National Aeronautics and Space Administration

Final Report

Workshop on Space Quantum Communications and Networks

Developing a Roadmap to Quantum Communications in Space
January 30 - 31, 2020
University of California, Berkeley
Berkeley, California 94720

30 September 2020

National Institute of Standards and Technology
U.S. Department of Commerce

Preface

In 2013-2014 NASA's Space Communications and Navigation (SCaN) program was the first to demonstrate optical communication technology with the Lunar Laser Communications Demonstration (LLCD) onboard NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. LLCD is a milestone in optical communications, transmitting data from lunar orbit to Earth at a rate of 622 megabits-per-second (Mbps), many fold faster than previous state-of-the-art radio systems flown to the Moon. LLCD not only demonstrated a record-breaking download rate but also an error free data upload rate of 20 Mbps; from 240 thousand miles away. LLCD's breakthrough technology has a laser-based space terminal that is half the weight of a comparable radio-based terminal while using 25 percent less power.

Continuing with its pathfinder missions in optical communications—SCaN's Laser Communications Relay Demonstration (LCRD), hosted on a U.S. Air Force spacecraft as part of the Space Test Program 3 mission in a geosynchronous orbit; and its Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) on the International Space Station (ISS), both planned for launch in 2021—will further enable NASA to collect more data in support of future science and human exploration missions. ILLUMA-T is designed to be an optical communications user terminal to demonstrate high bandwidth data transfer between low Earth orbit (LEO) and the ground, through the geosynchronous LCRD relay. ILLUMA-T will be the first demonstration of a LEO user of the LCRD system, pointing and tracking from a moving spacecraft at LEO to a geosynchronous equatorial orbit (GEO) satellite and vice versa, end-to-end operational utility of optical communications, and 51 Mbps forward link to the ISS from ground.

Leveraging optical communications, the burgeoning second quantum revolution promises to significantly improve NASA's mission in various scientific, exploration, and technological enterprises, but especially in space-to-ground and deep space communications and navigation. This is because in free space, quantum communications and navigation will almost exclusively be based on optical channels and platforms. This is a strategic capability NASA SCaN is actively striving and planning for. NASA will be advancing technology and capabilities in partnership with other government agencies as well as the commercial sector, which will be key to creating economic opportunities and national growth. The NASA-NIST Berkeley workshop represents a robust and powerful launch pad of ideas for NASA and its partners to design, build, and facilitate the utilization of the first space-to-ground links for America's future quantum networks. While the scope of the anticipated applications of this space quantum platform is already impressive, those yet-to-be-discovered are perhaps the ones that will ultimately define and judge the success of this workshop. NASA SCaN and its partners look forward and are eager to translate this success into the building blocks of the future of quantum information science and its wondrous applications, both in space and on Earth.

Badri A. Younes
Deputy Associate Administrator for
Space Communications and Navigation (SCaN)
Human Exploration and Operations Mission Directorate
NASA Headquarters
Washington, D.C.

September 30, 2020

Workshop Participants

Name	Organization	Email
Alena, Richard	NASA ARC	richard.l.alena@nasa.gov
Antsos, Dimitri	JPL/Caltech	dimitrios.antsos@jpl.nasa.gov
Barghouty, Nasser	NASA HQ	nasser.barghouty@nasa.gov
Battle, Philip	AdvR, Inc	battle@advr-inc.com
Beckwith, Steve	UC Berkeley SSL	svwbeckwith@berkeley.edu
Behrman, Elizabeth	Wichita State University	behrman@math.wichita.edu
Biswas, Rupak	NASA ARC	rupak.biswas@nasa.gov
Boroson, Don	MIT Lincoln Laboratory	Boroson@ll.mit.edu
Burdine, Robert	NASA HQ	robert.v.burdine-1@nasa.gov
Carim, Altaf	Department of Energy	Altaf.Carim@science.doe.gov
Carpenter, Brad	NASA HQ	bcarpenter@nasa.gov
Casas, Joseph	NASA MSFC	joseph.casas@nasa.gov
Chelmins, David	NASA GRC	chelmins@nasa.gov
Chow, Edward	JPL/Caltech	edward.t.chow@jpl.nasa.gov
Clark, William	General Dynamics	william.clark@gd-ms.com
Cooper, LaVida	NASA GSFC	lavida.d.cooper@nasa.gov
Dixon, Ben	MIT Lincoln Laboratory	ben.dixon@ll.mit.edu
Dolinar, Sam	JPL/Caltech	sam.dolinar@jpl.nasa.gov
Drake, Benjamin	Department of Defense	benjamin.l.drake3.civ@mail.mil
Durden, Jimmy	NASA HQ	jimmy.d.durden@nasa.gov
Eblen, Pat	NASA HQ	pat.eblen@nasa.gov
Eustice, Scott	UC Berkeley	scott_eustice@berkeley.edu
Figueroa, Eden	Stony Brook University	eden.figueroa@stonybrook.edu
Gauthier, Daniel	Ohio State University	gauthier.51@osu.edu
Gilkin, Neil	UC Berkeley	glikin@berkeley.edu
Govindan, TR	NASA ARC	tr.govindan@nasa.gov
Grabbe, Shon	NASA ARC	shon.grabbe@nasa.gov
Grice, Warren	Qubitekk	wgrice@qubitekk.com
Guha, Saikat	University of Arizona	saikat@optics.arizona.edu
Halford, Alexa	NASA GSFC	alexa.j.halford@nasa.gov
Hamilton, Scott	MIT Lincoln Laboratory	shamilton@ll.mit.edu
Hosseini, Sona	JPL/Caltech	sona.hosseini@jpl.nasa.gov
Isaacs, Josh	UC Berkeley	jaisaacs@berkeley.edu
Israelsson, Ulf	JPL/Caltech	ulf.israelsson@jpl.nasa.gov
Jackson, Mark	Cambridge Quantum Computing	mark.jackson@cambridgequantum.com
Katz, Evan	NASA GRC	evan.j.katz@nasa.gov

Name	Organization	Email
Knight, Scott	Ball Aerospace	jsknight@ball.com
Kwiat, Paul	UI Urbana - Champaign	kwiat@illinois.edu
Lamas-Linares, Antia	Speqtral Quantum Technologies, Inc.	antia@speqtralqt.com
Lee, Catherine	MIT Lincoln Laboratory	Catherine.Lee@ll.mit.edu
Lekki, John	NASA GRC	john.d.lekki@nasa.gov
Mapar, Jalal	Department of Homeland Security	jalal.mapar@hq.dhs.gov
Mohageg, Makan	JPL/Caltech	makan.mohageg@jpl.nasa.gov
Nagel, James	L3 Harris	James.nagel@l3harris.com
Nam, Sae Woo	NIST	saewoo.nam@nist.gov
Nguyen, Ho Nam	UC Berkeley	honamnguyen95@gmail.com
Noroozian, Omid	NASA GSFC	omid.noroozian@nasa.gov
O'Gorman, Bryan A.	UC Berkeley	bogorman@berkeley.edu
Paudel. Uttam	Aerospace Corporation	uttam.paudel@aero.org
Perez, Mario	NASA HQ	mario.perez@nasa.gov
Peters, Nick	Oak Ridge National Laboratory	petersna@ornl.gov
Poole, Eric	NASA GSFC	eric.l.poole@nasa.gov
Raymer, Michael	Oregon	raymer@uoregon.edu
Rieffel, Eleanor	NASA ARC	eleanor.rieffel@nasa.gov
Robledo, Dalila	UC Berkeley	luzdal@berkeley.edu
Sadleir, John	NASA GSFC	john.e.sadleir@nasa.gov
Saif, Babak	NASA GSFC	babak.n.saif@nasa.gov
Schmittberger, Bonnie	MITRE Corporation	bschmittberger@mitre.org
Shapiro, Ira	MITRE Corporation	ishapiro@mitre.org
Shaw, Harry	NASA GSFC	harry.c.shaw@nasa.gov
Shaw, Matt	JPL/Caltech	mathew.d.shaw@jpl.nasa.gov
Siegler, Nick	JPL/Caltech	nicholas.siegler@jpl.nasa.gov
Stamper-Kurn, Dan	UC Berkeley Physics	dmsk@berkeley.edu
Storm, Mark	Fibertek, Inc	mstorm@fibertek.com
Strekalov, Dmitry	JPL/Caltech	dmitry.v.strekalov@jpl.nasa.gov
Thill, Matt	JPL/Caltech	matthew.d.thill@jpl.nasa.gov
Tubbs, Allan	Aerospace Corporation	allan.d.tubbs@aero.org
Tzinis, Irene	NASA HQ	irene.a.tzinis@nasa.gov
van Bibber, Karl	UC Berkeley NE	karl.van.bibber@nuc.berkeley.edu
Vazirani, Umesh	UC Berkeley CS	Vazirani@cs.berkeley.edu
Villoresi, Paolo	University of Padova - DEI	paolo.villoresi@dei.unipd.it
Williams, Carl	NIST	carl.williams@NIST.gov

Name	Organization	Email
Younes, Badri	NASA HQ	badri.younes-1@nasa.gov
Yu, Nan	JPL/Caltech	nan.yu@jpl.nasa.gov
Zhang, Zheshen	University of Arizona	zsz@email.arizona.edu
Zhu, Miao	AOSense, Inc	mzhu@aosense.com
Zhuang, Quntao	University of Arizona	zhuangquntao@email.arizona.edu

Quantum Workshop participants (University of California, Berkeley/R. Lettieri).

Table of Contents

1.0 Executive Summary

From measurement, to timing, to remote sensing, to computing and networking, quantum-enhanced and quantum-based technologies are promising an era of unparalleled precision, speed, and security of data and information. Over the last two decades, laboratory instruments and experiments exploiting quantum phenomena have matured to enable these and other applications, ushering in the new discipline of "quantum engineering".

For quantum information science and technology in particular, rapid advances in quantum optics, driven by rapid progress in microfabrication technologies, precision measurements, and development of coherent radiation sources, have recently enabled space-based demonstrations of new communications and networking technologies and protocols. These new quantum technologies are poised to significantly enhance the efficiency and security of data and information transfer—in space and between space and ground—to levels simply unattainable via radio or optical channels, pushing the frontiers and reach of space-based science and space exploration.

NASA's Space Communications and Navigation (SCaN) program and the National Institute of Science and Technology (NIST) co-sponsored a two-day workshop in January 2020 on space quantum communications and networks. The workshop was hosted by the Space Sciences Laboratory of the University of California, Berkeley. About 70 invited technical and program leaders from academia, industry, and government agencies defined science goals and technology requirements for a future NASA "quantum mission" that is fully aligned with the National Quantum Initiative (NQI) vision for a space-ground quantum network. This NQI vision is also a strategic milestone in SCaN's plans for NASA's space-based quantum communications and networks.

The overall technical objectives of the Workshop were to (*i*) critically evaluate various mission design concepts, (*ii*) converge on a small subset of quantum communication and networking experiments suitable for space applications, and (*iii)* identify key technology gaps and promote new and emerging technologies to enable NASA's "quantum mission" within a 5-year horizon.

At the Workshop, participants were divided into four panels—focusing on mission goals, concepts, technology requirements, and mission systems architectures—for two full days of discussions and deliberations. These discussions and deliberations continued after the Workshop through June, with the panel members participating in a series of bi-weekly virtual meetings led by the panel chairs and SCaN program officers.

Details of the various findings and recommendations for the *goals*, *concepts*, *technology,* and *systems architectures* of NASA's quantum mission make up the bulk of this report. The report, with its salient findings and the four top-level recommendations as summarized below, define a strategy and a path forward for NASA and its partners that is fully aligned with NQI's "A Strategic Vision for America's Quantum Networks".

For mission goals: Science and engineering goals for a future quantum mission have been identified along with the connection of these goals to national priorities for a quantum network, NASA's high-level goals, and to the capabilities that can be enhanced or enabled through the utilization of quantum communications. Networked quantum computing, quantum-enhanced sensor arrays, and enhanced communication applications all rely on the distribution of quantum entanglement—the primary resource that enables most quantum-enhanced technologies.

Varying in difficulty and complexity, these envisaged capabilities also have varying functional needs. Capabilities with the highest degree of difficulty are associated with the networking of quantum computers, as they have the greatest number of as-yet-unrealized functional needs. For such applications, emphases should be on long-term research and development efforts, coupled with increasingly more complex space-based demonstrations. However, for quantum communications and networking, entanglement distribution and swapping are fundamental needs that support nearly all identified capabilities and hence should be pursued in a relatively short- term strategy (5-7 years). NASA will work with other government agencies as well as the commercial sector to advance this technology and capabilities. These advances will create new economic opportunities and promote national growth.

For mission concepts: Among a number of viable mission concepts, a multi-stage approach to establish linkable quantum entanglement distribution and swapping capability within the continental United States (i.e., ground stations up to 1200 km apart) and between the United States and other continents (on the order of 6000 km) is realizable in the five-to-seven year horizon. This staged approach concept is envisaged to demonstrate system performance well beyond current capabilities. In addition, even in its early stages, it can provide capabilities deemed impossible to achieve with any other flown or proposed quantum communications mission.

To better manage program risk by proving performance of critical technology subsystems, the staged approach is recommended. Although it is based on technology that is available today, the staged approach concept is nevertheless designed to support future technologies as they mature.

For mission technology requirements: For an *operational* quantum network with intra- and inter-continental entanglement distribution capabilities, a set of key technologies and system specifications were identified and prioritized. These include quantum sources, detector arrays, single-photon receivers, optical terminals (for both space and ground applications), quantum modems, and quantum memories, in addition to system-level analysis tools.

To support potential candidate concepts and leverage commercially available components, key system specifications have been identified and prioritized. Targeted investments in relevant technology challenges are highlighted and designed to meet key system requirements that will enable a national capability demonstration and operational service within this decade.

For mission systems architectures: The vision here is to optimally architect a space-based quantum network that can support many users simultaneously by delivering entanglement on-demand at a high rate, while maintaining a requisite high fidelity. Optimized architectures from the “elementary link”, namely, a single satellite delivering heralded entanglement of a given fidelity and at a given rate, to inter-continental scale connectivity are evaluated. Open questions and challenges to satellite-enabled quantum networks are identified and addressed.

Design of systems architectures must be optimized in synergy with the technology development effort. Also, orbit and other mission parameters will need to be designed such that the NASA-architected quantum network is seamlessly forward-compatible with future additions and upgrades.

2.0 Introduction

2.1 The Promise of Quantum-Enhanced Technologies

The field of quantum information science (QIS) has advanced continuously since the inception over 35 years ago of the quantum analogue of the Turing machine (Duetsch 1985). The past several years in particular have brought a major surge, as many of the promises shift from vaguely envisaged functionalities to practical and realizable quantum-enhanced capabilities. In part, that has occurred due to an increased understanding of what QIS can—and cannot—do, even as more and more potential applications are discovered. Such resolution capabilities span the range of quantum computation (new algorithms of much broader interest and relevance than the original code-breaking algorithm by Shor; Shor 1995), metrology (where entanglement and distributed sensors can lead to sensitivity simply impossible with classical systems), and communication (where questions involving the "quantum internet" have evolved from "if" to "when" and "how"). Simultaneously, our ability to produce, manipulate**,** and control quantum systems has grown rapidly, from the noisy single-qubit superconducting devices of two decades ago to the recent Google Sycamore 54-qubit processor; from bulky quantum optical experiments that occupy an entire optical table or two (or three), to modern devices that aim to achieve the same functionality in an integrated photonic chip the size of a postage stamp.

What will these new, quantum-enhanced technologies enable? A fault-tolerant quantum computer could implement ultra-fast optimization algorithms and ultra-precise simulations for material science, chemistry, and medicine. These advancements in turn, can lead, for example, to new functional materials, more efficient fertilizers, and rapid development of vaccines for future pandemic events. Quantum-enhanced sensors will enable a new range of metrological applications; from fundamental understanding of complex condensed-matter systems, to eventual real-world devices: consider the medical impact of a wearable '"Magnetic Resonance Imaging (MRI) vest" that could produce the same information as a current room-sized imager at a fraction of the size, time, and cost! At a much larger scale, distributed quantum sensors, such as an entanglement-connected "global telescope", could bring imaging resolution orders of magnitude more precise than any existing methods of observation—a new stellar window, both for looking outward, but also for examining our own planet.

One key element is the ability to link together these devices through quantum entanglement to realize a single, distributed quantum system. Such a capability requires one to faithfully and reliably transmit quantum data, potentially over long distances, which is the primary function of a quantum network, whether space-based or terrestrial. By combining advanced entanglement sources, quantum memories, and detectors, one can, in principle, implement quantum repeaters able to transfer the fragile quantum states over much longer stretches than the information-carrying photons themselves can travel. In addition to connecting quantum processors and sensors, such a quantum internet would enable long-distance quantum communication protocols that are interesting in their own right, such as provably secure communication and the ability to remotely—and privately—program a distant quantum computer.

2.2 The Timing of This Workshop

Even as quantum research efforts have been ramping up around the world over the past few years, including the $1.1B Quantum Technology Flagship initiative in Europe and the $11B creation of the Chinese National Laboratory for Quantum Information Science, the United States Government in August 2018 declared its own major "National Quantum Initiative" (NQI) to advance quantum information science and technology in the U.S. Specifically—and building on decades of investment in QIS and its underlying science and technology by the National Science Foundation (NSF), Department of Defense (DOD), Department of Energy (DOE) and other government agencies—the National Quantum Initiative pledged further major funding to support the National Institute of Standards and Technology (NIST) and to establish several large NSF- and DOE-funded quantum centers for basic and applied QIS research. In addition to these large, focused efforts, with an expected investment totaling more than $1B, the DOE and NSF respectively have committed more than $200M and $30M to over 100 QIS projects over the next few years. This is in addition to a rapidly growing industrial involvement, from large quantum efforts such as those at IBM, Intel, Google, and Microsoft, to numerous smaller companies and startups backed by private investments. These are all potential partners as NASA pursues its plan to advance technology and capabilities in partnership with other government agencies and the commercial sector. These investments will spur economic growth and create economic opportunities for Americans.

There has also been an ever-increasing rate of U.S. government workshops on QIS, from the first ones held by NIST and DOD a quarter of a century ago, to more than ten in the last year alone. At one of these, the Workshop on U.S.-European Union (EU) Cooperation on Quantum Information Science and Quantum Technologies (held in Washington, D.C. in September 2019), the notion of a "trans-Atlantic quantum link" arose as an enabling milestone on the path to a global quantum internet. However, such a link would be very challenging in the near term—perhaps even out of reach—due to the current immaturity of the required technologies, if one were limited to transmission through fiber optic cables. Instead, it was envisioned that satellites could be used as a quantum "bridge", supplying entangled photons that would connect local quantum networks on either continent. This concept was also discussed, and its relevance highlighted, at the February 2020 DOE Quantum Internet Blueprint Workshop, held in New York City, though there in the context of facilitating trans-continental and shorter quantum links before a full quantum repeater-enabled network could be implemented. The transcontinental, space-ground link is explicitly called for in "A Strategic Vision for America's Quantum Networks," released by the White House's National Quantum Coordination Office in February 2020.

Responding to the recent interest in space-enabled quantum communications, this workshop—co-sponsored by the National Aeronautics and Space Administration (NASA) and NIST—was intended as a mechanism to gather and debate input from a variety of informed and interested parties across the U.S. government, national laboratories, academia, and the private sector. The timing of the workshop was in some sense critical. Had it been held much earlier, the requisite quantum technologies would not have been available; in fact, some of them still need substantial development before an actual launch. If it were held any later, the U.S. would almost certainly lose out on the opportunity to be the world-leader in the areas of space-based and space-enabled QIS. To be sure, while many QIS developments over the past three decades were realized by U.S. researchers, not all recent progress has been developed within the U.S. In particular, between 2016 and 2018, the Chinese Micius satellite (Ren 2017) convincingly performed several significant quantum communication demonstrations. While not enabling per se—the rates of entanglement were too low—these proof-of-concept experiments *did* show that quantum communication to and from a space platform is technologically viable. Moreover, as highlighted in this document, there are compelling reasons to pursue quantum communications and networking in space, as well as a technologically realizable—if quite challenging—path to achieve such goals.

2.3 The Objectives of the Workshop and Final Report

The Workshop on Space Quantum Communications and Networks brought together technical and program leaders from academia, industry, and government agencies who, over two days, began the discussion to determine which critical quantum technologies for space communications and networking NASA and its partners need to develop and mature to achieve an efficiently-designed and executed quantum space mission.

The technical objectives of this Workshop were to:

1) Critically evaluate various mission design concepts for a space-based quantum communication and networking mission;
2) Converge on a small subset of quantum communication and networking experiments suitable for space applications;
3) Identify key technology gaps, and promote new and emerging technologies, to enable such a mission within a 5-year horizon.

2.4 The Organization of the Workshop and Subsequent Activities

The Workshop was sponsored by NASA's Space Communications and Navigation (SCaN) program and NIST. NIST was pleased to co-sponsor the workshop with NASA as it embarks on this effort, as NIST has a long history of working closely with NASA. It was held on January 30 and 31, 2020 and hosted by the Space Sciences Laboratory of the University of California at Berkeley and attended by approximately 70 participants. While attendance at the workshop was by invitation only, all presentations, discussions, and deliberations were kept at the open and publicly-available level.

The Workshop opened with a series of technical talks by keynote speakers highlighting the latest developments in quantum communications and networking science and technologies to help set the stage for in-depth panel discussions focusing on the space mission goals, mission concepts, mission technology requirements and gaps, and mission systems architectures. Keynote speakers were: Dr. Carl Williams (NIST), Dr. Scott Hamilton (MIT-Lincoln Lab), Prof. Paul Kwiat

(University of Illinois, Urbana-Champaign), Dr. T.R Govindan (NASA ARC), Prof. Umesh Vazirani (University of California, Berkeley), and Dr. William Clark (General Dynamics Mission Systems). Their presentation materials can be found at: https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings.

On the afternoon of Day 1, the participants were split into four splinter groups led by session chairs focusing on four key aspects of the future NASA quantum space mission:

- *Mission Goals*, Dr. John Lekki (NASA GRC);
- *Mission Systems Architectures*, Prof. Saikat Guha (University of Arizona);
- *Mission Concepts*, Dr. Eleanor Rieffel (NASA ARC);
- *Mission Technologies*, Dr. Babak Saif (NASA GSFC).

On Day 2, the groups met into the late afternoon and reported out to the plenary at the conclusion of the day and the Workshop. Between February and June 2020, the four session chairs worked together with a subset of the participants, as well as with each other, to capture and advance the inputs and discussions from the Workshop. Some of the concepts were advanced further by researching more details and in some cases conducting analyses to support key points. In subsequent months, time was spent investigating other concepts, but the main conclusions from the Workshop remained. While the key mission technologies discussed in the subgroups were captured, prioritization and details were given to the subset of those technologies that enabled the proposed missions. This has hopefully resulted in a more cohesive final report. The full draft of the report was reviewed among the Workshop sub-group participants before final compilation.

The overall intention is that this report has captured a large set of inputs from a broad group of experts from which NASA, NIST, and other government agencies can draw from and prioritize in their future quantum communications and networking plans. It is also intended to inform these government agencies on what is possible in the near and medium terms to advance a quantum space satellite capable of demonstrating important, first-of-its-kind, quantum capabilities at large scales.

2.5 References

Duetsch, D. 1985. "Quantum theory, the Church-Turing principle and the universal quantum computer", *Proceeding of the Royal Society of London A 400*: 97.

Ren, J.-G. *et al*. 2017. "Ground-to-satellite quantum teleportation," *Nature 549*: 70.

Shor, P. W. 1995. "Scheme for reducing decoherence in quantum computer memory," *Physical Review A 52*: R2493.

3.0 Mission Goals

Authors: John Lekki (NASA GRC); William Clark (General Dynamics Mission Systems), Paul Kwiat (University of Illinois at Urbana-Champaign), Michael Raymer (University of Oregon), Nicholas Peters (Oak Ridge National Laboratory)

3.1 Introduction

3.1.1 How Quantum Communications Relates to the NASA Mission

Quantum Information Science (QIS) incorporates quantum computing, quantum sensing, and quantum communications, and has significant potential to impact capabilities that are important for space exploration, Earth science, and aeronautics. There are two main driving ideas behind the proposed deployment of quantum communications in space: 1) Space-based quantum communications can work synergistically with terrestrial local fiber networks to provide long-distance connectivity between metro area networks; 2) A space-based quantum network will simultaneously advance many goals of NASA's mission, which is to "drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth". This mission speaks to a need for tangible results in these areas of study. While understanding quantum entanglement is largely a scientific pursuit at present, we argue here that quantum communications is projected to impact a broad range of NASA-relevant scientific areas (planetary, heliophysics, astronomy, and Earth science) as a technological enabler. Similarly, there are ways in which systems that utilize space-based quantum communications may impact technology development, provide for economic vitality, and improve our ability to take care of the Earth. Because of the revolutionary potential of the quantum internet, The White House National Quantum Coordination Office has recommended that the nation undertake the following activities in the next five years to realize the vision for a quantum internet (emphasis is ours).

> *"Over the next five years, companies and laboratories in the United States will demonstrate the foundational science and key technologies to enable quantum networks, from quantum interconnects, quantum repeaters, and quantum memories to high-throughput quantum channels* ***and exploration of space-based entanglement distribution across intercontinental distances****. At the same time, the potential impact and improved applications of such systems will be identified for commercial, scientific, health and national security benefits." (White House National Quantum Coordination Office 2020)*

We believe that NASA, in cooperation with its academic, industry and other government agency partners, is well-suited to support the national goal of developing space-based entanglement distribution and its application to creating larger quantum networks, not only to enable more science and exploration, but also to ensure economic opportunities and national growth.

In Figure 1, we show some of the envisioned ways in which quantum communications may play a central part of a future with operational QIS capabilities. As examples, quantum communications networks may connect future researchers throughout the nation to quantum computers, where they can conduct investigations into medicine and materials by performing quantum chemistry and structure calculations, as well as other known applications of quantum computing. Sensors may be connected through a quantum network to enable sensor-array-based assessments of local aquifers or plate tectonic fault lines. And quantum communications networks may support secure information transfer through many protocols that are relevant to communications security, such as quantum key distribution (QKD), blind (private) quantum computing, or secure multi-party computation.

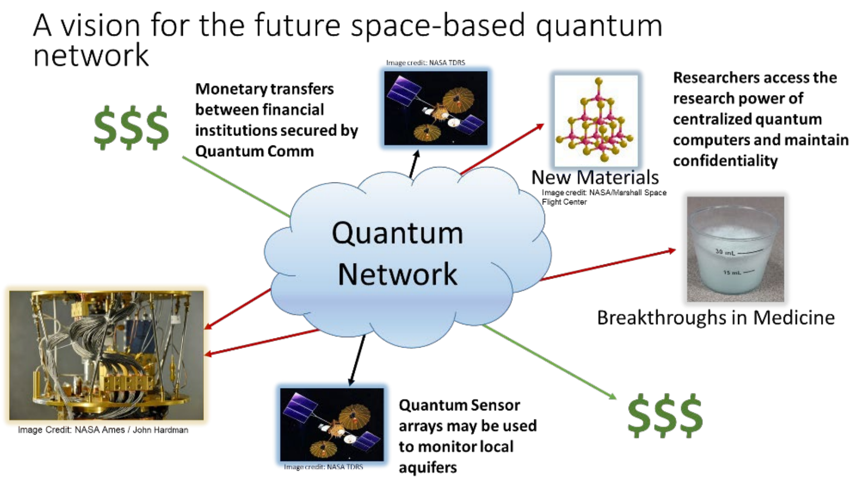


Figure 1. A vision of how a space quantum communications network might fit with future capabilities.

It is anticipated that the quantum network needed to realize this vision will eventually be one that combines fiber optic links, terrestrial point-to-point free-space links, as well as space-based long-distance free-space optical links. Fiber optic networks are inviting for use in quantum communications, but there are several challenges that must be overcome. Quantum signals cannot be amplified to overcome signal loss, so to cover long distances they must be regenerated by quantum repeaters, which are presently technologically challenging. Therefore, to cover long distances, satellite-based quantum communication is attractive due to its $1/r^2$ scaling of signal attenuation, rather than the exponential loss suffered in fiber. For this reason, it is anticipated that a quantum communications network will have local fiber optic networks as well as long-haul space-based optical links. Satellite-based entanglement "bridges" could be used to directly connect transcontinental and trans-Atlantic Quantum Local Area Networks (QLANs)—preliminary estimates indicate that entangled pairs could be shared at rates exceeding 10^6 in a single pass of a Medium Earth Orbit (MEO) satellite. Such a capability may be a crucial intermediate step while efficient robust repeaters are developed (some estimates predict one would need over 100 repeaters to establish a fiber trans-Atlantic link).

In this chapter, we enumerate those ways in which quantum communications may impact the NASA mission as "Goals". These are the goals that technologists would want to be cognizant of as they work to make space-based quantum communications a reality. The goals are areas of active research, and as such, there is significant work needed to confirm that quantum communications will provide useful new and significant capabilities and practical advantages over competing techniques. The same caveat holds true for quantum computation, but there is already clear evidence for the benefit of quantum sensors in some instances, such as Laser Interferometer Gravitational-Wave Observatory (LIGO).

Quantum communications shows promise for building enhanced sensor arrays, enhanced communications capabilities, and also for connecting quantum computers or quantum cloud computing. These three main categories, shown in Figure 2, generally group the multiple ways in which quantum communications may play a role in future space-based systems. All of these categories are made possible by the transmission, or distribution, of quantum entanglement—the primary resource that enables most quantum-enhanced technologies.

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

Figure 2. General areas where quantum communications can impact the NASA mission with examples of goals that may fit in those categories.

For example, in the quantum-enhanced sensor array category, quantum communications are used to entangle two or more sensor nodes connected by a substantial distance. This connection may be used to create very large synthetic aperture sensor arrays with greatly increased resolution and sensitivity. A dramatic example of the power of classical synthetic sensor arrays is the 2019 first-ever image of a black hole (Figure 3). This remarkable image was obtained by combining various radio-frequency telescopes located around the planet into one synthetic aperture that was the size of the Earth. The data from each telescope was computationally combined using an interferometric technique so that the image could be resolved. This is a technique that is possible using radio frequencies but cannot be accomplished in the same manner at optical frequencies over very long baselines. Quantum entanglement may allow long-baseline synthetic sensor arrays to be created in the optical and near-infrared domains, either on the ground or in space.

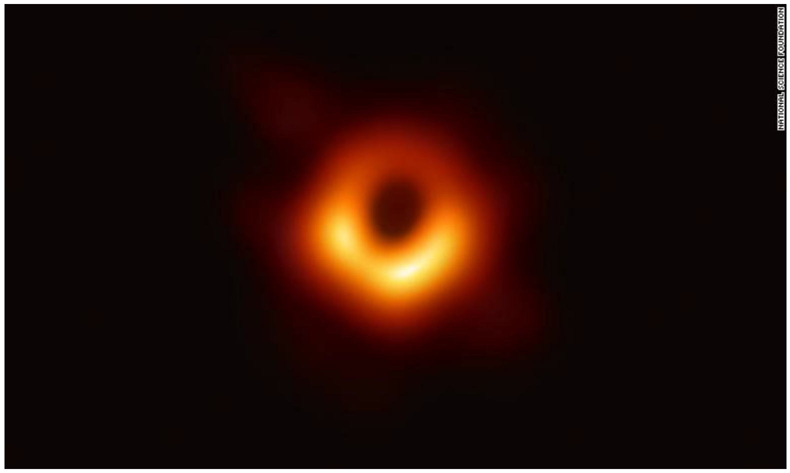


Figure 3. An example of the power of sensor arrays in the classical RF realm. The first picture of a black hole was generated in 2019 from a radio telescope array (Event Horizon Telescope Collaboration).

Similarly, in the category of enhanced communication, entanglement distribution could be used to facilitate large synthetic transceiver apertures for communications purposes. These apertures can increase beam confinement, which will provide gain in transmission that is proportional to the separation of the apertures. On the receiver side, the background noise can be greatly reduced with better beam localization (though the overall signal strength is still a function of the total area of the combined receiver apertures, not the synthetic aperture size). Another potential benefit of distributing entanglement to a receiver array is to utilize squeezed light to reduce the noise floor for certain measurements, as was recently demonstrated (Xia 2020); this can directly improve the signal-to-noise ratio (SNR) for the overall receiver and is similar to what was accomplished with LIGO.

Quantum networks may impact NASA, NIST, and the nation in numerous ways by enabling advances in networked quantum computing, quantum-enhanced sensor arrays, and entanglement-enhanced communications capabilities. In 2019, the National Academy of Science recommended that NASA explore fundamental physics for the purpose of addressing scientific exploration.

> *"RECOMMENDATION: The National Aeronautics and Space Administration, in coordination with other federal agencies, should increase investments in theory and experiment for both space- and laboratory-based fundamental atomic, molecular, and optical science that are needed to address key questions in astronomy, astrophysics, and cosmology." (National Academy of Sciences Engineering Medicine, 2019)*

We find that quantum communications is one of the central areas where the recommendation from the National Academy of Science can be realized, through investments in fundamental quantum information science with the goal of addressing key questions that NASA seeks to answer about the universe. The following section will expand upon the three general areas where quantum communications has the potential for significant impact, by discussing several specific examples from each area.

3.2 Capabilities

3.2.1 Identified Capabilities from the Scientific Literature and Subject Matter Experts

In this section we present specific examples from the literature, and in some limited cases from discussion at the workshop, of cases where it is envisioned that quantum communications will provide a new capability beyond what is possible classically. Although there are still few examples where a clear practical quantum advantage has been shown—as is the case for the LIGO quantum-enhanced gravity wave detector—these examples illustrate how the fundamentally strong correlations present in entanglement may be leveraged through research and development to realize dramatic system improvements. Each of the following capabilities has a description, a short declaration of the possible purpose of the enhanced system, the anticipated benefit, a key milestone, and a time range when we anticipate the capability may be realized. The key milestones underscore what significant issues we believe need to be addressed to realize each capability, often highlighting a need that could be the focus of an applied quantum communications research program.

3.2.2 Anticipated Benefits, Key Research Needs, the Root of Quantum Advantage

Very Long Baseline Interferometry (VLBI)

When light collected by two or more separated telescopes is made to interfere, it can yield a spatial resolution exceeding that of either telescope individually (Monnier 2003). Quantum techniques have been proposed to provide a boost in sensitivity and resolution of such stellar interferometry methods. The key resource needed to achieve such enhancement is entanglement between quantum systems located at the two telescopes, which may be provided in real time by propagating photons to the telescopes (Gottesman, Jennewein, and Croke 2012), or buffered in quantum memories for more efficient use as signal photons arrive (Khabiboulline *et al*. 2018). The entangled qubits provide the needed phase references to monitor the relative path lengths along different paths from the source to each telescope, allowing image reconstruction of the source. Such schemes could be used to look “up” at astronomical sources, or “down” at terrestrial sources.

Purpose: imaging exoplanets, the solar system, and looking at Earth orientation; arrays of transmitters and receivers

Anticipated Benefit: Increased angular resolution, synthetic aperture pointing, and tracking for deep space communication

Key Milestone: Demonstrate higher resolution only possible with q-network; determine to what extent of a quantum repeater is needed to get a quantum advantage

Potential time when capability developed: 2030 – 2040

Quantum secure communications below the rate-loss limit

Communications security can be fundamentally improved with the addition of quantum communications tools and protocols including quantum random number generators (Herrero-Collantes and Garcia-Escartin 2017), quantum key distribution (QKD) [(Bennett and Brassard 1984), (Ekert 1991), (Hwang 2003)] and quantum digital signatures (Gottesman and Chuang 2001), even without the availability of yet unrealized quantum repeaters. The security of the quantum communications protocols is rooted in the rules of measuring a quantum object. In the repeaterless context, such communications would be typically limited by the fundamental rate-loss bound [(Takeoka, Guha, and Wilde 2014), (Pirandola *et al*. 2017)]. While a number of recent twin-field QKD demonstrations show this limit can be surpassed under some circumstances [(Minder *et al.* 2019), (Liu *et al.* 2019), (Wang *et al*. 2019), (Zhong *et al.* 2019), (Fang *et al.* 2020), (Chen *et al.* 2020)], these approaches add complexity and do not scale in performance the way that quantum repeaters are expected. As such, more established protocols based upon prepare and measure [(Bennett and Brassard 1984), (Hwang, 2003)], as well as entanglement (Ekert 1991), are attractive for most use cases. In particular, QKD is one of the most mature quantum technologies and can be used in the near term to distribute symmetric keys to enable secure communications over high loss channels.

Purpose: Provide core cryptographic functions based upon quantum mechanics, such as key distribution and authentication, that do not rely on technology assumptions, e.g., how difficult it is currently to compute the answer to some mathematical problems.

Anticipated Benefit: Command and control assurance.

Key Milestone: The development of rigorous acceptance standards where the gaps between security proofs and experimental implementation can be made arbitrarily small.

Potential time when capability developed: 2025.

Quantum communications above the terrestrial rate distance limit

Under ideal circumstances, free-space optical transmission has loss that scales quadratically with increasing distance. However, the Earth's curvature ultimately limits the transmission distance to line-of-sight terrestrial quantum communications, making optical fiber transmission the default choice for long-distance terrestrial quantum networks. As the optical fiber length increases, the loss increases exponentially. To exceed terrestrial rate-loss distances, space-based platforms can eliminate the limitations imposed by the Earth's curvature to leverage the advantageous rate scaling of free-space transmission compared to fiber transmission. Thus, space-based platforms promise to enable quantum communications at rates and distances that are not possible terrestrially with technology likely to be available in the next ten years. A *hybrid* solution would use satellite-based entanglement "bridges" to connect local fiber-based quantum networks.

Purpose: Long-Haul Quantum Internet.

Anticipated Benefit: Command and control assurance, communicate over greater distances or loss channels.

Key Milestone: Demonstration of routine quantum communications at rates over distances not possible presently on the Earth's surface.

Potential time when capability developed: 2030.

Remote/blind quantum computing

There is tremendous potential for quantum processors to solve critical problems—quantum simulation, rapid optimization, enhanced machine learning—that are intractable with classical computers. However, given the scientific and technological challenges surrounding the creation of a large-scale quantum processor, it is likely that relatively few of them will exist. Users will therefore desire to remotely program them, just as we currently perform calculations on distant supercomputers on the cloud. However, given the importance and/or sensitive nature of many of the problems—e.g., creating more efficient fertilizer, searching health data for subtle correlations, designing improved drugs—there must be a method to *securely* remotely program a quantum computer, analogous to the classical processing task of "homomorphic encryption" (computing on encrypted data). The process of "blind quantum computing" [(Broadbent, Fitzsimons, and Kashefi 2009), (Fitzsimons 2017)] allows this, but requires quantum states to be sent from the programmer to the computer.

Purpose: Secure health data, basic research, cloud quantum computing.

Anticipated Benefits: Data being processed is secure; results and ,even the algorithm itself, is not known to anyone but the remote programmer; programmer learns of attempts to eavesdrop on the computation.

Key Milestones: Quantum computer capable of running useful algorithm, error-corrected quantum repeater necessary to extend maximum remote programming distance; quantum memory to enable accumulation of quantum instructions, assuming computation rate exceeds communication rate.

Potential time when capability developed: 2035 to 2050.

Distributed quantum computing

The power of quantum processing scales exponentially with the number of logical qubits. However, to achieve fault-tolerant quantum computing, one will likely need an additional large overhead of qubits for quantum-error correction. Connecting isolated sub-processors has been proposed as a promising avenue to address the experimental challenges of initializing, controlling, and reading out a large number of qubits on a single physical platform (Buhrman and Röhrig 2003); such scalability concerns are motivating distributed-memory multicomputer architectures, and there are indications that error correction itself may be more efficient (Van Meter and Devitt 2016). In addition to the inherent engineering advantage of such a modular approach, such distributed quantum computers would benefit from coherent processing across all the individual processors (Beals *et al.* 2013), leading to computational capabilities that greatly exceed those of any single component.

Purpose: Enhance the capabilities and scalability, and hence feasibility, of quantum processors.

Anticipated Benefit: Interconnecting quantum processors provides an exponential computing speed increase with respect to isolated devices (Cuomo, Caleffi, and Cacciapuoti. 2020).

Key Milestones: Transduction of qubits from native quantum computing energy scales to flying qubits and back into native quantum computing formats; quantum computer capable of running useful algorithm; high-rate error-corrected quantum communications link.

Potential time when capability developed (Van Meter 2016): 2035-2050.

Quantum-enhanced transceiver

Classical communication from deep space suffers extreme losses from diffraction, where the angular spread of a signal at wavelength λ from a telescope with aperture size *D* is λ/*D*, leading to spot sizes on Earth that are many orders of magnitude larger than the receiving telescope's optics. If one can *coherently* drive transmitter apertures that are separated by even modest amounts (e.g., 1 km), the effective multi-source diffraction pattern on Earth can be many orders of magnitude smaller and brighter. The challenge is maintaining the precise phase coherence of the telescopes, without which the location of the interference maximum will wander rapidly. Distributed quantum signals (which are known to offer superior phase determination per photon over classical signals [(Dowling 2008), (Lee *et al.* 2016)] may be used to improve or simplify the source phase synchronization.

At the encoding level, to enhance deep-space-to-Earth optical communications, where signals at the receiving end are "photon starved," the optimal strategy is known theoretically to be to encode as much information as possible in each photon (Boroson 2018). This can be done by encoding information in a stream of single photons arriving in one of many possible time slots, or one of many frequency bins, or in one of many "temporal modes", which are spread across a certain time-frequency domain [(Boroson 2018), (Banaszek 2019)]. Recognizing orthogonal time-frequency photon code words can be accomplished using recently developed nonlinear-optical techniques, which is of particular use when the transmitted signals are confined to a narrow spectral range, preventing easy separation in the frequency domain [(Banaszek, Jachura, and Wasilewski 2019), (Brecht *et al.* 2015)].

Purpose: Improve communication rates (useful for low light); detection of small, distant, weak objects and sources.

Anticipated Benefit: Increased range for power-limited signals with finite-sized receiver apertures—the signal strength from a quantum-synchronized phased-array transmitter could be many orders of magnitude stronger on Earth; superior to homodyne detection, which can also filter out broadband background noise, but which suffers from shot noise from the reference laser local oscillator.

Key Milestones: Demonstrate quantum-enhanced phase stabilization of classical transmitters; development of efficient, practical time-frequency-mode decoding techniques, preferably using all linear optics and fast modulators.

Potential time when capability developed: 3-5 years for the above stated milestones.

Applications of atomic-clock network

A network of atomic clocks in orbiting satellites could potentially be used to improve communication security and navigation, as well as enable scientific applications such as higher resolution geodesy [(Kómár, et al. 2014), (Mehlstäubler et al. 2018)]. Connecting the clocks with a high-performance classical link, such as an optical frequency comb link, will get most of the benefit in terms of clock performance improvement; however, if one can remotely entangle different clocks, or atom interferometers, there may be an improvement in overall accuracy and SNR.

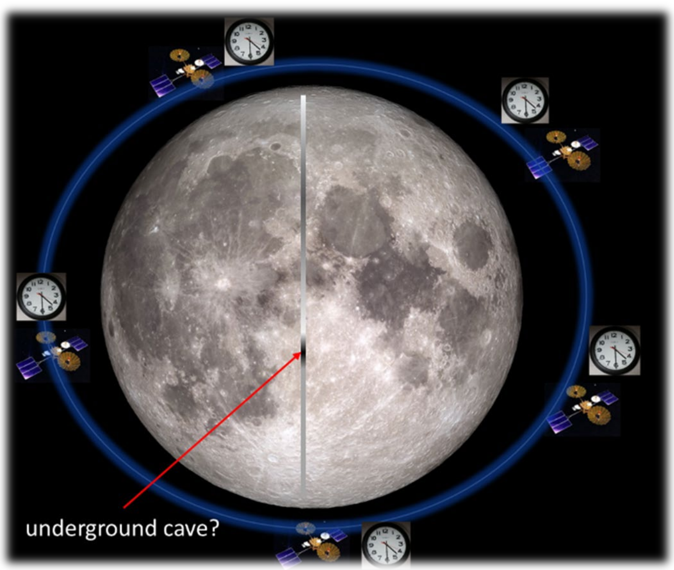


Figure 4. An Illustration of how a network of satellites with interconnected atomic clocks might be used for lunar or planetary geodesy (NASA/Evan Katz).

With additional satellites and with high sensitivity, it may be possible to obtain data with much higher resolution than is currently possible. This improved accuracy may be enough, e.g., to enable high-resolution measurement of gravity anomalies, such as changes in local aquifer levels.

Purpose: Enable distributed sensing, security; improved position, navigation, and timing (PNT); geodesy; primary standard distribution; General Relativity/Terrestrial reference frame in relation to celestial reference frame (altimetry).

Anticipated Benefit: Higher resolution geodesy, improved navigation, improved security.

Key Milestone: High accuracy time transfer in space.

Potential time when capability developed: 2035 to 2045.

Entangled field-sensor network

Entanglement in all of its forms, from discrete to continuous, is finding use in a multitude of applications [(Barzanjeh *et al*. 2015), (Colangelo *et al*. 2017), (Lopaeva *et al.* 2013), (Tan *et al*. 2008), (Tse *et al*. 2019), (Xia *et al.* 2020), (Zhang *et al*. 2015)]. However, the methods used to generate entanglement, usually through spontaneous parametric down-conversion or four-wave mixing (discrete variable) and cavity-enhanced parametric amplification (continuous variable) generally results in entangled photonic states at optical frequencies.

For some applications, like deep-space sensing and communications, the optical domain is fine; however, in many environments optical transmissivity/loss can be the limiting factor. Radio frequency (RF) and microwave electromagnetic radiation, on the other hand, have generally good propagation characteristics in many environments, which has allowed ubiquitous weather radio and microwave communications and sensing here on Earth.

To use entanglement to enhance RF and microwave applications, some form of transduction is required. Either the entanglement is down-converted from optical to RF/microwave frequencies, or RF/microwave signals are up-converted to optical frequencies and used in conjunction with entangled photonic states to enhance the performance of some measurement. Given the efficiency of current methods of transduction, the latter is significantly more practical, and when measurements are performed in the optical domain, shot noise becomes the performance barrier. To overcome this barrier, squeezed states, or continuous-variable (CV) entangled states become the preferred resource for performance improvement.

One well-known application of CV multi-partite entanglement is the use of squeezed states of light to enhance the sensitivity of the Laser Interferometer Gravitational-wave Observatory [(Aasi *et al*. 2013), (Abadie *et al*. 2011), (Acernese *et al*. 2019)].

The use of CV entanglement has now been successfully applied to single-node RF phase sensing (Colangelo *et al*. 2017), and most recently to a network of RF sensors (Xia *et al.* 2020). In both cases, the RF signals of interest are upconverted to optical frequencies using electro-optical modulation (EOM), where the optical carrier signal is a CV entangled state, and homodyne detection is used to extract the phase and/or amplitude information. In the single-node/sensor case, the improvement in sensitivity is due to the squeezing realized at the detector, and in Yi Xia (2020) that resulted in approximately 4 dB of improvement. However, when the CV entanglement is distributed among a network of sensors, through a variable beam splitting (VBS) network, additional performance improvement may be realized, above and beyond those associated with classical array gains. In Yi Xia (2020), joint amplitude and difference/angle of arrival measurements were performed, resulting in an additional 3 dB of improvement. One potential issue is that the beneficial effects of squeezing are quite loss dependent, a consideration for long-distance applications.

Purpose: Higher resolution field measurements.

Anticipated Benefit: Increased link distance, reduced aperture, phased array pointing.

Key Milestones: Realize high on-chip squeezing on integrated photonic chip, enabling broader application of these techniques to operational communications and sensing systems.

Potential time when capability developed: 2030 to 2040.

Spacecraft array with linked onboard quantum processors

This capability is admittedly not known to be specifically discussed in the literature, but is a suggestion that has come out of the workshop discussions that we believe merits consideration. Arguably the most important components in a spacecraft are the multiple onboard computers that operate the spacecraft systems. When quantum computers mature it is likely that spacecraft developers will find significant opportunities to use their unique capabilities, just like their classical counterparts, for improved spacecraft cognitive decision making, accelerated data analysis, or sensor fusion for high bandwidth sensors. Quantum algorithms for machine deep learning and artificial intelligence have been developed (Carleo *et al.* 2019), and computers based on these may have many potential benefits if deployed in future spacecraft. Once these processors are incorporated, it is also anticipated that these spacecraft will be used in swarm configurations where several spacecraft are operating in unison for a purpose such as remote sensing. Such spacecraft would likely share quantum resources, sensing or computing, through quantum communications links to achieve enhanced operational capabilities, either improved sensing, processing, or decision making.

Purpose: Local decision making, defeat time lag, process data locally.

Anticipated Benefit: Higher autonomy; reduce quantum and classical communication requirements on space-to-Earth link by processing data locally, including from quantum sensors.

Key Milestone: Design and engineering of a robust quantum processor that functions in a spacecraft environment and meets Size, Weight, and Power (SWaP) requirements.

Potential time when capability developed: 2035 to 2050

3.2.3 Capabilities Summary

Many space-based quantum network capabilities have been identified that would be of value to NASA and NIST. These fall into three areas, presented in order of priority: quantum computing network, quantum-enhanced sensor networks, and quantum-enhanced communications. Supporting the development of the quantum internet by providing long-haul quantum communications links that bridge remote quantum networks will have enormous benefit to the nation as a whole, and as such could be considered the primary capability goal. In the near term, such a link could connect research networks at various national labs and research institutions to help facilitate the advent of an intercontinental quantum network. Quantum-enhanced sensor arrays is the goal most directly in line with NASA's mission, but does not have the same immediate broad impact to the entire nation, so is considered the secondary capability goal. Quantum-enhanced communication likewise has significant potential benefit for NASA, and is clearly worthwhile for pursuit, but has a smaller envelope of applicability and thus is ranked last; nevertheless, it is likely that this capability will be the first to be demonstrated (en route to the other goals) given its comparatively lower implementation challenges.

Within these areas there is a large amount of ongoing critical research, with even more needed. For example, there are many open questions on each of the topics listed above: how significantly will quantum memories reduce the required resources for quantum-enhanced VLBI; what is the tradeoff between two-way communication and larger instruction sets for remote quantum programming; which remote or nonlocally error-corrected architectures are optimal for high-latency interconnections in distributed quantum computing, etc.

While we anticipate that quantum communications will produce significant benefits for the overall NASA mission, not every capability outlined here is a guaranteed winner. It will take substantial research to understand clearly where quantum communications-enabled systems will outperform classical systems. For example, they likely will not provide raw rates sufficient for direct video streams or voice communication, but they could potentially enable extraordinary applications, such as a quantum internet or synthetic sensing apertures larger than Earth.

3.3 Functional Subsystems Needed to Support These Desired Capabilities

The capabilities introduced in the previous section are ambitious and far reaching. As a part of the roadmap to a space-based quantum network, we have sought to analyze those capabilities and provide a breakdown of the critical subsystems or functions needed to develop each one. With this mapping of functional needs, it will be possible to understand how each piece—such as entanglement sources for entanglement swapping—fits into the larger scheme and supports the development of these overarching goals. In Table 1, we provide a best-estimate mapping of functional needs for each of the previously described capabilities; we then provide a description of each subsystem/function to more fully explain its purpose.

Capabilities / Critical Subsystems and Functions	VLBI	Secure Comms Below RLL	Secure Comms Above RLL	Cloud/Blind Quantum Computing	Distributed Quantum Computing	Enhanced Transceiver	Clock Network	Field Sensor Network
Entanglement Swapping	X		X	X	X	X	X	X
Quantum Memory	X		X	X	X		X	X
Photon Detectors	X	X	X	X	X	X	X	X
High-Resolution Clock/Sync	X	X	X	X	X	X	X	X
Doppler Correction	X		X	X	X			
Single-photon Frequency Conversion	X		X	X	X		X	X
Stabilize Polarization Diversity	X	X	X	X	X	X	X	X
Quantum Non-demolition Measurement	X		X	X	X			
Feed-forward Operation on Teleported Qubit	X		X	X	X		X	X
Quantum Repeater				X				
Quantum Transducer				X	X	X	X	X
Quantum Error Correction				X	X		X	X
Classical Time Transfer							X	X
Quantum Processor	X			X	X			
Field Sensors								X

Table 1. Mapping of functional needs to capabilities.

3.3.1 Description of Functional Developments

Entanglement swapping

Entanglement swapping is the process in which entanglement can be created between two quanta that have never interacted physically [(Żukowski *et al.* 1993), (Pan *et al.* 1998)]. It is a powerful method that creates enhanced correlation between system nodes. For example, two sets of entangled photons can be generated where the first set has photon 1 and 2 and the second set has photon 3 and 4. By interfering one photon from each set, say photons 2 and 3, at a beam splitter, followed by a well-chosen measurement, it is possible to entangle the other two photons (1 and 4) even though they never interact. If the rate of such a process can be made high enough, it will enable creating entanglement between two or more quantum memories separated by continental or even intercontinental scales. Enabling this capability would be a truly breakthrough achievement, which could be utilized to create quantum links for communication, distributed processing or high-precision distributed sensor arrays.

Note that while *terrestrial* demonstrations of entanglement swapping have been reported [(Pan *et al.* 1998), (Jin *et al.* 2015), (Sun *et al.* 2017), (Zopf *et al.* 2019)], it will be a major success to achieve entanglement swapping between sources that are in relative motion. Important developments needed to accomplish this goal include the following: very high-precision synchronization (on picosecond scales), to ensure that the two interfering photons arrive at the beam splitter at the same time; very high generation rates of entangled photons, to ensure success of the swapping protocol, which in many cases is probabilistic; and deterministic sources or multiplexed sources with reduced unwanted multi-pair generation probabilities, which will enable much higher rates.

Quantum memory

Quantum memories, which can store qubits while preserving their coherence and entanglement, are needed for long-distance quantum communications (for quantum repeaters) as well as for the operation of quantum computers. Note that in addition to storage time and efficiency, the memory must faithfully store the quantum state carried by the photon, and the memory bandwidth must match the photon bandwidth (or a transducer is needed). Furthermore, the memory must have sufficient "depth"—ability to simultaneously store and retrieve photons in different spectral-temporal modes, e.g., time-bins. Finally, for many applications it is critical that the memory be *heralded*, i.e., there is a way to discern whether the memory has successfully stored a quantum state without reading it out (Brennen, Giacobino, and Simon 2015). Demonstrated platforms for memories include cold gases, warm vapors, single atoms or ions, color centers in diamond, and rare-earth ion-doped crystals, all-optical delays (Victora *et al.* 2019), and hybrids (Pang *et al.* 2020). Shorter duration, high-depth memories can improve the performance of probabilistic sources of entanglement, and improve the rate of synchronized events from independent sources [(Kaneda *et al.* 2017), (Bhaskar *et al.*

2020), (Brennen, Giacobino, and Simon 2015)]. Proposals have analyzed the creation of entanglement at useful rates over global distances via quantum repeaters with satellite links and quantum memories on the ground (Boone *et al.* 2015). Locating memories in space will further extend the reach of useful entanglement distribution. Quantum memories are also a critical component for very long baseline interferometry (VLBI), to reduce the required number of distributed quantum resources from one per possible spectral-temporal mode to one per *occupied* mode from the object to be observed (Khabiboulline *et al.* 2018).

Quantum nondemolition measurement

Many of the sources envisioned for these applications are probabilistic, e.g., the statistics of pairs from spontaneous parametric down conversion are thermal, meaning that the maximum probability to produce exactly one pair is 25%. The quantum memories are also not 100% efficient, and the channel certainly has losses. The performance of many of the protocols would be greatly improved if one could know when the photon was actually emitted (from source or memory) or transmitted (through a lossy channel), so that a reattempt could made if the photon was lost. A quantum nondemolition measurement detects the presence of a photon without absorbing it (the photon changes the quantum state of, e.g., an atom, in a detectable way). However, care must be taken that the quantum nondemolition (QND) measurement not collapse the quantum state of the photon being used to carry the quantum information. Experimentally, there has been some recent progress toward useful QND measurements, both in the optical [(Reiserer, Ritter, and Rempe 2013), (Sun *et al.* 2018)] and microwave regimes (Kono *et al.* 2018). However, performance is still not sufficient to be advantageous in a real system at this time.

High-efficiency, low-jitter photon detectors in space

Many of the applications require photon detections to happen on the space platform; even for applications where both photons are transmitted to ground stations, it will still be critical to be able verify operation of the source locally on the transmission platform, by detecting them. For this purpose, one needs detectors with high efficiency, low jitter (to enable running at high rates and not confuse photons from subsequent pairs), and low Size, Weight and Power (SWaP). Superconducting nanowire detectors currently meet the first two criteria; efficiencies above 98% (Reddy 2019), and time jitter as low as 3 ps have been reported (Korzh *et al.* 2020), though it should be noted that these characteristics are not currently achievable in a single device architecture. Additionally, there has been recent progress in observing photon number resolution—being able to distinguish between zero, one, and more than one photon (Cahall *et al.* 2017); such a capability, e.g., greatly improves the operation of single- and entangled-photon sources based on (probabilistic) pair generation. In all cases requiring superconducting detectors, appropriate flight-ready cryogenics would be needed for the SWaP constraint.

Avalanche photodiodes (APDs) have slightly lower efficiencies (~70-80% for the visible and near-IR, somewhat lower around 1550 nm), and somewhat higher jitter (~70-400 ps); however, they have the advantage that they require only modest cooling, and thus have a much smaller SWaP. Recent methods using advanced pulse-gating techniques have achieved hundreds of megahertz detection rates [(Thomas, Yuan, and Shields 2012), (Bienfang *et al.* 2016)]. New detector technologies for the telecom wavelength band are desired; one possibility is to implement nonlinear wavelength conversion (e.g., from telecom to visible), which would enable the use of the better-performing silicon APDs (VanDevender and Kwiat 2007). One potential issue with APDs is the effect of radiation, which is known to substantially increase dark counts in avalanche photodiodes [(Tan *et al*. 2013), (Moscatelli *et al.* 2013)], though there is preliminary data indicating that optical annealing methods may mitigate this (Lim *et al.* 2017).

High-resolution clocks and time synchronization

High-resolution clocks and time synchronization are essential for all modern communication and sensing applications. Arguably the most taxing of applications and environments are deep space in nature, from navigation of space vehicles to extremely sensitive metrology platforms, such as long baseline arrays, requiring exquisite clock performance to ensure mission success. Today's best clocks, while capable of meeting these performance requirements, are still too large, too heavy, consume too much power, and have not been designed to survive the harsh environments of launch, space operation, and landing on distant bodies, such as the Moon and Mars. Clocks in use on space platforms, such as GPS, GLONASS, and BeiDou global navigation systems, are still based on atomic microwave transitions, and are subject to daily updates/synchronization with Earth ground systems to correct for drift. To correct for these deficiencies, efforts are underway to migrate to atomic and ionic systems that support optical transitions, whose higher optical frequencies reduce the fractional instability [(Ludlow *et al.* 2015), (Takamoto *et al*. 2005), (Mehlstäubler *et al.* 2018)]. Today significant work is underway to reduce the size and power requirements of optical atomic clocks—through the use of fiber and compact chip-scale integrated photonic structures—to make such systems flight worthy. Recent frequency-comb experiments have achieved sub-femtosecond-level time transfer between nodes in relative motion (Sinclair *et al.* 2019). Here, the advent of optical frequencies combs, realized initially with mode-locked lasers, made efficient frequency translation to microwave frequencies possible, allowing cycles to be counted using electronic devices (Fortier and Baumann 2019).

Doppler correction

There are at least two respects in which Doppler frequency-shift correction is necessary for many of these applications. First, to achieve entanglement swapping, one needs to implement a Bell-state measurement, which is usually implemented by combining the two photons on a beam splitter and looking for a particular outcome, i.e., each output port of the beam splitter had a single photon. However, this method reveals a genuine Bell state only if the two photons are indistinguishable at the beam splitter. This means they must arrive simultaneously, to much better precision than their durations (in turn given by their reciprocal bandwidths), which for many of the applications here is 1-10 ps. Because the sources are moving relative to one another, some means to synchronize them is needed. The photons must also be indistinguishable in their frequencies for the Bell-state analysis to truly signify entanglement. Although the relative motion of the sources will introduce a small Doppler shift ($\Delta f/f$ = (1± v/c)), for a typical platform moving at ~10 km/s). This relative shift is only 3×10^{-5}, much less than the bandwidth, i.e., can be neglected unless one is using much narrower bandwidth sources (note, however, that many existing quantum memories *do* require such narrow bandwidths).

If one is using time-bin encoding, where the qubit states 0 and 1 are represented by two different time bins, then the relative motion of the transmitter and receiver will lead to a (longitudinal) velocity-dependent change in the separation, which *does* need to be corrected. This can be accomplished by sending along a reference beam (at a different frequency), as has been demonstrated (Chapman *et al.* 2019).

Quantum transducers

For implementing hybrid QIS systems, which use diverse material systems for photonic sources and quantum memories (e.g., color centers and cold atoms), quantum interconnect techniques are needed for "impedance matching" between the different platforms. [(Kurizki *et al*. 2015), (Loncar and Raymer 2019)]. For example, both the carrier frequency and temporal wave-packet shape of emitted photons need to be optimized for absorption in a quantum memory. Methods are needed for implementing frequency and bandwidth conversion without photon loss or loss of coherence. Such unitary operations can be accomplished using linear optical methods (such as a time lens [(Salem, Foster, and Gaeta 2013), (Sośnicki and Karpiński 2018)]) or nonlinear optical methods (such as pulsed sum-frequency conversion) (Brecht *et al.* 2015). Such manipulation of temporal wave packets of single photons is also useful for encoding quantum information in higher dimensional state space, offering increased security and flexibility for QIS systems (Brecht *et al.* 2015).

Stabilization/polarization diversity

Mitigation of polarization changes in fiber optic classical and quantum communications systems is frequently needed. In the context of quantum communications, this is often necessary even if the quantum encoding does not use polarization due to the polarization sensitivity of other components, for example phase modulators, which frequently only modulate a single polarization mode with high extinction. For free-space optical channels, relative motion between transmitters and receivers as well as atmospheric turbulence can cause changes in their relative local polarization reference frames.

Requirements for polarization stabilization will need to be evaluated for each particular concept of operations and quantum encoding. As an example, polarization diversity techniques used in coherent classical communications may find application for continuous variable quantum communications. However, a systems analysis will be needed to determine if other solutions (such as active polarization tracking and correction) may be more advantageous for other reasons (for example size, weight, and power considerations).

Feed-forward operation on teleported qubit

The Bell state analysis that is at the heart of the teleportation and entanglement swapping protocols can give any one of four possible answers; for linear optics systems only two of these are useful, definitively identifying two of the four Bell states. Depending on which Bell state was detected, the other photon will need a corrective operation. This is known as "feed-forward", because it needs to be implemented before that photon is detected. In some cases such correction may be unnecessary (e.g., one is only trying to distribute entanglement, and it is sufficient to know *which* entanglement was transmitted after the fact; or, if one only keeps one of the four Bell-state signatures, then no correction is needed, as the receiving photon will already be in the correct state).

Quantum error correction

Error correction is required in any communication in order to meet bit error rate requirements and is especially necessary in quantum communications because of the fragility of quantum states. The optical photon channel has different levels of susceptibility to the inducement of error depending on the photon state being transmitted. For instance, polarization and time-bin encoding are relatively insensitive to transmission effects through the atmosphere while phase is very susceptible. Additionally, the quantum communication components within ground stations, satellites, and other network components, will have their own decoherence issues. This means that error correction will be a necessity for computational links.

For quantum communications, we can use similar approaches to what has been used before, such as repetition codes that use a series of repetitions and quantum gates to correct for bit-flip and phase-flip errors. This is the basis of the Shor code and is accomplished by encoding a single logical qubit in nine physical qubits, in three sets of three. Within a set the differences between qubits 1 and 2, and 2 and 3, are measured non-destructively to determine whether an error has occurred.

Research into this area will be required in order to implement robust error correction and to determine the optimal locations for it in the quantum links. For instance, is it needed in every node or should it be at just the source and destination or something in between? A primary issue is photon loss for long distance transmission [(Bergmann and van Loock 2016), (Muralidharan *et al*. 2014)], so a likely key area of focus will be on error correction for low probability of qubit transfer. To that end, recent results indicate that encoding multiple qubits (or higher-dimensional quantum states) onto a single photon can lead to significant improvements in the efficiency and efficacy of quantum error correction in lossy channels (Piparo *et al*. 2020).

Quantum repeater

Recent theoretical results have established that fundamental limits on quantum communications rates exist for lossy channels [(Takeoka, Guha, and Wilde 2014), (Pirandola *et al*. 2017)]. To exceed these limits requires fairly specialized functionality, for example, that which is provided by proposed quantum repeaters. There have been many proposed quantum repeater concepts that leverage different physical platforms in an effort to establish quantum communications that can exceed the aforementioned fundamental bounds (Muralidharan *et al*. 2016). For discrete variable qubits, these proposals range from distributing entanglement and then performing entanglement swapping and purification (Briegel *et al.* 1998), to encoding quantum information in multi-photon states, with quantum error correcting codes implemented at each quantum repeater node (Muralidharan *et al*. 2014). In the latter proposal, it was shown that fault-tolerant quantum communication is possible, although the total loss between quantum error correction operations must be below 50%; i.e., this will likely not apply for any space links. While not as well studied, recent continuous variable quantum repeater proposals (Dias, Hosseinidehaj, and Ralph 2020) have been theoretically shown to exceed the bound in (Pirandola *et al*. 2017).

A great deal of research progress must be made in this area to enable quantum communications that avoid vanishingly small rates over high-loss channels. Concepts of how to deploy and operate space-based quantum repeater networks will need to be developed once the prerequisite demonstrations show that exceeding the fundamental rate loss bounds is possible.

Quantum processor

The power of quantum computation comes from encoding information in a non-classical way, enabling quantum algorithms to harness effects at the heart of quantum mechanics, such as entanglement, for computational purposes. Many quantum algorithms have been shown to provably outperform the best classical algorithms with applications ranging from cryptography to material science, though much research remains to be done to determine the breadth of quantum computing’s impact. While substantial engineering efforts are underway, the current processors are noisy intermediate-scale quantum (NISQ) processors—relatively small and somewhat error-prone prototypes—and much work remains to create quantum processors of the size and robustness needed to solve application-scale problems. Nevertheless, the speed of the quantum hardware development is impressive, with Google’s processor passing the first quantum supremacy threshold last year, meaning that Google—with collaborators NASA and Oak Ridge National Laboratory—exhibited a set of computations running on quantum hardware providing output that could not be obtained in a reasonable amount of time on even the world's largest supercomputer. This milestone means that quantum computing has entered a new era, enabling the exploration of quantum algorithms beyond where classical simulation is feasible, due to its exponential overhead; one can anticipate a substantial broadening of areas in which quantum computing is known to have an advantage over conventional computing.

Important developments needed to achieve large-scale robust processors include: long decoherence times, fast and reliable quantum gates, fast and reliable measurement and initialization, and limited crosstalk and high parallelism; all at levels that enable fault-tolerant quantum computing. A diverse array of approaches is being explored, including superconducting, trapped ions, neutral atoms, all-optical, and silicon qubit processors. Algorithmic advances are also needed to realize applications that will still be advantageous using the Noisy Intermediate-Scale Quantum (NISQ) processing capabilities likely to be available over the next decade or two. Special-purpose quantum processors are also of interest, with quantum repeaters being one example.

Background noise rejection

Quantum photonic links can suffer from unwanted background light. For remediation, signal photons may be situated in narrow spectral bands or short temporal slots, and synchronized filters applied to pass the signal and block most of the background light. Typically, in such techniques a tradeoff arises between transmission of the signal and blockage of the background. As demonstrated in (Shahverdi *et al.* 2017), the tradeoff can be overcome using coherent temporal filters ("pulse gates"), which act coherently on the optical field rather than incoherently on its intensity. (Brecht *et al.* 2015) Such coherent filters greatly reduce the false counts from unwanted background, and by increasing the state fidelity of detected photons they will improve the entanglement distribution rate. Such coherent filtering can also offer improvements in VLBI, where the terrestrially distributed quantum photonic states must be indistinguishable from those from the object to be observed.

3.3.2 Summary of Functional Development Needs

Enabling a fully functional space-based quantum communication network across the entire application space will require a concerted and long-term effort. We find that there is a significant range of difficulty in realizing these capabilities. Some capabilities have a lower number of functional needs, while others require many. We find that capabilities such as secure communication are of lower complexity, at least for research environments, than those for sensor systems. We also find that the highest degree of difficulty are those capabilities associated with the networking of quantum computers, as they have the greatest number of as-yet-unrealized functional needs. To further elucidate the degree of difficulty for each functional need, the authors and workshop participants have made estimates of the time frames when each functional development will be realized for space utilization; these estimates are provided in the following section.

3.4 Anticipated Development Timeline

Obviously, not all the previously described functional developments require the same amount of effort. Some, such as entanglement swapping or enhanced photon detection, can be realized in the near term, while the most difficult—quantum repeaters, non-demolition measurements and quantum processors—are still far from deployment in space-based systems. Even within these functional categories there is a great deal of variability. For instance, the anticipated complexity for a quantum processor to support a sensor application, such as VLBI, is envisioned to be substantially less than one required to support full-scale, error-corrected quantum computing. Here we have assembled the anticipated development times for the previously described functional needs, obtained by polling workshop participants and others who are cognizant in the field. These are given as best estimates only. It should also be noted that, in general, space-deployment of functional elements will lag about five years behind when a technology is proven in a lab.

Doppler correction	2022
Stabilize polarization diversity	2022
Entanglement swapping between relatively moving sources	2025
Feed-forward operation on teleported qubit	2025
Low SWaP, high efficiency, low jitter, photon detectors in space	2025
High resolution clock and sync	2025
Background noise rejection	2025
Single-photon frequency and bandwidth conversion	2025
Quantum error correction	2030
Quantum memory	2030
Quantum transducer (ex: photon to microwave)	2025 - 2035
Fault-tolerant quantum repeater	2035
Quantum non-demolition measurement	2035
Full-scale error-corrected quantum processor	2030 - 2040

Table 2. Anticipated year in which each functional element is expected to be spaceflight ready.

3.5 Timeline for Functional Developments to Capabilities

Based upon the estimated times in which these developments will be available for utilization in space systems, we can begin to estimate when some of the capabilities dependent on them can be realized, as shown in Figure 5, which illustrates how increasingly complex capabilities are enabled through a layered development. As this is a temporal estimation of an estimated complexity, we are not attempting to be rigorous in providing exact times, but we can begin to show which capabilities would likely be first, and which will take the longest to realize.

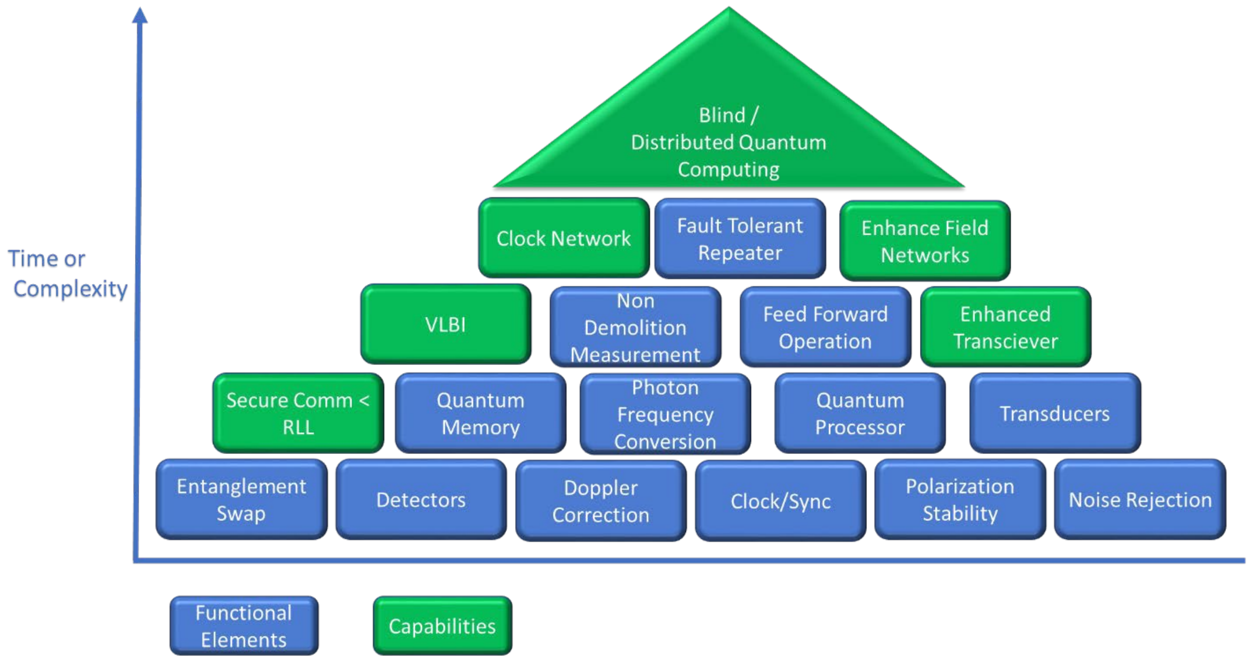


Figure 5. Illustration of how increasingly complex capabilities can be realized as functional elements are developed.

It is anticipated that space-based quantum network development will, most appropriately, take place in a more discrete fashion rather than as a continuum, as missions will be distributed in time due to expense, and not all technologies are likely to be available at the same time. We anticipate that a layered approach will enable some capabilities in the near term and also lay the foundation for future, increasingly complex capabilities. Based upon the estimated time at which functional elements will be available for spaceflight from Table 2, and the functional element mapping in Table 1, we can start to anticipate when the various capabilities can be realized. For instance, functional elements for a quantum computing network through space channels are likely 15+ years away, but the secure communications or sensing network components could be available in 5 to 10 years.

As a final note, because the technologies will be developed over a significant range of time, we strongly recommend that the ground stations be utilized as test-bed laboratories. This will allow for the latest technologies to be tested with space-based quantum communications links and will be a technology accelerator for the overall quantum network.

3.6 Conclusion

In this chapter the authors have sought to connect the national priorities for a quantum network to high-level goals of NASA and, subsequently, to capabilities that can be enhanced or enabled through the utilization of quantum communications. We find that there are a number of capabilities that could potentially be enabled by space-based quantum networks in the three prioritized general categories of networked quantum processing, quantum-enhanced sensor arrays, and enhanced communication applications. As an initial complexity estimation, these capabilities have been further tied to the functional developments needed to make each goal successful. Based upon that estimation we also find that the highest-value goal, networked quantum processing, is also the most difficult and furthest from full realization. In subsequent chapters, mission concepts, technologies, and architectures will be discussed that will be needed to make these functional elements, and subsequent capabilities, a reality. The authors hope that these connections and timelines will allow individual technology or mission developments to be understood in the context of the eventual goals that NASA and NIST have for space-based quantum communication.

3.7 References

Aasi, J., Abadie, J., B. Abbott *et al.* 2013. "Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light." *Nature Photonics*, 7: 613-619.

Abadie, J., B. Abbott, R. Abbott *et al.* 2011. "A gravitational wave observatory operating beyond the quantum shot-noise limit." *Nature Physics*, 7: 962-965.

Acernese, F., M. Agathos, L. Aiello, A. Allocca, A. Amato, S. Ansoldi, S. Antier *et al*. 2019. "Increasing the Astrophysical Reach fo the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light." *Physical Review Letters*, 123, 231108.

Banaszek, K., M. Jachura, and W. Wasilewski. 2019. "Utilizing time-bandwidth space for efficient deep-space communication." *International Conference on Space Optics — ICSO 2018, 11180*, 111805X.

Barzanjeh, S., S. Guha, C. Weedbrook, D. Vitali, J. H. Shapiro, and S. Pirandola. 2015. "Microwave quantum illumination." *Physical Review Letters*, 114, 080503.

Beals, R., S. Brierley, O. Gray, A. W. Harrow, S. Kutin, N. Linden, D. Shepherd, and M. Stather. 2013. "Efficient Distributed Quantum Computing." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*.

Bennett, C. H. and G. Brassard. 1984. "Quantum cryptography: public key distribution and coin tossing." *Proc. IEEE International Conference on Computers, Systems and Signal Processing*: 175–179, IEEE.

Bergmann, M. and P. van Loock. 2016. "Quantum error correction against photon loss using multi-component cat states." *Phys. Rev. A, 4*(4), 042332.

Bhaskar, M. K., R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park, D. Englund, M. Lončar, D. D. Sukachev, and M. D. Lukin. 2020. "Experimental demonstration of memory-enhanced quantum communication." *Nature, 580:* 60-64.

Bienfang, J. C., A. Migdall, A. Restelli, and W .H. Farr. 2016. *US Patent No. 9,401,448.*

Boone, K., J. P. Bourgoin, E. Meyer-Scott, K. Heshami, T. Jennewein, and C. Simon. 2015. "Entanglement over global distances via quantum repeaters with satellite links." *Physical Review A, 91*(5), 052325.

Boroson, D. M. 2018. "On achieving high performance optical communications from very deep space". In H. H. Boroson (Ed.), *Free-Space Laser Communication and Atmospheric Propagation XXX.* SPIE.

Brecht, B., D. V. Reddy, C. Silberhorn, and M. G. Raymer. 2015. "Photon temporal modes: a complete framework for quantum information science." *Physical Review X, 5*(4), 041017.

Brennen, G., E. Giacobino, and C. Simon. 2015. "Focus on quantum memory." *New Journal of Physics, 17*(5), 050201.

Briegel, H.J., W. Dür, J.I. Cirac, and P. Zoller. 1998. "Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication." *Phys. Rev. Lett., 81*, 5932.

Broadbent, A., J. Fitzsimons, and E. Kashefi. 2009. "Universal Blind Quantum Computation." *50th Annual IEEE Symposium on Foundations of Computer Science*: 517–26, IEEE.

Buhrman, H. and H. Röhrig. 2003. "Distributed Quantum Computing. *Mathematical Foundations of Computer Science*." DOI: https://doi.org/10.1007/978-3-540-45138-9_1

Cahall, C., K. L. Nicolich, N. T. Islam, G. P. Lafyatis, A. J. Miller, D. J. Gauthier, and J. Kim. 2017. "Multi-Photon Detection Using a Conventional Superconducting Nanowire Single-Photon Detector." *Optica*: 1534-1535.

Carleo, G., I. Cirac, K. Cranmer, L. Daudet, M. Schuld, N. Tishby, L. Vogt-Maranto, and L. Zdeborová. 2019. "Machine learning and the physical sciences." *Reviews of Modern Physics, 91*(4), 045002.

Carney, D., P. C. Stamp, and J. M. Taylor. 2019. "Tabletop experiements for quantum gravity: a user's manual." *Classical and Quantum Gravity*, 034001.

Chapman, J.C., T. M. Graham, C. K. Zeitler, H. J. Bernstein, and P. G. Kwiat. 2019. *Time-bin and Polarization Superdense Teleportation for Space Applications.* Retrieved from arXiv: https://arxiv.org/abs/1901.07181.

Chen, J.P., C. Zhang, Y. Liu, C. Jiang, W. Zhang, X. L. Hu, J. Y. Guan, Z. W. Yu, H. Xu, J. Lin, and M. J. Li. 2020. "Sending-or-Not-Sending with Independent Lasers: Secure Twin-Field Quantum Key Distribution over 509 km." *Phys. Rev. Lett., 124*, 070501.

Colangelo, G., F. M. Ciurana, G. Puentes, M. W. Mitchell, and R. J. Sewell. 2017. "Entanglement-enhanced phase estimation without prior phase information." *Physical Review Letters*, 118, 233603.

Cuomo, D., M. Caleffi, and A. S. Cacciapuoti. 2020. "Towards a Distributed Quantum Computing Ecosystem." *IET Quantum Communication*. DOI: https://doi.org/10.1049/iet-qtc.2020.0002.

Dias, J., N. Hosseinidehaj, and T. C. Ralph, T. 2020. *Quantum repeater for continuous variable entanglement distribution.* Retrieved from arXiv: https://arxiv.org/abs/2004.06345.

Dowling, J. P. 2008. "Quantum optical metrology – the lowdown on high-noon states." *Contemporary Physics,* 49: 125–143. DOI: https://doi.org/10.1080/00107510802091298.

Ekert, A. K. 1991. "Quantum cryptography based on Bell's theorem." *Phys. Rev. Lett., 67*: 661–663.

Fang, X.T., P. Zeng, H. Liu, M. Zou, W. Wu, Y. L. Tang, Y. J. Sheng, Y. Xiang, W. Zhang, H. Li, and Z. Wang. 2020. "Implementation of quantum key distribution surpassing the linear rate-transmittance bound." *Nat. Photonics*.

Fitzsimons, J. F. 2017. "Private quantum computation: an introduction to blind quantum computing and related protocols." *npj Quantum Inf , 3*(23). DOI: https://doi.org/10.1038/s41534-017-0025-3.

Fortier, T. and E. Baumann. 2019. "20 years of development in optical frequency comb technology and applications." *Nature Communications Physics*, 2: 153.

Gottesman, D., T. Jennewein, and S. Croke. 2012. "Longer-baseline telescopes using quantum repeaters." *IEEE J. of Sel. Top. in Q. Elec.,* 109(7), 070503.

Gottesman, D. and I. Chuang. 2001. "Quantum Digital Signatures." *arXiv:quant-ph/0105032*.

Herrero-Collantes, M. and J. C. Garcia-Escartin. 2017. "Quantum random number generators." *Rev. Mod. Phys.,* 89, 015004.

Hwang, W. -Y. 2003. "Quantum Key Distribution with High Loss: Toward Global Secure Communication." *Physical Review Letters,* 91, 057901.

Jin, J., M. G. Puigibert, L. Giner, J. A. Slater, M. R. Lamont, V. B. Verma, M. D. Shaw, F. Marsili, S. W. Nam, D. Oblak, and W. Tittel. 2015. "Entanglement swapping with quantum-memory-compatible photons." *Phys. Rev. A*, 012329.

Kaneda, F., F. Xu, J. Chapman, and P. G. Kwiat. 2017. "Quantum-memory-assisted multi-photon generation for efficient quantum information processing." *Optica*, 1034.

Khabiboulline, E.T., J. Borregaard, K. De Greve, and M. D. Lukin. 2018. "Nonlocal Optical Interferometry with Quantum Networks." arXiv preprint: https://arxiv.org/abs/1809.01659.

Kómár, P., E. M. Kessler, M. Bishof, L. Jiang, A. S. Sorensen, J. Ye, and M. D. Lukin. 2014. "A quantum network of Clocks." *Nature Physics*: 582-587.

Kono, S., K. Koshino, Y. Tabuchi, A. Noguchi, and Y. Nakamura. 2018. "Quantum Non-Demolition Detection of an Itinerant Microwave Photon." *Nature Physics*: 546-549.

Korzh, B., Q. Y. Zhao, J. P. Allmaras, S. Frasca, T. M. Autry, E. A. Bersin, A. D. Beyer, R. M. Briggs, B. Bumble, M. Colangelo, and G. M. Crouch. 2020. "Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector." *Nat. Photonics*: 250-255.

Kurizki, G., P. Bertet, Y. Kubo, K. Mølmer, D. Petrosyan, P. Rabl, and J. Schmiedmayer. 2015." Quantum technologies with hybrid systems." *Proceedings of the National Academy of Sciences, 112*(13): 3866-3873.

Lee, S. Y., C. W. Lee, J. Lee, and H. Nha. 2016. "Quantum phase estimation using path-symmetric entangled states." *Sci Rep*, 30306.

Lim, J. G., E. Anisimova, B. L. Higgins, J. P. Bourgoin, T. Jennewein, and V. Makarov. 2017. "Laser annealing heals radiation damage in avalanche photodiodes." *EPJ Quantum Technol.*

Liu, Y., Z. W. Yu, W. Zhang, J. Y. Guan, J. P. Chen, C. Zhang, X. L. Hu, H. Li, C. Jiang, J. Lin, and T. Y. Chen. 2019. "Experimental Twin-Field Quantum Key Distribution through Sending or Not Sending." *Phys. Rev. Lett., 123*, 100505.

Loncar, M. and M. G. Raymer. 2019. *Development of Quantum InterConnects for Next-Generation Information Technologies.* Retrieved from arXiv preprint: https://arxiv.org/abs/1912.06642.

Lopaeva, E. D., I. R. Berchera, I. P. Degiovanni, S. Olivares, G. Brida, and M. Genovese. 2013." Experimental realization of quantum illumination." *Physical Review Letters*, 110, 153603.

Ludlow, A., M. Boyd, J. Ye, E. Peik, and P. Schmidt. 2015. "Optical Aomic Clocks." https://arxiv.org/abs/1407.3493v2.

Minder, M., M. Pittaluga, G. L. Roberts, M. Lucamarini, J. F. Dynes, Z. L. Yuan, and A. J. Shields. 2019. *Nat. Photonics, 13*, 334.

Mehlstäubler, T. E., G. Grosche, C. Lisdat, P. O. Schmidt, and H. Denker. 2018. "Atomic clocks for geodesy." *Reports on Progress in Physics*, *81*(6), 064401.

Monnier, J. 2003. "Optical interferometry in astronomy." *Reports on Progress in Physics, 66*(5), 789.

Moscatelli, F., M. Marisaldi, P. Maccagnani, C. Labanti, F. Fuschino, M. Prest, A. Berra, D. Bolognini, M. Ghioni, I. Rech, and A. Gulinatti. 2013. "Radiation tests of single photonavalanche diode for space applications." *Nucl. Instr. Meth. Phys. Res.*: 65-72.

Muralidharan, S., J. Kim, N. Lütkenhaus, M. D. Lukin, and L. Jiang. 2014. "Ultrafast and Fault-Tolerant Quantum Communication across Long Distances." *PHYSICAL REVIEW LETTERS, 112*.

Muralidharan, S., L. Li, J. Kim, N. Lütkenhaus, M. D. Lukin, M, and L. Jiang. 2016. "Optimal architectures for long distance quantum communication." *Sci Rep*, 20463.

National Academy of Sciences Engineering Medicine. 2019. *Consensus Studies Report. Manipulating Quantum Systems: An Assessment of Atomic, Molecular, and Optical Physics in the United States.* National Academy of Sciences.

Pan, J. W., D. Bouwmeester, H. Weinfurter, and A. Zeilinger. 1998. "Experimental Entanglement Swapping: Entangling Photons That Never Interacted." *Phys. Rev. Lett., 80*, 3891-3894.

Pang, X.L., A. L. Yang, J. P. Dou, H. Li, C. N. Zhang, E. Poem, D. J. Saunders, H. Tang, J. Nunn, I. A. Walmsley, and X. M. Jin. 2020. "A hybrid quantum memory–enabled network at room temperature." *Science Advances, 6*.

Piparo, N. L., M. Hanks, C. Gravel, K. Nemoto, and W. J. Munro. 2020. "Resource reduction for quantum error correction using quantum multiplexed photons." *Phys. Rev. Lett.*: 3-4.

Pirandola, S., R. Laurenza, C. Ottaviani, and L. Banchi. 2017. "Fundamental limits of repeaterless quantum communications." *Nat Commun , 8*, 15043.

Reddy, D. V., A. E. Lita, S. W. Nam, R. P. Mirin, and V. B. Verma. 2019. "Achieving 98% system efficiency at 1550 nm in superconducting nanowire single photon detectors." *Rochester Conference on Coherence and Quantum Optics (CQO-11).* Rochester: OSA.

Reiserer, A., S. Ritter, and G. Rempe. 2013. "Nondestructive Detection of an Optical Photon." *Science*: 1349-1351.

Salem, R., M. A. Foster, and A. L. Gaeta. 2013. "Application of space–time duality to ultrahigh-speed optical signal processing." *Advances in Optics and Photonics, 5*(3): 274-317.

Shahverdi, A., Y. M. Sua, L. Tumeh, and Y. P. Huang. 2017. "Quantum parametric mode sorting: Beating the time-frequency filtering." *Scientific reports, 7*(1): 1-12.

Sinclair, L.C., H. Bergeron, W. C. Swann, I. Khader, K. C. Cossel, M. Cermak, N. R. Newbury, and J. D. Deschênes. 2019. "Femtosecond optical two-way time-frequency transfer in the presence of motion." *Phys. Rev. A*, 023844.

Sośnicki, F. and M. Karpiński. 2018. "Large-scale spectral bandwidth compression by complex electro-optic temporal phase modulation." *Opt. Express*: 31307-31316.

Sun, Q.C., Y. F. Jiang, Y. L. Mao, L. X. You, W. Zhang, W. J. Zhang, X. Jiang, T.Y. Chen, H. Li, Y. D. Huang, and X. F. Chen. 2017. “Entanglement swapping over 100 km optical fiber with independent entangled photon-pair sources,”. *Optica, 4*: 1214-1218.

Sun, S., H. Kim, Z. Luo,G. S. Solomon, and E. Waks. 2018. "A single-photon switch and transistor enabled by a solid-state quantum memory." *Science*: 57-60.

Takamoto, M., F. L. Hong, R. Higashi, and H. Katori. 2005. "An optical lattice clock." *Nature Letters*, Vol 435.

Takeoka, M., S. Guha, and M. Wilde. 2014. "Fundamental rate-loss tradeoff for optical quantum key distribution." *Nat Commun, 5*, 5235.

Tan, S.H.,B. I. Erkmen, V. Giovannetti, S. Guha, S. Lloyd, L. Maccone, S. Pirandola, S. and J. H. Shapiro. 2008. "Quantum illuminations with Gaussian states." *Physical Review Letters*, 101, 253601.

Tan, Y. C., R. Chandrasekara, C. Cheng, and A. Ling. 2013. "Silicon avalanchephotodiode operation and lifetime analysis for small satellites." *Opt.Express*, 16946.

Thomas, O., Z. L. Yuan, and A. J. Shields. 2012. "Practical photon number detection with electric field-modulated silicon avalanche photodiodes." *Nature Comm.*, 644.

Tse, M., H. Yu, N. Kijbunchoo, A. Fernandez-Galiana, P. Dupej, L. Barsotti, C. D. Blair, D. D. Brown, S. E. Dwyer, A. Effler, and M. Evans. 2019."QuantumEnhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy." *Physical Review Letters*, 123, 231107.

Van Meter, R., and S. J. Devitt. 2016. "The Path to Scalable Distributed Quantum Computing." *Computer*. DOI: https://doi.org/10.1109/mc.2016.291.

VanDevender, A. P. and P. G. Kwiat. 2007. "Quantum transduction via frequency up-conversion." *J. Opt. Soc. Amer. B*, 295.

Victora, M., F. Kaneda, F. Bergmann, J. J. Wong, A. Graf, and P. Kwiat. 2019. "Time-multiplexed methods for optical quantum information processing." In S. G. R. W. Boyd (Ed.), *Quantum Photonics: Pioneering Advances and Emerging Applications.* Springer Series in Optical Sciences.

Wang, S., D. Y. He, Z. Q. Yin, F. Y. Lu, C. H. Cui, W. Chen, Z. Zhou, G. C. Guo, and Z. F. Han. 2019. "Beating the Fundamental Rate-Distance Limit in a Proof-of-Principle Quantum Key Distribution System." *Phys. Rev. X, 9*, 021046.

White House National Quantum Coordination Office. 2020. *A Strategic Vision for America's Quantum Networks.* The United States Government.

Xia, Y., W. Li, W. Clark, D. Hart, Q. Zhuang, and Z. Zhang. 2020. "Demonstration of a Reconfigurable Entangled Radio-Frequency Photonic Sensor Network." *Physical Review Letters, 124*(15).

Zhang, Z., S. Mouradian, F. N. Wong, and J. H. Shapiro. 2015. "Entanglement-enhanced sensing in a lossy and noisy environment." *Physical Review Letters*, 114, 110506.

Zhong, X., J. Hu, M. Curty, L. Qian, and H. K. Lo. 2019. "Proof-of-Principle Experimental Demonstration of Twin-Field Type Quantum Key Distribution." *Phys. Rev. Lett., 123*, 100506.

Zopf, M., R. Keil, Y. Chen, J. Yang, D. Chen, F. Ding, and O. G. Schmidt. 2019. "Entanglement Swapping with Semiconductor-Generated Photons Violates Bell's Inequality." *Physical Review Letters*. DOI:https:/doi.org/10.1103/physrevlet.

Zukowski, M., A. Zeilinger, M. A. Horne, and A. K. Ekert. 1993. "Event-ready-detectors" Bell experiment via entanglement swapping." *Phys. Rev. Lett., 71*: 4287-4290.

4.0 Mission Concepts

Authors: Eleanor Rieffel (NASA ARC); Shon Grabbe (NASA ARC), Paul Kwiat (University of Illinois), Makan Mohageg (JPL/Caltech), Michael Raymer (University of Oregon)

4.1 Introduction: Key Objectives, Issues Addressed, and Overview of Impact on the Field

The goals and capabilities described in the Goals chapter all require a reliable, space-based system to distribute linkable quantum entanglement to one or more ground stations. Here we introduce qEDISON, a 7-year 3-phase concept to meet these requirements. The concept relies only on technologies that exist today, while its modularity enables the flexibility to incorporate future technology as it becomes available. Full implementation would demonstrate entanglement swapping[1] between distant ground locations for the first time, achieved through two space-to-ground links. It implements a repeatable module that could be the basis for a full quantum network.

As outlined in the White House Office of Science and Technology Policy (OSTP) document "A Strategic Vision for America's Quantum Networks", an orbital quantum entanglement distribution system will enable trans-Atlantic, trans-continental, and inter-space quantum communication at rates sufficient to create entanglement between multiple pairs of nodes in a quantum network, achieve quantum secured communications, and demonstrate essential elements for a long-distance quantum "internet". This will eventually enable a plethora of critical new capabilities: remote and secure usage of quantum computers [(Broadbent, Fitzsimons, and Kashefi 2009), (Barz *et al.* 2012), (Fitzsimons 2017)]; distributed quantum processing to multiply the quantum advantage of separated quantum processors [(Buhrman and Rohrig 2003), (Broadbent and Tapp 2008) (Van Meter and Devitt 2016), (Cuomo, Caleffi, and Cacciapuoti 2020)]; quantum-ensured security of communication channels and other assets [(Bennett and Brassard 1984), (Schmitt-Manderbach *et al.* 2007), (Scarani *et al.* 2009), (Yin *et al.* 2020)]; entanglement-enhanced distributed quantum sensors [(Degen, Reinhard, and Capellaro 2017), (Quntao, Preskill, and Jiang 2020)]; long baseline interferometry-based telescopes [(Gottesman, Jennewein, and Croke 2012), (Khabiboullin *et al.* 2019)]; and new applications still being discovered, even as our scientific understanding of the power of quantum information processing grows.

Our objective is to define a mission concept that eventually provides quantum network capabilities across the continental United States of America, and between the U.S.A and Europe. Local, short-range quantum networks can exist over fiber optic channels between users. As the distance between nodes exceeds about 100 km, free-space channels perform with greater

[1] "Entanglement swapping" refers to the protocol where one half of each of two separate pairs of entangled particles—here photons—are measured jointly, in a measurement known as Bell-state analysis (BSA). Contingent on the BSA outcome, the other two photons—which have never been together—are then caused to be entangled. This step is the central ingredient of a quantum repeater.

efficiency than fiber channels. To support links at continental scales without using quantum repeaters—until they are available—requires that the quantum communication spacecraft has simultaneous line-of-sight to the ground stations. The ground stations in this space-ground network may in turn act as nodes in local, fiber-based terrestrial quantum networks. We call our proposed concept qEDISON, Quantum Entanglement Distribution In Space Optical Network. The qEDISON concept supports a "quantum network of quantum networks" by distributing linkable entanglement through the space-ground links. It is also possible—and somewhat easier—to distribute nonlinkable entanglement; while such entanglement can be used for quantum cryptography, it cannot be connected to other networks, i.e., it does not enable one to implement "entanglement swapping", the critical element in a quantum repeater. The qEDISON concept focuses on a space platform capable of supporting trans-continental and trans-Atlantic quantum links. It relies on technologies that exist today—it does not require quantum memories, quantum repeaters, or in-flight cryogenic systems; however, qEDISON is flexible enough to remain future-compatible with such systems as they become available.

4.2 Summary of qEDISON Concept

The overarching goal is to provide modular capability for conducting distribution of linkable entanglement and entanglement swapping based on technologies that exist today, across intra- and inter-continental distances using a scalable, space-based platform. Europe-North America, East Coast-West Coast, and even Hawaii-Japan entanglement swapping operations are possible using qEDISON. Such a system might have:

- Entangled photon source (EPS), quantum optical detector system, local Bell-state verification system, and one or two gimbaled telescopes and supporting infrastructure onboard the International Space Station (ISS) or other low Earth orbit (LEO) platform, coupled to optical receiver(s) on the ground, or in space;
- Medium Earth orbit (MEO) spacecraft equipped with an entangled photon source, local Bell-state verification system, a pair of gimbaled telescopes, and a pair of large-aperture beam directors, coupled to large-aperture optical receivers on the ground;
- Two or more ground stations appropriately outfitted to act as receivers and equipped with a Bell-state analysis (BSA) system, including a matched EPS, to allow teleportation and entanglement swapping. The ground stations may thus interface with terrestrial quantum communications networks.

The fly-over of the space platform allows various ground stations to be accessed. The result would be a unique capability to create a network of networks via entanglement swapping

Linkable Quantum Entanglement

The resource provided by the proposed qEDISON concept is ***linkable quantum entanglement***, the distribution of quantum optical light of immediate utility. The light has well-defined spectrum, photon time of arrival, and polarization projection. A linkable quantum entanglement source can directly support quantum networking and sensing applications. In contrast, while substantially higher raw rates might be achieved with a ***non-linkable quantum entanglement*** source, where photons subtend a wide range of coupled quantum degrees of freedom, a non-linkable source is virtually useless for networking, quantum sensing, and distributed quantum processing.

between the ground nodes enabled by the quantum communications links in space (Boone *et al.* 2015).

Although the essential required technologies for qEDISON all exist at some level today, there is significant technology development required prior to designing and deploying the eventual MEO spacecraft. Thus, qEDISON is divided into three stages. Each stage will perform groundbreaking experiments while increasing overall system capability through a phased implementation that lowers overall program risk. The mission concepts described below provide the capability of supporting multiple 2-to-5-node quantum communications networks based on entanglement swapping. The mission concepts do not require quantum repeaters or quantum memories in either the flight or the ground terminals. However, the concepts outlined below are future-compatible with quantum memory technology as it matures.

Each stage represents an increased system capability and increased complexity. The expected dollar-value commitments required to succeed at each stage are about equivalent, and the principal risks associated with each successive stage are retired in those stages. In qEDISON, execution of quantum key distribution (QKD) serves as a standard method to quantify the quantum optical channel; however, as it does not require entanglement swapping, QKD is not a driving demonstration of the mission concept.

4.2.1 Stage 1

Stage 1 provides space-to-ground and possibly space-to-space entanglement swapping capabilities. It deploys a linkable entangled photon source (EPS), quantum optical detector system, a pair of gimbaled telescopes, and supporting infrastructure onboard a LEO satellite, e.g., the International Space Station (ISS) (Figure 1). The two telescopes on the LEO satellite will serve to route independently the signal and idler photons generated by the in-flight entangled photon source. For example, the two telescopes on the qEDISON satellite could close links with two ground stations within ~1000 km of each other (Figure 2). Or, one telescope could direct signal photons to the ground while the second telescope directs idler photons to a spacecraft target (Figure 3)[2]. As a first experiment in this concept stage, only *one* of the photons from the satellite transmitter needs to be sent to the ground for entanglement swapping, while the other is measured locally on the satellite (Fig. 1b); this substantially enhances the rate of successful entanglement-swap events, e.g., by a factor of ~2-100 (depending on the channel loss) (Johnson

[2] Note that whether the transmitted photons are sent to a ground terminal or another spacecraft may influence the wavelength decision; in particular, the ground terminal can be assumed to have access to cryogenically cooled superconducting detectors (which are the preferred solution for detecting photons around 1550 nm). Other spacecraft, e.g., CubeSats, will almost certainly *not* have this capability, instead employing silicon avalanche photodiodes (APD), which can only detect out to ~850 nm. For example, the Canadian quantum receiver satellite QEYSSat is designed with receivers around 800 nm. Therefore, designing capability to talk with these assets may recommend a non-degenerate EPS on the qEDISON satellite, with one photon around 800 nm and the other at 1550 nm; the former could be sent to other space platforms, the latter to ground stations. One additional advantage of this dual-wavelength approach is that the preliminary single-downlink experiment can be accomplished using only Si APDs on the satellite, i.e., with no reliance on spaceflight-qualified cryogenics for superconducting detectors.

et al. 2020), making testing and troubleshooting of the entanglement swapping considerably easier.

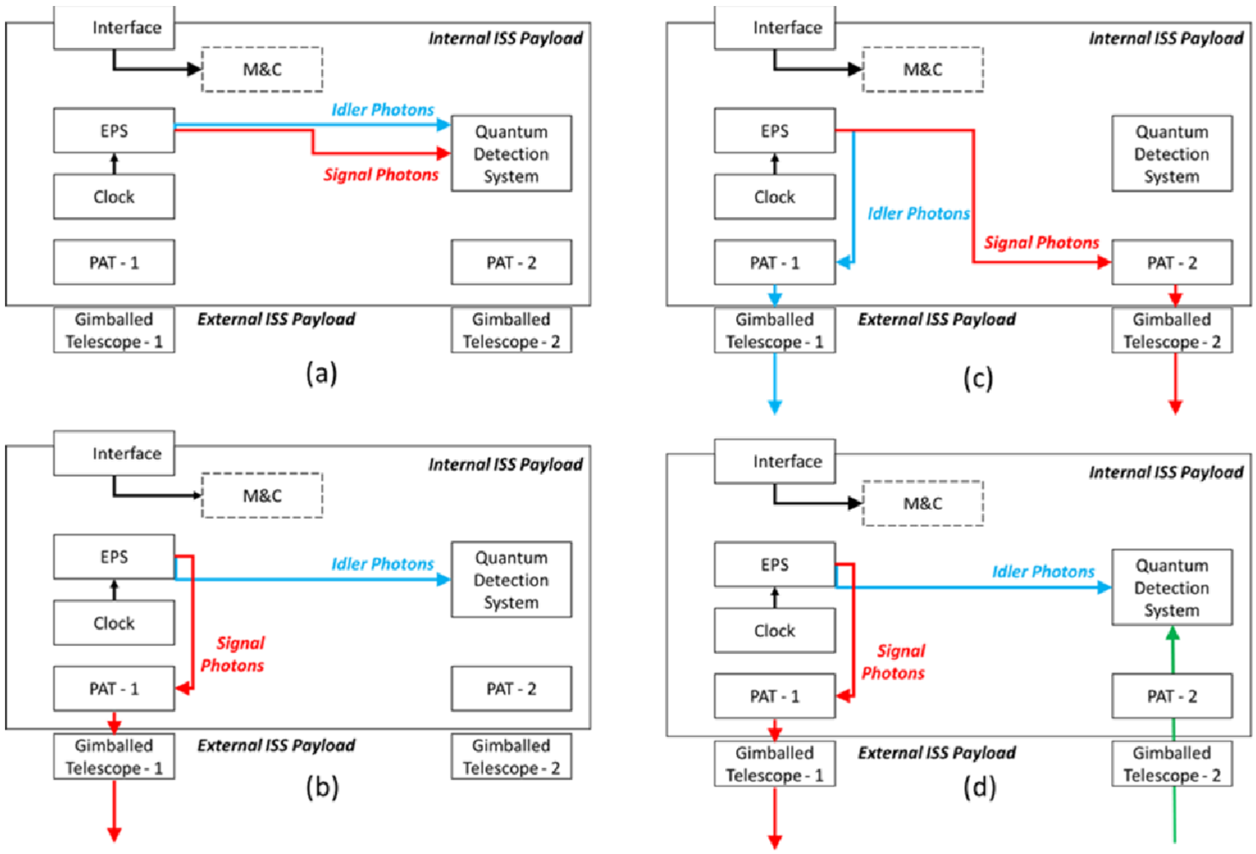


Figure 1. Modes of operation of the Stage 1 LEO satellite terminal, here shown as the ISS. (a) Diagnostic mode. The signal and idler photons generated by the entangled photon source (EPS) are directed to the Quantum Detection System for in-flight diagnostics. (b) Single downlink. The idler photon is measured on the spacecraft, while the signal photon is directed towards the receiver via gimbaled telescope, controlled by a Pointing and Tracking (PAT) system. For entanglement swapping, the signal photon at the receive telescope (not shown) is interfered in a BSA with an identical signal from a terrestrial EPS. A successful measurement means the two idler photons are then entangled. (c) Double downlink for entanglement distribution (note that one of the photons could equivalently be directed to another space receiver). Assuming the receivers each possess identical EPS and BSA capabilities, one can create a double-entanglement swap, effectively realizing a 5-node quantum communication network: the qEDISON satellite, the two BSAs at the receive telescopes, and the two end stations. (d) Quantum receiver option. One of the telescopes can be used as a receiver for quantum signals, e.g., entangled photons from another space platform.

One or more ground stations, appropriately outfitted, act as receivers. The ground stations may interface with terrestrial quantum communications networks, which are outfitted with a local EPS and a Bell-state Analysis (BSA) system. An incident signal photon from the space node is entangled with a locally generated signal photon from the local EPS using the BSA to effectuate the entanglement swapping (which, using existing all-optical methods, is successful in up to 50% of trials [(Vaidman and Yorna 1999), (Calsamiglia and Lutkenhaus 2001)]. Stage 1 will allow the first demonstration of genuine space-ground teleportation and entanglement swapping.[3] We estimate (Johnson *et al.* 2020) that with 0.3-m transmit telescopes and sources operating at a 10 GHz pump-repetition rate (though only producing pairs every ~20 pulses), one could achieve with a 1 m (4 m) telescope single ground station over 600,000 (20 million) entanglement swaps per satellite pass, 8500 double entanglement swaps to two 4-m telescopes separated by 500 km, and 1000 double entanglement swaps per pass to two 4-m telescopes separated by 1200 km. The raw capability in the last example is over 200 million distributed entangled photon pairs per satellite pass; to put this into perspective, the very recent announcement of entanglement-based quantum key distribution by the Micius satellite achieved only ~1000 pairs/pass, requiring nearly an hour of data collection (>14 passes) to generate 370 quantum-secured bits (Yin *et al.* 2020).

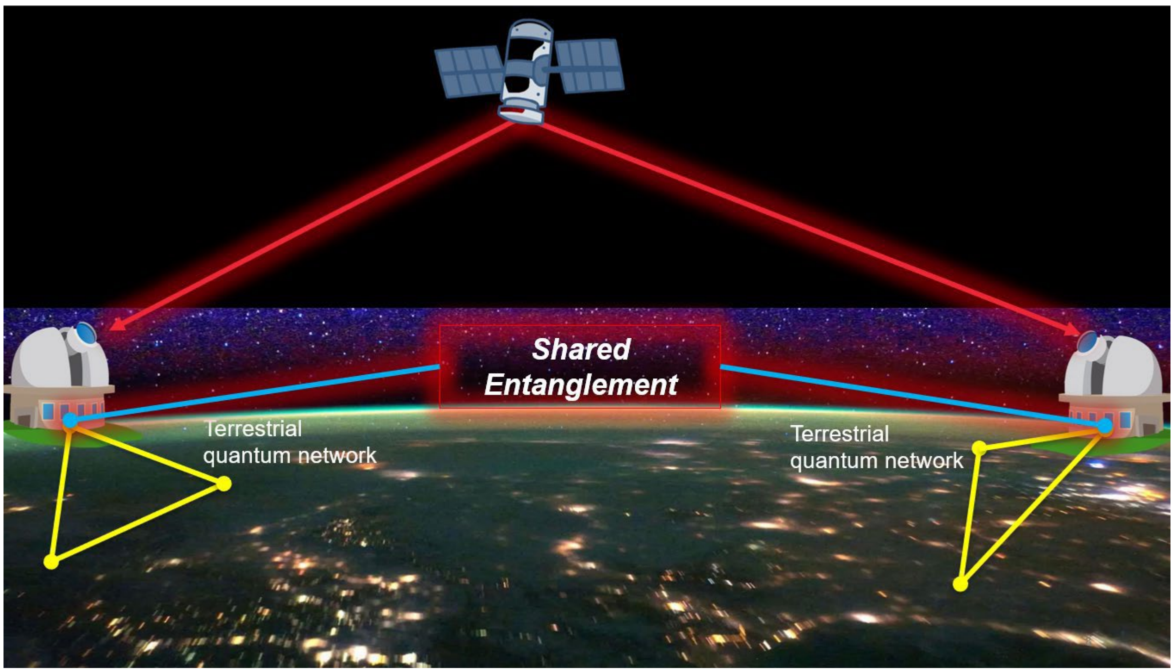


Figure 2. Stage 1 provides entanglement distribution and swapping between two ground stations that may in turn be part of two, geographically separated, fiber-based quantum networks. The maximum ground distance between the receivers (1200 km) is limited by the low altitude of an ISS-type orbit.

[3] It should be noted that while the Chinese Micius experiment *did* report on teleportation (Ren *et al.* 2017), in their demonstration both entanglement sources were co-located at the same ground station, i.e., *not* in relative motion as would be needed for a *practically useful* application of entanglement swapping.

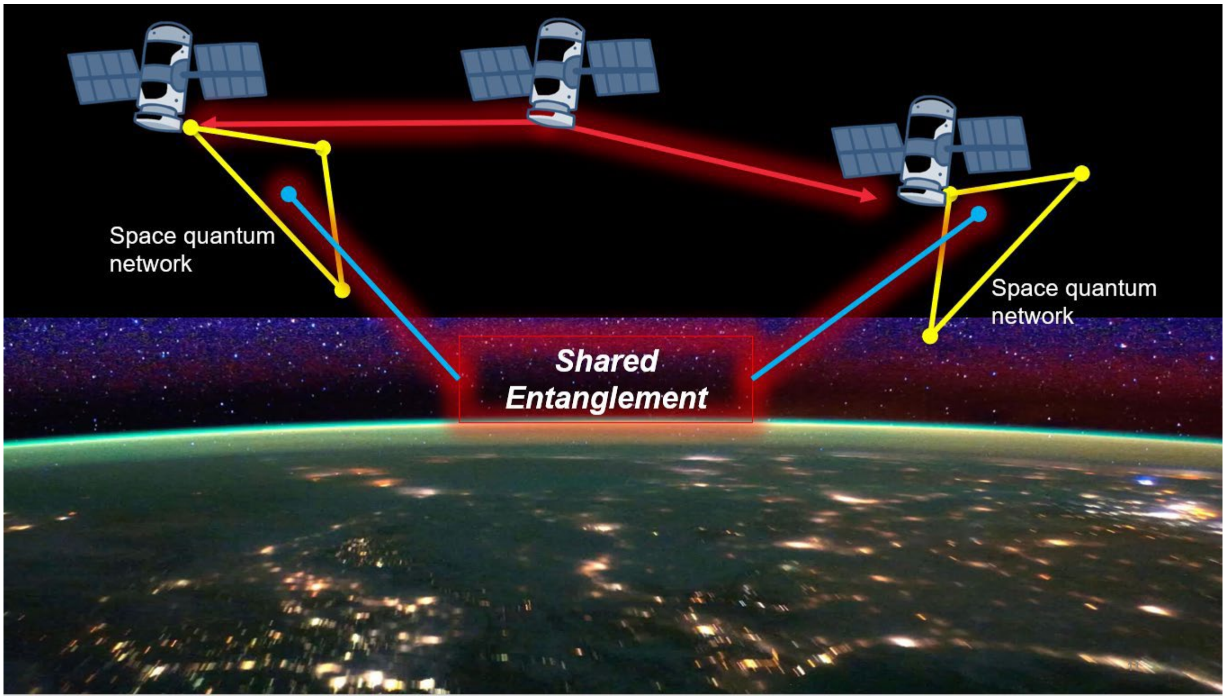


Figure 3. Stage 1 provides entanglement distribution and entanglement swapping between two space terminals that may in turn be part of two space-based quantum networks.

As an option, Stage 1a, the satellite may also include distribution of *hyperentangled* states from the qEDISON satellite to the ground stations; these encode quantum information in multiple degrees of freedom (most likely polarization and time-bins), to convey more quantum information per photon [(Kwiat 1997), (Barreiro *et al.* 2005), (Imany 2019)]. It was recently reported that such encoding can in fact lead to substantially more efficient quantum error correction over lossy channels (Piparo *et al.* 2020). Hyperentangled states may also be used to implement various advanced quantum communication protocols, including superdense teleportation (whose transmitted states are useful resources, e.g., for blind quantum computing [(Graham *et al.* 2015), (Chapman *et al.* 2020)] and hyperentanglement-based quantum key distribution (which generates more secret bits per photon, and is more tolerant to errors than usual QKD) [(Cerf, Karlsson, and Gisin 2002), (Simon and Sergienko 2014), (Wang *et al.* 2009)].

As shown in Fig. 1d, a further option of Stage 1 uses one of the gimballed telescopes as a *receiver* of quantum signals instead of a transmitter. This modification allows the unit to act as a quantum transceiver, both transmitting and receiving optical quantum information. Thus, a key capability provided by Stage 1 is the ability to close link with other quantum flight missions planned for launch within the next 5 years. Our international partners are planning launches of flight EPS systems (Singapore/UK's SPooQy mission), flight quantum receiver systems (Canada's QEYSSat mission), and flight transceiver systems (Germany's QUBE mission). Deploying an American quantum flight and ground terminal network opens the door to unique experiments with these partner space missions that are otherwise not possible with existing infrastructure (Figure 4). Other American allies—principally Italy, Australia, Japan, and France—have announced plans to launch additional quantum communications spacecraft in the years to come.

One preliminary demonstration could use corner cubes mounted on the exterior of another spacecraft (not necessarily one of the quantum-specific ones listed above) as a reflective target for the flight transmitter. That is, one of the entangled photons is reflected off the spacecraft corner cube and back into the receive channel (one of the transmit telescopes used in reverse) of the qEDISON quantum terminal. This simple test would represent a space-to-space version of the primary achievement of the Micius spacecraft, and retire risk related to space-to-space two-node links.

In an advanced phase in Stage 3, an additional capability could be added, relying on simultaneous two-way quantum communication between two platforms; this could be enabling for other protocols, e.g., quantum-enhanced clock synchronization (Kómár *et al.* 2014).

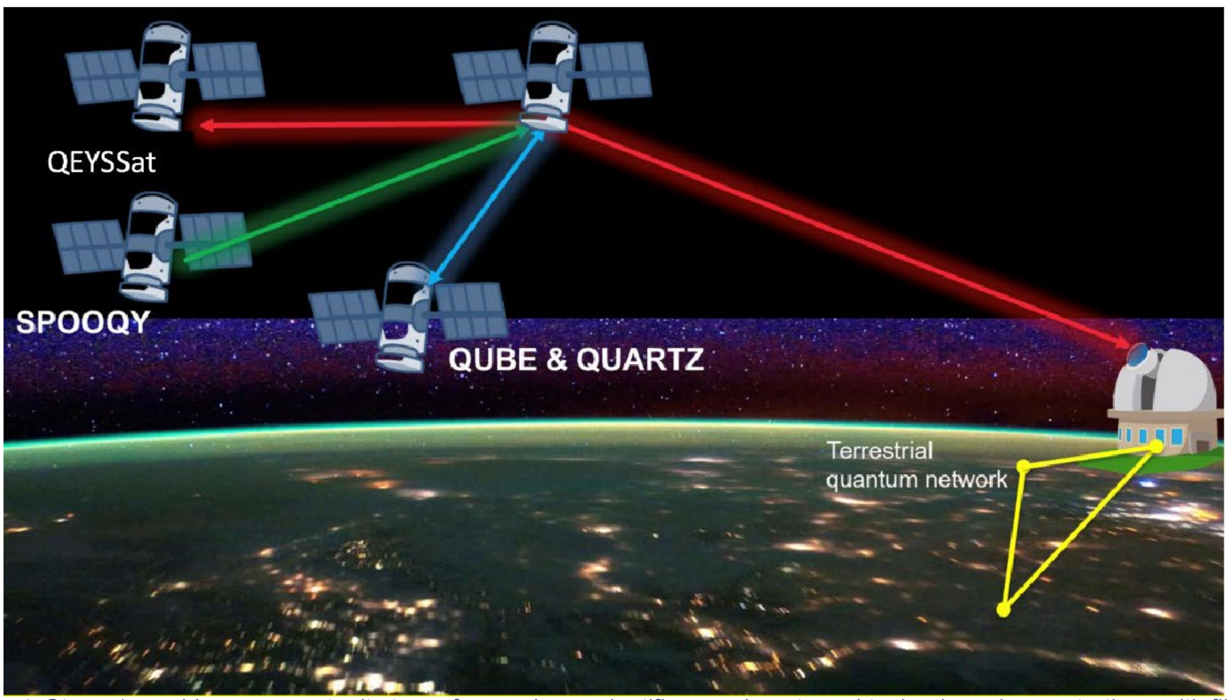


Figure 4. Stage 1 provides an opportunity to perform unique scientific experiments and technology demonstrations with flight missions planned by allied nations: QEYSSat (Canada), SPooQy (Singapore), QUBE (Germany), and QUARTZ (Germany).

The Stage 1 platform can serve as a testbed for advanced quantum communications technologies as they mature. The modularity of the initial system design will support these and other future upgrade opportunities. For example, the Stage 1 platform could be used to qualify flight quantum memories, advanced photon sources, and flight cryogenic detectors. Future users of the modular upgrade opportunity are other government agencies, scientific researchers, and commercial enterprises. This type of flight platform will help the nascent American quantum communications industry advance on pace with or beyond its international competitors.

The estimated time to implement Stage 1 is T+5 years.

4.2.2 Stage 2

A MEO spacecraft with two large (1-m class) apertures, outfitted with a high-rate, space-qualified EPS can distribute entanglement between two nodes (space or ground), as shown in Figures 5 and 6. Preliminary link analyses suggest the total entanglement swapping rate from the MEO platform is high enough to support useful applications. In particular, a MEO satellite at an altitude of ~3500 km could deliver entangled pairs to receivers with trans-continental or trans-Atlantic separations at rates exceeding 500,000/s (Figure 7), assuming 4 m receiver telescopes. Because the transmitter maintains sight of both ground stations for ~10 minutes, the total number of anticipated coincidences per pass is 350 million (Johnson *et al.* 2020).

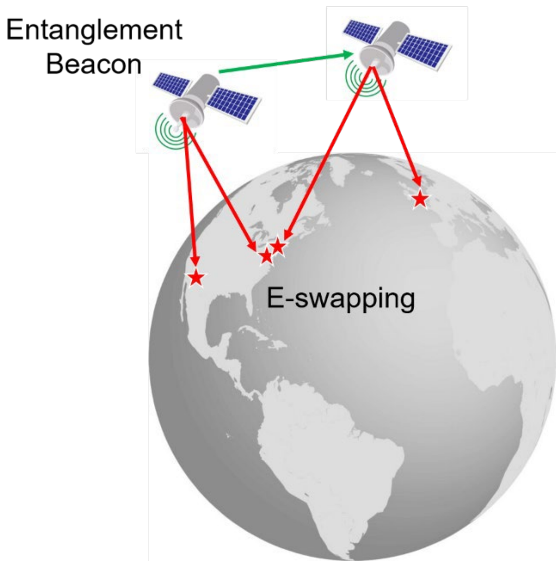


Figure 5. A two-terminal MEO spacecraft can distribute entanglement between ground stations in the U.S.A. and Europe, across the continental United States, or between a ground station and a spacecraft node, such as the Stage-1 transceiver.

Note that one could also consider a GEO-orbit satellite, which would allow the connection to ground stations separated by a longer baseline (up to ~13,800 km, assuming that the receive telescopes can only acquire a signal that originates from an elevation angle above 20 deg, due to atmospheric scattering and turbulence). However, the quadratic signal falloff with link length then reduces the expected coincidence rate to only ~300/s, likely too low to permit any useful entanglement swapping (whose rates are much further suppressed).

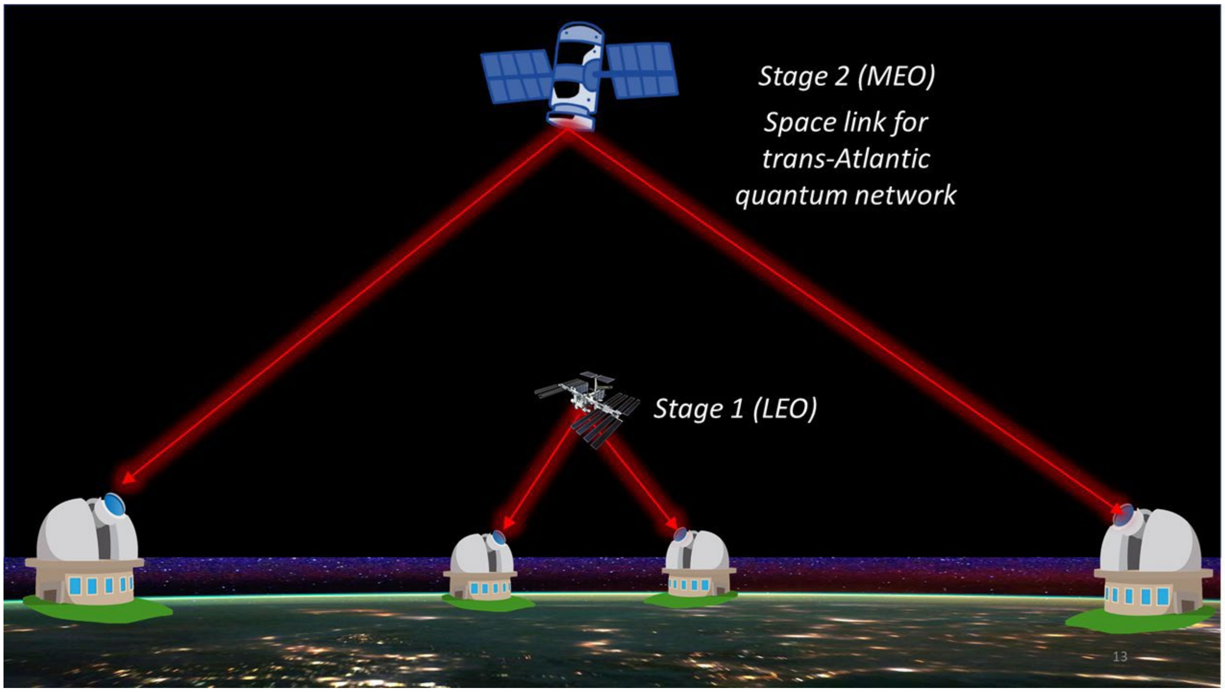


Figure 6. Stage 2 MEO spacecraft compared to Stage 1 LEO spacecraft. The higher orbital altitude provides capability to connect two quantum networks on different continents.

If the two ground stations are interfaced with terrestrial quantum networks over fiber, then Stage 2 provides the unique capability to create a network of networks via entanglement swapping between the ground nodes. Thus, a fiber-based quantum network in Europe (such as Secure Communication based on Quantum Cryptography (SECOQC) in Austria) could be networked with a U.S. fiber-based quantum network (such as the Massachusetts Institute of Technology-Lincoln Lab's Quantum Network Testbed). Or, an East Coast fiber-based quantum network could connect to fiber networks in the Midwest (e.g., Chicago Quantum Exchange) or the West Coast (e.g., Caltech/JPL's INtelligent Quantum NEtworks & Technologies (INQNET)). These and other potential "networks of quantum networks" can serve U.S. strategic defense, scientific, and economic development interests.

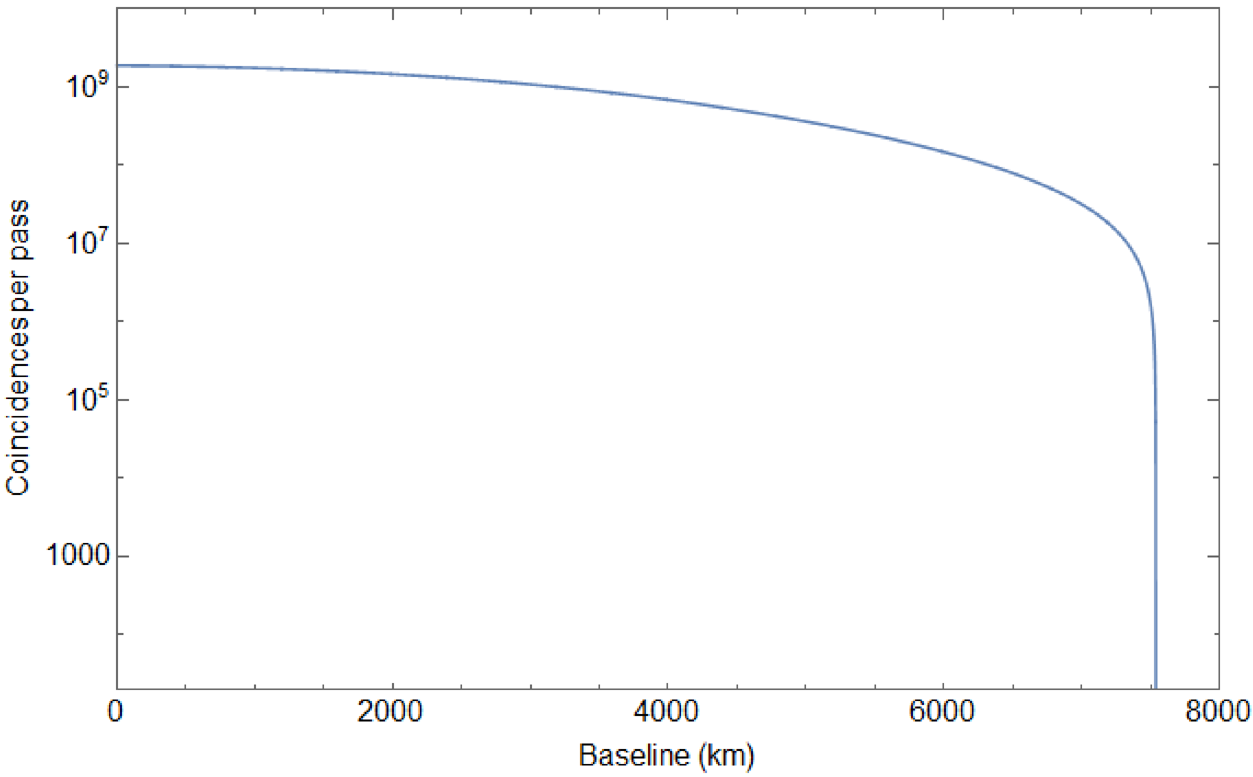


Figure 7. Predicted coincidences per pass for the MEO spacecraft at orbital altitude of 3800 km (Johnson et al. 2020). The number of coincidences is plotted as a function of the baseline separation between ground stations measured along the Earth sphere. The MEO spacecraft is assumed to be outfitted with a pair of 1-m aperture telescopes transmitting at 1550 nm through a turbulent atmosphere down to 4-m aperture ground receivers. The clock rate of the entangled photon source on board the spacecraft is 10 GHz, with a spontaneous parametric down conversion (SPDC) pair production probability of 0.05.

The estimated time to implement Stage 2 is T+7 years, assuming parallel development of Stage 1 and Stage 2. The additional flight technology development required for Stage 2 is the gimbaled 1-m aperture flight terminals. Optically, the photon source and quantum detection system used in the Stage 2 terminal is decidedly similar to the Stage 1 configuration (Figure 1); one potential difference depends on whether the Stage 1 EPS uses entangled pairs with both photons at ~1550 nm (as in the Stage 2 MEO concept), or one at 1550 nm and the other at ~800 nm (compatible with non-superconducting detectors, e.g., as will be employed by the Canadian QEYSSat quantum receiver satellite).

Note that even when Stage 2 is operational, the Stage 1 satellite will still be the preferred entanglement distribution system to connect ground stations separated by up to 1200 km, with 5-20 times higher rates (depending on the application and ground-station separation) than will be possible with the Stage 2 system, the latter being preferable only for longer ground-station baselines.

4.2.3 Stage 3

Stage 3 provides the capability to close a space-to-space quantum link relying only on technologies that exist today, yet is flexible enough to remain compatible with future technologies, such as quantum memory, as they become available. This can be between the LEO node of Stage 1 or the MEO satellite of Stage 2 and an appropriately outfitted spacecraft in LEO or MEO. Here we focus on the LEO-to-LEO option. Allowed orbital configurations are limited by the tracking performance of the gimbaled telescopes. Potentially, these could include spacecraft in the same orbit, where the distance between them is fixed, spacecraft in orbits with opposite sense, in which case each node is in a unique inertial frame, or spacecraft in decidedly different orbital altitudes. Here we consider satellites in the same orbit, which is chosen to correspond to the same “axis” as the line connecting to the two intended ground stations (see Fig. 8).

In Stage 3, we envision that the second satellite is outfitted with a pair of telescopes, and acts as a photon “relay”, receiving the photon from the first satellite and redirecting it to its ground station. Stage 3 thus provides the capability to conduct entanglement swapping between two ground stations through the space-to-space link between the two spacecraft nodes (Figure 8). Adjusting the range between spacecraft provides capability to connect ground stations that are farther apart at the expense of the entanglement swapping rate. For example, if the ground stations are separated by 5000 km (i.e., a trans-Atlantic link), then LEO satellites at 400 km altitude will optimally be separated by ~5100 km; if 1-m (4-m) telescopes are used on the satellites (ground), then over 20 million linkable entangled pairs may be distributed per pass, leading to over 150,000 single entanglement-swap events. This assumed the space link was made using photons at 1550 nm; if instead that link is closed with photons at 800 nm, which are then frequency converted to 1550 nm for the downlink, these rates are increased by about 3 (Johnson *et al.* 2020).

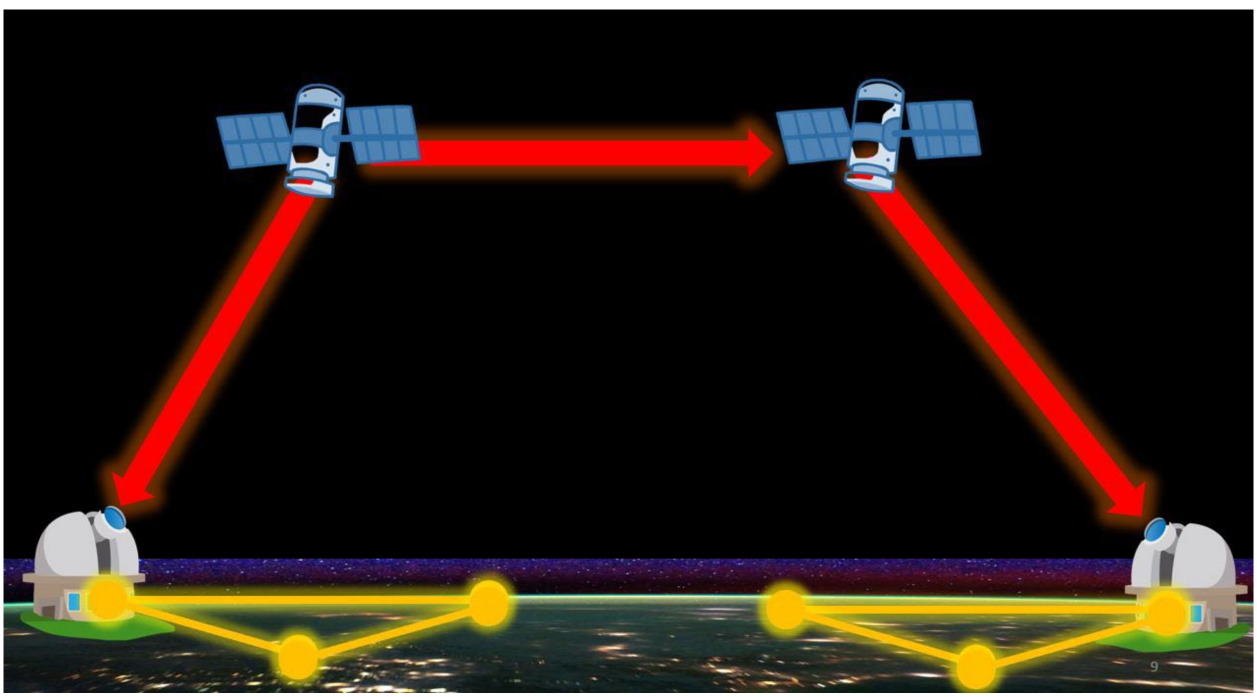


Figure 8. Ground-to-ground entanglement swapping via a space-to-space link in Stage 3. Here, the orbital altitude of the spacecraft would allow connecting quantum networks on nearly opposite sides of the planet. For spacecraft in LEO, ground stations separated by 5000 km can be readily connected.

If the two ground stations are interfaced with terrestrial quantum networks over fiber, then Stage 3 provides the capability to create a network of networks via entanglement swapping between the ground nodes.

The estimated time to implement Stage 3 is T+7 years. This is the same duration as Stage 2, since the development of the ground stations can take place in parallel to the development of the second flight unit.

The qEDISON demonstrations would each involve many intermediate characterization steps:

- All in space**:** verifying rates, verifying entanglement quality (tomography);
- Single downlink: verifying rates, verifying entanglement quality (tomography), Bell inequality test, QKD;
- Single downlink: Bell state analysis with photons in known states (i.e., both photons horizontally polarized, so this becomes just a Hong-Ou-Mandel two-photon interference test);
- Single downlink: Bell state analysis with photons in known states, but with using, e.g., all combinations of H, V, R, and L; this is then a “measurement-device-independent QKD” result (if the error rates are low enough);
- Single downlink: Bell state analysis with entangled photon from satellite, arbitrary photon from ground source; this is effectively a quantum teleportation experiment (the state of the ground photon is measured on the photon that stayed on the satellite);
- Single downlink: Bell state analysis with entangled photons from both sources; this is entanglement swapping;
- Double downlink: repeat all others, with direct detection of one photon and the above sequence on the other one;
- Double downlink: repeat all of the above, now using both ground sources (if the rates allow it).

Table 1 contains a high-level overview of the three stages associated with the qEDISON concept described above. Please note that the column labeled ‘Future’ is a placeholder for future missions that leverage new technologies, such as quantum memory, or apply qEDISON for applications, such as quantum-enhanced clock synchronization.

	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3	Future
Description	Space-to-ground entanglement swapping from LEO	Distribution of hyperentangled states from LEO to ground	Transceiver for second space telescope for space-space comm	Trans-continental or trans-Atlantic entangled pair distribution	Ground-to-ground through a space-space link	Simultaneous two-way quantum comm (clock sync); quantum memory, etc.
Orbit(s)	LEO	LEO	LEO	MEO; LEO	MEO; LEO	MEO; LEO
Telecom Receiver Station(s)	Single ground or (2) within 1,200 km	Single ground or (2) within 1,200 km	ISS; international partner (e.g., SPooQy, QEYSSat, QUBE)	(2) ground; or (1) ground and Stage 1 space node	(2) Ground and (1) space	(2) Ground and (1) space
Telecom Transmit Station	LEO	LEO	International partner (e.g., SPooQy, QEYSSat, QUBE); corner cube on another spacecraft	MEOsSpacecraft	(2) Space MEO/LEO	(2) Space MEO/LEO
Visible Receive Station(s)	None	None	International partner; corner cube on another spacecraft [C1]	None	Space "relay"	Other space quantum network nodes
Visible Transmit Station	None	None	qEDISON; international partner; corner cube on another spacecraft	None	qEDISON	Other space quantum network nodes
Satellite/ Spacecraft	Single (e.g., ISS)	Single (e.g., ISS)	International partner; corner cube on another spacecraft	MEO Spacecraft	MEO spacecraft; optionally Stage 1 spacecraft or international partners	MEO spacecraft; optionally Stage 1 spacecraft or international partners
Entanglement Distance	Single downlink: LEO to ground; double downlink: up to 1200 km baseline	LEO to Ground	100-1000 km	MEO to ground; up to 6000 km baseline for double downlink	MEO to ground; up to 6000 km baseline for double downlink	Various

Table 1. Summary of qEDISON stages.

Tables 2 through 5 summarize key capabilities needed to realize the qEDISON stages. Capabilities are presented in separate tables only to improve readability.

	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3	Future
Local Entanglement Generation and Verification in Space	**X**	**X** (local hyperentangle-ment generation)	**X**	**X**	**X**	**X**
Entanglement Distribution	**X** (1 photon, space-to-ground); 2 photons, space to 2 ground	**X** (1 photon, space to ground)	**X** (1 photon, space-to-space)	**X** (2 photons, space-to-ground, or one to ground, one to space)	**X** (space-ground and space-space-ground)	**X**
Receive Single Entangled Photon in Orbit			**X**	Maybe to Stage 1 space node	**X**	**X**
Bi-directional Transmission of Entangled Photons			Maybe			**X**

Table 2. Capabilities needed to realize qEDISON stages. X was used to indicate that the stage requires the capability.

	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3	Future
Entanglement Swapping	**X**			**X**	**X**	**X**
Hyperentanglement-based Protocols (e.g., super-dense teleportation, remote q processing)		**X**				

Table 3. Continuation of capabilities needed to realize qEDISON stages. X was used to indicate that the stage requires the capability.

	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3	Future
High Rep-Rate Efficient Detector in Flight	**X** For single-downlink (double downlink requires detector only to verify source operation)	**X**	**X**	(double downlink requires detector only to verify source operation)	(double downlink requires detector only to verify source operation)	**X**
Cryogenic Detector in Flight	Maybe (depends on source wavelength choice)	Maybe (depends on source wavelength choice)	Maybe (depends on source wavelength choice)	Maybe (depends on source wavelength choice)	Maybe (depends on source wavelength choice)	Likely
Transmit Visible Wavelength			**X**		**X**	
Variable Baseline Distance	Maybe (within 1200 km)		**X**	**X**	**X**	**X**
Down Link and Space Link			**X**	Maybe to Stage 1 space node	**X**	**X**
Multi-node (>2)	**X**			**X**	**X**	**X**

Table 4. Continuation of capabilities needed to realize qEDISON stages. X was used to indicate that the stage requires the capability.

	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3	Future
Quantum Memory	No dependency but future compatible	No dependency but future compatible	No dependency but future compatible	No dependency but future compatible	No dependency but future compatible	Compatible when available
Orbit-to-orbit Transfer			**X**	Maybe to Stage 1 vehicle	**X**	**X**
Intra-continental Distribution	**X** Double downlink within 1200-km baseline			**X**	**X**	**X**
Inter-continental Distribution				**X**	**X**	**X**
Quantum Data Service (space-space, ground-space, etc.)	**X**	Maybe	Maybe	**X**	**X**	**X**

Table 5. Continuation of capabilities needed to realize qEDISON stages. X was used to indicate that the stage requires the capability.

4.2.4 Advanced Source Architectures

In our design and analysis above, we considered high-rate sources of high-fidelity entangled photon pairs, but assumed these were created probabilistically, e.g., via the process of spontaneous parametric downconversion or four-wave mixing. One substantial drawback of this is the prevalence of unwanted multi-pair events. For any given pulse, the number of photon pairs produced by the crystal is determined through statistics of a thermal distribution: $P(k) = \frac{\mu^k}{(\mu+1)^{k+1}}$, where P($k$) is the probability of producing k photon pairs in a pulse with an average number of pairs per pulse μ. This has a maximum value P(1) = ¼ when μ = 1. Driving with a stronger pump energy results in fewer single-pair pulses, and a high number of double-pair and higher order events; these events are not usable as a quantum communication resource and actually add noise to the communication process. Decreasing μ reduces these unwanted double-pair events, but also results in a sparsity of the desired single photon-pair events, leading to an inefficient poor-quality communication channel. For the satellite source, a probability P(1) between 1-5% is the approximate correct operational range to maintain high rates while having a manageable contribution from emission events with more than one pair.

Of paramount concern to entanglement-swapping with current technology is the emission of multiple photon pairs from entanglement sources on the ground. Specifically, the rate of double-pair events (which can lead to false swapped-entanglement indicators) needs to be less than the rate of received photons from the satellite, *including the link losses they incur*. The most straightforward solution is to attenuate the pump at each ground station, so that the ground sources are driven at considerably smaller pair production probabilities than the satellite sources, severely reducing the rate of single- and double-entanglement swaps. In some cases, photon number resolving (PNR) detectors can identify events where more than one pair of photons is created[4]. This identification in turn can be communicated classically to other network nodes so that any detection events within the flagged time bins will be excluded from subsequent processing; we have assumed this PNR-enhanced method is used in the previous estimations.

Incorporating multiplexing into the ground sources, along with photon-number-resolving techniques, allows one to increase the single-pair emission probability of each source while keeping the double-pair noise suppressed (again at the cost of detecting the non-swapped photons). For example, with 16 multiplexing bins and a trigger efficiency of 95% (the total probability a heralding photon is collected and detected), double entanglement-swap rates of up to 165,000 per pass could be achieved (assuming a MEO satellite with 1-m telescopes transmitting to two ground stations with 4-meter telescopes, separated by 5000 km), an improvement of 100 times over the non-multiplexed case. A 20-fold increase is likewise seen in single entanglement-swap rates, increasing from ~800,000 to over 17 million swaps per pass.

---

[4] This is only true if the total detection efficiency—including any losses—is very high (> 90%), i.e., this does not help if the measurement is made after a lossy channel. Also, in order to make this measurement, one needs to use the source photons that are not part of the Bell state analysis, i.e., the entire process is then necessarily post-selected, and one cannot perform the usual feed-forward corrections on these photons, based on the results of the Bell state analysis.

Note that this multiplexing could be in the form of additional time-bins (though one then needs to ensure that the scheme is compatible with the variable interpulse spacing due to the relative motion of the satellite), additional frequency modes (though one then needs to ensure that the photons still have the requisite purity, i.e., they cannot be spectrally entangled with their partners or the entire Bell state analysis will not work), additional sources (i.e., in different spatial modes, though then one requires an ultra-low loss switch network to map them all onto the one spatial mode that feeds the Bell state analyzer), or perhaps a hybrid of these.

Significant advantages could also be gained through use of upgraded sources on the satellite as well, e.g., incorporating heralded memories or multiplexing to enable increased rates—higher single-pair to multi-pair ratios—but these also require quite low losses to enable significant advantages. For example, assume 10 spectrally multiplexed *deterministic* entanglement sources (performance beyond our previous assumptions), all operating at 10 GHz, where this is now the *actual* rate of pairs, since, by definition, a deterministic source does not need to be driven weakly to prevent multiple-pair events.

These sources could be incorporated into the overall qEDISON architecture by also having identical 10-channel deterministic sources on the ground stations. The system effectively has 10 independent chances to perform entanglement-swapping. The overall rates would be much higher than those listed above, since it is nearly guaranteed that any photon successfully received from the satellite will have a partner on the ground.

Roughly, if the repetition rate is *R* (10 GHz), and the channel transmission is *T*, then the rate of double entanglement swapping is:

$$RR_{ssssssss} = RR\,[1-(1-TT^{2})^{10}]/4$$

where $1-(1-TT^{2})^{10}$ is the likelihood that at least one pair of entangled photons is transmitted to the ground and detected, and 1/4 = $(1/2)^2$ is the double Bell swap success probability. For -15 dB (the approximate link loss from MEO with 1 and 4-m telescopes), this is 2.5 x 10^7/s. Without the multiplexing the rate is approximately 10x less. The principle performance boost derives from the assumption that the sources are deterministic, so that the single-pair generation rate can equal the repetition rate, on both the space and the ground systems. Deterministic low-noise entanglement sources, like quantum memories, are thus a desirable future technology development, though not required for the qEDISON phases described above.

These and other source architecture trades will be conducted in the early phases of the qEDISON mission. Advanced multiplexed or deterministic sources may be introduced to the ground stations during the stages of qEDISON, as they become available. Consider that technology development will be required to lift these to the level where they are advantageous.

4.2.5 Quantum Memories

Our concept does not require quantum memories since they have not yet been demonstrated with sufficient efficiencies or “depth” (how many independent qubits can be stored), but the incorporation of quantum memories at the nodes would greatly improve the overall success rate in an entanglement swapping scenario when there are probabilistic sources of entanglement. Assuming a *heralded* memory for each spectral-temporal channel, the system could automatically determine *which* memory element has been filled with a photon from the satellite, and which element has been filled with a photon from the ground source; at this stage these photons may have arrived in different time bins, or may have different frequencies. The system would then automatically direct those specific photons to the Bell state analyzer (potentially after delaying and/or shifting the frequency of one of them accordingly, to match the other, as required for legitimate Bell state analysis). Such methods have recently enabled 30x synchronization enhancements for Bell state analysis (Kaneda *et al.* 2017) and the first demonstration of quantum communication that beats the direct transmission limit (Bhaskar *et al.* 2020). However, it should be stressed that neither of those experiments had the sort of heralded memories that would be needed for the application discussed here.

If longer-term, large-depth memories become available, another option is to use them to transfer satellite-carried quantum states as the satellite flies over the receiving ground stations (the coherence time of the memory is required to be about equivalent to the satellite transit time from one ground station to another; for a Europe-U.S.A. link, this is approximately 10 minutes). When flight quantum memories reach this level of performance with near unity coupling to the optical modes, this option becomes potentially attractive, as one can then connect very remote ground stations, but couple to each of them from LEO, with its much lower link loss.

Quantum memories may be introduced to future missions after Stages 2 and/or 3. All other technical risks associated with space quantum optical links would have been retired by the close of Stage 3. Depending on the state of quantum memory technologies, demonstration systems could be deployed on ground stations before or during the three stages of qEDISON. Initially, the qEDISON flight terminals can operate with quantum memories located at the ground stations. This configuration would allow testing quantum network architectures that utilize quantum memories. Pathfinder flight quantum memories could subsequently be deployed on the Stage 1 LEO platform if it is on the ISS.

4.2.6 qEDISON Ground Station

We considered qEDISON ground telescopes with 1- and 4-m apertures, and assumed that each photon transmitted from space experiences an additional -7 dB loss, split between source (-2 dB), transmitter telescope (-2 dB), receiver telescope (-1.5 dB), and detection (-1.5 dB). For comparison, in the Deep Space Optical Communications (DSOC) program, the flight terminal is composed of an off-axis parabolic mirror assembly yielding less than 3 dB of net loss. The Optical Communications Test Laboratory (OCTL) ground station operated by JPL has a 1.0-m terminal with less than 1.5 dB of loss. If these efficiencies scale to qEDISON, that leaves 2 dB of design margin to maintain the stated quantum communication rates. Note: This includes effective loss from detector efficiency.

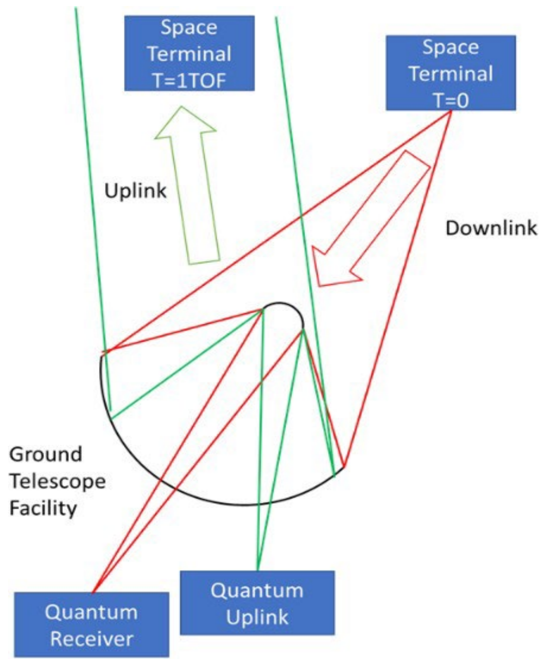


Figure 9. Uplink point-ahead angle diagram.

For the MEO system, the “point-ahead angle” requirements determine the optical configuration. The time of flight between a ground station and a MEO spacecraft overhead at 3800 km altitude is 1 ms; if we assume a sufficient link can be established for elevation angles greater than 20 degrees, the transmission range extends to 6000 km, corresponding to a delay of 20 ms. Within that interval, the MEO spacecraft displacement is 80-120 m. The point-ahead angle in this case is 80 m/3800 km or 21 microradians for the overhead case, up to 32 microradians for the usable portion of the fly-over. The field of view of the ground receiver uplink must be centered upon and track required point-ahead angle. Simultaneously, the ground receiver downlink channel is offset from the uplink angle by the same 21 microradians. Alternative configurations are to use smaller diameter telescopes or to design the telescope to have a wide field of view, at the cost of increasing loss and introducing noise to the receiver system.

Furthermore, the telescope must be able to track both MEO and LEO spacecraft, maintaining pointing accuracy through the duration of the track. Nighttime operation of the telescope is preferred though not required. Adaptive optics will likely be required to couple the telescope to single-mode optical fiber (required to maintain high-fidelity entanglement swapping) and approach the receiver performance limit. This presents greater challenges for the larger diameter telescopes, as shown in Figure 10.

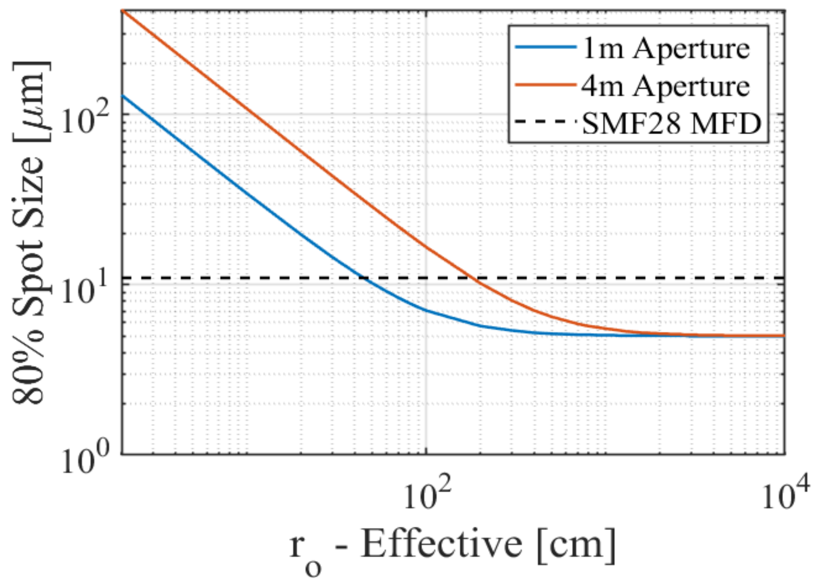


Figure 10. Required atmospheric seeing for efficient coupling to single-mode fiber SMF28. 4.0-m telescope requires effective seeing of 200 cm, while the 1.0-m telescope requires 40-cm effective seeing. Both telescopes are assumed to have the same F# of F/2 (Kopeika 1998).

Atmospheric seeing of 20-80 cm may be achievable with fast tip/tilt/piston control to a high-stroke deformable mirror. Improving the seeing beyond this value would likely require full WFE (Waveform Error) control and potentially necessitate use of a guide star.

Two primary wavelength ranges were identified for qEDISON: between 780-850 nm and the optical C-band (1550–1570 nm). The 780-850 nm band is selected to ensure compatibility with near-term commercial and international space quantum missions, and to allow flight systems to operate non-cryogenically cooled receivers. The C-band is selected for interoperability with fiber telecommunications infrastructure across the planet. Note that even if qEDISON uses, e.g., 800 nm and 1550 nm, the ground-station entanglement sources can produce both photons in the telecom. The only essential constraints are that:

1. One of the photons must match the wavelength/bandwidth/pulse duration of the downlinked photon;

2. The two photons from the source must be spectrally entangled (spatial entanglement would also be detrimental, but is effectively eliminated by the use of single-mode fiber).

3. The ground source must be precisely temporally synchronized with the photons arriving from the satellite. In particular, the Bell-state analysis that underlies teleportation and entanglement swapping requires that the two interfering photons be intrinsically indistinguishable; this means they must essentially arrive at the measurement beam splitter simultaneously to much better than 1 picosecond. (The challenge here is that the sources are in relative motion, so the distance the satellite photon must travel is changing very rapidly as the satellite approaches and flies over.)

The overall performance of the qEDISON ground receiver scales inversely with the dark count rate of the detection system. The high clock rate proposed requires the ground station timing jitter, count rate, and reset time requirements to be compatible with 10-GHz sources[5]. Additional precision timing infrastructure in the ground station may be required to achieve temporal acquisition and synchronization.

The location of the ground stations within the United States depends on the ultimate application. To enable entanglement swapping and networking with fiber-based networks requires locating the ground stations near population centers, national laboratories, and industrial centers. The increased scintillation and atmospheric turbulence inherent with deployment near these areas is a challenge traditional astronomical observatories avoid by going to locations with intrinsically better atmospheric seeing and lower light pollution. Mountaintop and desert observatories could be used for performing proof of concept demonstrations and scientific experiments, but are not perfectly suited to provide the “infrastructure” needed to advance U.S. industry. Investment in new ground stations is likely required.

Although the ground-station entangled photon being “swapped” is envisioned to be in the telecom range, that source still needs to be very close to the receive telescope to enable the required time synchronization. However, the other photon from the source could be transmitted via optical fiber up to about 20 km, at the cost of reducing the overall entanglement swapping success rate[6]. This may give more flexibility in selecting downlink sites.

[5] For single-downlink experiments (Stage 1), the usable repetition rate depends on the limits of the spacecraft detectors; if high-speed APDs (Avalanche Photodiode) are used, the repetition rate may need to be reduced to 2-5 GHz, which would also lessen the requirements at the ground station.

[6] Note that adding loss via this terrestrial fiber will largely eliminate any advantage of using Photon Number Resolving detectors to eliminate unwanted multiple-pair events from the ground sources. Additionally, the extra delay of such a fiber will preclude the incorporation of ground-source multiplexing, since that outer photon must be detected promptly to indicate which of the multiplexed sources actually produced a pair.

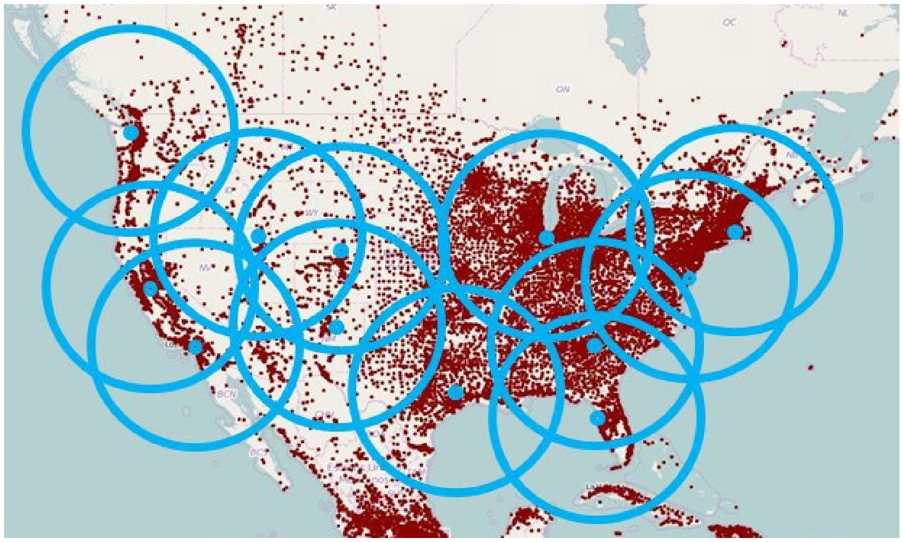


Figure 11: An example of deploying ground stations so that major population centers and federal research centers are connected through qEDISON. The circle radii correspond to roughly 1100 km, less than the reach of both the Stage 1 LEO and Stage 2 MEO satellites; for this ground station separation the Stage 1 performance is considerably higher.

The qEDISON ground station is an excellent location to perform application and network system experiments. As such it would be a natural laboratory where academic, government and private industry researchers could conduct technology assessment and development. It is anticipated that several promising technologies will emerge while the spacecraft is being developed and so it is of the most benefit to keep the rigid aspects of the ground station to a minimum. Large key infrastructure such as the telescope, adaptive optics, synchronization hardware, and the like will need to be specified long in advance and are not the best candidates for experiment. But other portions of the ground system could be experimental. In this concept the synchronization signal and the entangled photon stream could be provided to users, who could then develop the latest in quantum memory, processors, frequency conversion, transduction, and many other technologies as part of an intercontinental quantum communication system.

The ground station laboratories could also connect to local fiber optic quantum networks that have many experimental nodes located in universities or national laboratories. This would allow, e.g., for a quantum network experiment in Ohio to interact with similar experimental networks in California, Arizona, New York, or any other location that has a ground station. As mentioned previously, even the Phase 1 mission concept could distribute entangled photon pairs at high rates to ground stations separated by up to 1200 km, enabling a 5-node quantum network via double entanglement swapping. It is envisioned that this concept would provide a significant boost to the quantum internet research that is currently being funded by the Department of Energy, the National Science Foundation, and others. Since there is so much potential benefit to having this long-distance interconnect for quantum network research, the ground stations will likely need to be located near population centers so that they get the most use. As these locations typically do have higher background light and aerosols, the ground station should have link margin so that it will have the capability for closing the link in non-ideal circumstances. No optical link will work through clouds, but the system should at least be able to handle typical air quality across the continental U.S.

4.3 Relation of qEDISON to Other Concepts

Multiple mission concepts were rigorously evaluated by the authors of this chapter. A comparison of qEDISON with alternative concepts follows in Table 6. Linking quantum optical networks between Europe and the U.S.A., between the U.S.A. and East Asia, and across the 50 states of the U.S.A. requires a MEO entanglement beacon—it cannot be achieved through fiber optics or terrestrial free-space links (in the absence of quantum repeaters). A pair of LEO spacecraft operating a space-to-space crosslink while connecting to distant ground stations would have less efficiency than a single MEO spacecraft with two independent telescopes. Moving the entanglement beacon to HEO or GEO will lower the system efficiency to the point where single and double entanglement swap operations will not be possible when noise is taken into account. Two independent teams (the authors of this chapter and a team lead by Lincoln Labs) determined that a LEO pathfinder reduces overall program risk and provides high-rate quantum communications resources for regional networking applications. Furthermore, the qEDISON concepts show that flight quantum memories are not required to achieve trans-continental entanglement distribution.

Network Type	Projected Operations	Maximum Range Between Ground Stations	Required Technology Development
Quantum Fiber Network	T + 1 year	200 km	None
Quantum Fiber Network++	T + 10 years?	10,000 km	Quantum repeaters
qEDISON – Stage 1 (LEO)	T + 5 years	1200 km	Flight quantum subsystem; ground receivers
qEDISON – Stage 2 (MEO)	T + 7 years	5000 km	Flight quantum subsystem; ground receivers; large aperture flight terminals
qEDISON – Stage 3 (LEO-LEO crosslink)	T + 5 years	5000 km	Flight quantum subsystem; ground receivers
MEO Beacon with Quantum Memory	T + 10+ years	5000+ km	Flight quantum subsystem; ground receivers; large aperture flight terminals; flight quantum memories
HEO/GEO Beacon	T + 7 years	10,000 km	Flight quantum subsystem; ground receivers; large aperture flight terminals; flight quantum memories

Table 6. Comparison of qEDISON to other mission concepts.

For all the mission configurations, the effectiveness of the architecture scales by many of the same general factors. First, the source of entangled photons operates at a clock rate of R with probability of creating an entangled pair of P ($0<P<1$). As an example, consider a mode-locked laser (a pulsed laser) pumping a nonlinear crystal to produce entangled photon pairs through the spontaneous parametric down conversion (SPDC) process. If the efficiency of producing entangled photon pairs per pulse through SPDC is P, the total usable flux of entangled photon pairs is the product R*P. (Recall that P must be kept below 0.01-0.05 to reduce the contribution from unwanted multi-pair events, cf. discussion in Sect. 4.2.4.) The rate of successfully recovering single photons across the quantum communication channel scales with the channel efficiency, while the rate for entangled pair distribution scales with the channel efficiency squared. Generally, the rate of recovered single photons will be P*R*Efficiency. Single-entanglement swapping introduces a second entangled photon source that operates with its own pair production probability. In the simple limit where both entangled photon sources operate at the same rate and same pair production probability, the rate of successful single entanglement swaps would be R*(P^2*Efficiency). However, as stated above, this will lead to an unacceptable level of false Bell-state measurements from double-pair events; to prevent this the ground source probability should be reduced by an extra factor of the link transmission (or somewhat less, if PNR detection is incorporated). Double-entanglement swapping introduces yet another EPS. Assuming symmetric channels between the primary EPS and the two receivers, the rate of successful double-entanglement swaps is lower because a) both transmitted photons need to be received, and b) each ground receiver EPS needs to produce photon pairs at the moment of reception. These efficiencies assume no noise, and usage of PNR detectors.

1) Terrestrial quantum links

Demonstration quantum optical networks connecting nearby nodes through terrestrial fiber channels have been reported across the world. Loss in optical fibers scales exponentially with distance—typically 0.2 dB/km for standard telecommunications grade SMF28e optical fiber. Local networks and municipal quantum networks could use available "dark" fiber (that is, fiber used for classical optical communications that does not include amplifiers or classical repeaters between nodes.) Regional quantum networks representing distances of 200-300 km have been demonstrated through fiber channels [(Tang *et al.* 2014), (Korzh *et al.* 2015)]; the current record distance in fiber is around 420 km, achieved by operating at very high repetition rate and very low success rate (Boaron *et al.* 2018).

Recall the entangled pair flux of R*P. For rate of 10 GHz, which represents the cutting edge of high rate EPS used today, the usable flux is $10*10^9$ pulse/s * 0.01 pair/pulse=100 Mpair/s. Transmission through 800 km of standard SMF28e fiber results in 160 dB of loss, driving the received flux down well below 1 pair/s—even in the limit of perfect detectors and zero noise.

Free-space quantum optical communications are in principle an alternative to fiber across horizontal links where there is line of sight. The maximum range of such a link is determined by the altitudes of the two nodes in the free-space channel, to avoid "clipping" due to the curvature of the Earth. Free-space link efficiency scales as the inverse of range squared. In comparison to the example above, an 800-km range between two diffraction-limited 10-cm telescopes results in a diffractive loss of 37 dB, considerably less than the fiber optical loss across the same distance. However, the need to have elevated sending and receiving telescopes has limited terrestrial free-space links to 144 km (Schmitt-Manderbach 2007).

In the specific case of terrestrial free-space links, there is an additional efficiency driven by blurring caused by atmospheric turbulence. Generally, horizontal links that are low in altitude suffer greatly from turbulence and are limited to 50-100 km ranges. A vertical link would suffer far less from turbulence because most of the turbulence induced blurring is incurred close to the surface of the Earth. A space-to-ground downlink has an extra advantage over a ground-to-space uplink. The former suffers the turbulence only at the end—the last several kilometers—of the photon propagation, and thus may be largely corrected using adaptive optics; the latter acquires a distorted beam at the beginning, leading to largely uncorrectable turbulence-induced losses. The losses inherent in long-range fiber-optic transmission and the limitations of horizontal free-space links are two key motivations for space-based quantum links, in addition to applications such as quantum-enhanced telescopes, which might require entanglement in space (Gottesman, Jennewein, and Croke 2012).

Quantum repeaters and quantum memories have been proposed as a future technology to circumvent the limits of terrestrial quantum networks. However, to the best knowledge of the authors, quantum memories do not yet exist in the state required to support robust quantum optical communications.

2) *Geostationary or HEO quantum beacon*

Another alternative considered by the concepts team is placing the two-telescope entanglement beacon in a high-altitude orbit or even a geostationary orbit. In this case, the total number of quantum communications events that will occur is the product of the rate at which the events occur and the integration time, T. The time T scales with the orbital radius (altitude + Earth radius) to the power of 3/2. Limiting operations to nighttime only has the advantage of greatly reduced background noise levels. This restriction further limits T to be less than the time between dusk and twilight for a given ground station. Recent advances in daytime quantum optical communications could be employed to allow daytime operations in any orbital scenario (Gruneisen 2019); however, if ultra-narrowband spectral filtering is used a means to suppress background, attention must be paid to the effect of the Doppler shift from the moving source. As discussed above, the communication rate scales inversely with powers of altitude squared, depending on the specific type of quantum communication (single photon, single eSwap, or double eSwap).

Optimization of the mission architecture requires optimizing the product of rate and T—the total number of successful quantum communication events that take place in the time interval. The authors of this chapter determined that there exists a unique orbital altitude to optimize the rate-T product for a given separation between ground stations. Trans-continental separations are optimized with orbital altitudes between 2500 and 5000 km, which is where qEDISON Phase 2 is proposed to deploy. In short, any advantage gained by having long integration time and relaxed tracking requirements associated with a HEO or GEO node is defeated by the increased loss associated with these longer-range channels. Specifically, with 1-m transmitting and 4-m receiving telescopes, we estimate only 1 million distributed entangled pairs per hour, likely far too low for any entanglement swapping (in the presence of noise).

3) *qEDISON: Quantum Entanglement Distribution in Space Optical Network*

qEDISON supports the system capability goals established at the Berkeley workshop. Although it is future-compatible with technologies that will greatly enhance performance, e.g., quantum memories, multiplexing, etc., qEDISON only requires technologies that exist today. All its application goals rely on a reliable, space-based entanglement swapping capability, precisely what qEDISON will provide. The staged implementation concept adds performance capabilities in increasingly complex stages. This approach manages technical risk by retiring the principal risks in the early implementation stages before the higher cost Stage 2 and Stage 3 systems are deployed.

The qEDISON concept described here is a modular system. Each module provides a set of capabilities. Adding additional linked modules expands the capabilities of the system. As technology matures, new modules could include quantum memories, quantum transceivers, quantum repeaters, or integrated quantum sensors. In this future scenario, the first qEDISON module continues to serve in the vital entanglement swapping capacity to secure long-range quantum optical links.

qEDISON will support linked quantum sensors (clock networks, arrays of atomic interferometers, and atomic field sensors), distributed quantum computing, cloud quantum computing, secure communications, and very long baseline optical interferometry. It does so by providing a robust, reconfigurable entanglement swapping capability through Earth-space and space-space channels. The underlying system requirements (such as wavelength and bandwidth) needed to achieve those technological application goals will almost certainly change in the future; qEDISON is flexible enough to support evolving requirements in future systems.

qEDISON’s modularity lends itself to integration with other quantum network nodes. This includes quantum communications spacecraft operated by private enterprise, quantum ground stations, and quantum optical links supporting scientific investigations. Linking qEDISON to network nodes deployed by strategic international partners is supported by the modular design. These interface opportunities may have different wavelength and bandwidth requirements than the baseline qEDISON design. The qEDISON baseline design focuses on the two most common wavelengths currently used and proposed for space quantum optical communications—the 810-nm NIR band and the 1550-nm telecom band. Applications requiring different wavelengths can be accommodated through use of quantum optical-to-optical transducers.

The proposed staged approach to implementing qEDISON manages the technical risks of implementing a MEO-based multi-aperture quantum spacecraft in Stage 2. In Stage 1, implementing single-downlink entanglement swapping will test the never-before-demonstrated Bell-state analysis between rapidly moving sources. Connection to multiple ground stations in Stage 1 demonstrates the ability to simultaneously track and distribute a precise synchronization signal to two receivers, realizing a true several-node quantum network. Stage 1a includes the possibility of also transmitting hyperentangled photons at high rates, which, while not necessary for entanglement swapping, enable several other useful quantum protocols, e.g., more efficient secure communication, more efficient quantum error correction (Piparo *et al.* 2020), and blind quantum computing. In Stage 1b, the range and relative velocity between space-based nodes can be controlled to exercise temporal tracking in a highly dynamic system. Operating with other space-based quantum nodes in Stage 1b exercises the pointing, acquisition, and tracking system for both spatial and temporal acquisition. The principal technical risks are retired prior to entering Stage 2, the MEO double-downlink spacecraft.

4) qEDISON options and open trade studies

Operational wavelengths and bandwidths for signal transmission, uplink beacon, and downlink beacon have not been finalized. A design trade would be conducted in the earliest stages of the program—to reuse an existing optical flight terminal or design a new one. Re-using an existing classical laser communications flight terminal predetermines spectral bands allocated to signal, beacon, and uplink. Engineering a new flight terminal ensures optimal support of the quantum optical degrees of freedom required for communications demonstrations with the primary ground systems, international quantum spacecraft, and private industry flight systems that potentially operate at different spectral bands. Re-using an existing flight terminal limits some of those design choices, but reduces overall program cost.

The International Space Station is a potential platform for deploying the Stage 1 flight system. Deployment on the ISS gives access to pressure-controlled environments inside the station and allows “upgrade” modules to be delivered periodically. Deployed aboard the ISS, the qEDISON Stage 1 system could be continuously upgraded to leverage the latest advances in quantum communications technologies, and to serve as a testing ground for advanced subsystems before commitment to future, stand-alone space missions. Deploying the Stage 1 system on a stand-alone LEO spacecraft has the advantages of operating at a precisely determined orbit and experiencing reduced platform dynamics—that will simplify pointing and tracking. Selecting the flight platform for the Stage 1 instrument is another key system trade that will be carried out early in the mission.

As noted above, qEDISON Stage 1 uses either one or two independent flight telescopes. Selecting the ISS as the flight platform allows a scenario where the two telescopes are delivered and installed at different times. This approach spreads required investment more evenly across the early years of system development and is expressed in the qEDISON Stage 1a-1c progression. For a dedicated LEO spacecraft, the 1a-1c progression represents a test plan sequence for a static spacecraft architecture.

qEDISON does not rely on quantum memory technology being ready for either the ground or the space system. With the understanding that source multiplexing and quantum memories will benefit future terrestrial networks as well as future space quantum terminals, qEDISON is designed to be future-compatible with such innovations as they become available. The qEDISON mission concept calls for flight quantum memories as a post Stage 3 mission, after all the other technical risks of implementing a trans-continental quantum entanglement swapping service have been retired.

Future development of quantum memories can simplify the flight system architecture. For example, consider a flight system quantum memory with coherence time equal to the orbital period of the spacecraft, and a number of single optical mode qubits in excess of the integrated flux of received photons for a particular flyby. The system could operate at lower orbital altitudes, efficiently transmitting photons to one ground station, storing their entangled partners in the quantum memory, then efficiently distributing those recalled photon states to a second ground system sometime later. In this scenario, any two ground stations anywhere on the Earth with common view of the spacecraft orbit can close high-rate and high-fidelity usable quantum links. However, a system based on these principles likely requires more than 10-years of focused development.

Space-to-space links are of considerable interest for future infrastructure development and scientific investigation. Depending on the wavelengths used, qEDISON will support space-to-space links with planned international spacecraft, retroreflectors, and future American quantum smallsats as opportunities become available. This will be achieved by placing appropriate requirements upon the space telescope terminals' field of regard.

Further alternative approaches to qEDISON include a) deploying a double-downlink MEO spacecraft without a LEO pathfinder, b) operating a LEO double-downlink spacecraft with onboard quantum memory, c) having a network of LEO spacecraft to provide continuous coverage of an array of ground stations and d) operating a double-downlink entanglement beacon from a geosynchronous equatorial orbit (GEO). Option (a) carries higher risk than qEDISON. In addition, as summarized in Table 1, the LEO node can serve as a "high rate" source to support future, one-way quantum communications channels, as well as a high-rate double-downlink option for ground stations with more modest baseline separations. Option (b) is a reasonable option for future systems where flight quantum memories are available. There are two options: the memory is combined with two onboard multiplexed entanglement sources to approximate a *deterministic* entangled pair source (requiring only a 0.1 – 1 microsecond memory); or the memory is used to transfer satellite-carried quantum states as the satellite flies over the receiving ground stations, requiring a storage time of tens of minutes. Link analysis shows that Option (c) cannot out-perform the MEO double-downlink for any of the applications, though it is a critical step towards a larger quantum network in space, which could enable nearly continuous linking of multiple ground stations. Finally, Option (d) seems less useful compared to the others, given the much higher losses—because the link loss is approximately 100x higher from GEO than MEO, the rate of coincidences is then 10,000 times lower; therefore, more entanglement can be distributed in a single MEO pass than in about 2-weeks accumulated entanglement distribution from GEO.

Capabilities Critical Subsystems and Functions	VLBI	Secure Comms Below RLL	Secure Comms Able RLL	Cloud Quantum Computing	Distributed Quantum Computing	Enhanced Receiver	Clock Network	Atomic Interfere Array	Field Sensor Network	Stage 1	Stage 1a	Stage 1b	Stage 2	Stage 3
Entanglement Swapping	X		X	X	X		X	X	X	X			X	X
Quantum Memory	X		X	X	X		X	X	X	F	F	F	F	F
Photon Detectors	X	X	X	X	X		X	X	X	X	X	X	X	X
High Res Clock/Sync	X	X	X	X	X		X	X	X	X				
Doppler Correction	X		X	X	X					X	X			
Single-photon Frequency Conversion	X		X	X	X		X	X	X					
Stabilize Polarization Diversity	X	X	X	X	X		X	X	X	X				
Quantum Non-demolition Measurement	X		X	X	X					F		F	F	F
Feed-forward Operation on Teleported Qbit	X		X	X	X		X	X	X	X	X	X	X	X
Decoy State		X												
Quantum Repeater				X						F	F	F	F	F
Quantum Transducer				X	X		X	X	X					
Quantum Error Correction				X	X		X	X	X					
Classical Time Transfer							X	X	X					
Atom Interferometer								X						
Field Sensors									X					

Table 7. Critical subsystems and functions identified in the Goals chapter (see Chapter 3) supported by each stage of qEDISON. "F" indicates that the qEDISON stage is future compatible with the technology with the inclusion of additional linked modules.

The proposed qEDISON mission concept will provide trans-Atlantic and intercontinental quantum entanglement distribution within 5-7 years.

4.3.1 Why We Do Not Highlight QKD

Quantum Key Distribution (QKD) is included here as a test—but not a long-term goal—of the system. The reason for including it as a test is that being able to generate a secure key is a necessary (but not sufficient) condition on the operational capabilities of the system, e.g., if the fidelity of the polarization entanglement is too low for secure QKD, it will also be insufficient for useful entanglement swapping. Similar arguments apply for carrying out tests of nonlocality; the ability to pass such tests is a necessary constraint on the sources.

Quantum Key Distribution is not considered a goal per se of the concept for several reasons:

- This decision is consistent with the National Strategic Overview for Quantum Information Science (September 2018);
- Various U.S. agencies have expressed disinterest in using QKD for secure communications—describing vulnerabilities that keep it from being used in practice—and have called for a broader view of what "quantum cryptography" should mean (Mailloux *et al.* 2016).
- QKD does not provide a means for public key encryption, and thus cannot replace the standard public key encryption protocols (e.g., Rivest-Shamir-Adleman (RSA), elliptic curve) that are broken by Shor's algorithms (his original paper included two algorithms, one for factoring—which breaks RSA—the other for the discrete-log problem—which breaks elliptic curve cryptography). Currently the leading candidates for "post-quantum" cryptography are based on learning with errors (LWE) or lattice problems that appear to be computationally challenging for both classical and quantum computing approaches.[7] "Post-quantum" public key methods are implementable in software without the need for new hardware, and are compatible with the existing software architecture, though they likely will require larger key sizes. Public key encryption enables the establishment of secure links between two parties that have never interacted before, which is why it is heavily used in internet commerce. The primary use of public key encryption is to enable the establishment of a shared key where there was no shared key before. That property is not possible with QKD, since it requires a small amount of key for authentication, as is true for symmetric key encryption in general. For this reason, some people suggest that QKD should really be have been named a "quantum key expansion (QKE)" protocol.[8]
- Experts are unconvinced of the practical security of current QKD implementations, given existing vulnerabilities and loopholes, and the existence of side-channel attacks. (As an example of a side-channel attack, the physicists describing the first QKD experiment joked that it was "unconditionally

[7] Although current proposals for "post-quantum" encryption may be demonstrated to be secure against the currently known quantum computing protocols, it is not proven—and many not be provable—that they are secure against any possible quantum or classical algorithm. For this reason, well before deployment cryptographic systems should be made public, with strong incentives for people to try break them, including contests with specified instances.

[8] Public key encryption does not require **any** prior interaction between the parties, let alone any shared randomness or shared secret. A public certification authority is needed to tie a person or company's public key to the correct identity, but that also ties the public. Further, the certification authority does not know the private key, so does not have access to information encrypted under it. A given entity only needs one public key, certified once, which can then be used many times. QKD, or classical analogs such a Diffie-Hellman, are inherently point-to-point, so simply do not provide this capability; they must have some prior shared randomness for authentication (or make use of public key encryption). If the efforts to establish secure post-quantum public key encryption fails, the infrastructure for secure transactions would need to be completely reworked and a much clunkier system would need to be put in place. Such clunky system, without public key encryption, is possible to construct, e.g. Merkle trees, and has been known for some time, but any such system loses many attractive properties, and QKD does not help keep these nice properties. For example, these systems need a higher level of trust for a third-party authenticator in place of the certification authority, and are not point-to-point so require different keys for every pair of entities instead of one per entity, have limited key reuse, etc.

secure against any eavesdropper who happened to be deaf," as recounted in [Brassard 2006].) Some of the side-channel attacks are mitigated by using entanglement-based QKD, where any side-information leakage carried by the photons will automatically be revealed by an increased error rate. Many of the reported "hacks" on QKD systems have exploited assumptions about the detectors. While more recent "device-independent" protocols avoid some of these loopholes others still exist, and the technologies needed to implement such protocols (i.e., sending photons from two independent ground stations to a satellite for Bell-state analysis) are not compatible with the proposed concept and are likely to be much more difficult to synchronize.

- If secure communications using QKD were a goal, there are implementation methods, e.g., using attenuated laser pulses and "decoy states", which are much easier, and would have higher rates. However, these other methods are not compatible with systems that enable entanglement-swapping, i.e., they do support the longer list of capabilities enabled by a true quantum network.

4.3.2 Limitations on Quantum Mechanics

There are two popular misconceptions about quantum communications that we wish to highlight. 1) It does not allow faster than light communication, and 2) quantum teleportation cannot be used as a means of transportation. Both of these claims are physically false in that they are incompatible with quantum mechanics. A third less prominent misconception is based on the "Holevo bound", which constrains how much information can be carried by a quantum system. While it is a mathematical fact that quantum communications channels can sustain twice the information capacity of a classical channel, one must always consider the resource implementation costs at a system level.

Limits on the capacity of quantum channels. The capacity limits of a quantum optical communication channel are expressed in the Holevo bound (Holevo 1973). In comparison to the capacity of classical optical communications over the same channel (Shannon 1948), Holevo predicted that the quantum optical channel would have twice the capacity. The mathematics predicts quantum optical communications would have double the information capacity as classical optical communications. However, as the noise level and loss level in the channel increases, the advantage of quantum communications diminishes rapidly, due to the requirement of sending single quantum states. For example, the data-rate transmitted through a classical channel can be increased by a factor of two by increasing the transmitter power by a factor of two, increasing the transmitter antenna by a factor of 1.44, lowering the receiver noise temperature, or improving beam formation. Put differently, one can readily overcome a 99% channel loss by sending a classical pulse that has around 500 photons, all with the same encoding; as long as any of them are successfully transmitted, one can recover the original message. In contrast, each quantum state needs to be encoded in its own photon. The complexity of implementing a quantum optical communications system must therefore be evaluated against the well-understood techniques used to improve classical channel efficiency. That is, the full system resource cost (in size, weight, power, and budget) needs to be weighed against the mathematical channel capacity. An evaluation of system resource usage must be applied to weigh the benefits of a quantum optical communications system against the costs. The factor of two alone is insufficient justification to deploy quantum optical communications systems—there are other, lower-cost means to achieve the same system level advantage.

Quantum Teleportation transfers quantum information not physical objects. Quantum teleportation refers to the noiseless transfer of the quantum mechanical wavefunction of one particle to another. Quantum teleportation does not represent teleportation of an object from one place to another. The reason for the name “teleportation” is that when a quantum state is teleported it is necessarily destroyed on the sending end before being it can be reconstructed on the receiving end. The qEDISON concept effectively will enable teleportation of quantum states, e.g., from systems in Europe to systems in America.

Communication is limited by the speed of light. The speed of light sets the ultimate limit for how fast information propagates through the universe. This is as true for quantum optical communications as it is for microwave communications. The wavefunction collapse of an entangled photon pair is apparently instantaneous, but for this process to manifest information requires sharing measurement results through classical communications channels. For example, violation of Bell’s inequalities, the signature of entanglement, can only be detected if the measurement results are communicated from one end of the experiment to another, which is limited by the speed of light. In quantum teleportation, the state on the receiving end can only be reconstructed once a classical signal, carrying measurement results from the sending end, has been received. Quantum mechanics obeys the general principle of “no faster than light signaling”.

4.4 References

Barreiro, Julio T., Nathan K Langford, Nicholas A. Peters, Paul G. Kwiat. 2005. “Generation of Hyperentangled Photon Pairs.” *Phys. Rev. Lett.*, Vol. 95, Issue 26: 260501-260506, DOI: https://doi.org/10.1103/PhysRevLett.95.260501.

Barz, Stefanie, Elham Kashefi, Anne Broadbent, Joseph F. Fitzsimons, Anton Zeilinger, Philip Walther. 2012. “Demonstration of Blind Quantum Computing.” *Science,* 20, Vol. 335, Issue 6066: 303-308, DOI: https://doi.org/10.1126/science.1214707.

Bennett, C. H. and G. Brassard. 1984. “Quantum cryptography: Public key distribution and coin tossing.” *Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing*, New York, Vol. 175: 8.

Bhaskar, M.K., R. Riedinger, B. Machielse, D.S. Levonian, C.T. Nguyen, E.N. Knall, H. Park, D. Englund, M. Lončar, D.D. Sukachev, and M.D. Lukin. 2020. “Experimental demonstration of memory-enhanced quantum communication.” *Nature*, Volume 580: 60–64, https://www.nature.com/articles/nphys3000.

Boaron, Alberto, Gianluca Boso, Davide Rusca, Cédric Vulliez, Claire Autebert, Misael Caloz, Matthieu Perrenoud, Gaëtan Gras, Félix Bussières, Ming-Jun Li, Daniel Nolan, Anthony Martin, and Hugo Zbinden. 2018. “Secure Quantum Key Distribution over 421 km of Optical Fiber.” *Phys. Rev. Lett.*, 121, 190502, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.190502.

Boone, K., J.-P. Bourgoin, E. Meyer-Scott, K. Heshami, T. Jennewein, and C. Simon. 2015. “Entanglement over global distances via quantum repeaters with satellite links.” *Physical Review A*, 91, 052325.

Brassard, G. 2006. “Brief History of Quantum Cryptography: A Personal Perspective.” *Proceedings of IEEE Information Theory Workshop on Theory and Practice in Information Theoretic Security,* Awaji Island, Japan: 19-23, arXiv:quant-ph/0604072.

Broadbent, Anne, Joseph Fitzsimons, and Elham Kashefi. 2009. “Universal Blind Quantum Computation.” *50th Annual IEEE Symposium on Foundations of Computer Science*: 517-26.

Broadbent, Anne and Alain Tapp. 2008. “Can Quantum Mechanics Help Distributed Computing?” *SIGACT News*, Vol. 39, No. 3: 67-76, DOI: https://doi.org/10.1145/1412700.1412717.

Buhrman, Harry and Hein Rohrig. 2003. “Distributed Quantum Computing.” *Mathematical Foundations of Computer Science*, Lecture Notes in Computer Science, Vol. 2747 DOI: https://doi.org/10.1007/978-3-540-45138-9_1.

Calsamiglia, J and N. Lutkenhaus. 2001. “Maximum efficiency of a linear-optical Bell-state analyzer,” *Appl. Phys. B: Lasers Opt.*, 72: 67-71.

Cerf, N. J., M. Bourennane, A. Karlsson, and N. Gisin. 2002. “Security of quantum key distribution using d-level system.” *Phys. Rev. Lett. 88*, 127902.

Chapman, J., T. Graham, C. Zeitler, and P.G. Kwiat. 2020. “Time-bin and polarization superdense teleportation for space applications>” *Phys. Rev. Applied*, to appear, arXiv: 1901.07181.

Cuomo, Daniele, Marcello Caleffi, and Angela Sara Cacciapuoti. 2020 “Towards a distributed quantum computing system.” *IET Quantum Communication*, Vol. 1, Issue 1: 3-8, https://digital-library.theiet.org/content/journals/10.1049/iet-qtc.2020.0002.

Degen, C. L., F. Reinhard and P. Cappellaro, 2017. “Quantum sensing.*” Reviews of Modern Physics 89*, 035002.

Fitzsimons, Joseph F. 2017. “Private Quantum Computation: An Introduction to Blind Quantum Computing and Related Protocols” *Npj Quantum Information*, DOI: https://doi.org/10.1038/s41534-017-0025-3.

Gottesman, Daniel, Thomas Jennewein, and Sarah Croke. 2012. “Longer-Baseline Telescopes Using Quantum Repeaters.” *Phys. Rev. Lett.* 109, 070503, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.109.070503.

Graham, T.M., H.J. Bernstein, T.-C. Wei, M. Junge, and P.G. Kwiat. 2015. “Superdense teleportation using hyperentangled photons.” *Nat. Comm. 6*, 7185.

Gruneisen, Mark T., Mark L. Eickhoff, Scott C. Newey, Kurt E. Stoltenberg, Jeffery F. Morris, Michael Bareian, Mark A. Harris, Denis W. Oesch, Michael D. Oliker,3 Michael B. Flanagan, Brian T. Kay, Jonathan D. Schiller, and R. Nicholas Lanning. 2019 “Adaptive-optics-enabled daytime field experiment for satellite-Earth quantum networking.” https://arxiv.org/abs/2006.07745.

Holevo, A.S. 1973. “Bounds for the Quantity of Information Transmitted by a Quantum Communication Channel.” *Probl. Peredachi Inf*., 9:3, 3-11*; Problems Inform. Transmission*, 9:3, 177-183.

Imany, Poolad, Jose A. Jaramillo-Villegas, Mohammed S. Alshaykh, Joseph M. Lukens, Ogaga D. Odele, Alexandria J. Moore, Daniel E. Leaird, Minghao Qi, and Andrew M. Weiner. 2019. “High-dimensional optical quantum logic in large operational spaces.” *npj Quantum Info 5*, 59, DOI: https://doi.org/10.1038/s41534-019-0173-8.

Johnson, Spencer J. *et al*. 2020. “Link Analysis and Optimization for Space-enabled Multi-Node Quantum Networks.” (manuscript in preparation).

Kaneda, F., F. Xu, J.C. Chapman, and P.G. Kwiat. 2017. “Quantum-memory-assisted multi-photon generation for efficient quantum information processing.” *Optica 4*:1034-1037, DOI: https://doi.org/10.1364/OPTICA.4.001034.

Khabiboulline, Emil T, Johannes Borregaard, Kristiaan De Greve, and Mikhail D Lukin. 2019. *PRA* 100(2).

Kómár, P., E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye, and M. D. Lukin. 2014. "A quantum network of clocks." *Nature Physics.* Volume 10: 582–587, https://www.nature.com/articles/nphys3000.

Kopeika, Norman S. 1998. "Blur in imaging through the atmosphere: a system engineering approach to imaging." *Proc. SPIE 3433, Propagation and Imaging through the Atmosphere II*, DOI: https://doi.org/10.1117/12.330240.

Korzh, Boris, Charles Lim, Raphael Houlmann, Nicolas Gisin, Ming Jun Li, Daniel Nolan, Bruno Sanguinetti, Rob Thew, and Hugo Zbinden. 2015. "Provably secure and practical quantum key distribution over 307 km of optical fibre." *Nature Photonics,* Vol. 9: 163-16, DOI: https://doi.org/10.1038/nphoton.2014.327.

Kwiat, Paul G. 1997. "Hyper-entangled states." *Journal of Modern Optics,* Vol. 44, Issue 11-12: 2173-2184, DOI: https://doi.org/10.1080/09500349708231877.

Mailloux, L. *et al*. 2016. "Quantum Key Distribution: Boon or Bust?." *Journal of The Cyber Security Information Analysis Center*.

Piparo, Nicolò Lo, Michael Hanks, Claude Gravel, Kae Nemoto, and William J. Munro. 2020. "Resource Reduction for Distributed Quantum Information Processing Using Quantum Multiplexed Photons." *Phys. Rev. Lett.* 124, 210503, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.210503.

Ren, J., P. Xu, H. Yong, *et al*. 2017. "Ground-to-satellite quantum teleportation." *Nature*, 549: 70-73, DOI: https://doi.org/10.1038/nature23675.

Scarani, Valeri, Helle Bechmann-Pasquinucci, Nicolas J. Cerf, Miloslav Dusek, Norbert Lutkenhaus, Momtchil Peev. 2009. "The security of practical quantum key distribution," *Rev. Mode. Phys*. 81 (3): 1301-1350, DOI: https://doi.org/10.1103/RevModPhys.81.1301.

Schmitt-Manderbach, Tobias, Henning Weier, Martin Fürst, Rupert Ursin, Felix Tiefenbacher, Thomas Scheidl, Josep Perdigues, Zoran Sodnik, Christian Kurtsiefer, John G. Rarity, Anton Zeilinger, and Harald Weinfurter. 2007. "Experimental Demonstration of Free-Space Decoy-State Quantum Key Distribution over 144 km." *Phys. Rev. Lett.* 98, 010504, DOI: https://doi.org/10.1103/PhysRevLett.98.010504.

Shannon, Claude E. 1948. "A Mathematical Theory of Communication." *The Bell System Technical Journal*, Vol. 27, 634-656: 379-423.

Simon, David S. and Alexander V. Sergienko. 2014. "High-capacity quantum key distribution via hyperentangled degrees of freedom." *New Journal of Physics*, Vol. 16, No. 6, DOI: https://doi.org/10.1088/1367-2630/16/6/063052.

Tang, Y.-L. *et al*. 2014. "Measurement-device-independent quantum key distribution over 200 km." *Phys. Rev. Lett. 113*, 190501.

Vaidman, L and N. Yorna. 1999. “Methods for reliable teleportation.” *Phys. Rev. A*, 59, 116.

Van Meter, Rodney and Simon J. Devitt. 2016. “The Path to Scalable Distributed Quantum Computing.” *Computer*, Vol. 49, Issue 9: 31-42, DOI: https://doi.org/10.1109/mc.2016.291.

Wang, Chuan, Li Xiao, Wan-ying Wang, Guang-yu Zhang, Gui Lu Long. 2009. “Quantum key distribution using polarization and frequency hyperentangled photons.” *Journal of the Optical Society of America B*, Vol. 26, Issue 11: 2072-2076, DOI: https://doi.org/10.1364/JOSAB.26.002072.

Yin, Juan, Yu-Huai Li, Sheng-Kai Liao, Meng Yang, Yuan Cao, Liang Zhang, Ji-Gang Ren, *et al.* 2020. “Entanglement-based secure quantum cryptography over 1,120 kilometres.” *Nature*, Volume 582: 501–505, https://www.nature.com/articles/s41586-020-2401-y.

Zhuang, Quntao, John Preskill, and Liang Jiang. 2020. “Distributed quantum sensing enhanced by continuous-variable error correction.” *New Journal of Physics*, Vol. 22.

5.0 Mission Technology

Authors: La Vida Cooper (NASA GSFC); Dan M. Boronson (MIT-LL), P. Ben Dixon (MIT-LL), Lee Feinberg (NASA GSFC), Matthew E. Grein (MIT-LL), Scott A. Hamilton (MIT-LL), Nicholas D. Hardy (MIT-LL), Paul Kwiat (University of Illinois), Catherine Lee (MIT-LL), Babak Saif (NASA GSFC), Harry Shaw (NASA GSFC), Matthew D. Shaw (JPL/Caltech), Neal W. Spellmeyer (MIT-LL)

5.1 Introduction

Quantum communication applications can be categorized in order of increasing difficulty as: systems that distribute and measure weak pulses (these are non-classical states in that they contain on average less than one photon per pulse), systems that distribute and measure entangled states, and systems that are enabled by connecting two non-classical systems. The development of entanglement-based quantum networks promises substantial benefit to quantum-enabled applications including distributed quantum sensing, improved timing/synchronization, multi-processor quantum computing over short-range interconnects, and distributed computing or secure communication over long-haul links. Photonic-based systems are the primary technology for realizing quantum networks due to the relative ease of photon transport while maintaining the quantum state. Significant development is required, however, to realize entanglement distribution rates commensurate with quantum network application requirements.

Distributing and measuring weak pulses enables BB84 type quantum key distribution (QKD) (Bennett and Brassard 1984) between a transmitter and a receiver. These systems are well understood and there are several commercial systems available, e.g. ID Quantique (Switzerland), QuantumCTek (China), Toshiba (Japan) and Qubitekk (US). These systems consist of a transmitter sending weak pulses of light prepared in one of several states (4 polarization states, for example), a receiver that can partly resolve the several states used (at the single photon level), and processing components to communicate classically between the receiver and transmitter and to synchronize and analyze the preparation and measurement results. Transmitters, receivers, and processors of this type have been implemented in space-based systems, demonstrating that architectures from space to ground, from ground to space, or between space platforms are possible. Multiple satellite-based QKD experiments have been conducted recently, including China's QUESS program which included successful QKD downlinks from their Micius satellite (Liao *et al.* 2017) to Chinese and Austrian ground terminals and Japan's SOTA lasercom terminal which was used to characterize polarization propagation from LEO to ground (as a precursor for QKD) for two different lasers on-board their SOCRATES satellite (Carrasco-Casado *et al.* 2013). The European Space Agency also used their Alphasat satellite to demonstrate detection of an attenuated coherent waveform produced by their Tesat lasercom terminal as a feasibility demonstration precursor for future continuous variable QKD utility (Günthner *et al.* 2017). A disadvantage to the BB84-style space-based QKD downlink is that the satellite itself must be a trusted component in the key exchange process, and any side channel from the satellite (e.g. if the details of which state is prepared is accidentally included in telemetry data) potentially puts key information at risk.

Distributing and measuring entangled states from a satellite enables Ekert-type quantum key distribution (Ekert 1991). An advantage of this approach is that the required cryptographic trust requirements for the satellite transmitter is reduced compared to BB84-type quantum key distribution because the transmitter does not know the cryptographic key. These systems consist of a transmitter that generates and independently transmits two entangled photons, two receivers that resolve the state at the single-photon level, and processing components to communicate classically between the receivers and to synchronize and analyze the measurement results. Multiple satellite-demonstrations of entanglement distribution have been accomplished recently including China's QUESS program and Micius satellite, which successfully demonstrated transmission of entangled photon pairs (where entanglement was deduced via post-processing detector counts) to two different ground terminals separated by approximately 1200 km (Yin *et al.* 2017) and Singapore's successful demonstration of entanglement source deployment and operation in space (Durak *et al.* 2016). Micius also went a step further and achieved a preliminary feasibility demonstration of low-rate space-to-ground entanglement-based QKD (J. Yin *et al.* 2017) for use in future space-based architectures.

QKD is the most accessible quantum communications application since it is relatively straightforward to characterize and can be implemented using widely available optical technologies. China, the European Union, Japan, and South Korea have made substantial investments in developing QKD systems and China is the first to adopt this technology for encrypting national systems. The United States, on the other hand, has not adopted QKD for a nationally-certified cryptographic system. Instead, the United States has focused on developing (with plans to deploy by 2030) post-quantum cryptographic algorithms that are invulnerable by design to a quantum computer running Shor's algorithm. Rationale provided by the United Kingdom's Communications-Electronics Security Group (CSEG) identifies multiple concerns with QKD as a nationally-certified cryptographic system including (also see arguments in Chapter 4):

1. QKD does not fully address the security architecture (e.g. authentication and scalability to large networks);
2. Commercial QKD systems have a number of practical limitations (e.g. short range and point-to-point protocols);
3. QKD systems are unlikely to be cost effective (e.g. costly operations and maintenance and device-independent QKD not yet viable);
4. As-implemented, QKD systems may not provide information-theoretic security (e.g. device imperfections and denial-of-service attacks).

Global industry, including in the United States, is putting significant effort into developing QKD systems today. What is far less mature, from a technological and application perspective, are entanglement-based quantum networks. This chapter focuses on entanglement-based quantum network space demonstration opportunities since support by the United States Government is required to realize this revolutionary quantum communications capability.

Connecting two non-classical systems is the most challenging quantum communication system and, in the long run, will provide the most utility. This type of system enables multi-node and quantum-repeater based quantum networks, increased sensor resolution (e.g. long baseline interferometry), teleportation-based quantum computer interconnects, and measurement device independent QKD (e.g. long-haul, multi-node QKD where intermediate nodes do not hold cryptographic key information). This type of system requires: sources of entanglement designed for optimum linking between the sources, a multi-particle Bell state measurement device that performs the connecting operation between the sources consisting of linear optical elements and single photon detectors, and processing components to communicate classically between systems and to analyze the Bell state measurement results. Neither sources optimized for multi-system Bell state measurements, nor Bell state measurement systems themselves have been demonstrated in space. Moreover, the synchronization of multiple sources across a space link has not been demonstrated. While China's Micius demonstrated teleportation (Ren *et al.* 2017), the two entanglement sources were co-located at a ground station and the teleported state was transmitted from the ground terminal to the satellite-based receiver. While this demonstration proved that quantum theoretical properties can be sent long distances through the atmospheric channel, all entangled photons were destroyed in tomography steps and the same quantum state was required to be "teleported" many thousands of times for each single, random reception at the spacecraft.

5.1.1 High-level NASA Role and Associated Goals

NASA endeavors to be a provider of networked entanglement resources to connect continents for space-to-space and space-to ground applications. NASA also has a goal of enabling national needs for the quantum internet and Other Government Agencies/ Departments as appropriate in support of the National Quantum Initiative and the expanding landscape of new user applications. The Agency strives to facilitate a customer interface into the space-based provided entanglement resources at GHz clock speeds unifying operational properties, achieving high-repetition rates (GHz), and devising quantum memory buffers and detectors to compensate for cascading operation losses, and the Agency will work to collaboratively address the tall poles in the critical path of providing this infrastructure and service.

5.1.2 Applications

Quantum networks enable new and more powerful applications with performance above that which could be obtained classically [(Kimble 2008), (Wehner, Elkhous, and Hanson 2018)]. Entanglement is the resource underlying the performance advantages of quantum networks: it is required for the teleportation of arbitrary quantum states (Bennett *et al*. 1993), such as the inputs or outputs of a quantum computation, and it also provides stronger-than-classical correlations between remote elements, such as distributed networks of quantum processors (Monroe *et al.* 2014), clocks (Komar *et al*. 2014), or sensors [(Knott *et al.* 2016), (Eldredge *et al.* 2018), (Cartledge 2019)]. To achieve these goals, the system architecture must provide a straightforward path for integrating new quantum communication technology, e.g. quantum repeaters, and new quantum-enabled applications/protocols. Providing entanglement resources from space is NASA's role in the emerging quantum network.

5.1.3 Key Attributes of Reference Mission Concepts for Technology Development

Many possible mission concepts can be created within the context of creating a space-based quantum communications and networking capability. Technology "Tall Poles" for enabling this capability are discussed here.

5.1.4 Technology Tall Poles for the Future Quantum GHz Internet

This chapter has identified the following technology gap tall poles that are required to meet the White House Office of Science and Technology Policy-mandated goals for a future GHz Quantum Internet. Table 1 contains the tall poles. These tall poles are early insights derived from a NASA SCaN-funded preliminary phased mission architecture study. Selected tall poles with sufficient source material are addressed in more detail in the text to the extent source material from the workshop exists.

During and following the workshop, participants and contributors engaged in robust discussion, analysis and assessment of key topics addressed in the technology chapter. Due to the novelty and nascent nature of many aspects of quantum networking, a variety of sub-discipline areas require additional research and development.

Technology	GHz Internet Need		Quantitative/Qualitative Requirements (if known)	
	Short- term need (1 –3 years)	Long-term need (4+ years)	Short-term	Long-term
Quantum Communications Link Budget Tool	YES	YES	One tool for all users or one agreed-upon set of algorithms and source data for preparing link budgets	Higher fidelity tools, algorithms, and source data
Quantum Entanglement Modem (flight and ground)	YES	YES	Characteristics depend upon modem architecture and capabilities	TBD
High-rate Entanglement Source	YES	YES	>10 GHz; 5 – 20% generation rate; CHSH (Clauser–Horne–Shimony–Holt) inequality>2 to 2.8	>100 GHz
Space Single-photon Receiver	YES	YES	TBD	TBD
Detector Arrays	YES	YES	SNSPDs>90% quantum efficiency; jitter<50 ps; dark count rate<1 kHz; compact, low-power readout electronics for SNSPDs; flight qualification of SNSPDs and demonstrated integration with flight cryogenic systems	SNSPD arrays with a maximum count rate of 100 Gcps or higher, and timing jitter below 1 ps; SNSPDs with operating temperature of 25 K or higher
Space Detector Cryocooler	YES	YES		Compact, low-power flight cryocoolers optimized specifically for the cryogenic requirements of SNSPD
Quantum Memory	NO	YES	1-20 ms storage time; buffer depth>10^3	TBD
Spontaneous Photon Down-conversion Memory Interface	NO	YES	SPDC ~ THz bandwidth; quantum memory ~10 MHz bandwidth; spectral buffer storage ~10^5	TBD
Quantum Error Correction Capability	NO	YES	~1e-5 BER	~1e-9 BER
Large-aperture Space Terminal	YES	YES	10 cm	25-30 cm

Table 1. Technology tall poles for future quantum GHz internet.

5.2 Key Capabilities and Technologies

The following paragraphs should be considered in light of the Other Topics for Further Consideration and Exploration in Section 5.3. These points require study and assessment.

5.2.1 Space Terminal Optical Module

Multiple considerations drive the design of lasercom terminal technology. For space quantum network demonstrations considered here, the space terminal must survive the launch and space environment, provide precision tracking of the ground terminal for the duration of an orbital pass, generate quantum/classical signal photons, and efficiently deliver them to the ground terminal.

NASA can choose from:

1. Heritage space terminal optical modules such as the Mobile, Agile, Scalable Optical Terminal (MAScOT) used on NASA's Laser Communications Relay Demonstration (LCRD);
2. Space-based optical telescopes under development for astronomy with their modifications for optical and quantum communications;
3. Other yet-to-be-identified space optical terminals.

5.2.2 Ground Terminals

The ground terminal must provide a collection aperture large enough to efficiently collect precious quantum signal photons, enable good atmospheric seeing, provide optical connectivity from the telescope to research laboratory space (connectivity to deployed optical fiber is also desirable), be capable of tracking a fast-moving LEO spacecraft, and efficiently receive very low-flux quantum signal photons in the presence of background noise photons and higher-flux classical lasercom signal photons.

For an optical signal propagating through the Earth's atmosphere, light collected at a receiver is impacted by multiple physical effects, including slowly-varying loss due to absorption or scattering and fast-varying intensity fluctuations due to atmospheric turbulence. This latter effect is caused by heterogeneity in the temperature and pressure of the atmosphere that lead to variations of the refractive index along the transmission path. These fluctuations produce optical path differences over the beam cross-section that can be a significant fraction of an optical wavelength. The resulting phase aberrations refract to become intensity fluctuations, known as scintillation, in the far field (Andrews and Phillips 2005). A point receiver in the far field will see time-varying irradiance that can vary as surges of several dB and fades of several tens of dB (Walther *et al.* 2010). If fading mitigation technology is not included in the design of the terminal, scintillation on the received signal has been experimentally observed to result in failure of the tracking loop and/or communication link (Lange *et al.* 2006). To minimize optical loss due to the atmospheric channel, quantum space and ground terminals discussed here will employ active tracking beam control via a fast-steering mirror to compensate beam tilt (Loney 1991), and adaptive optics at the ground terminal to compensate higher-order turbulence-induced aberrations (Lavigne *et al.* 1998).

The influence of background noise must be carefully managed in a free-space quantum communications entanglement-swap system since bosonic quantum information transfer is achieved on a per-received single-photon basis. High-sensitivity single-photon receivers are an attractive option, but due to appreciable detector (or array) size, the optical system must be carefully designed. Solar photons (during daytime operation), Lunar photons (during nighttime operation), and non-signal classical photons (e.g. PAT beacon or classical lasercom) can all result in in-band and adjacent-band photons that can degrade reception of a quantum signal in a free-space system. Using the formalism described in (Boroson 2018), the noise photon flux and its impact on the performance of a photon-counting receiver can be quantified. To minimize the impact of background photons in a space or ground photon-counting receiver, the system will utilize: high-flux entanglement sources to maximize the quantum signal flux, large receiver telescope apertures and careful management of the number of spatial-temporal background noise modes incident on the single-photon detector array. A description of how to apply these design trades for deep space lasercom ground terminals (analogous to ground terminals considered here) is described in (D.M. Boroson 2018).

Photographs of four candidate U.S. territory ground terminals are shown in Figure 1.

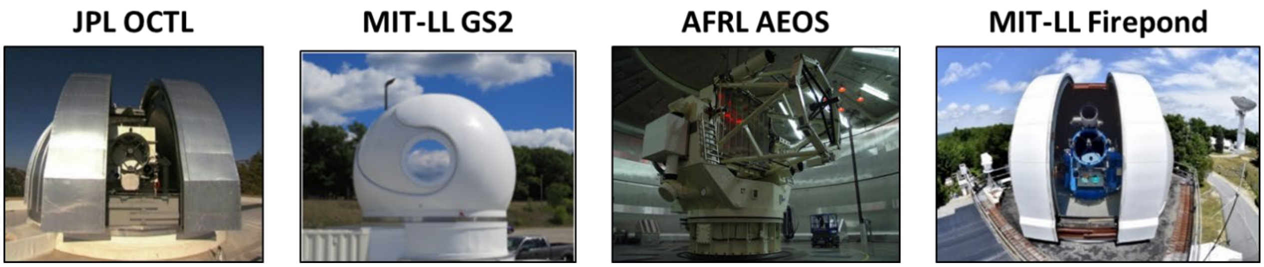


Figure 1. Ground terminals: JPL's 1-m OCTL, MIT-LL's 0.6-m GS2, AFRL's 3.7-m AEOS, and MIT-LL's 1.2-m Firepond.

5.2.3 MAScOT Space Terminal Quantum Modem

New technology development will be required to implement the quantum modem (especially for the flight modem) that includes a high-rate entanglement source (including a master clock mode-locked laser), high-efficiency single-photon detectors, and future quantum memory.

In the next sections, we focus on critical quantum modem technology, namely the high-rate entanglement source, single-photon array to aid near term early phase architectural implementation and quantum memory to enable mid to longer term architectures for enhanced quantum network demonstrations.

5.2.3.1 High-Rate Entanglement Source Technology

A crucial quantum technology is the entangled photon pair source (EPPS). To distribute entanglement in a quantum network, the EPPS must produce high-quality entanglement at high rates. For that entanglement to be useful, either for quantum applications or for operations such as the Bell state measurement (BSM) [(Michler *et al.* 1996), (Lütkenhaus, Calsamiglia, and Suominen 1999)], the EPPS must produce entangled states with a high value of spectral purity. This is relevant because many quantum applications and operations, including the BSM, rely on high-visibility two-photon interference. The photons produced by the EPPS should not carry undesirable distinguishing information that reduces the interference visibility. Such distinguishing information is often overlooked and most difficult to eliminate in the frequency degree of freedom (Grice and Walmsley 1997). Spectral purity quantifies the frequency correlations between the two entangled photons; high spectral purity is good because it corresponds to a small amount of distinguishing information.

In addition to these requirements, an EPPS in a space payload must also satisfy the payload size, weight, and power (SWaP) constraints, and it must also be ruggedized to survive the environmental conditions of launch and orbit. Furthermore, the EPPS must also be compatible with the rest of the space-ground system, such as the single-photon detectors and the lasercom hardware. This can impact the choices of EPPS wavelengths, bandwidths, and the entanglement degree of freedom (e.g., polarization entanglement or time-bin entanglement).

Finally, a heralded entanglement distribution scheme (Żukowski *et al.* 1993), such as a downlink entanglement swap demonstration, requires the ability to synchronize multiple EPPSs. A successful entanglement swap requires detecting four-photon coincidence events. Without quantum memories, this requires the EPPSs to emit photon pairs at the right times so photons can interfere at the BSM.

The most mature technology for high-rate entangled photon pair generation is spontaneous parametric downconversion (SPDC) (Kwiat *et al.* 1995). An SPDC-based EPPS can be described as the combination of three components: a pump source, a nonlinear crystal, and an entanglement generation scheme. SPDC is a nonlinear optical process in which a pump photon with frequency ω_p is downconverted into two daughter photons, called signal and idler photons, with frequencies ω_s and ω_i, respectively, such that energy and momentum are conserved. To generate useful entanglement, the outputs of two (or more) SPDC processes are combined in a method such that it cannot be determined which process produced a given photon pair.

There have been a small number of previous demonstrations of SPDC sources in space. China's Micius satellite payload included a polarization-entangled source (Yin *et al*. 2017). The pump was a continuous-wave (CW) laser diode, the nonlinear crystal was a bulk periodically poled potassium titanyl phosphate (PPKTP) crystal, and the polarization entanglement was generated using a Sagnac interferometer. Singapore's Center for Quantum Technologies (CQT) has tested multiple SPDC sources in space, including one that only generated correlated (but not entangled) photon pairs (Tang *et al.* 2016) and a more-recently launched EPPS based on multiple beta-barium borate (BBO) crystals pumped by a CW laser diode (Durak *et al.* 2016).

None of the SPDC sources flown in space to date are suitable for quantum networking. CW-pumped sources do not scale to high entanglement swap rates because SPDC produces pairs probabilistically. To achieve any useful four-photon coincidence rate over a space-ground link, the SPDC sources must operate with pulsed pumping and a shared clock.

Furthermore, none of the SPDC sources flown to date produced spectrally pure photons. The requirement for spectral purity strongly drives both the crystal and pump choices. Spectral purity can be obtained by spectral filtering (Carrasco-Casado *et al.* 2016), which has the detrimental effect of lowering the pair rate. Periodically poled materials, such as PPKTP or periodically poled lithium niobate (PPLN), have high nonlinear coefficients and thus are often chosen for efficient SPDC. PPKTP has the additional advantage of intrinsic spectral purity near the telecom C- and L-bands, due to the group-velocity matching (GVM) condition. This intrinsic spectral purity can be further enhanced by engineering the periodic poling [(Brańczyk *et al.* 2011), (Dixon, Shapiro, and Wong 2013)].

Under GVM, spectral purity is obtained by matching the pump and crystal (phase-matching) bandwidths. Narrower phase-matching bandwidths, i.e., longer crystals, are desirable because they provide more efficient SPDC and they ease the system requirements for synchronization at the BSM. The maximum achievable crystal length is currently a few tens of mm, corresponding to pumping with picosecond pulses from a mode-locked laser (MLL). This requirement for the pump bandwidth extends the existing requirement that the SPDC sources use pulsed pumping to achieve useful entanglement swap rates. The rate is directly proportional to the system clock rate; thus, high-rate MLLs are essential. Stable, low-timing-jitter picosecond-pulse MLLs are common for repetition rates less than 1 GHz, but GHz class picosecond MLLs are more difficult to obtain. The most common laboratory approach to generating spectrally pure photon pairs at high rates is to build a passive temporal multiplexer outside the laser (Greganti *et al*. 2018), but this approach is not well-suited to operation in space.

Finally, there are many considerations affecting the entanglement generation scheme, which includes both the entanglement degree of freedom and the optomechanical setup. The space-based EPPS needs to produce high-quality entangled states in a low-SWaP and rugged package. Polarization is the most commonly used degree of freedom for long-distance free-space optical quantum communication. There are multiple methods for generating polarization entanglement using SPDC, such as multiple crystals (Kwiat *et al.* 1995), Sagnac interferometers (Kim, Fiorentino, and Wong 2006), or the beam-displacer method (Evans *et al.* 2010). These methods have different merits in terms of the entangled state quality and the optical alignment stability. The first two have been used for space-based EPPSs [(Tang *et al.* 2016), (Durak *et al.* 2016)], demonstrating their robustness. On the ground, the beam-displacer method has produced the highest entangled state quality, with visibilities greater than 99.6% (Shalm *et al.* 2015), and its alignment is designed to be low-SWaP and stable, but it has never been demonstrated in space. These methods are generally based on bulk crystals, which make it more difficult to achieve high pair generation rates. Compared to bulk, SPDC in waveguides can be orders of magnitude more efficient [(Fiorentino *et al.* 2007), (Zhong *et al.*2009)], but generating polarization entanglement using waveguides is currently much less mature [(Meier, Kaneda, and Kwiat 2018), (Meyer-Scott *et al.* 2018)] (see Section 5.3 Other Topics for Further Consideration and Exploration).

Waveguided SPDC motivates the consideration of time-bin entanglement, which is well-suited for a robust, and compact space-based EPPS: SPDC can be efficiently generated in a fiber-coupled waveguide device, and the early-late time-bin superposition can be produced using a commercial telecom delay-line interferometer (DLI). Choosing time-bins increases the overall system complexity, affecting the synchronization and the single-photon detectors. It is challenging to use time-bin states with a moving platform because the satellite motion induces a Doppler shift that changes the early-late separation during the satellite's pass. However, this additional complexity due to time-bins can likely be concentrated almost entirely at the ground station.

In summary, a space-based EPPS needs to produce:

1. high-quality entanglement,
2. of spectrally pure photons,
3. at high rates,
4. in a rugged and low-SWaP package.

Various combinations of some of these requirements have been demonstrated to date, but no single EPPS has met all four requirements.

5.2.3.2 Superconducting Nanowire Single Photon Detector Technology

Time-resolved single photon detectors are an essential driving technology for space-to-ground quantum communication. Both on the spacecraft and on the ground, effective high-rate quantum communication requires single photon detectors with high efficiency, low timing jitter, high maximum count rates, and low dark count rates. To make optimal use of existing NASA investments in free-space laser communication technologies, it is ideal for the single photon detectors to have all of these properties at telecommunication wavelengths near 1550 nm.

The most advanced detectors available for time-resolved single photon counting in the infrared are superconducting nanowire single photon detectors (SNSPDs). Since their first demonstration in 2001 (Gol'tsman *et al.* 2001), SNSPD performance has steadily improved in all of the above metrics. SNSPDs have become the detectors of choice in a wide range of quantum information experiments and have been successfully fielded in space-to-ground optical communication demonstrations such as the Lunar Laser Communication Demonstration [(Boroson, *et al*. 2014), (Biswas *et al.* 2014)]. They are also planned for use on the ground in upcoming NASA laser communication demonstrations such as the Deep Space Optical Communication project (Biswas *et al.* 2018) and the Optical to Orion project (Robinson *et al.* 2018). To fully realize the potential of space-to-ground quantum communication in the NASA SCaN phased architectural concept, SNSPDs may be the optimal choice in both the space and ground terminals. While SNSPDs have been a critical enabling technology for quantum communication experiments on the ground, they have never been demonstrated in space flight applications. The development of flight-qualified SNSPDs and associated hardware is crucial for the continuing evolution of high-performance space-to-ground communication capabilities in the coming decade. Depending on the material and the design, SNSPDs typically operate at temperatures of 1-4 K, where a variety of space cryogenic technologies have been successfully demonstrated. However, there will always be a class of low-cost mission concepts where flight cryogenics is not practical due to cost and SWaP concerns. For these applications, it is also necessary to have flight-qualified semiconductor detectors such as InGaAs single-photon avalanche diodes (SPADs) that can operate with reduced performance, but without deep cryogenic cooling. For Phase 1 the option of using optimized silicon APDs in space must be in the trade space, if one uses non-degenerate sources (e.g., 800 nm measured locally), which would then eliminate the need to have cryogenic detectors in space for Phase 1; recently these detectors have demonstrated timing jitters below 50 ps, and rates greater than 100 MHz, comparable to SNSPDs (with efficiencies approximately 50%). There is the possibility of using Transition Edge Sensor technology, which has true photon number resolution capability and high absorption efficiency but at a slower rate than SNSPDs. Also, Geiger-mode Avalanche Photodiodes (APDs) Silicon and III-V technologies are lower cost, lower performance detector alternatives more amenable to missions aboard small platforms such as CubeSats.

In the following sections, we consider each of the relevant detector performance metrics for time-resolved single photon counting, discuss their relevance to space-to-ground quantum communication, review the state of the art, and discuss potential technology gaps and areas requiring investment.

System Detection Efficiency at telecommunication wavelengths is important on both the space and ground terminals. On the space terminal, high efficiency is important to enable high-throughput heralding and Bell state measurement. On the ground side, high efficiency is necessary due to the severe optical channel losses encountered in a space-to-ground downlink. Given single-mode fiber coupling, large detector active areas are not likely to be required. Tungsten silicide SNSPDs have recently been demonstrated with a system detection efficiency above 98% at 1550 nm (Reddy *et al.* 2019). While the demonstrated efficiency of SNSPDs is clearly sufficient for quantum communication on both the space and ground terminals, it is important to recognize that not all parameters can be simultaneously optimized. Technology development may be necessary to ensure that high efficiency (>85%) can be achieved while attaining the other requirements.

Timing Jitter is the statistical uncertainty in the photon arrival time registered by the detector. Typical units used for characterizing jitter are the 1-sigma (or rms) width of the instrument response function, the full width at half maximum (FWHM), and the full width at 1% (FW1%), which reflects the long-time "tail" of the detection statistics. Low timing jitter (i.e. high timing resolution) is crucial for maintaining a high clock rate in quantum communication systems, and for enabling time-bin encoding schemes at the source. For the 10 GHz clock rates envisioned in the near future, FWHM timing jitter of 15 ps and FW1% timing jitter of 40 ps is necessary for the detectors and readout electronics combined. To support 100 GHz clock rates in the future, single-picosecond timing jitter will be required. The present timing jitter record for SNSPDs is 2.7 ps FWHM in a specialized niobium nitride (NbN) device with very low efficiency (Korzh *et al.* 2020) and 11 ps in an SNSPD with an 86% detection efficiency (Zadeh *et al.* 2018). In the future, improvements in the nanofabrication process must be made to realize detectors that simultaneously achieve few-picosecond timing resolution while maintaining efficient coupling to single-mode fiber, and to further reduce the timing jitter to the 1-ps threshold. In addition to the timing jitter of the detectors, it is also important to consider the timing jitter that is generated by the readout electronics. A single-channel time-to-analog converter has recently been demonstrated and commercialized with 3 ps FWHM timing jitter and was successfully used with a low-jitter SNSPD (Becker *et al.* 2019), but a high channel count time tagger with such high time resolution has yet to be developed.

Maximum Count Rate of the detector is the largest event rate that can be handled by the detector and the time tagging electronics. It is typically characterized by the "3 dB point", the photon count rate for which the system detection efficiency drops by 50% due to blocking loss. While the large downlink channel loss means that the photon count rate at the ground terminal is unlikely to exceed 10 Mcps, the heralding rates at the source could be as high as 3-10 Gcps. Depending on the material used, single-element SNSPDs typically have a minimum dead-time ranging from a few to tens of ns, which corresponds to effective 3 dB maximum count rates of tens of megacounts per second. To counter this, a commonly used technique is to illuminate an array of independent SNSPD sensor elements, to approach gigacount-per-second event rates [(Biswas *et al.* 2018), (Dauler *et al.* 2007)]. While 1 Gcps count rates in 64-element arrays are currently the state of the art in both SNSPD detectors and time-tagging readout electronics, high-rate sources will require maximum detector count rates of 10 Gcps on the space terminal, requiring larger pixel counts or on-chip signal combining to increase the event rate on each readout channel.

Photon Number Resolution (PNR), the ability for a detector to conclusively discriminate between the presence of one photon and multiple photons in an optical pulse, is an important property for detectors used in quantum communication. Entangled photon sources based on spontaneous parametric down-conversion or four-wave mixing stochastically produce higher-order multi-photon events, which interfere with quantum communication protocols in various ways. As a result, such photon sources are typically pumped with limited power to reduce the number of multi-photon events that are generated. With PNR detectors on the flight terminal, it is possible to increase the brightness of the source by separately heralding multi-photon events and removing them with post selection. It is also possible to use PNR detectors to enable the multiplexing of entangled photon sources (Kiyohara, Okamoto, and Takeuchi 2016).

While PNR capabilities have not typically been available for single photon detectors used in quantum information experiments, two closely related schemes have recently been demonstrated that achieve PNR using SNSPDs [(Cahall *et al.* 2017), (Zhu *et al.* 2019)], demonstrating high fidelity between single-photon states and two-photon states (Zhu *et al.* 2019). To fully realize the potential performance of high-rate sources of entangled photons, it will be necessary to develop detectors and readout electronics that can support high-fidelity PNR while maintaining high performance in the other performance parameters described here.

Dark Count Rate must be low for single-photon detectors used in quantum communications. In the ground terminal, the dark counts of the detector must be significantly lower than the in-band sky backgrounds to avoid becoming a dominant source of noise. On the flight terminal, low dark counts are important to realize high-fidelity sources. In SNSPDs, the intrinsic dark counts can be extraordinarily low, on the order of 1e-5 cps. However, care must be taken in the design of cryogenic optical systems to effectively shield the detectors from mid-infrared thermal backgrounds while maintaining high throughput at near infrared wavelengths of interest. In fiber-coupled systems, 2 Hz false count rates have been reported while maintaining a system detection efficiency of 68% (Cohen *et al.* 2015), and lower false count rates are possible with further engineering.

Operating Temperature and Cryogenic Requirements must be considered in the system design since SNSPDs, depending on the material choice and the wavelength of interest, typically operate best at temperatures of 1-4 K. For space flight applications, there exist a variety of high-TRL technologies that have been demonstrated to achieve this temperature range in space, including liquid helium cryostats (Holmes *et al.* 2001), adiabatic demagnetization refrigerators (Shirron *et al.* 2016), and closed-cycle Helium-3 Joule-Thompson cryocoolers [(Crook *et al.* 2016), (Sato *et al.* 2016)]. There has been a long history of NASA technology development in flight cryogenics for astrophysics applications that can be leveraged in the near term to realize SNSPD instruments in space. In the future, however, the practicality of flying SNSPDs will be greatly enhanced by developing SNSPDs based on high-temperature superconductors with an operating temperature above 25 K, where flight cryogenics is far less demanding in terms of size, weight, power and cost. Preliminary explorations on SNSPD technology have been undertaken using yttrium barium copper oxide (YBCO) (Arpaia *et al.* 2015) and magnesium diboride (MgB_2) (Shibata, Akazaki, and Tokura 2013), although considerable research in material deposition processes needs to be undertaken to develop thin films which are of sufficient quality to implement high-performance SNSPDs.

Suitability for Space Flight must also be considered since SNSPDs have never been space qualified or demonstrated in a space environment. While SNSPDs are expected to be extremely radiation-tolerant, it is necessary to perform rigorous radiation testing consistent with Earth-orbiting mission profiles. It is also necessary to develop SNSPD packaging and interconnect solutions that will be robust to launch vibrations and shock. One crucial area requiring more extensive technology development will be the development of flight-qualifiable readout electronics for SNSPDs. Low-power, radiation-tolerant application-specific integrated circuits (ASIC) for high-rate, high channel count, low timing jitter SNSPD readout is a key outstanding technology area for implementing SNSPDs in space.

As discussed above, detector technology for time-resolved single photon counting has evolved by leaps and bounds within the past 20 years. In particular, SNSPDs have had a transformative impact on the fields of quantum information science and free-space laser communication. While many of the requirements for high-rate space-to-ground quantum communication have been realized in the laboratory, several key areas still require technology development in order to take full advantage of high-rate quantum communication from space.

Short term (1-3 years):

1) **Advanced detectors meeting the above requirements simultaneously.** As discussed above, near-term demonstrations of quantum communication from space require detectors with 15 ps FWHM time resolution, greater than 85% system detection efficiency, 10 Gcps maximum count rates, and background-limited dark count rates at 1550 nm. While all of these properties except the maximum count rate have been demonstrated individually in the laboratory, no single detector system has been developed that can meet these metrics simultaneously. This will require basic research and development in SNSPD design and nanofabrication processes.

2) **Compact, low-power readout electronics for SNSPDs.** Readout electronics that can transform output pulses from an SNSPD into a high-rate digital data pipeline consistent with the above requirements remains an open area requiring further technology development. This development is envisioned in three stages: A) development of prototype laboratory readout electronics meeting the above requirements based on field programable gate array (FPGA) technology, B) integration of the resulting readout methodologies into a low-power ASIC platform, and C) flight qualification of the resulting ASIC.

3) **Flight qualification of SNSPDs, and demonstrated integration with flight cryogenic systems.** To establish readiness for space flight, the radiation tolerance of SNSPDs and their readout electronics must be rigorously demonstrated.

Furthermore, robust packaging and interconnect solutions must be developed in accordance with flight design principles. It is further necessary to demonstrate the compatibility of SNSPDs with existing flight cryogenic systems, by building an SNSPD demonstration testbed based on flight-like cryogenic hardware.

Long term (4-7 years)

1) **SNSPD arrays with a maximum count rate of 100 Gcps or higher, and timing jitter below 1 ps.** This is critical to implementing ultra-high-rate entangled-photon sources in the future with clock rates approaching 100 GHz. This will require significant blue-sky research into novel SNSPD device designs, superconducting materials, nanofabrication processes, and ultra-high-speed readout electronics.

2) **SNSPDs with operating temperature of 25 K or higher.** As discussed above, this will enable the operation of SNSPDs in space with reduced complexity and SWaP in the cryogenic system. Opportunities for development include the deposition and optimization of high-temperature superconductors in thin-film form, and for the development of fabrication processes for SNSPDs that can take advantage of these new developments in materials.

3) **Compact, low-power flight cryocoolers optimized specifically for the cryogenic requirements of SNSPDs.** Long-life flight cryocooler development at temperatures of 4 K and below has primarily targeted the needs of large infrared and x-ray space telescopes, which have much larger cooling power requirements than are generally needed to operate SNSPDs. By developing compact, low-power flight cryocoolers optimized specifically for the needs of SNSPDs, it is possible in the future to reduce the size, weight, power and cost for flight cryogenic systems needed to operate SNSPDs.

5.2.3.3 Quantum Memory and Photonic Interface

The development of entanglement-based quantum networks offers the promise of new technology capabilities for distributed systems that are beyond what can be achieved classically. Space-based quantum links offer significant benefit in two areas: they can increase the available range compared to fiber networks; and they provide a novel environment within which the quantum systems can operate. These benefits come at the expense of requiring the fundamental link to be a full space-to-ground link, which does not necessarily have the optimum length or characteristics for quantum technologies and requires technologies to be space-qualified. Quantum memories are not required to fulfill a space-based quantum entanglement demonstration.

To date, space-based quantum network systems have not focused on developing and incorporating quantum memory capability. However, the eventual incorporation of quantum memories is needed for two reasons; to decrease inherent rate-loss in multi-span link, and to store the distributed entanglement for use in a coordinated manner.

Space-links place particular challenges on quantum memories, since their development and space-worthiness are some of the least mature of required quantum network technologies. Links in the 1000 km to 5000 km distance range will require memory coherence times of tens of milliseconds. System clock rates needed for useful quantum network applications are in the megahertz to gigahertz range, indicating quantum memories best operate at these rates, and must have a memory depth of several thousand to several million.

The basic task of network-compatible quantum memories is to store quantum states that have been transmitted across distance, generally via photon, and to do it in a way that successful storage can be heralded without destroying the quantum state. This can be done with several types of memory as illustrated in Figure 2. In a read-type memory, shown in Figure 2a, the memory generates shared entanglement between the memory and a photon that is emitted or read out. This memory type is sufficient to distribute shared heralded entanglement between remote quantum memories by incorporating an all-optical entanglement swap apparatus between the memories. In a write-type memory, shown in Figure 2b, a quantum memory receives a photon and writes its quantum state into the memory. This method can be used to distribute shared heralded entanglement between remote memories by using an entanglement source or a read-type memory as a source of photonic quantum states, however the optical bandwidth and center frequency of the received photon must match the acceptance bands of the memory system. This can be achieved naturally or by frequency conversion techniques. In a buffer-type memory, shown in Figure 2c, a received photon is delayed for a controllable amount of time. This type of memory can be used to distribute shared heralded entanglement between remote memories by using an entanglement source or a read-type memory as a source of photonic quantum states, and again the optical bandwidth and center frequency of the received photon must match the acceptance bands of the memory system.

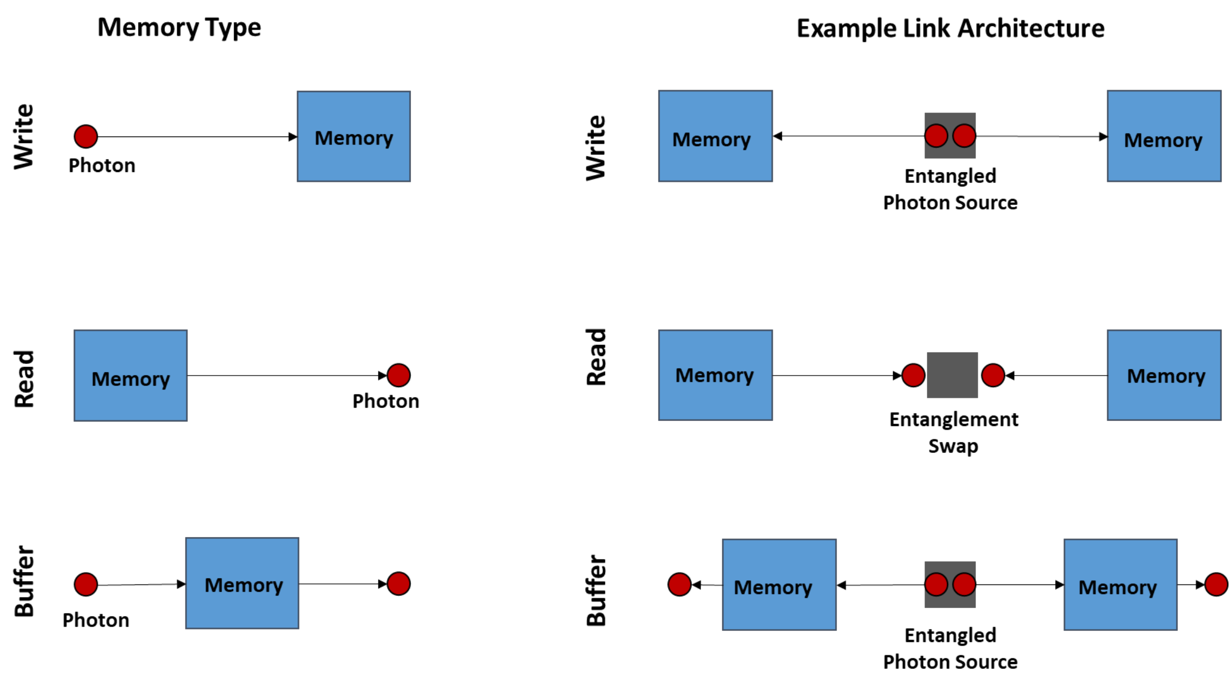


Figure 2. Quantum memory technology can be broadly categorized into absorption- and emission-based. a) Absorption-based memory writes a photonic qubit into a stored quantum memory qubit while b) emission-based memory generates a photonic qubit from a stored quantum memory qubit. c) Buffer memory provides a "random access" quantum memory capability by utilizing both absorption and emission properties of quantum memory technology. Developing memory technology with a photonic interface is a primary challenge today.

There are several promising candidate technologies for ground- or space-based quantum network compatible quantum memories including: optical delay lines, atomic vapors, doped crystals, trapped atoms and ions, color centers in diamond, and superconducting qubits. Each technology offers a different blend of technology development, required infrastructure, storage time, memory depth, clock rate, feasibility of interfacing with a photon, ability to herald stored entanglement.

Optical delay lines are the most mature memory technology. They consist of a fiber or free-space delay loop and a fast-switchable gate such as a Pockel's cell to controllably load or unload a photon into the loop, and would operate as a buffer-type memory. These memories have an inherent photonic interface, and they have been shown to store quantum states for hundreds of nanoseconds at a clock rate of 100 MHz [(Kaneda *et al.* 2017), (Kaneda and Kwiat 2019)].

Atomic vapor clouds consist of an evacuated gas cell with vapor of gas such as rubidium in it. These memories act as a write type memory by causing a weak excitation that results in a single photon emission, or as a buffer type memory by using electromagnetically induced transparency techniques. In these ways, they have natural photonic interfaces. Individual gas cells have been shown to have storage times of microseconds (Wang *et al.* 2019) and have been shown to store up to 100 quantum states (Jiang *et al.* 2019). Demonstrations linking multiple atomic vapor cloud memories have been shown (Yu *et al.* 2020).

Rare-earth doped crystals rely upon photon echo phenomena to act as a buffer-type memory. These memories have demonstrated storage times of up to 10 microseconds with efficiencies of up to tens of percent—albeit not simultaneously. Individual memories have shown storage of hundreds of quantum states and have been shown to be scaled via scalable patterning processes. Demonstrations linking multiple rare earth doped crystal memories have been shown with overall communication rates of 2 Hz (Humphreys *et al.* 2018).

Trapped atoms and ions consist of a magneto-optical trap system containing a single atom or ion. These memories have an inherent optical transition that interfaces photons to the electronic energy level that forms the memory quantum state. These interfaces, however, have photon/atom interaction efficiencies limited to several percent, due to the challenges of collecting a large solid-angle from the emission of a single point-particle. Individual atoms have demonstrated coherence times of up hundreds of seconds (Wang *et al.* 2017). Each atom stores one quantum state but arrays of several individually addressable atoms have been demonstrated. These memories can operate as both read-type and write-type memories and can do so in a heralded manner. More recently, researchers have managed to connect multiple atomic ensemble memories, with an efficiency approaching 0.1% (Jing *et al.* 2019).

Color centers in diamond, such as nitrogen-vacancy (NV), silicon vacancy (SiV), and germanium vacancy (GeV) consist of a single point defect in a diamond crystal lattice. A single carbon atom is substituted with a different atom, and one or more neighboring carbon atoms removed and their lattice site left vacant. These memories have an inherent photonic interface in the form of the “zero-phonon-line” of the defect’s electron spin, which acts as the memory. Individual memories have demonstrated coherence times of several milliseconds, and can operate at clock rates of tens to hundreds of megahertz (Sukachev *et al.* 2017). Each color center can store one quantum state, however systems of tens of individually addressable color centers on a single device have been demonstrated by taking advantage of scalable patterning capabilities of optical waveguides in the diamond lattice surrounding the color center (Wan *et al.* 2019), however diamond lattice strain causes different emission center wavelengths. These memories have been shown to operate as both read-type and write-type memories and can operate in a heralded manner [(Wan *et al.* 2019), (Bhaskar *et al.* 2019)]. Demonstrations of linking multiple NV systems have been shown, however they have low total communication rates, with levels of 0.001 events per second (Hensen *at al.* 2015).

Superconducting qubits consist of a lithographically patterned radio-frequency circuit that is held at millikelvin temperatures in a dilution refrigerator. At these temperatures, the quantized nature of the current in the circuit can be used as a qubit. Individual superconducting qubits have shown coherence times of tens to hundreds of microseconds, operating at clock rates of up to several megahertz (Kjaergaard *et al.* 2020). Each circuit can store one quantum state, however systems of tens to hundreds of individually addressable superconducting circuits in a single dilution refrigerator have been shown (Arute *et al.* 2019). Superconducting qubit systems have benefited from significant development for use as a monolithic quantum processor, however the primary limitation of superconducting qubit systems for use as a networked quantum memory system is the comparative lack of development of a photonic interface. It is challenging to convert a superconducting circuit’s radio-frequency quantum state to an optical frequency with both high efficiency and low noise. Current demonstrations have either achieved low noise and conversion efficiency of less than 1%, or higher conversion efficiencies—up to 47%—but with poor noise performance (Lambert *et al.* 2020). Conversion both to and from optical frequencies has been demonstrated, indicating that these memories could operate as read-type, write-type, and buffer-type memories, and could all operate in a heralded manner (Johnson *et al.* 2010). However, there have been no system demonstrations showing two superconducting qubits linked via converted optical photons.

To date, most quantum memory efforts have focused on demonstrating either proof-of-principle or long memory storage times between remote systems. There have been some recent demonstrations that have focused on the goal of increasing the memory depth, but none focused on the goal of increasing the overall system by maximizing the achievable clock rate and multiplexing multiple systems together.

All candidate technologies have significant limitations that must be overcome. Delay lines must develop a manner to herald that they have captured a photonic state, rare-earth doped crystals must develop long storage times with high efficiency, trapped atoms must develop a scalable interface system, superconducting qubits must develop an RF to optical conversion system, and atomic vapor clouds and color centers must develop larger scaling capabilities. In addition to these challenges, all systems require significant system level integration and interface development.

5.3 Other Topics for Further Consideration and Exploration

1. Quantum link calculation standardization
2. Quantum Networked Systems Engineering
3. Details behind the demonstration of 99% spectral purity without any spectral filtering
4. Discussion of what constitutes an efficient waveguide entanglement source
5. Utility of non-SNSPD detectors
6. Discussion on details of memory organization, depth and accessing
7. Roles of superdense coding, hyperentanglement and quantum distillation
8. Continuous variable vs discrete variable entanglement and those implications
9. Development of Level 1 requirements needed for pre-formulation
10. Impact of NASA 7120 Project Management Requirements to reference mission concept implementation
11. Management of the Classical Channel for quantum communications

5.4 Conclusion

NASA has a goal of providing quantum entanglement as a future resource to complement their current operational Space, Near-Earth, Deep Space communication networks. Quantum entanglement is the primary resource for enabling a quantum network that can transfer fragile quantum information bits between distributed locations. NASA is investing in quantum networking capabilities to enable U.S. and international partnered-development of enhanced-performance non-classical sensing, precision timing and navigation, multi-processor quantum computing, and secure communication systems. To develop quantum entanglement as a resource in NASA communications systems, multiple operational pathfinders are being analyzed multiple operational pathfinders are being analyzed, targeting a phased single-span and dual-span quantum network. To enable these pathfinders and, ultimately, an operational entanglement resource capability, critical technology development is required including space and ground optical terminals, high-rate entanglement sources, single-photon detectors and quantum memory. NASA is well positioned for successful execution of this effort due to its long space heritage and current leadership position in developing optical communication technologies for classical communication systems.

5.5 References

Andrews, L.C. and R. J. Phillips. 2005. *Laser Beam Propagation through Random Media, 2nd Edition*. SPIE Press.

Arpaia, R. *et al*. 2015. "High-temperature superconducting nanowires for photon detection." *Physica C: Superconductivity and its Applications*, Vol. 509: 16-21.

Arute, F., K. Arya, R. Babbush, *et al*. 2019. “Quantum supremacy using a programmable superconducting processor.” *Nature*, Vol. 574: 505–510.

Becker, W. *et al*. 2019. “4.4 ps IRF width of TCSPC with an NbN Superconducting Nanowire Single Photon Detector.” *Becker & Hickl application note*.

Bennett, C.H. and G. Brassard. 1984. “Quantum cryptography: Public key distribution and coin tossing.” *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing*: 175-179.

Bennett, C.H. *et al*. 1993. “Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels.” *Phys. Rev. Lett.*, Vol. 70: 1895-1899.

Bhaskar, M.K., R. Riedinger, B. Machielse, D.S. Levonian, C.T. Nguyen, E.N. Knall, H. Park, D. Englund, M. Lončar, D.D. Sukachev, and M.D. Lukin. 2019. “Experimental demonstration of memory-enhanced quantum communication.” https://arxiv.org/abs/1909.01323.

Biswas, A. *et al.* 2014. "LLCD operations using the optical communications telescope laboratory (OCTL)." *Proc. SPIE 8971*, Free-Space Laser Communication and Atmospheric Propagation XXVI.

Biswas, A. *et al*. 2018. "Deep space optical communications." *Proc. SPIE 10524*, Free-Space Laser Communication and Atmospheric Propagation XXX.

Boroson, D.M. *et al*. 2014. "Overview and results of the lunar laser communication demonstration." *Proc. SPIE 8971*, Free-Space Laser Communication and Atmospheric Propagation XXVI.

Boroson, D.M. 2018. "Performance limits and simplified analysis of photon-counted noisy free-space optical links." *Proc. SPIE 10524*, Free-Space Laser Communication and Atmospheric Propagation XXX.

Brańczyk, A.M., A. Fedrizzi, T.M. Stace, T.C. Ralph, and A.G. White. 2011. “Engineered optical nonlinearity for quantum light sources.” *Opt. Express*, Vol. 19: 55-65.

Cahall, C. *et al*. 2017. "Multi-photon detection using a conventional superconducting nanowire single-photon detector." *Optica*, Vol. 4: 1534-1535.

Carrasco-Casado, A. *et al*. 2016. “LEO-to-ground polarization measurements aiming for space QKD using Small Optical TrAnsponder (SOTA).” *Optics Express*, Vol. 24, Issue 11: 12254-12266.

Cartledge, E. 2019. “Quantum sensors: a revolution in the offing.” *Optics and Photonics News*: 24-31.

Cohen, J.D. *et al*. 2015. "Phonon counting and intensity interferometry of a nanomechanical resonator." *Nature*, Vol. 520: 522-525.

Crook, M. *et al*. 2016. "Development of a 2K Joule-Thomson closed-cycle cryocooler." *International Cryocooler Conference*, Vol. 17: 9-18.

Dauler, E.A. *et al*. 2007. "Multi-element superconducting nanowire single-photon detector." *IEEE Transactions on Applied Superconductivity*, Vol. 17.2: 279-284.

Dixon, P.B., J.H. Shapiro, and F.N. C. Wong. 2013. “Spectral engineering by Gaussian phase-matching for quantum photonics.” *Opt. Express*, Vol. 21: 5879-5890.

D.M. Boroson. 2018. “On achieving high performance optical communications from very deep space.” *Proc. SPIE 10524*, Free-Space Laser Communication and Atmospheric Propagation XXX.

Durak, K. *et al.* 2016. “The next iteration of the small photon entangling quantum system (SPEQS-2.0).” *Proc. SPIE 9762*.

Ekert, A. K. 1991. “Quantum cryptography based on Bell’s theorem.” *Phys. Rev. Lett.*, Vol. 67, Issue 6: 661–663.

Eldredge, Z., M. Foss-Feig, J.A. Gross, S.L. Rolston, and A.V. Gorshkov. 2018. “Optimal and secure measurement protocols for quantum sensor networks*.” Phys. Rev. A 97*, 042337.

Evans, P.G., R.S. Bennink, W.P. Grice, T.S. Humble, and J. Schaake. 2010. “Bright Source of Spectrally Uncorrelated Polarization-Entangled Photons with Nearly Single-Mode Emission.” *Phys. Rev. Lett.,* Vol. 105, 253601.

Fiorentino, M. *et al*. 2007. “Spontaneous parametric down-conversion in periodically poled KTP waveguides and bulk crystals.” *Opt. Express*, Vol. 15: 7479-7488.

Gol’tsman, G. N. *et al*. 2001 “Picosecond superconducting single-photon optical detector.” *Appl. Phys. Lett.*, Vol. 79: 705.

Greganti, C. *et al*. 2018. “Tuning single-photon sources for telecom multi-photon experiments.” *Opt. Express*, Vol. 26: 3286-3302.

Grice, W.P. and I.A. Walmsley. 1997. “Spectral information and distinguishability in type-II down-conversion with a broadband pump.” *Phys. Rev. A*, Vol. 56: 1627-1634.

Günthner, K. *et al*. 2017. “Quantum-limited measurements of optical signals from a geostationary satellite.” *Optica*, Vol. 4, Issue 6: 611-616.

Hamilton, S.A. *et al*. 2019. “Overview of NASA’s National Space Quantum Laboratory Program.” IAC-19-B2.7.12, *70th International Astronautical Congress (IAC)*, Washington D.C., United States (21-25 October 2019).

Hensen, B., H. Bernien, A.E. Dréau, *et al*. 2015, “Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres.” *Nature*, Vol. 526: 682–686.

Holmes, W. *et al*. 2001. "Performance comparisons of space borne cryostats." *Cryogenics*, Vol. 41: 865-870.

Humphreys, P.C., N. Kalb, J.P.J. Morits*, et al*. 2018. “Deterministic delivery of remote entanglement on a quantum network.” *Nature*, Vol. 558: 268–273.

Jiang, N., Y. Pu, W. Chang, *et al*. 2019. “Experimental realization of 105-qubit random access quantum memory.” *npj Quantum Inf.*, Vol. 5, 28.

Jing, Bo, Xu-Jie Wang, Yong Yu, Peng-Fei Sun, Yan Jiang, Sheng-Jun Yang, Wen-Hao Jiang, Xi-Yu Luo, Jun Zhang, Xiao Jiang, Xiao-Hui Bao & Jian-Wei Pan. 2019. “Entanglement of three quantum memories via interference of three single photons.” *Nature Photonics*, Volume 13: 210–213.

Johnson, B., M. Reed, A. Houck, *et al*. 2010. “Quantum non-demolition detection of single microwave photons in a circuit.” *Nature Phys.,* Vol. 6: 663–667.

J. Yin *et al*. 2017. “Satellite-to-Ground Entanglement-Based Quantum Key Distribution.” *Phys. Rev. Lett.,* Vol. 119: 200501.

Kaneda, F., F. Xu, J. Chapman, and P. G. Kwiat. 2017. "Quantum-memory-assisted multi-photon generation for efficient quantum information processing." *Optica*, Vol. 4: 1034-1037.

Kaneda F. and P. G. Kwiat. 2019. “High-efficiency single-photon generation via large-scale active time multiplexing.” *Science Advances*, Vol. 5, no. 10.

Kim, T., M. Fiorentino, and F.N.C. Wong. 2006. “Phase-stable source of polarization-entangled photons using a polarization Sagnac interferometer.” *Phys. Rev. A*, Vol. 73, 012316.

Kimble, H. J. 2008. “The quantum internet.” *Nature*, Vol. 453: 1023-1030.

Kiyohara, T., R. Okamoto, and S. Takeuchi. 2016. "Realization of multiplexing of heralded single photon sources using photon number resolving detectors." *Opt. Express*, Vol. 24: 27288-27297.

Kjaergaard, M., M.E. Schwartz, J. Braumüller, P. Krantz, J.I.-J. Wang, S. Gustavsson, and W.D. Oliver. 2020. “Superconducting Qubits: Current State of Play.” *Annual Review of Condensed Matter Physics*, Vol. 11:1.

Knott, P. A. *et al*. 2016. “Local versus global strategies in multiparameter estimation.” *Phys. Rev. A*, Vol. 94, 062312.

Komar, P. *et al*. 2014. “A quantum network of clocks.” *Nat. Phys.*, Vol. 10: 582-587.

Korzh, B.A. *et al*. 2020. “Demonstrating sub-3 ps temporal resolution in a superconducting nanowire single-photon detector.” *Nature Photonics*, in press.

Kwiat, P.G. *et al*. 1995. “New High-Intensity Source of Polarization-Entangled Photon Pairs.” *Phys. Rev. Lett.*, Vol. 75: 4337-4341.

Lambert, N.J., A. Rueda, F. Sedlmeir, and H.G.L. Schwefel. 2020. “Coherent Conversion Between Microwave and Optical Photons—An Overview of Physical Implementations.” *Adv. Quantum Technol.*, Vol. 3: 1900077.

Lange, R. *et al*. 2006. "142 km, 5.625 Gbps Free - Space Optical Link Based on Homodyne BPSK Modulation." *Proc. SPIE 6105*: 6105A-1:9.

Lavigne, B.M. *et al*. 1998. "Horizontal Line-of-Sight Turbulence Over Near-Ground Paths and Implications for Adaptive Optics Corrections in Laser Communications." *Appl. Opt.*, Vol. 37: 4553-4560.

Liao, S.-K., *et al*. 2017. “Satellite-to-ground quantum key distribution.” *Nature*, Vol. 549: 43–47.

Loney, C.G. 1991. "Design of a High-Bandwidth Steering Mirror for Space-Based Optical Communications." *Proc. SPIE 1543*: 225-235.

Lütkenhaus, N., J. Calsamiglia, and K.-A. Suominen. 1999. “Bell measurements for teleportation,” *Phys. Rev. A*, Vol. 59: 3295-3300.

Meier, K.A., F. Kaneda, and P. G. Kwiat. 2018. “Towards nondegenerate polarization entanglement from a waveguide downconversion source.” *Proc. SPIE 10659*, Advanced Photon Counting Techniques XII.

Meyer-Scott, E. *et al*. 2018. “High-performance source of spectrally pure, polarization entangled photon pairs based on hybrid integrated-bulk optics.” *Opt. Express*, vol. 26: 32475-32490.

Michler, M. K. Mattle, H. Weinfurter, and A. Zeilinger. 1996. “Interferometric Bell-state analysis.” *Phys. Rev. A*, Vol. 53: R1209-R1212.

Monroe, C. *et al.* 2014. “Large-scale modular quantum computer architecture with atomic memory and photonic interconnects.” *Phys. Rev. A*, Vol. 89, 022317.

Reddy, D.V. *et al*. 2019. "Achieving 98% system efficiency at 1550 nm in superconducting nanowire single photon detectors." *Conference on Coherence and Quantum Optics*, Optical Society of America.

Ren, J.-G. *et al*. 2017. “Ground-to-satellite quantum teleportation.” *Nature*, Vol. 549: 70–73.

Robinson, B.S. *et al*. 2018. "Laser communications for human space exploration in cislunar space: ILLUMA-T and O2O." *Proc. SPIE 10524*, Free-Space Laser Communication and Atmospheric Propagation XXX.

Sato, Y. *et al*. 2016. "Development of 1K-class Joule–Thomson cryocooler for next-generation astronomical mission." *Cryogenics*, vol. 74: 47-54.

Schmid, Christian *et al*.2009. "Quantum teleportation and entanglement swapping with linear optics logic gates." *New J. Phys.*, Vol. 11: 033008.

Shalm L.K. *et al*. 2015. "Strong Loophole-Free Test of Local Realism." *Phys. Rev. Lett.*, Vol. 115, 250402.

Shibata, H., T. Akazaki, and Y. Tokura. 2013. "Fabrication of MgB2 nanowire single-photon detector with meander structure." *Applied Physics Express*, Vol 6.2, 023101.

Shirron, P. J. *et al*. 2016. "Design and on-orbit operation of the adiabatic demagnetization refrigerator on the Hitomi soft x-ray spectrometer instrument." *Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray*, Vol. 9905, International Society for Optics and Photonics.

Sukachev, D.D., A. Sipahigil, C.T. Nguyen, M.K. Bhaskar, R.E. Evans, F. Jelezko, and M.D. Lukin. 2017. "Silicon-Vacancy Spin Qubit in Diamond: A Quantum Memory Exceeding 10 ms with Single-Shot State Readout." *Phys. Rev. Lett.,* Vol. 119.

Tang, Z. *et al*. 2016. "Generation and Analysis of Correlated Pairs of Photons aboard a Nanosatellite." *Phys. Rev. Applied*, Vol. 5, 054022.

Walther, F.G. *et al*. 2010. "Air-to-Ground Lasercom System Demonstration Design Overview and Results Summary." *Proc. SPIE 7814*: 78140Y-1:9.

Wan, N.H., T.-J. Lu, K.C. Chen, M.P. Walsh, M.E. Trusheim, L. De Santis, E.A. Bersin, I.B. Harris, S.L. Mouradian, I.R. Christen, E.S. Bielejec, and D. Englund. 2019. "Large-scale integration of near-indistinguishable artificial atoms in hybrid photonic circuits." https://arxiv.org/abs/1911.05265.

Wang, Y., M. Um, J. Zhang, *et al*. 2017. "Single-qubit quantum memory exceeding ten-minute coherence time." *Nature Photon.,* Vol. 11: 646–650.

Wang, Y. J. Li, S. Zhang, *et al*. 2019. "Efficient quantum memory for single-photon polarization qubits." *Nat. Photonics*, Vol. 13: 346–351.

Wehner, S. D. Elkouss, and R. Hanson. 2018. "Quantum internet: A vision for the road ahead." *Science*, Vol. 362: 303.

Yin, J. *et al*. 2017. "Satellite-based entanglement distribution over 1200 kilometers." *Science*, Vol. 356: 1140-1144.

Yu, Y., F. Ma, X. Luo, *et al*. 2020. "Entanglement of two quantum memories via fibres over dozens of kilometres." *Nature*, Vol. 578: 240–245.

Zadeh, I.E. *et al*. 2018. "A single-photon detector with high efficiency and sub-10ps time resolution." https://arxiv.org/abs/1801.06574.

Zhong, T., F.N. Wong, T.D. Roberts, and P. Battle. 2009. "High performance photon-pair source based on a fiber-coupled periodically poled KTiOPO4 waveguide." *Opt. Express*, Vol. 17: 12019-12030.

Zhu, D. *et al*. 2019. "Resolving photon numbers using a superconducting tapered nanowire detector." A*rXiv preprint,* https://arxiv.org/abs/1911.09485.

Żukowski, M., A. Zeilinger, M. A. Horne, and A. K. Ekert. 1993. "'Event-ready-detectors'" Bell experiment via entanglement swapping." *Phys. Rev. Lett.*, Vol. 71: 4287-4290.

6.0 Mission Architectures

Authors: Saikat Guha (University of Arizona); Richard Alena (NASA ARC), Don Boroson (MIT-LL), William Clark (General Dynamics), Ben Dixon (MIT-LL), Sam Dolinar (JPL/Caltech), Dirk Englund (MIT), Lee Feinberg (NASA GSFC), David C. Folta (NASA GSFC), Warren Grice (Qubitekk), Josh Isaacs (UC Berkeley), Mark Jackson (Cambridge Quantum Computing), Paul Kwiat (University of Illinois), Catherine Lee (MIT-LL), Babak Saif (NASA GSFC), Leandros Tassiulas (Yale), Matthew Thill (JPL/Caltech), Don Towsley (UMass-Amherst), Carl Williams (NIST), Quntao Zhuang (University of Arizona)

6.1 Architecting a Satellite-enabled Quantum Internet

The quantum internet is being architected, supported by multiple national and international initiatives. The Department of Energy (DoE) has recently announced its intent in building up a large program to that effect. The National Science Foundation (NSF) recently announced a $51M "Center for Quantum Networks", to be led by the University of Arizona, aimed at architecting the quantum internet. The *quantum internet* will be a vast communication network providing fault-tolerant, high-rate quantum communications service, i.e., transferring qubits reliably over long distances, connecting quantum processors of various kinds (computers, co-processors, sensors, communications receivers, quantum data centers, etc.), supporting different forms of qubit technologies and interfaces. It will support faithful transmission of qubits at high rates among multiple user groups supporting new applications that are not possible with today's technology. The quantum internet is an upgrade of today's internet, and will surpass the capabilities of the modern internet because of the unique advantages of *entanglement*—a coordination of the quantum states of particles serving as computational bits that is not present in the realms of classical physics. Quantum entanglement will improve the internet in at least two important ways. First, it will enable physics-based communication security that cannot be compromised by any amount of computational power. Second, the quantum internet will create a global network of quantum gadgets amassing a computational resource that is fundamentally more powerful than classical processors connected via classical data communications. It will bring unprecedented advances in distributed computing and enable secure access to quantum computers for the public. The quantum internet would revolutionize national security, data privacy, drug discovery, novel material design, and push the frontiers of science with ultra-sensitive telescope conglomerates tied together with entanglement.

The objective of this chapter is to summarize the workshop discussion and to address known issues and open questions in architectural considerations of building a long-distance, fault-tolerant quantum internet supported by transcontinental and intercontinental *satellite-assisted* quantum links. We will discuss the various architectural choices, their pros and cons (with regards to network performance and suitability to various applications of a space-based and space-assisted quantum network), and how those considerations flow down to choices and metrics on quantum devices such as entanglement sources, quantum memory, quantum processing, frequency-conversion and transduction efficiencies, photon detector capabilities, and software considerations such as quantum error correction codes, entanglement distillation protocols, and quantum network routing algorithms and scheduling protocols. We also address the questions of optimal satellite node placements, e.g., a combination of LEO and MEO orbits, and orbit-type trade-offs, in maximizing network performance, under resource constraints.

Due to a sharp decrease of rate with growing distance that is unique to quantum communications [(Takeoka, Guha, and Wilde 2014), (Pirandola *et al.* 2017)], increasing the reach of a high-speed ground-based quantum internet will need to be supported by fault-tolerant quantum repeaters—a special-purpose quantum processor built using quantum memories, quantum logic gates on qubits held in those memories, and an interface to the photonic domain. Repeaters will be installed along the lengths of optical fiber. Satellite-based long-distance links will complement quantum repeaters and will likely be the only means to enable transcontinental and links across oceans in the foreseeable future.

6.2 Background

6.2.1 Propagation of Light Over a Free-space Path

The power transmissivity, η, is the fraction of the transmit power that is collected by the receiver. For ground links, $\eta = e^{-\alpha L}$ for for a length-*L* fiber path (Takeoka, Guha, and Wilde 2014), where α translates to roughly 0.2 dB/km for single-mode telecom fiber. For propagation at center wavelength λ over an *L*-meter line-of-sight path over vacuum, the diffraction-limited transmissivity of the fundamental Gaussian beam is given by $\eta_d \approx D \equiv A_t A_r/(\lambda L)^2$ in the far-field regime, i.e., when the free-space Fresnel-number product $D_f \ll 1$. Here, A_t and A_r are the areas of the exit pupil of the transmit telescope, and the entrance pupil of the receive telescope respectively. When $D_f \gg 1$, the fundamental mode has near-unity transmissivity, and multiple (roughly D_f) orthogonal spatial modes can be simultaneously employed, each of whose diffraction-limited transmissivities is close to 1. Atmospheric portion of a α_1-meter propagation path accrues an additional attenuation $\eta_s \sim e^{\alpha L}$ from scattering and absorption, resulting in an overall transmissivity, $\eta = \eta_d \eta_s$. This atmospheric extinction can vary from 0.2 dB/km in exceptionally clear weather, to upwards of 300 dB/km in a very dense cloud or fog. These large attenuation values in heavy fog are important because they can reduce the uptime or availability of optical communications systems, either classical or quantum. Atmospheric turbulence along that L1-meter causes an additional factor of transmissivity (loss) that is a spatio-temporal random process whose characteristics have been well studied. Receiver-side adaptive optics (AO) can be used for a satellite-to-ground downlink, to mitigate turbulence. Finally, pointing, acquisition and tracking (PAT) needs to be an integral part of the design of the satellite-to-ground link. MIT Lincoln Laboratory and Jet Propulsion Laboratory have amassed decades of experience in AO and PAT technologies, which will need to be leveraged for designing a quantum link.

Let us consider an example. For a *L*=2700 km downlink that traverses 3 km of atmosphere at 0.5 dB/km of loss, assuming a 1 m (diameter) transmit telescope, and a 2 m receive telescope, at λ=1550 nm, we get $D_f = 0.14$, which implies that only the fundamental Gaussian mode is usable, and its power transmissivity is roughly $\eta_d \approx 0.14$. Atmospheric extinction of 1.5 dB translates to $\eta\eta_{ss} \approx$ 0.7, resulting in $\eta\eta \approx$ 0.1. For an L=1000 km satellite-to-satellite link, with $\lambda\lambda$= 800 nm, assuming 1 m telescopes at either end, we get $DD_{ff} =$ 0.96, which implies that the fundamental mode has transmissivity $\eta\eta \approx 1$, and it might be possible to employ one to two higher-order spatial modes, as parallel communication channels, albeit with a lower transmissivity. Doing the latter will come with technical challenges of generating and separating orthogonal spatial modes, such as Laguerre-Gauss (LG) or Hermite-Gauss (HG) modes, which may not be worth the additional cost and complexity, for $DD_{ff} =$ 0.96. However, for a nearer-field space-based link, with $DD_{ff} =$ 4 or more, using higher-order spatial modes will bring significant performance enhancement by providing a multiplier to the rate.

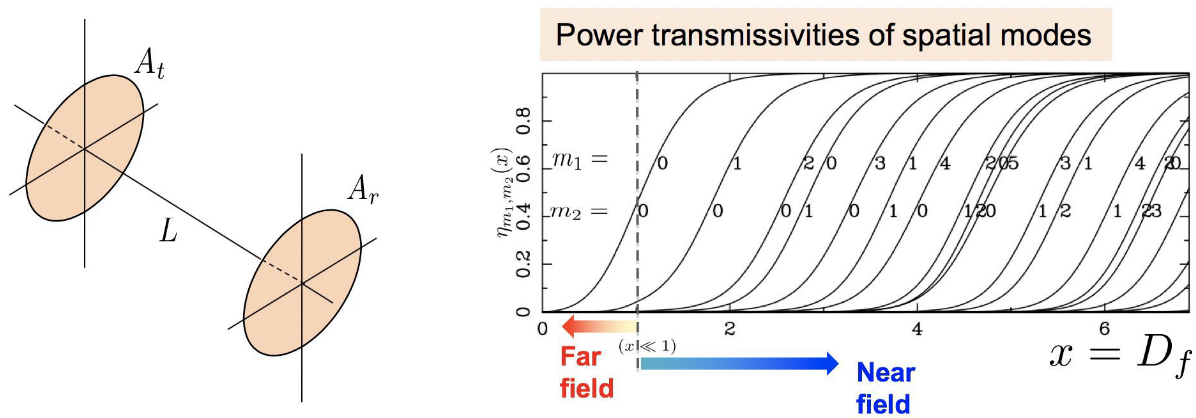


Figure 1. [Left] Free-space channel over a line-of-sight propagation path. [Right] The power transmissivities of the canonical mutually-orthogonal spatial modes for the aperture geometry and propagation geometry. These spatial modes for circular pupils are Prolate-Spheroidal wave functions.[9]

6.2.2 Entanglement Generation Rate

The maximum attainable entanglement rate over a channel of transmissivity $\eta\eta$ is -log(1 $- \eta\eta$), which is $\approx$ 1.44$\eta\eta$, for $\eta\eta \ll$ 1, measured in units of *ebits* (pure Bell states shared between two parties) per transmitted optical spatio-temporal-polarization mode (Pirandola et al. 2017). The ebits/second rate is ebits/mode times modes/second (in Hz, determined by the source modulation bandwidth and the detector bandwidth). Quantum repeaters can be inserted along the length of the optical channel, when feasible, in order to circumvent the above said direct-transmission rate-loss limit -log(1 $- \eta\eta$) ebits per mode [(Guha *et al.* 2015), (Muralidharan *et al.* 2016), (Pant *et al.* 2017)]. Classical communications rate also decreases with increasing loss (diminishing transmissivity), but it can be increased, in principle, no matter how lossy the channel is, by increasing transmit power. For quantum communications, the bits-per-mode rate is just a function of loss. Additionally, the level of any amount of excess noise, e.g., detector dark click

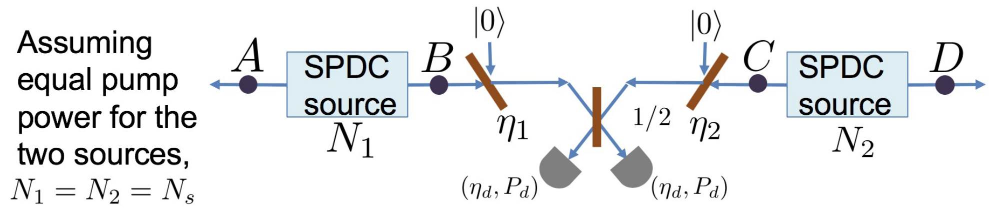
[9] Transmitting mode i=(m,n) from a set of orthogonal modes in the transmitter's pupil results in the receiver receiving mode i among a set of orthogonal modes in the receiver's pupil. These mode pairs are indexed by two integers (m,n). With free-space Fresnel number product $D_f \equiv A_t A_r/(\lambda L)^2 \ll 1$, the channel is in the far-field regime, where only the first (fundamental) mode has any appreciable transmissivity, and hence the higher-order modes are not useful for communications. In this regime, the transmissivity of the fundamental mode, $\eta_{0,0} \approx D_f$.

rate, thermal noise in the channel, electronic noise in the detectors, etc., determines a *maximum viable range*, after which the entanglement rate sharply falls to zero. In a recent experiment done by researchers at Harvard and MIT, quantum communication at a rate exceeding the aforementioned repeaterless rate-vs.-loss bound was shown for the first time, using a node that employed Silicon-vacancy (SiV) center based quantum memories (Bhaskar *et al.* 2020).

6.2.3 Heralded Entanglement Generation Over an Elementary Link

The *elementary link* is a probabilistic, yet heralded, entangled pair of qubits generated across a (ground-to-satellite, ground-to-ground, or satellite-to-satellite) link, whose quality is quantified by the rate *R* (entangled qubit pairs per second) with a guaranteed fidelity of *F*, a number between 0 and 1 that quantifies how "close" that final end-to-end entangled state of two qubits is to the pure Bell state $|\psi\rangle = (1/\sqrt{2})[|10,01\rangle + |01,10\rangle]$, expressed in the "dual rail" qubit basis: $|0\rangle_L \equiv |10\rangle, |1\rangle_L \equiv |01\rangle$. In this chapter, we will limit our discussion to pulsed spontaneous parametric downconversion (SPDC) based entanglement sources, and "dual rail" qubits, where the qubit's "0" state and the "1" state are encoded as |10> and |01> respectively, i.e., one photon being present in the first polarization mode versus the second (orthogonal) polarization mode (of a given spatio-temporal mode of a pulse of light) encodes the logical 0 and 1 states of the qubit. The pure Bell state is shown in red font in Figure 2. The SPDC source also generates vacuum, two-pairs, three-pairs, etc., of photons, in a coherent superposition, where the probability amplitude of each of those terms is governed by the pump power, which can be captured in a single parameter N_s, the mean photon number per mode.

While rate (in pairs per second) at a given fidelity threshold, e.g., F = 0.99, is a reasonable operational metric to quantify the quality of the elementary link, or that of the end-to-end entanglement generation of several concatenated links, a more accurate figure of merit of quality of the elementary link (or that of a concatenation of several elementary links) is the distillable entanglement of final end-to-end state. This is a single number E, measured in "ebits per second", that quantifies the rate at which perfect (pure) Bell states can in principle be distilled from many copies of the noisy end-to-end entangled state, assuming a fault-tolerant quantum processor. This number may be hard to achieve even with fault-tolerant quantum processors carrying out entanglement distillation, since ideal block purification codes (purifying n qubit pairs into k higher-fidelity qubit pairs, k<n) and their quantum logic will be necessary. Ideally, one should analyze the attainable entanglement distillation rate at a desired fidelity, obtained from the raw heralded entanglement obtained, attainable with realistic quality (say, linear-optical, or atomic) quantum logic employed for the entanglement distillation.



$$|\psi\rangle_{AB} \approx \sqrt{p_0}|00,00\rangle + \sqrt{p_1/2}(|10,01\rangle + |01,10\rangle) + \sqrt{p_2/3}(|20,02\rangle - |11,11\rangle + |02,20\rangle)$$

$|M^+\rangle$: Single-photon polarization entangled Bell state

$p_0 = 1/(N_s+1), p_1 = N_s/(1+N_s)^2, p_2 = 1 - p_0 - p_1$ (ignoring 3-pairs and higher)

Probability that the BSM succeeds, P_s < ½, depends upon $N_s, \eta_1, \eta_2, \eta_d, P_d$

Fidelity of the end-to-end state (with the Bell state), $F = \langle M^+|\rho_{AD}|M^+\rangle$

Quality of the elementary link: rate of generation of states, ρ_{AD} at a desired Fidelity F

Figure 2. The "elementary link": a heralded entangled qubit pair AD, produced via a linear-optical Bell state measurement (BSM), connecting two polarization-entangled photon pairs. There are many possible configurations of this elementary link. For example, if the source AB is on a satellite, and the source CD is at a ground station, η_1 will include losses at the source, and the free-space downlink channel, and be much smaller than η_2, which will include only losses at the source. In another configuration, both sources may be on two different satellites, and the BSM is at a ground station, in which case the losses will be more symmetric, but could be different if the two downlinks have different ranges. The mean photon number per mode NN_{ss} is determined by the pump power. Increasing NN_{ss} increases the rate of generation of the single-pair Bell state (desired), but also increases the generation of the two-pair term, which diminishes F.

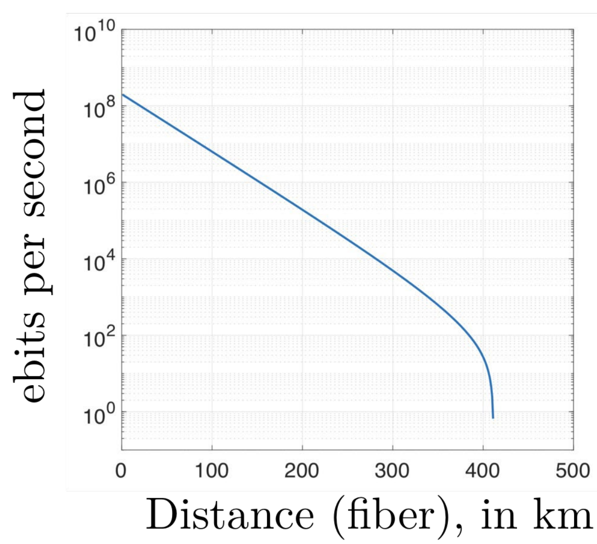


Figure 3. Rate versus distance of an elementary link of the form shown in Figure 2, which assumes two-pair terms of the SPDC source have been completely suppressed (e.g., by multiplexing), 10 GHz repetition rate, 5% single-pair generation rate, single-photon-detectors for BSMs of quantum efficiency 90% and dark click probability per pulse gate of 3×10^{-5}. This plot uses results from Guha et al. 2015 and assumes propagation over single mode optical fiber of 0.15 dB/km loss. Including the effect of multiple pair emissions, and optimizing the pump power to maximize the distillable entanglement for any elementary link, or concatenations thereof, can be computed using results from Krovi et al. 2016.

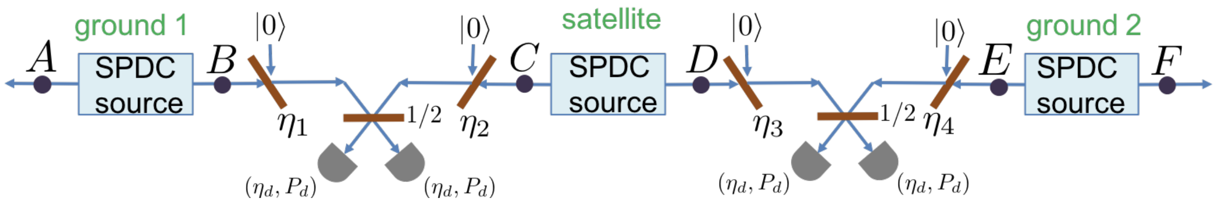


Figure 4. An example of a chain of elementary links for a "double downlink" configuration, where a single pair source in a satellite streams down entangled qubit pairs to two ground stations, each of which employs a local SPDC-based entanglement source and a linear-optical BSM to herald entangled qubit pairs across A and F.

Finally, multiple elementary links can be concatenated, with additional BSM stages, to produce end-to-end entanglement over a longer range, as shown in Figure 4. In this example, the SPDC source CD is in a satellite, and the sources AB, and EF are at two ground stations, which could be several thousands of kilometers apart. If both BSMs are successful, qubits (encoded in polarization mode pairs) A and F are entangled. The fidelity and the rate both degrade through multiple concatenated connections. The ways to improve them are by (1) multiplexing multiple heralded SPDC sources with low pump power, so that the effective two-pair probabilities can be reduced without sacrificing rate, (2) using photon number resolving detectors for the BSMs to enable higher pump power by enabling "culling out" of the spurious entanglement swapping events caused by detector dark clicks and occasional multi-photon events, and (3) by using end-to-end purification and entanglement distillation, which will require quantum memories and additional quantum processing power at the end nodes.

Figure 5 shows two example simulated orbits, pertaining to an architecture sketched in Figure 4, where a single source in a LEO satellite transmits to two ground telescopes located in Boston and the Canary Islands, respectively.

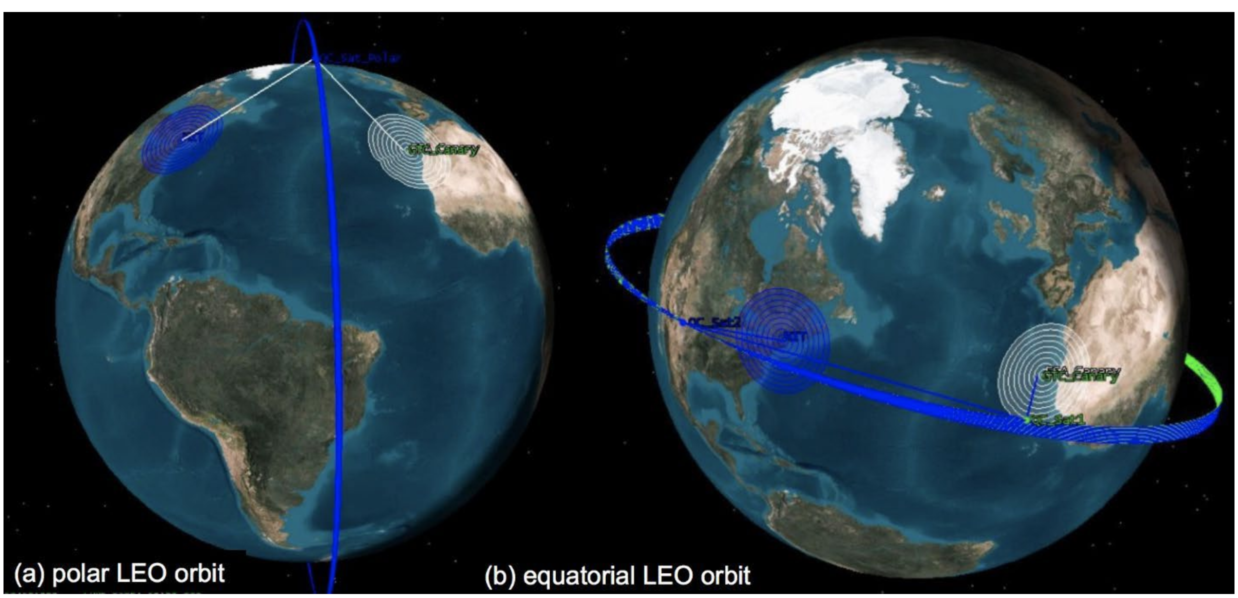


Figure 5. Simulated (polar and equatorial) low Earth orbits (NASA/David Folta).

6.2.4 Quantum Repeaters to Build Larger Entanglement Networks

There is a wide variety of quantum repeater and router protocols being researched, most of which use Bell state measurements (BSMs) as a building block. BSM is a two-qubit (often, destructive) measurement that can *fuse* two elementary entangled links (each entangled link being a two-qubit Bell state shared across a network's edge) incident at a node, into one entangled link over a two-hop path. For a linear chain of repeater nodes, where each repeater is equipped with quantum memories and employs BSMs and switches, the end-to-end entanglement rate can be shown to outperform what can be attained with a direct link connecting the communicating end nodes, with the rate R $\sim \eta\eta^{ss}$ ebits per mode with $ss < 1$[(Guha *et al.* 20150, (Pant *et al.* 2017)]. As we discussed above, the entanglement rate with a direct quantum communication link must scale as R $\sim \eta\eta$.

Further, communicating parties Alice and Bob situated in a quantum network can take advantage of multi-path routing—with the same repeater-node capabilities as above, but able to dynamically switch BSM applications from one time slot to the next across locally-stored qubits that are entangled with different neighboring nodes, based on current link-state knowledge of neighboring links—to attain an entanglement rate that exceeds what is possible along a predetermined linear repeater chain along a single shortest path connecting Alice and Bob (Pant *et al.* 2019).

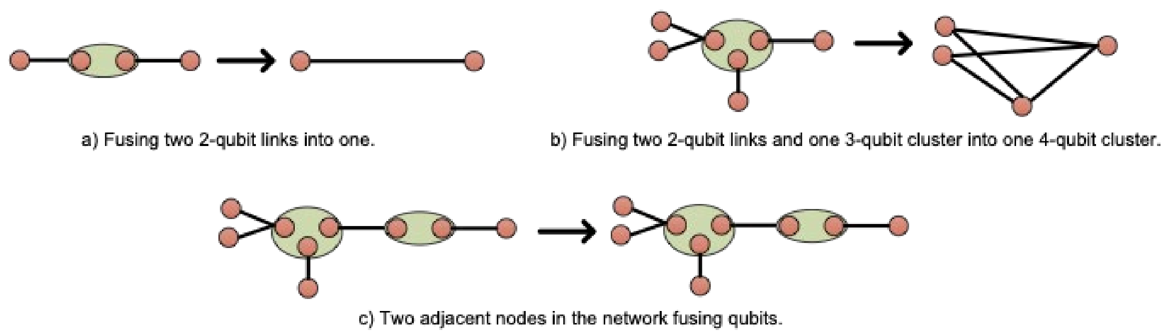


Figure 6. A schematic showing how quantum projective measurements (e.g., BSM or 3-qubit GHZ state) on a group of qubits belonging to different entangled fragments of qubits can connect those fragments into larger entangled clusters.

As discussed above, quantum sources, memories, and entanglement swaps can be used to provide raw heralded entanglement between two distant quantum memories at a given rate (entangled qubit pairs per second) with a quality guarantee, such as the fidelity of the heralded pairs. However, the above resources are not sufficient to build a scalable entanglement-distribution quantum network. The quality of the raw entanglement heralded between quantum memories generated this way, over an elementary link, will not be sufficient to scale up the network, via BSMs alone. One will need to "purify" that entanglement, which will require additional quantum processing capabilities on the qubits held in the quantum memories, and will also accrue an associated classical communications and computing overhead.

A quantum network can provide one of two equivalent services as its core network service: (1) *one-way:* transmitting (a stream of) qubits reliably from point A to point B (note that the qubits in the quantum data stream can be entangled with one another), and (2) *two-way:* generating a stream of entangled Bell states (ebits) between quantum memories held at point A and point B. The reason these two services are equivalent is the following: If a network has been designed to transfer qubits reliably (one-way network architecture), one can generate entangled two-qubit Bell states locally at point A, and use the network to transmit reliably one half (one qubit) of each of the two-qubit Bell states to point B, thereby establishing shared entanglement between the two points. So, service type (1) can be converted to service type (2). Similarly, if a network has been architected to provide service type (2), i.e., establishing shared entanglement between points A and B, if A needs to faithfully transport a stream of qubits to B, it can consume one pre-shared Bell state (and two bits of classical communication) to transfer one qubit at a time to B. This protocol, known as teleportation, converts the resource established by service type (2) into service type (1). Even though the two above services are *equivalent*, there are major architectural tradeoffs in a network designed in one way or the other. Service type (1) will need forward error correcting quantum codes for faithful transmission of qubits. They work by encoding a block of k qubits into a (larger) block of n qubits, n > k, and the receiver decodes the block of n qubits back into the original k qubits despite the n qubits having traversed through noisy transmission. On the other hand, service type (2) will need entanglement distillation and purification protocols. These work by converting n noisy two-qubit Bell pairs distributed between A and B, into fewer (k < n) Bell pairs that are near perfect, i.e., close to the pure Bell state. We will use the term "error correction" generically for both above methods, tied to one-way and two-way architectures, respectively. The rate k/n in both above error correction schemes will be determined by the quality of the link, e.g., propagation path loss, source and detector imperfections. There are various genres of quantum repeaters of both kinds and associated error-correction codes being investigated (Muralidharan *et al.* 2016). Different forms of encoding the qubit into the photon, and studying which are the most tolerant to channel losses and other forms of error, are also an active subject of research (Li *et al.* 2017).

> Initial designs of satellite based quantum networking is likely to be done using a two-way architecture, since it does not rely on more advanced quantum processors, which are not currently available. One-way architectures will give superior rate and latency performance, but will need devices, memories and processors not currently available.

Although quantum repeater research may not be part of a NASA-led architecture study, it is important that the satellite-based entanglement distribution link designs are commensurate with the requirements of what a ground-based future repeatered quantum internet is likely to need. At the very least, the entangled photons that are distributed must be of the sort that can be used for the required Bell state measurements; absent this, their primary value would be for Ekert-style entanglement-based QKD, as they would not enable any of the protocols portrayed in Figs. 2-4, 6. For this reason, the workshop group discussed architectures in the context of being incorporated into a repeatered quantum internet. The section below discusses various considerations of such a future-looking network architecture study, which includes many open research questions.

6.3 Quantum Network Architecture Considerations

6.3.1 Two-way Quantum Network Architecture

The most rudimentary type of two-way quantum network architecture is shown in Figure 7. An *elementary link* is a link between two memories (which could be either ground based, or space based; see Figures 2 and 8) that attempts the generation of shared Bell states among qubits held at each location at some rate, and each attempt succeeds with a probability *p* that is proportional to the total transmissivity of each of the link.

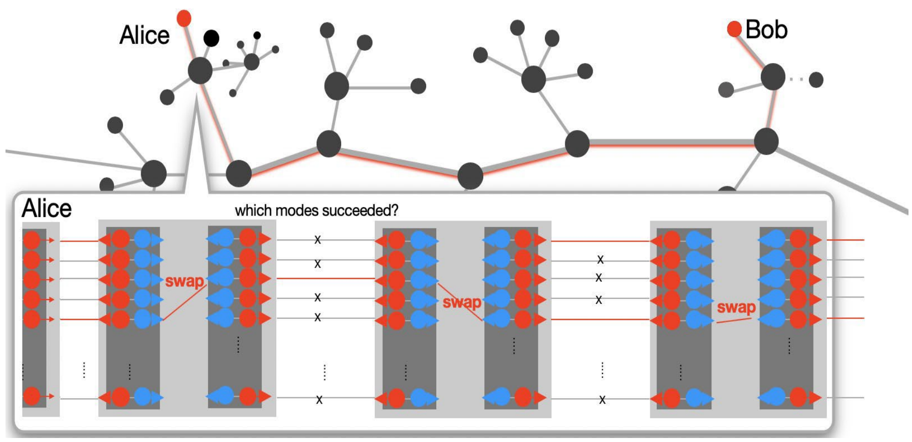


Figure 7. A basic multiplexed two-way quantum repeater architecture (Pant et al. 2017).

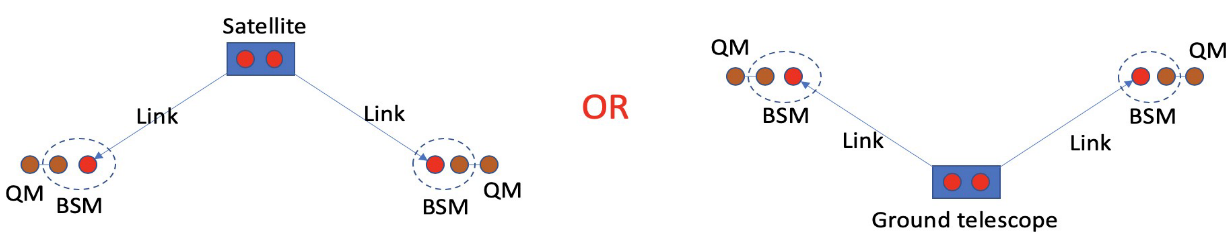


Figure 8. Two possible designs of an "elementary link" of a satellite-assisted two-way quantum network architecture: (a) satellite-based BSM, (b) ground-based BSM.

The choice among the two layouts for the elementary link shown in Figure 8 will determine the placement of the entanglement sources, detectors, and quantum memory (in satellite vs. ground). There are obvious payload, cryostat and size, weight, power, and cost (SWaP-C) considerations. The advantage of the architecture in Figure 8(a) is that the satellite node only needs an entanglement source, but no photon detection capability or quantum memory, and may be preferable over the design (b). It also makes it easy in terms of network engineering (e.g., adding a satellite node to meet a future network-level performance metric). Adaptive optics overheads are also likely to be less for an optical frequency space-to-ground downlink (as opposed to an uplink), which also favors design (a). On the other hand, having the quantum memories and detectors in the satellite as in design (b), at space temperatures, may reduce the cryo-cooling requirements and may result in better coherence times of the quantum memories.

A fairly simple calculation shows that despite imperfect sources and lossy detectors, enabling the quantum repeater nodes with switches (in addition to BSM capability) alone can help outperform the end-to-end direct-transmission rate-loss limit (Guha *et al.* 2015). The end-to-end rate scales as $\eta\eta^{ss}, ss < 1$, as opposed to scaling as $\eta\eta$. However, when there are “non-loss” errors, e.g., other operational errors due to noise in the channel, detectors, and imperfect qubit measurements in the memories, the heralded entanglement is not *pure.* In addition to the switches, the repeater nodes will need more advanced quantum logic to purify the entanglement created.

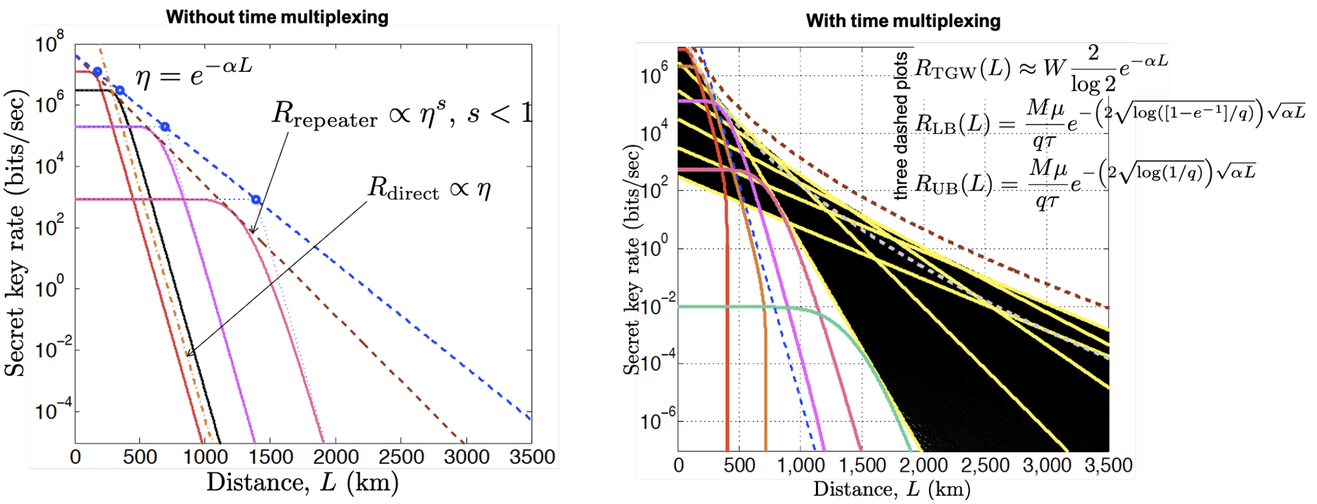


Figure 9. Time-multiplexed entanglement swaps at memories (holding on a qubit from one time step entangled with one neighboring link and swapping with a qubit from another time step entangled with another neighboring link) could greatly improve entanglement rates, notably by resulting in sub-exponential rate-distance tradeoff.

Important research questions include:

1. *Classical communications and synchronization overhead:* Entanglement generation over a link that has more than 3 dB of loss requires a two-way authenticated (but insecure) classical communications link. Even though classical communications is much easier than quantum communications, we must be cognizant of the classical communication bandwidth needed, especially for long-range satellite-enabled links, where such classical communication (either over RF or lasercom) must co-exist with the quantum data links. Question: How much classical communications is needed (per entangled qubit pair of a certain target fidelity created), when distillation and purification protocols have been accounted for, to support a single elementary link? How to design the “classical layer” of communication, for synchronization across the two ground stations, as well as pointing, acquisition and tracking (PAT)?
2. *Entanglement distillation and purification protocols:* If the channels and/or the detectors used to perform BSMs add excess noise (not just incur pure loss), then the resulting heralded ebits are noisy, and thus the entanglement generation cannot be simply stated

in terms of a probability of success of generating an ebit. One needs to extend the known protocols and rate calculations developed to include explicit schemes to distill fewer close-to-unit fidelity Bell states starting from a larger number of noisy Bell states, a step known as purification. Question: How to best extract good quality entanglement from (the poorer quality) raw entanglement generated between qubit pairs over an elementary link, by developing low overhead (block) purification codes, realizable with linear-optical all-photonic and/or atomic quantum logic of realistic gate qualities?

3. *Optimal time-multiplexing:* If quantum memories are allowed to hold on to qubits from multiple time steps (entangled with different neighboring links) and mix-and-match them in doing swaps (by temporal switching within a memory-based repeater node), there can be a significant performance improvement over protocols that do not employ time multiplexing. Given the constraints on memory-coherence time (how many time cycles can a memory hold on to a qubit), quantum processing logic available on the qubits held in the quantum memories, and switching losses, network topology, and entanglement demand, what is the optimal amount of time-multiplexing that should be used?

Rate-distance scaling	Repeater conditions
$R(L) \propto We^{-\alpha L}$,	no quantum repeater (direct point to point communication;)
$R(L) \propto We^{-s\alpha L}$, $s < 1$	dual rail qubits, probabilistic BSM, no temporal multiplexing ($m = 1$);
$R(L) \propto We^{-\beta\sqrt{\alpha L}}$.	same as above, but optimum m (i.e., optimally multiplexing over time).

4. *Scheduling protocol:* In a chain of network nodes, what schedule of BSMs (entanglement swaps) and purification would maximize the final (high-fidelity) entanglement rate, and minimize the resource overheads (memory, processing, sources, detectors, switches, etc.)? Should purification be deferred all the way to the end parties, or should it be done at the elementary link level, or somewhere in between? There has been initial work on this issue (Jiang *et al.*2007), but extending that to complex and realistic quantum network architectures remains open. This problem becomes even more interesting when a swarm of satellites is used, in a complex topology involving multiple criss-crossing orbits, supplying entanglement to several ground stations spanning the globe. The optimal dynamic scheduling of actions at each satellite and ground node, including BSM, purification, and time multiplexing (holding on to a qubit in a memory for a stipulated period of time) will depend upon various device metrics such as memory coherence times, gate fidelities, link losses, and network topology.

6.3.2 One-way Quantum Network Architecture

The class of protocols we discussed in Section 6.3.1 involve generating entanglement over elementary links, holding them in quantum memories at nodes for however long is needed to pair them with one another across neighboring links, then stitching them into longer-range entanglement using BSMs (swaps). An alternative to this approach is for the sender Alice to generate many entangled pairs locally, encode k copies of entangled pairs into one logical (error protected) Bell state, transmit that one hop over to the first repeater node—which performs a quantum decoding—followed by re-encoding the logical Bell state, and transmission to the next hop, etc., until the receiver Bob receives his half of the logical entangled state. At this point Alice and Bob communicate over the classical channel to distill clean ebits. Recent studies have shown that one-way protocol can be more resource efficient at the nodes, i.e., require fewer sources, memories and detectors, by about an order of magnitude while achieving the same end-to-end rate. However, the quantum logic needed at the network nodes is comparable to a small quantum computer.

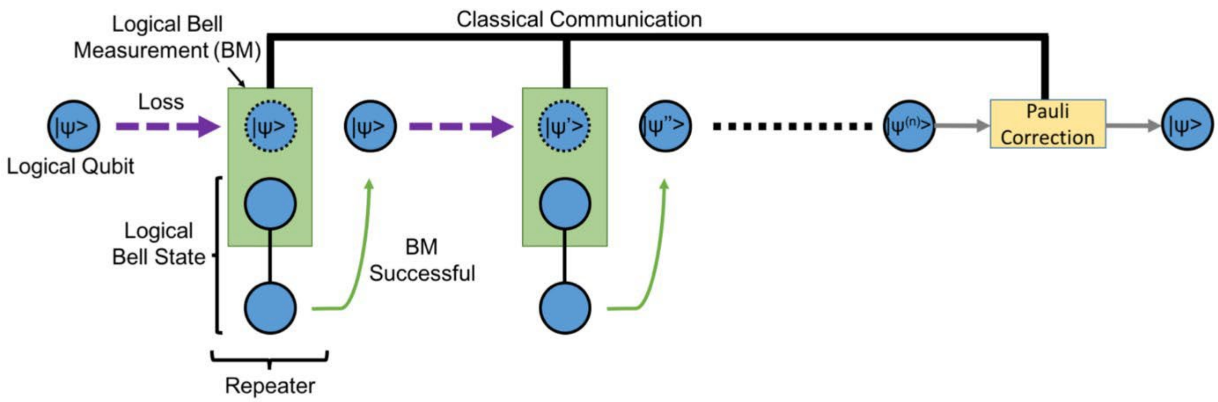


Figure 10. A high-level view of a one-way chain of quantum nodes in a network.

Important research questions include:

1. *Performance comparisons with specific quantum memory capabilities:* with corresponding two-way scheme built with the same devices
2. *Resource allocation protocols:* for one-way architecture at the networking layer will look different than two-way protocols; i.e., how to provision memories, frequencies (if using multiple spectral channels), BSMs, distributing shared code overheads among multiple simultaneous entanglement flows?
3. *Interoperability:* If a quantum data packet must traverse multiple network types en route to its destination, how do we interconnect and interoperate a two-way network with a one-way network? For example, this interoperability question may arise in routing quantum packets between a local-area high-speed one-way network and a transcontinental two-way network.

6.3.3 Choice of Qubit Encoding

Most quantum network demonstrations to date have used heralded spontaneous parametric downconversion (SPDC) sources of entanglement, which produce what are known as dual-rail qubits, where one photon in one of two orthogonal (polarization, temporal, or spectral) modes encodes the two states of the qubit.

There are multiple alternative ways to encode the qubit in photon, and there are competing tradeoffs in terms of qubit state preparation and the ease of doing gates. For example, Gottesman-Kitaev-Preskill (GKP) encoding of the qubit has recently been found to be the most loss-tolerant form of qubit encoding (Li *et al.* 2017), and methods of generating them have been found (Su, Myers, and Sabapathy 2019). Recent work has also shown potential large benefits to using higher dimensional encoding, e.g., simultaneously qubits in polarization and time bins, or using more than two time bins or spectral modes [(Piparo *et al.* 2020), (Piparo *et al.* 2019)].

Important research questions include:

1. *Resource-performance tradeoffs:* among different qubit choices: which qubit form requires more devices per repeater node, to achieve a given end-to-end rate vs. fidelity performance? What are the resource overheads for generating qubits and entangled qubits in these various qubit forms?
2. *Quantum memory compatibility:* What forms of quantum memory (ion, cold atom, superconducting, silicon vacancy centers) is best compatible with the chosen photonic qubit form (dual rail, single rail, GKP, hex-GKP, etc.), and also taking into account the frequency of the photon and bandwidth of the photonic qubit, and the memory.
3. *All-photonic quantum repeater nodes:* the action of quantum memory is mimicked by multi-qubit photonic entangled states [(Pant *et al.* 2017), (Azuma, Tamaki, and Lo 2015)]. If one wishes to construct repeater nodes that do not employ matter-based quantum memories—that will be readily compatible with the SPDC, linear-optical BSM and PNR detection-based elementary link discussed in Section 6.2—one will need sources of multi-photon entangled states, which can double up as an all-photonic quantum memory and processor. Design of all-photon repeaters taking into account the full continuous-variable (CV) description of SPDC-based single-photon and entanglement sources, i.e., including the effects of the multi-pair emission terms and lossy PNR detectors, remains an open question, which—if successful—will benefit the design of an all-photonic long-distance quantum network, assisted by SPDC-based long-distance satellite-enabled elementary links.

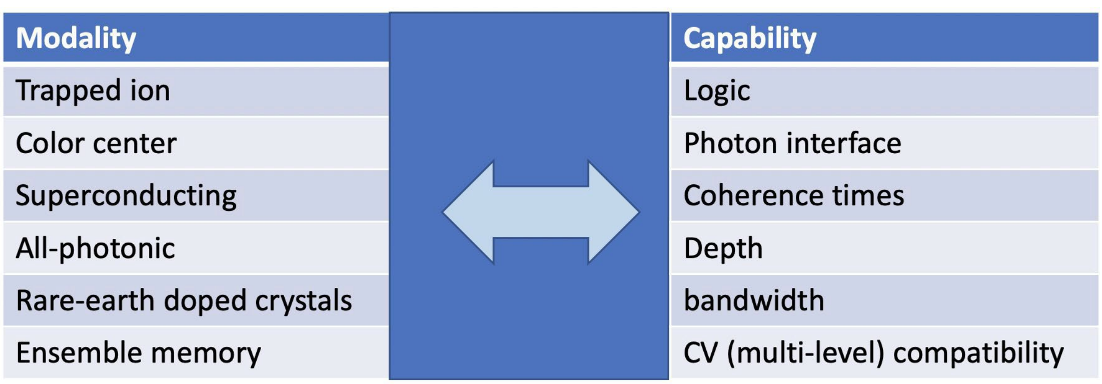


Figure 11. Different modalities of quantum memory and various facets of those memories (and processors), to be considered.

6.4 Design and Operation of a Satellite-based Quantum Network

6.4.1 Entanglement Distribution Protocols

For the purposes of the ensuing discussion, we will consider the following simple model. In each time slot, each network edge attempts to establish an entangled (elementary) link: a Bell state of two qubits, each residing in a quantum memory at nodes on either end of the link. In every time slot, each link is established successfully, with probability p, which is proportional to the transmissivity of the optical link. Subsequently, each node, based on local link-state information (i.e., which neighboring links succeeded in that time slot), and the knowledge of the location of the communicating parties Alice and Bob, decides which pairs of successful links to attempt to fuse using, for example a BSM. The two qubits that are fused with a BSM at a node, held in quantum memories, are destroyed in the measurement process, while creating an entangled (Bell) state among the two qubits at the far ends of the two links, thus creating a two-hop entangled link traversing two network edges. A fusion attempt succeeds with probability q. As was shown recently, with a simple distance-vector fusion rule, the achievable entanglement generation rate exceeds what is possible with a fusion schedule along a predetermined single shortest path connecting Alice and Bob (Pant *et al.*2019). This multipath rate advantage only requires local link-state information (success-failure outcomes of nearest neighbor links alone). Global link-state information is unrealistic, but if available, it can further improve the rate-distance scaling. Despite this rate advantage from multipath entanglement routing (be it with local or global link-state information), the end-to-end rate decays exponentially with the distance L between the communicating parties Alice and Bob, for any value of p and q less than 1.

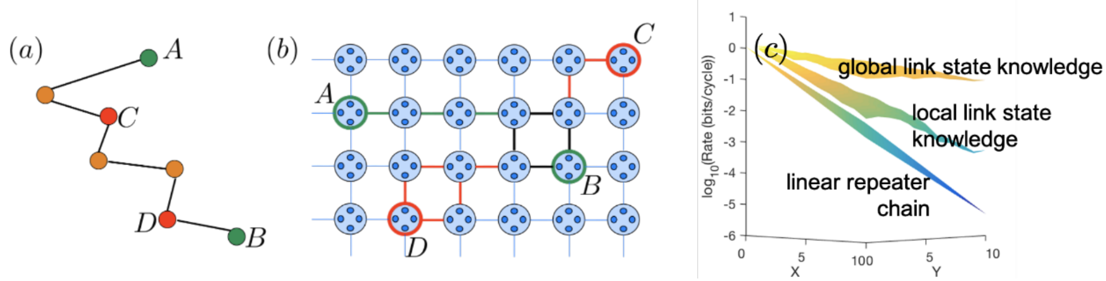


Figure 12. Cartoon of a generic node in the quantum network.

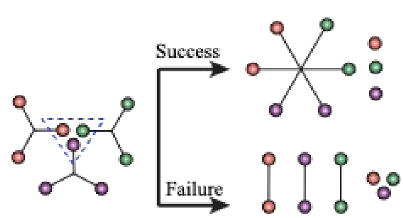


Figure 13. Three-fusion attempt on three 3-GHZ states

In recent work (Patil *et al.* 2020), a protocol was proposed that allows nodes to use n-qubit Greenberger-Horne-Zeilinger (GHZ) projective measurements, i.e., n-fusions, that can fuse n successful links at a node (to create an n-qubit entangled GHZ state held between n neighboring nodes). Implementing n-fusion is, in principle, not much harder than 2-fusions (Bell measurements) in solid-state qubit memories, e.g., color centers in diamond, and trapped-ion quantum processors. Let us take the success probability of n-fusion attempts as q. If we allow even 3-fusions at the repeater nodes, there is a non-trivial regime of (p, q) where this protocol generates entanglement at a rate that stays constant with the end-to-end rate L. This protocol only uses local link state knowledge, but requires a single-round of end-to-end classical communications that adds to the latency of the protocol.

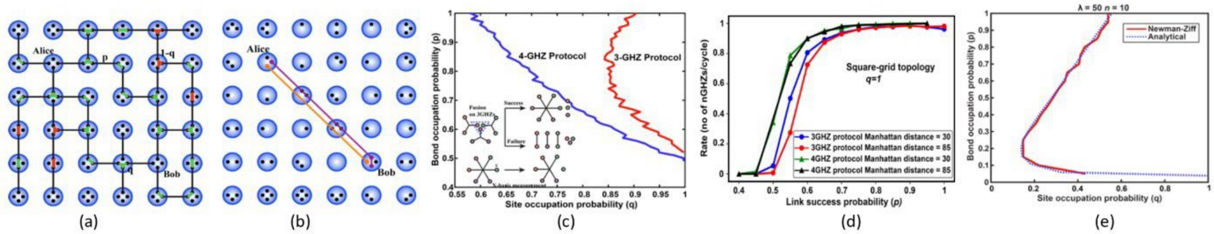


Figure 14. Quantum networking enabled by multi-qubit swap operations can enable distance-independent end-to-end entanglement generation rate.

Much remains to be done in designing entanglement distribution protocols for scalable quantum networks, assisted by satellite-based long-distance swapping service.

Important research questions include:

1. *Entanglement allocation protocols with dynamic and limited state information.* With multiple satellite-based quantum networks, one will need to develop protocols for end-to-end entanglement allocation that connect single-hop entanglement generation attempts dynamically between satellites and ground stations, so as to provide maximum end-to-end entanglement rates and fidelity to multiple communicating parties at ground stations.
2. *Account for realistic decoherence models for quantum memories.* The longer we store a qubit in memory, the lower its fidelity becomes, usually de-grading exponentially with time with an exponent determined by device considerations. This must be considered in designing routing protocols. Time multiplexing helps improve rates, but also degrades the qubits in the memory.

6.4.2 Orbit Trades, Satellite Node Placement, and Operation

We envision a future where an array of satellites will serve entanglement service around the globe between multiple groups of ground stations, serving multiple forms of entanglement, and serving multiple applications, on demand.

Such an architecture may involve LEO-assisted ground links, MEO-assisted LEO links, and hybrid orbit types. It may include the use of satellites that serve as a source of entanglement, and perhaps in addition routing an optical signal simply by collecting quantum light sent by another satellite and re-beamforming down to a ground station. There are important dynamic properties, such as trajectories that can be pre-calculated, and others such as varying atmospheric conditions, that cannot be pre-calculated and must be compensated for by adaptive optics. One could also envision *disruption tolerant networking* (DTN), where a satellite "hands over" stored quantum information to another while they transit each other. The design of network routing protocols—with such appropriate handovers based on memory coherence times, relative orbit placements and durations—forms a whole array of research challenges that have yet to be investigated. Finally, there is the network design problem: If we can select the number of satellites, how do we optimize the topology design, so as to maximize the overall network performance (e.g., "rate region" that it can support among a collection of user groups)? We recommend that NASA designs the initial program in such a way that, even if the initial deployment involves a single satellite, it is designed to be simple, yet remotely-reconfigurable—e.g., source with variable pump power, remotely controllable electro-optics to control a multiplexed source, pointing acquisition and tracking, and reconfigurable telescopes to act as collection optics and "reflecting" a collected beam down to another satellite or a ground station—such that, the network is forward-compatible as NASA (or other domestic or international agencies) decides to deploy more satellites into a richer, more powerful quantum network architecture.

6.5 Application-specific Considerations on Architecture

Different kinds of entanglement will be needed for different applications, e.g., discrete-variable (DV) two-qubit Bell states for quantum key distribution, n-qubit DV GHZ states for multiparty key exchange, continuous-variable (CV) n-mode entangled Gaussian states for enhancing, e.g., a distributed laser interferometer gravitation-wave observatory (LIGO). Any one form of entanglement service—along with fully equipped fault-tolerant memories and processors that may become available in the future—is equivalent to any other form of entanglement. In other words, even if the network is designed to support dual-rail qubit-based entanglement, it can be converted to n-qubit DV GHZ states, or n-mode CV entangled states. However, it is important to keep in mind the application(s) of most importance and relevance to the NASA mission, and its entanglement need, in architecting the satellite-based quantum network.

6.6 References

Azuma, Koji, Kiyoshi Tamaki, and Hoi-Kwong Lo. 2015. “All-Photonic Quantum Repeaters.” *Nature Communications* 6: 6787.

Bhaskar, M. K., R. Riedinger, B. Machielse, D. S. Levonian, C. T. Nguyen, E. N. Knall, H. Park *et al*. 2020. “Experimental Demonstration of Memory-Enhanced Quantum Communication.” *Nature* 580, no. 7801: 60–64.

Guha, Saikat, Hari Krovi, Christopher A. Fuchs, Zachary Dutton, Joshua A. Slater, Christoph Simon, and Wolfgang Tittel. 2015. “Rate-Loss Analysis of an Efficient Quantum Repeater Architecture.” *Physical Review*, A 92, no. 2: 022357.

Jiang, Liang, Jacob M. Taylor, Navin Khaneja, and Mikhail D. Lukin. 2007. “Optimal Approach to Quantum Communication Using Dynamic Programming.” *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 44: 17291–96.

Krovi, H., S. Guha, Z. Dutton, J. A. Slater, C. Simon, and W. Tittel. 2016. “Practical Quantum Repeaters with Parametric down-Conversion Sources.” *Applied Physics*. B, Lasers and Optics, https://link.springer.com/article/10.1007/s00340-015-6297-4.

Li, Linshu, Chang-Ling Zou, Victor V. Albert, Sreraman Muralidharan, S. M. Girvin, and Liang Jiang. 2017. “Cat Codes with Optimal Decoherence Suppression for a Lossy Bosonic Channel.” *Physical Review Letters* 119, no. 3: 030502.

Lo Piparo, Nicolò, Michael Hanks, Claude Gravel, Kae Nemoto, and William J. Munro.2020. “Resource Reduction for Distributed Quantum Information Processing Using Quantum Multiplexed Photons.” *Physical Review Letters* 124, no. 21: 210503.

Muralidharan, Sreraman, Linshu Li, Jungsang Kim, Norbert Lütkenhaus, Mikhail D. Lukin, and Liang Jiang. 2016. “Optimal Architectures for Long Distance Quantum Communication.” *Scientific Reports* 6: 20463.

Pant, Mihir, Hari Krovi, Dirk Englund, and Saikat Guha. 2017. “Rate-Distance Tradeoff and Resource Costs for All-Optical Quantum Repeaters.” *Physical Review*, A 95, no. 1: 012304.

Pant, Mihir, Hari Krovi, Don Towsley, Leandros Tassiulas, Liang Jiang, Prithwish Basu, Dirk Englund, and Saikat Guha. 2019. “Routing Entanglement in the Quantum Internet.” *Npj Quantum Information 5*, no. 1: 1–9.

Patil, Ashlesha, Mihir Pant, Dirk Englund, Don Towsley, and Saikat Guha. 2020. “Entanglement Generation in a Quantum Network at Distance-Independent Rate.” arXiv [quant-Ph], May 14, 2020. arXiv: http://arxiv.org/abs/2005.07247.

Piparo, Nicolò Lo, William J. Munro, and Kae Nemoto. 2019. “Quantum Multiplexing.” *Physical Review A*. DOI: www.doi.org/10.1103/physreva.99.022337.

Pirandola, Stefano, Riccardo Laurenza, Carlo Ottaviani, and Leonardo Banchi. 2017. “Fundamental Limits of Repeaterless Quantum Communications.” *Nature Communications* 8: 15043.

Su, Daiqin, Casey R. Myers, and Krishna Kumar Sabapathy. 2019. “Conversion of Gaussian States to Non-Gaussian States Using Photon-Number-Resolving Detectors.” *Physical Review,* A 100, no. 5: 052301.

Takeoka, Masahiro, Saikat Guha, and Mark M. Wilde. 2014. “Fundamental Rate-Loss Tradeoff for Optical Quantum Key Distribution.” *Nature Communications* 5: 5235.

7.0 Summary of Salient Findings and Conclusions

Listed below are abstracted summaries from the four chapters on mission goals, concepts, technology requirements, and systems architecture. The abstractions below are meant to convey the salient findings and the high-level recommendations in these four focus areas.

7.1 For Mission Goals

In the Goals chapter, the authors have sought to connect the national priorities for a quantum network to NASA's high-level goals, and subsequently to capabilities that can be enhanced or enabled through the utilization of quantum communications. We find that there are a number of capabilities that could likely be enabled by space-based quantum networks in the three prioritized general categories of networked quantum computing, quantum-enhanced sensor arrays, and enhanced communication applications. All of these categories are made possible by the distribution of quantum entanglement—the primary resource that enables most quantum-enhanced technologies.

Enabling a fully functional space-based quantum communication network across the entire application space will require a concerted and long-term effort. We find that there is a significant range of difficulty in realizing these capabilities. Some capabilities have a lower number of functional needs, while others require many. We find that capabilities such as secure communication are of lower complexity, at least for research environments, than those for sensor systems. We also find that those capabilities having the highest degree of difficulty are associated with the networking of quantum computers, as they have the greatest number of as yet unrealized functional needs. Based upon that estimation we find that the highest-value goal, a satellite linked general-purpose quantum network capable of, for example, connecting quantum computers, is also the most difficult. It will require a long-term research and development effort consisting of increasingly more complex demonstrations.

7.2 For Mission Concepts

In the Mission Concepts chapter, we detail Quantum Entanglement Distribution in Space Optical Network (qEDISON). qEDISON is a staged approach to establish linkable quantum entanglement distribution and entanglement swapping capabilities within and between the United States and other continents. This capability supports quantum networking, quantum computing, and quantum sensing applications. Stage 1 establishes high-fidelity, high-rate quantum communications capability between ground stations up to 1200 km apart—sufficient for creating a robust quantum optical link between regional quantum networks within the United States. qEDISON Stage 2 extends the capability to support ground station separation of up to 6000 km—sufficient to link American quantum networks with networks in Europe or East Asia. qEDISON will demonstrate system performance up to six orders of magnitude beyond (or "over a million times") what the Chinese Micius satellite achieved. It will provide quantum communications capabilities impossible to achieve with Micius, or any other proposed international quantum communications mission known to the authors.

The staged approach is recommended to manage program risk by proving performance of critical technology subsystems within the United States during Stage 1. These subsystems include implementing a robust time-synchronization protocol, applying a distributed pump architecture, implementing quantum communications using an adaptive optic system, and using high-rate, low-jitter, and low-noise ground system receivers. The value of focusing the development of these subsystems within the USA to foster the growth of a national quantum industry cannot be overstated. In particular, the Stage 1 achievements together will enable the first demonstration of entanglement linking between moving platforms. qEDISON is also future compatible—it is based on technologies that are available today, but is architected to support future technologies, such as quantum memories, when they become available. This is achieved by emphasizing linkable quantum entanglement—distributing high-fidelity entangled photon pairs that are usable by ground quantum networks, sensors, and computers.

7.3 For Mission Technology

NASA has an objective to serve as an operational Quantum Network provider, where intra-continental and intercontinental entanglement distribution is a service made available to users to enable U.S. national need and goals. Multiple demonstration architectures and mission concepts have emerged for consideration to enable this objective, and while additional analysis and verification is required to mature these early concepts, key technology tall poles and systems specifications have been identified for the concepts shared within this. Key technology tall pole highlights include quantum sources, detector arrays, single-photon receivers, optical terminals (space and ground), quantum modems, quantum memories, and other tall poles listed in the technology chapter. A key underlying capability gap also exists in the area of quantum networking analysis tools/approaches to enable standardized end-to-end telecommunications analysis of the quantum service provided and the interdependence of the underlying systems inclusive of the network access links and interfaces.

Due to the nascent nature of quantum networking, reaching a broad consensus was not a goal of the technology section, but rather understanding the technology and engineering landscape resulting from the various current mission concept approaches under development. Select and targeted investments in the applicable technology tall poles and engineering challenges to meet key systems requirements for a validated concept will enable a national capability demonstration and operational service within this decade.

7.4 For Mission Architecture

In the Architectures chapter, the authors envision, explore, and examine various architectural choices in satellite-based entanglement-distribution links to provide intercontinental-scale connectivity in the future quantum internet. The chapter discusses architecting a network supporting many users simultaneously that can deliver entanglement on-demand at a high rate, while maintaining a requisite high fidelity. The chapter discusses the mathematical foundations behind a single “elementary link”—a single satellite delivering heralded entanglement of a given fidelity and at a given rate—and discussed how such elementary links can be strung together into a larger network.

The Architectures chapter identifies many challenges and open questions with regards to most optimally designing and scaling a satellite-enabled quantum network, which should be investigated alongside a technology-development program that implements a single-satellite elementary link. Such investigations may be best coordinated with the National Institute of Science and Technology (NIST) and the National Science Foundation (NSF) who are investing in architecting the U.S. ground-based quantum internet. Examples of considerations include: how to create a network that is compatible with a diverse set of quantum memory and processor technologies, and what is the most resource-optimal way to architect a network that delivers fault-tolerant entanglement of multiple kinds to support multiple applications (such as quantum-enhanced long baseline imaging, distributed quantum computing, and quantum-secured communications) simultaneously among multiple user groups. The chapter recommends that NASA, at the outset of the initial technology-development program that implements a single-satellite elementary link, carry out a thorough investigation of orbit trades, placement of satellites in LEO and/or MEO orbits, and how to provision them, so that the NASA-architected quantum network is seamlessly forward-compatible to additions and upgrades.

List of Abbreviations

Acronym	Meaning
AO	Adaptive Optics
APD	Avalanche Photodiode
ASIC	Application-Specific Integrated Circuit
BBO	Beta-Barium Borate
BSA	Bell State Analysis
BSM	Bell State Measurement
C&DH	Command and Data Handling
CHSH	Clauser-Horne-Shimony-Holt (inequality)
cps	Count Per Second
CQT	Center for Quantum Technologies
CV	Continuous-Variable (entanglement)
CW	Continuous Wave (laser diode)
dB	Decibel
DLI	Delay-Line Interferometer
DOD	Department of Defense
DOE	Department of Energy
DSCO	Deep Space Optical Communications
DTN	Disruption Tolerant Network
DV	Discrete-Variable (entanglement)
EOM	Electro-Optical Modulation
EPPS	Entangled Photon Pair Source
EPS	Entangled Photon Source
ESA	European Space Agency
EU	European Union
FPGA	Field Programable Gate Array
FW1%	Full Width at 1%
FWHM	Full Width at Half Maximum
GEO	Geosynchronous Equatorial Orbit
GeV	Germanium Vacancy
GHZ	Greenberger-Horne-Zeilinger (measurements)
GKP	Gottesman-Kitaev-Preskill (encoding)
GLONASS	Global Navigation Satellite System (Russian)
GNSS	Global Navigation Satellite System (general)
GPS	Global Positioning System
GVM	Group Velocity Matching
HG	Hermite-Gauss (mode)
Hz	Hertz
InGaAs	Indium Gallium Arsenide (detector)
INQNET	INtelligent Quantum NEtworks & Technologies
ISS	International Space Station

Acronym	Meaning
JPL	Jet Propulsion Laboratory
K	Kelvin (temperature)
LCRD	Laser Communications Relay Demonstration
LEO	Low Earth Orbit
LG	Laguerre-Gauss (mode)
LIGO	Laser Interferometer Gravitational-Wave Observatory
LWE	Learning With Errors
MAScOT	Modular, Agile, Scalable Optical Terminal
MEO	Medium Earth Orbit
MgB2	Magnesium Diboride (superconductor)
MIT-LL	Massachusetts Institute of Technology (Lincoln Laboratory)
MLL	Mode-Locked Laser
MRI	Magnetic Resonance Imaging
NASA	National Aeronautics and Space Administration
NASA ARC	NASA's Ames Research Center
NASA GRC	NASA's Glenn Research Center
NASA GSFC	NASA's Goddard Space Flight Center
NbN	Niobium Nitride
NIR	Near Infrared
NISQ	Noisy Intermediate-Scale Quantum (processor)
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NV	Nitrogen Vacancy
OSTP	Office of Science and Technology Policy
OTCL	Optical Communications Test Laboratory
PAT	Pointing, Acquisition, and Tracking (system)
PNR	Photon Number Resolution
PNT	Position, Navigation, and Timing
PPKTP	Periodically Poled Potassium Titanyl Phosphate
PPLN	Periodically Poled Lithium Niobate
qEDISON	Quantum Entanglement Distribution in Space Optical Network
QIS	Quantum Information Science
QKD	Quantum Key Distribution
QLAN	Quantum Local Area Network
QND	Quantum Nondemolition (measurement)
QSA	Quantum State Analyzer
QTS	Quantum Teleportation from Space
RF	Radio Frequency
RLL	Run-Length Limited
RSA	Rivest-Shamir-Adleman (algorithm)
S/C	Spacecraft
SECOQC	Secure Communication based on Quantum Cryptography

Acronym	Meaning
SiV	Silicon Vacancy
SNR	Signal-to-Noise Ratio
SNSPD	Superconducting Nanowire Single Photon Detector
SPAD	Single-Photon Avalanche Diode
SPDC	Spontaneous Parametric Downconversion
SWAP(-C)	Size, Weight, and Power (-Cost) (requirements)
TRL	Technology Readiness Level
US(A)	United States (of America)
VBS	Variable Beam Splitting
VLBI	Very Long Baseline Interferometry
WFE	Waveform Error
YBCO	Yttrium Barium Copper Oxide (superconductor)

Workshop Agenda

Workshop on Space Quantum Communications and Networks Agenda
Developing the Roadmap to Quantum Communications in Space

Thursday, January 30, 2020	Function	Presenter
8:00am - 8:30am	Registration	Irene Tzinis / Jimmy Durden (NASA HQ)
8:30am - 8:45am	Welcome	Randy Katz, Vice Chancellor for Research UC Berkeley
8:45am - 9:00am	Logistics	Nasser Barghouty (NASA HQ)
9:00am - 9:30am	NASA SCaN Vision	Badri Younes (NASA HQ)
9:30am - 10:00am	NIST, Quantum Communications, and Clocks	Carl Williams (NIST)
10:00am - 10:30am	Current and Near-Future Experiments for Quantum Communications from Space	Paul Kwiat (University of Illinois - UC)
10:30am - 11:00am	Quantum Technology & NASA	T.R. Govindan (NASA ARC)
11:00am - 11:15am	BREAK	
11:15am - 11:45am	Leveraging Quantum in Communications & Sensing Systems - *A System's Perspective*	William Clark (General Dynamics Mission Systems)
11:45am - 12:15pm	Unconditional Security in Quantum Cryptography and Computation	Umesh Vazirani (UC Berkeley)
12:15pm - 12:30pm	Group Photo	
12:30pm - 1:30pm	LUNCH (box lunch for those who reserved or on your own)	
1:30pm - 2:30pm	Quantum Teleportation from Space (QTS)	Scott Hamilton (MIT-Lincoln Lab)
2:30pm - 3:00pm	Panel Discussions vs. Points of Departure	John Lekki (NASA GRC)
3:00pm - 4:45pm	Panel Discussions	Panel Chairs
4:45pm - 5:15pm	Day 1 Wrap-up	Nick Siegler (NASA JPL)
7:00pm	DINNER (pay at location) Skates on the Bay 100 Seawall Dr, Berkeley, CA 94710 in Skates Banquet - Bay View Room	

Workshop on Space Quantum Communications and Networks Agenda
Developing the Roadmap to Quantum Communications in Space

Friday, January 31, 2020	Function	Presenter
8:30am - 8:45am	Day 2 Warm-up	Nick Siegler (NASA JPL)
8:45am - 10:30am	Panel Discussions (continue)	Panel Chairs
10:30am - 10:45am	BREAK (and Chairs Meeting)	
10:45am - 12:00pm	Panel Discussions (continue)	Panel Chairs
12:00pm - 1:00pm	LUNCH (box lunch for those who reserved or on your own)	
1:00pm - 1:30pm	Panel Summation #1	John Lekki (NASA GRC)
1:30pm - 2:00pm	Panel Summation #2	Eleanor Rieffel (NASA ARC)
2:00pm - 2:30pm	Panel Summation #3	Babak Saif (NASA GSFC)
2:30pm - 2:45pm	BREAK	
2:45am - 3:15pm	Panel Summation #4	Saikat Guha (University of Arizona)
3:15pm - 4:00pm	General Discussions / Expectations	Nasser Barghouty (NASA HQ)
4:00pm - 4:15pm	Closing Remarks	Badri Younes (NASA HQ)
4:15pm - 4:30pm	Closing Remarks	Dan Stampur-Kurn (UC Berkeley)

Acknowledgements

Part of this report was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The Workshop organizers would like to particularly thank Irene Tzinis and Dr. Nick Siegler for their overall organization of the two-day event and Dr. Steven Beckwith and Doris Via of the Space Sciences Lab at the University of California (Berkeley) who helped with local planning. NASA's SCaN program would like to thank the editor, Angela Peura, and Dr. Nick Siegler for their coordination of the final document and excellent cat herding skills. Lastly, we thank all the participants of the Workshop and those who continued to work afterwards in synthesizing the ideas and discussions that commenced in Berkeley in January of 2020.

National Aeronautics and Space Administration

www.nasa.gov

National Institute of Standards and Technology
U.S. Department of Commerce