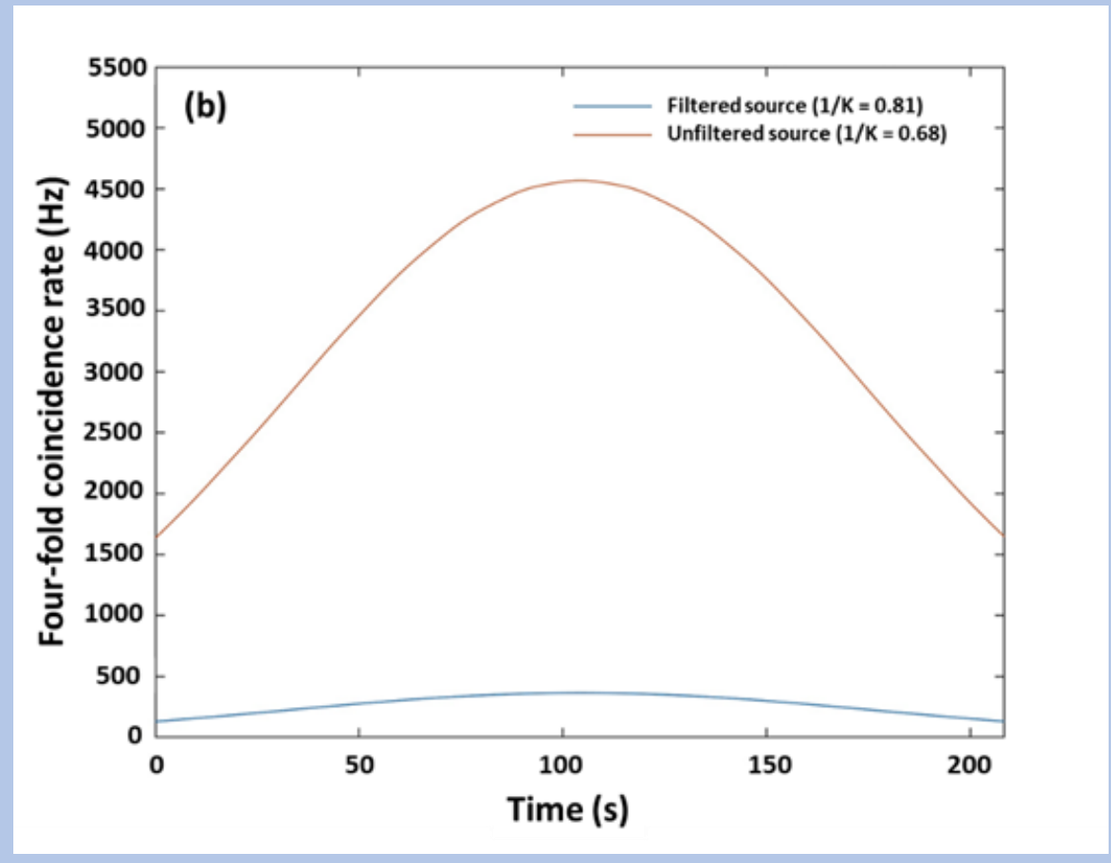


Example: Assessing components to system requirements

Network Analysis

Rate and Fidelity of an Uplink Entanglement Swap





*The fidelity is shown for three different detector dark count probabilities $\nu_d = 10^{-6}, 10^{-5}, 10^{-4}$ and a pair generation probability $p_{ij} = 0.013$ prior to filtering.

PC-12 Flying laboratory interconnected with on the laboratories in the Aerospace Communications Facility

National Aeronautics and Space Administration

Key measures of quantum network performance:

The **rate** R at which quantum states can be transmitted

- A higher rate allows for higher system bandwidth

The **fidelity** F of the quantum state transmission

- A higher fidelity improves measurement SNR

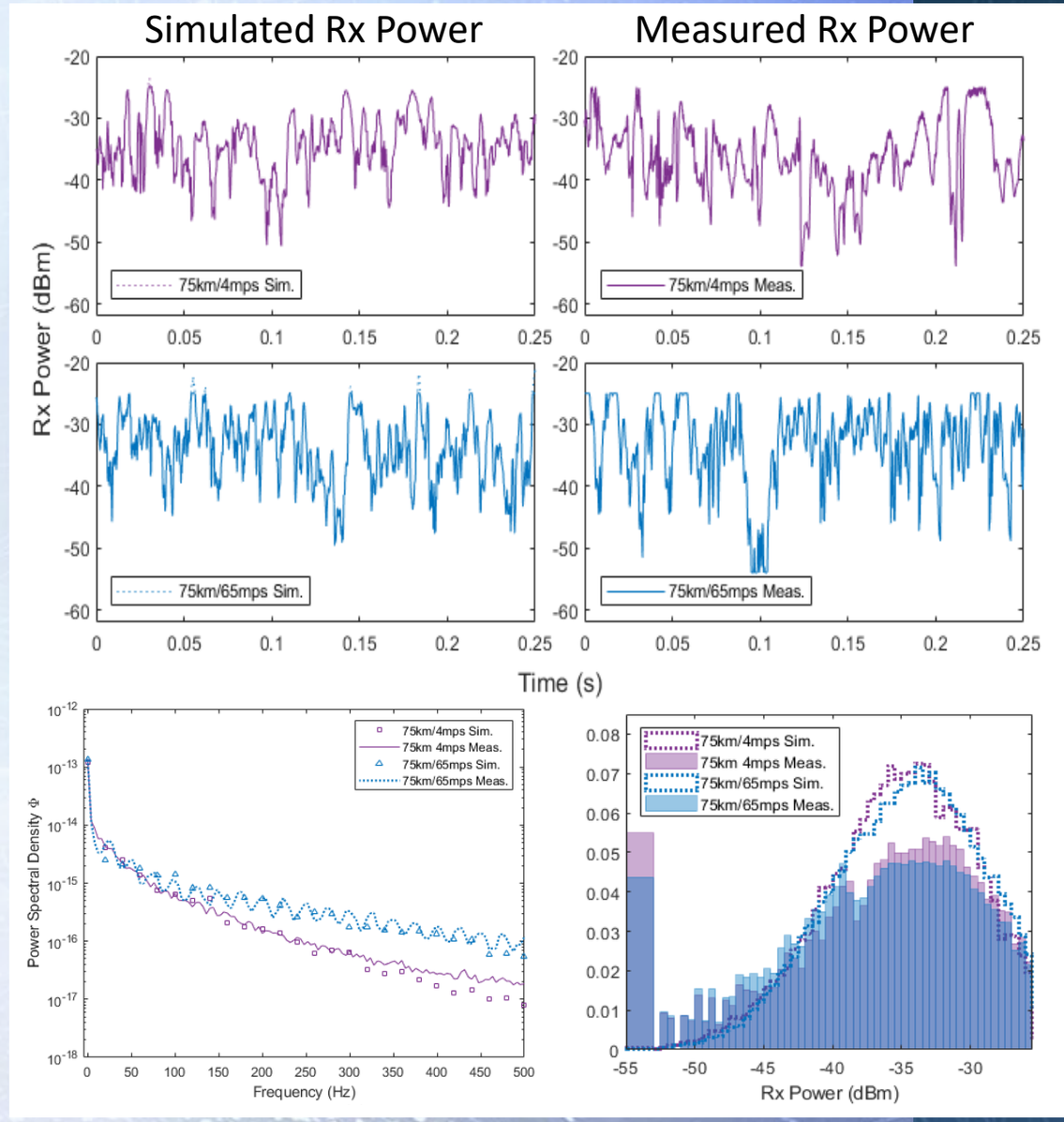






Validation of simulation from flight test data

- **Chahine, Yousef K., et al. "Laser beam propagation simulations of long-path scintillation and fade with comparison to ground-to-aircraft optical link measurements." *Optical Engineering* 60.3 (2021): 036112-036112.**
- **Performed validation study of simulated scintillation and fade profiles based on optical link measurements from a 60-110 km ground-to-aircraft laser communications experiment performed at GRC.**
- Validated scaling of fade statistics with slew rates



A concept of VLBI utilizing Quantum Hard Drives in ground telescopes

- In principle, an array of ground telescopes utilizing a long duration quantum memory that is able to store many photon events ~2^{18} for approximately 25 minutes when utilizing an adapted approach to VLBI introduced by Bland-Hawthorn, J., Sellars, M. J., & Bartholomew, J. G. (2021). Quantum memories and the double-slit experiment: implications for astronomical interferometry. *JOSA B*, *38*(7), A86-A98.
- In Bland-Hawthorn the concept of operations is
  1. Utilize at least two telescopes each with a quantum hard drive to store observations of a given object
  2. Upon completing the observation bring the two quantum hard drives together
  3. Release the photon states from the two hard drives and observe photon self interference
  4. From interference fringes obtain high angular resolution of the object under investigation
  5. Return quantum hard drives to telescopes and repeat.

A concept of VLBI utilizing Quantum Hard Drives in satellites in formation flight

- In principle, a constellation of satellites utilizing a long duration quantum memory that is able to store many photon events ~2^{18} for approximately 25 minutes when utilizing an adapted approach to VLBI introduced by Bland-Hawthorn, J., Sellars, M. J., & Bartholomew, J. G. (2021). Quantum memories and the double-slit experiment: implications for astronomical interferometry. *JOSA B*, *38*(7), A86-A98.
- In Bland-Hawthorn the concept of operations is
  1. Utilize at least two telescopes each with a quantum hard drive to store observations of a given object
  2. Upon completing the observation bring the two satellites close enough so a quantum link can be established
  3. Release the photon states from the two hard drives, send the contents of one via an optical link, for reception and observe photon self interference
  4. From interference fringes obtain high angular resolution of the object under investigation
  5. Satellites continue orbit and restart process

Orbit Phase:

1. Preparation for observation (10min)
2. Observation (15 min)
3. Preparation for communication (10 min)
4. Communication and Measure interference (10 min)
5. Repeat on other side

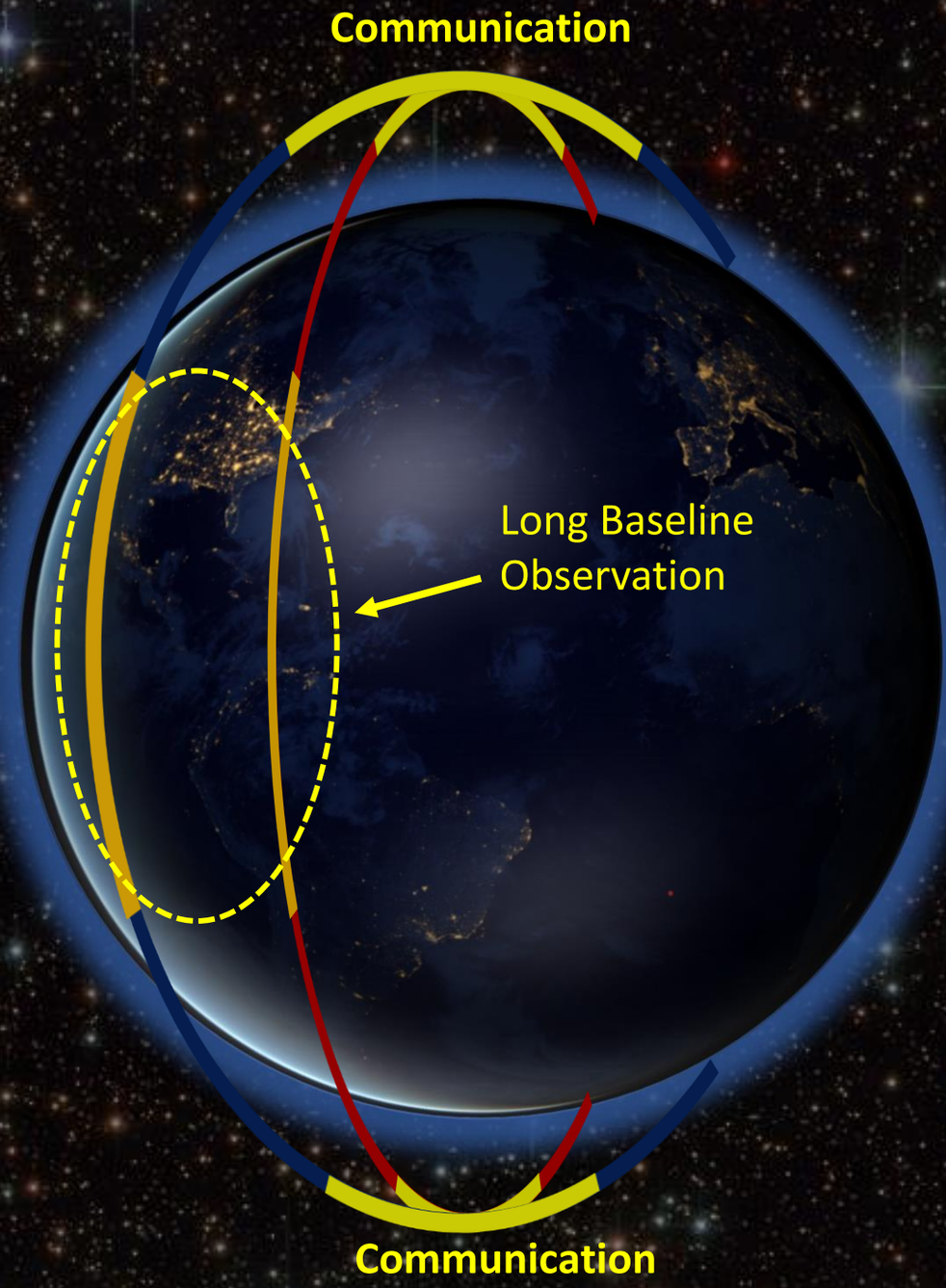
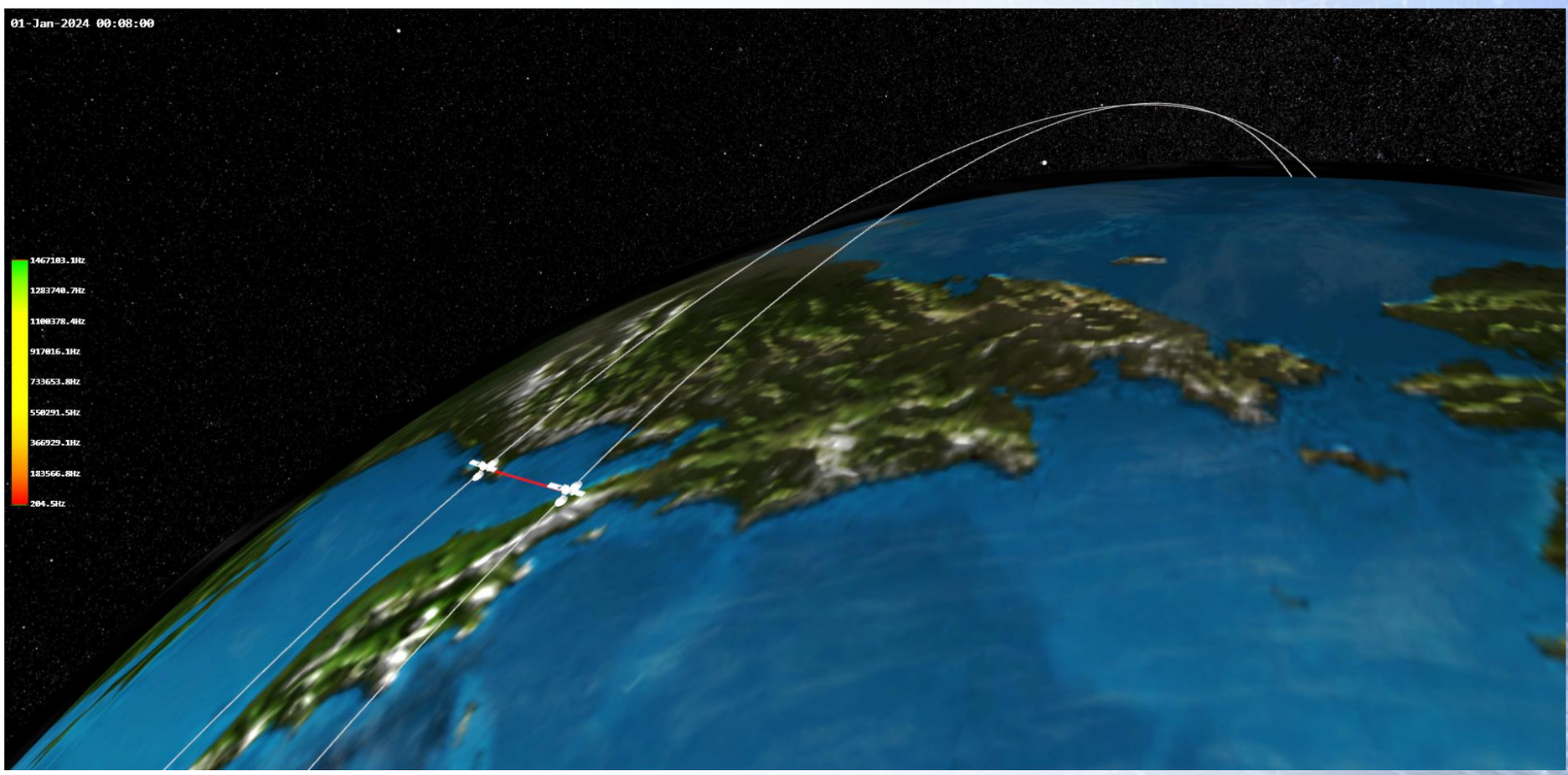
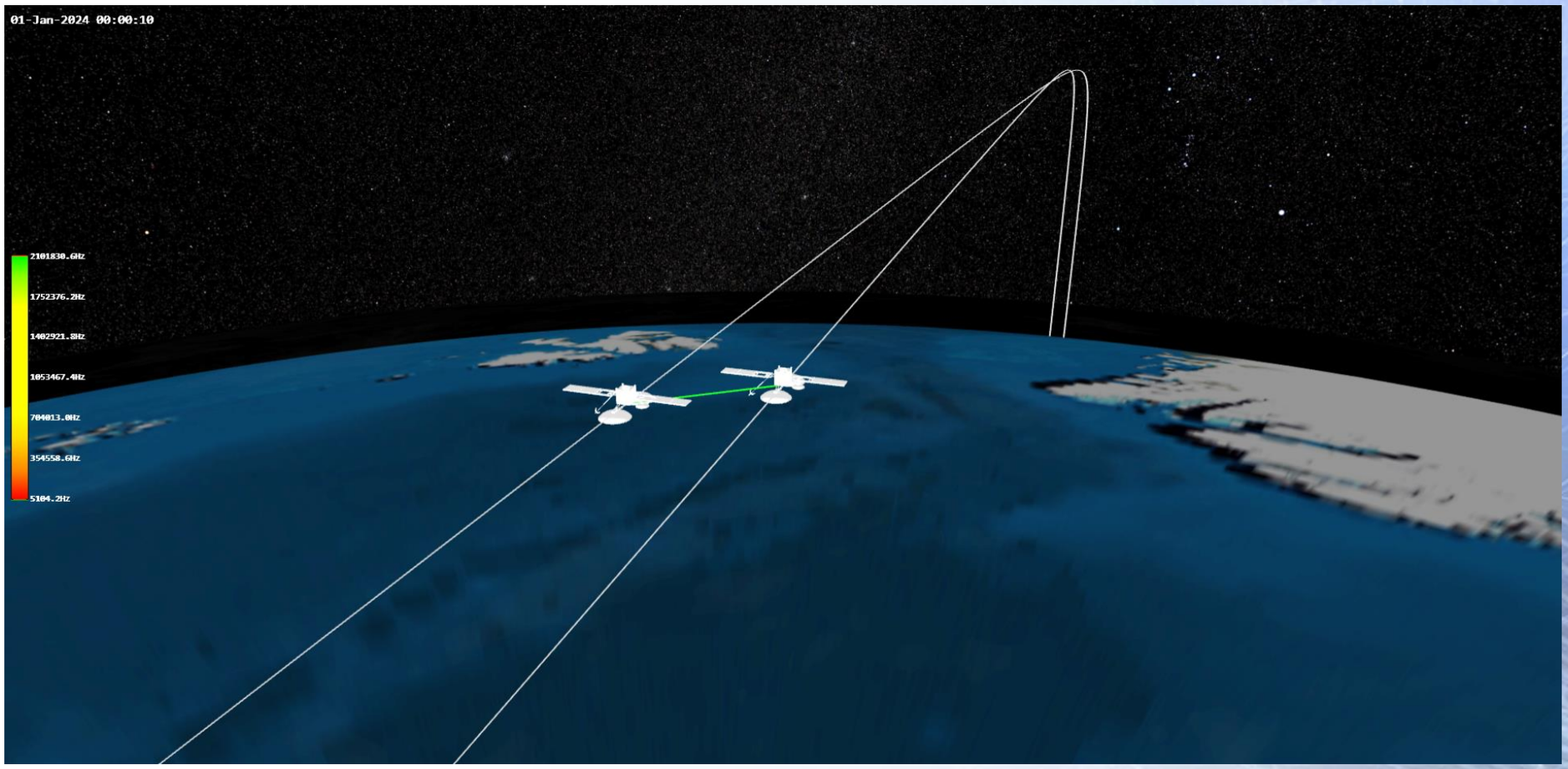


Image credit: ESA/NASA

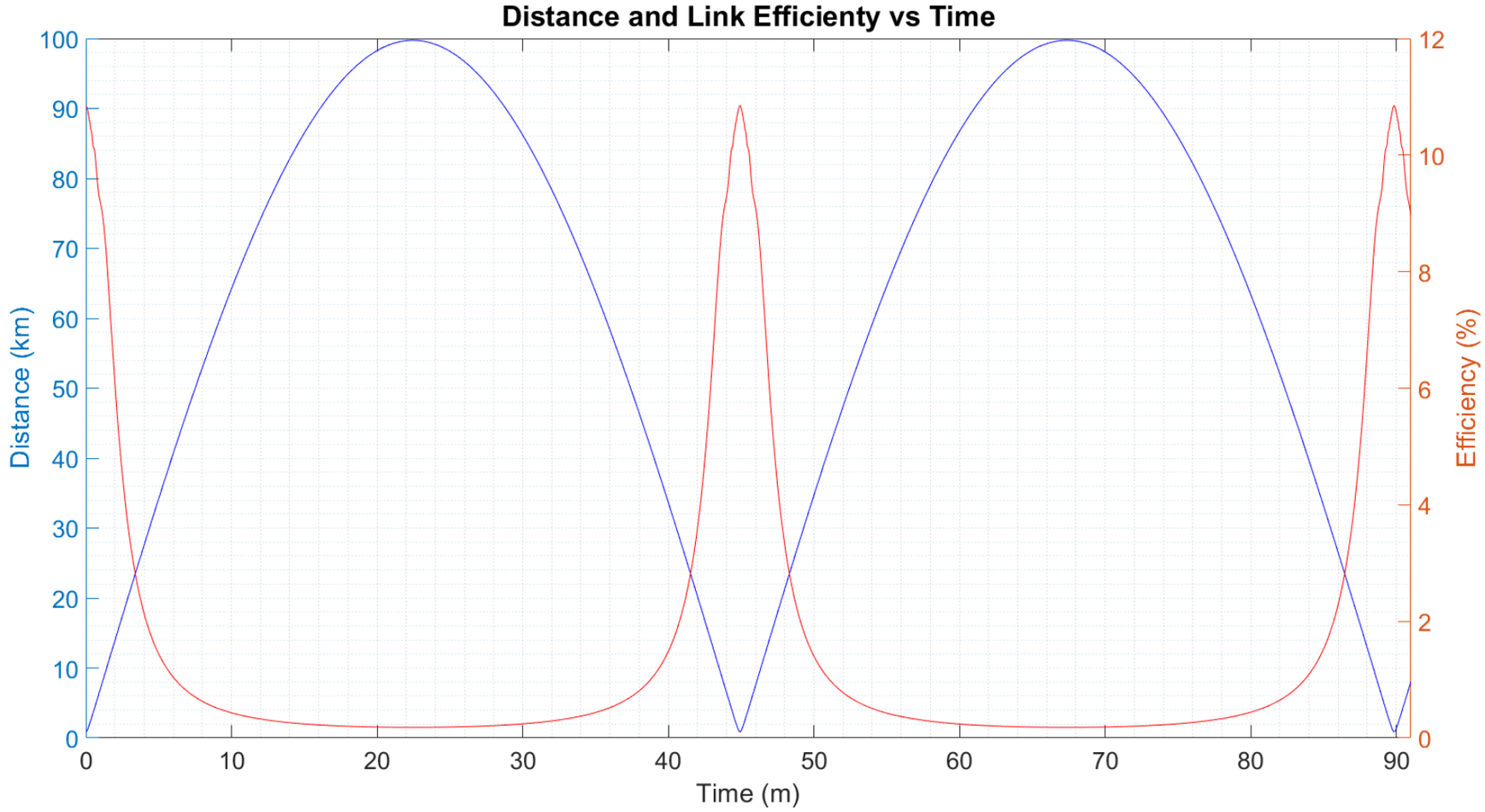
Modeled Quantum link performance during observation phase



Modeled Quantum link performance during observation phase

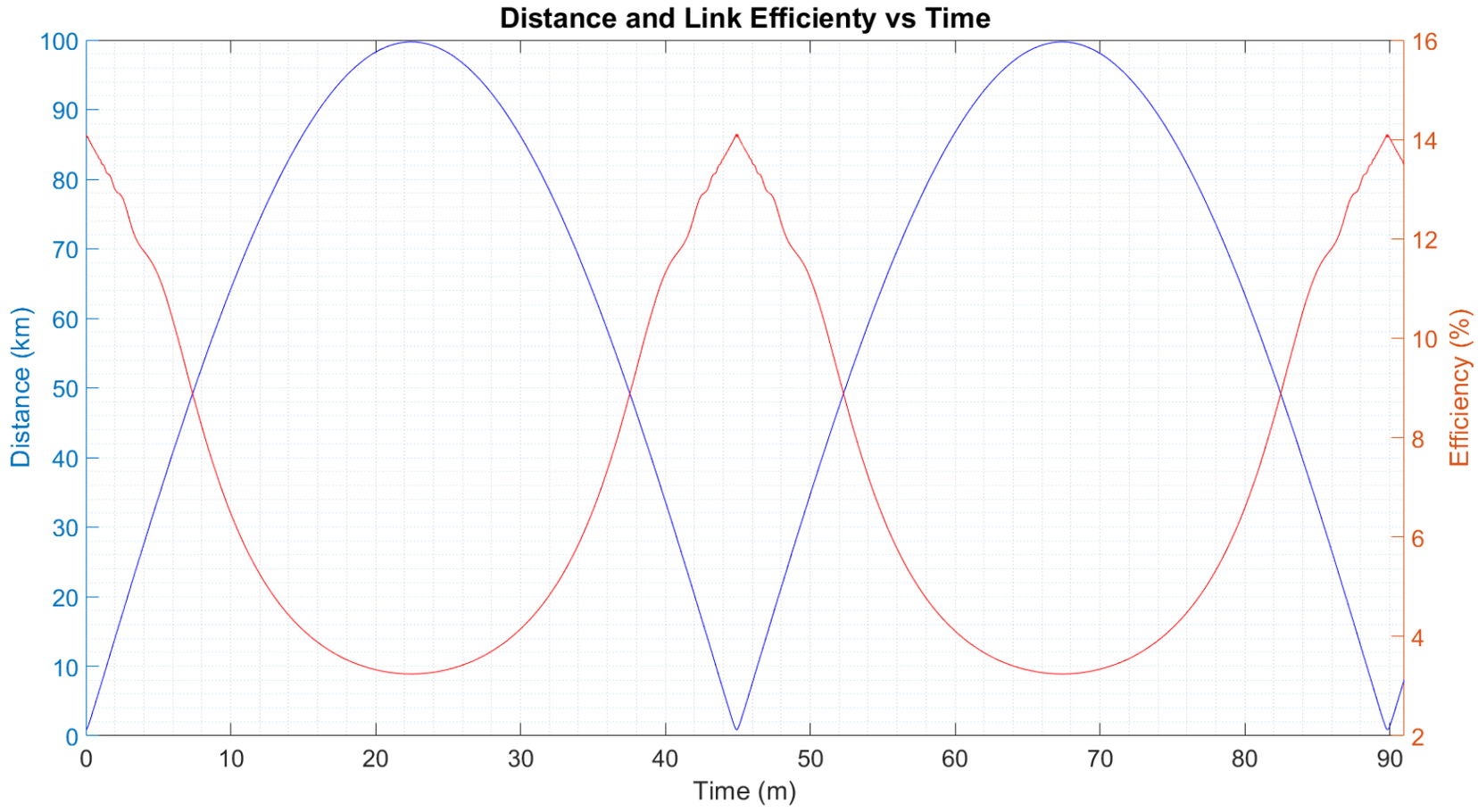


Orbital spacing and photon transfer efficiency



- Nominal Optical Comm Aperture
- Fiber coupling

Orbital spacing and photon transfer efficiency



- 2x Nominal Optical Comm Aperture
- Free space coupling

Observation parameters for example study case

Assumptions:

- Observation Wavelength 580 nm, 10 bands of 5 MHz bandwidth
- 10,000 photonic modes or photons per voxel can be stored
- Observation efficiency: 10%
- Telescope diameter: 2.4 m
- Observation photon rate 4×10^7 photons / sec nm
- Photon rate over 50 MHz band: 2.3×10^3 photons / second
- Duty Cycle limitations: 50%
- Observational: 1.15×10^3 photons / second
- Time separated by more than 90 km: 765 seconds
- Total observation photons stored: 841×10^3

Requirement: must exchange 841,000 photon states per communication pass

QIS System Analysis

Quantum Communications System Parameters

- Quantum communication telescope aperture: 10 cm
- Maximum Photon communication readout rate: $2x10^4$/ second
- Required photons per observation to be transmitted: 841,000
- Time for transfer: 425 seconds

Model output:

- Photon transfer efficiency above 10% for first configuration is only 78 seconds with 10 cm aperture.
- Not enough time of high-fidelity photon transfer to readout memory

Takeaway:

Utilize model, metrology, etc. to make changes to quantum communication receiver to increase time exceeding 10% efficiency to greater than 425 seconds, such as second configuration

Takeaways



- NASA is studying and developing quantum technologies for applications that utilize Quantum Sensors, Quantum Computation, or Quantum Networking, with a current focus on sensing.
- An integrated QIS approach is also being considered for the future
- GRC is utilizing an integrated metrology approach (measurements, testbed and models) for enabling aerospace network applications
- We can develop interesting strategies for developing QIS (such as VLBI in space) but these strategies require deep dives in quantum system engineering as well as instrument analysis

Acknowledgements

This work was supported by the NASA Aeronautics Convergent Aeronautics Solutions, the NASA Space Communications and Navigation (SCaN) programs and the Glenn Research Center Communications & Intelligent Systems Division.

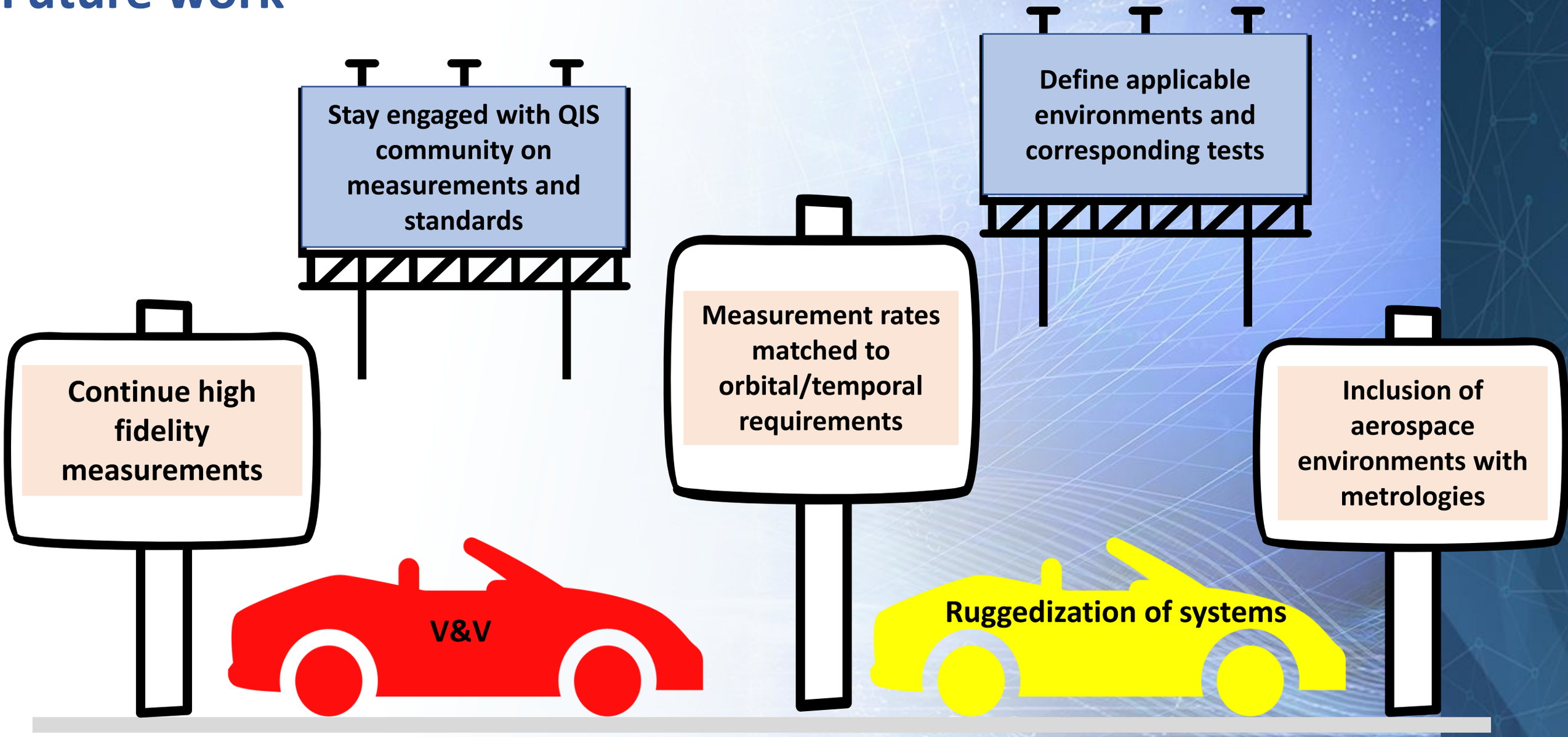

01-Jan-2024 07:22:09
4306.3Hz
3592.8Hz
2879.4Hz
2165.9Hz
1452.5Hz
739.0Hz
25.5Hz
LA
GRC
Boston
Credit to NASA GRC

Quantum Networking Decreases Measurement Uncertainties

Sensor Type	uncertainty scaling factor $\Delta\Phi$	*Example benefits using 500 probes and 50 nodes*
Single Classical (M=1)	$\sim\frac{1}{\sqrt{N}}$	~0.045
Single Quantum Enhanced (M=1)	$\sim\frac{1}{N}$	~0.002
Classical network (M>1)	$\sim\frac{1}{\sqrt{MN}}$	~0.006
Quantum network (M>1)	$\sim\frac{1}{MN}$	~0.00004

Quantum provides lower uncertainties versus classical methods. Additional networking further reduces uncertainty. All of which allows for measuring with precision beyond classical limitations.

Future work


Stay engaged with QIS community on measurements and standards
Define applicable environments and corresponding tests
Continue high fidelity measurements
Measurement rates matched to orbital/temporal requirements
Inclusion of aerospace environments with metrologies
V&V
Ruggedization of systems

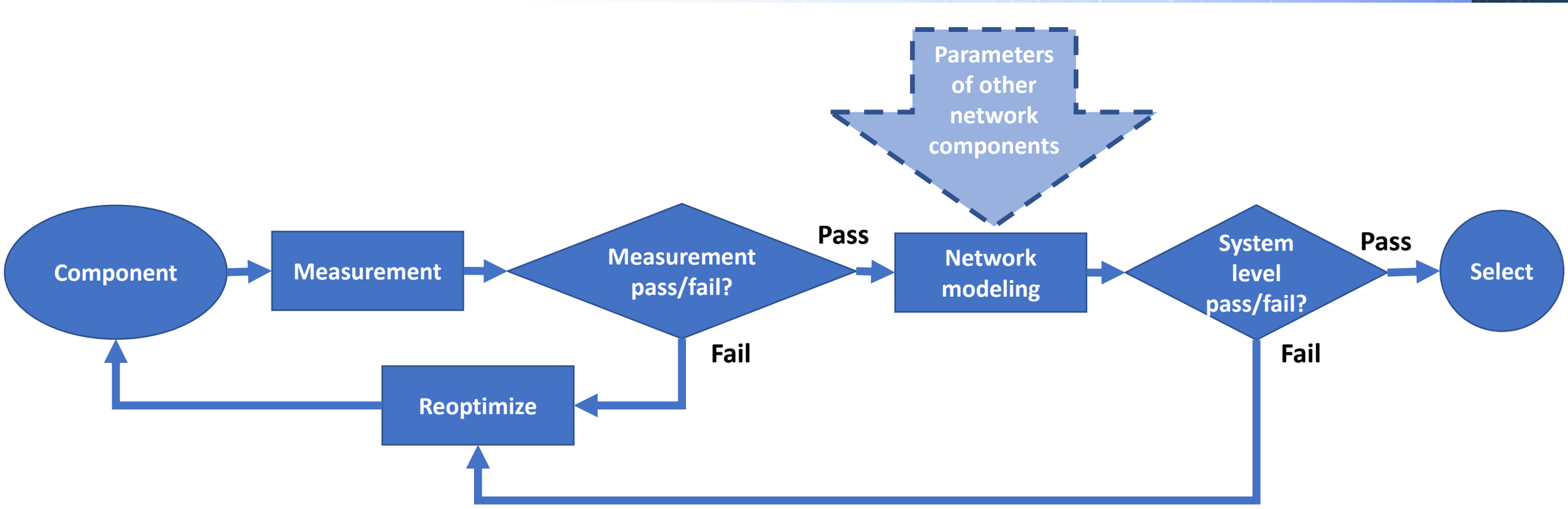
Example - Metrology Capabilities Needed for Sources

Source Performance Parameter	Measurement
R_s = source repetition rate	Autocorrelation
	Frequency resolved optical grating
	Jitter
p_s = photon source generation probability	Coincidence to accidentals
	Klyshko efficiency
	Single photon brightness
$g_s^{(2)}$ = source second-order correlation	Hanbury Brown and Twiss
	Single photon brightness
	Coincidence to accidentals

Rate = $f\left(R_s, p_s, g_s^{(2)}, \eta_c, p_c, \mathcal{I}_c, \eta_d, \nu_d, \rho_d, R_m, p_m, \eta_m, \nu_m, \tau_m\right)$

Fidelity = $F\left(p_s, g_s^{(2)}, \eta_c, p_c, \mathcal{I}_c, \eta_d, \nu_d, \rho_d, p_m, \eta_m, \nu_m, \tau_m\right)$

Flow for Assessing Component and Network Performance



Process is reversable depending on provided component or network parameters

Benefits of approach with noted challenges

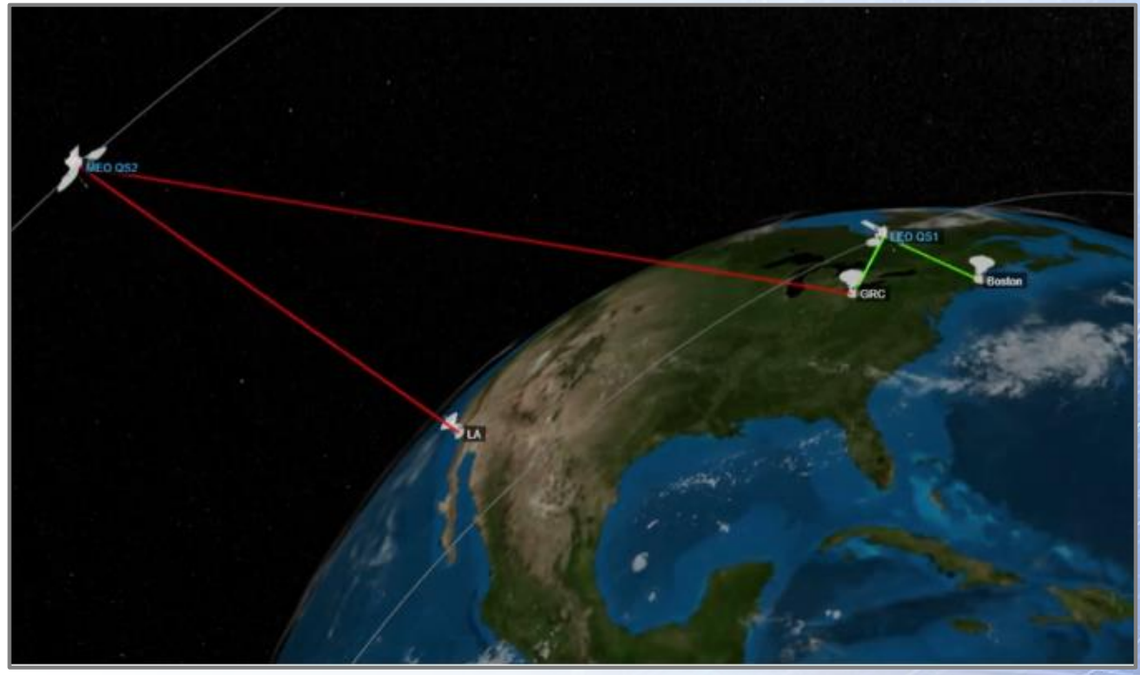
Benefits

- Variable extended baselines (>90 km)
- Baseline derived resolution increased by 180 x over 500 m array
- SNR no longer a function of atmospheric coherence
- Implies less to no need for adaptive optics
- Reduced background due to atmospheric scattering
- No need for quantum repeaters to increase baseline to earth size (still need classical link to synchronize and determine baseline distance)

Challenges

- Doppler shift
- Memory in space
- Cryo cooling in space
- Synchronization
- Continuously measured distance between satellites to track phase difference

Assessing quantum network performance



Key measures of quantum network performance:

The **rate** R at which quantum states can be transmitted

- A higher rate allows for higher system bandwidth

The **fidelity** F of the quantum state transmission

- A higher fidelity improves measurement SNR