IAC-19-B2.7.12

Overview of NASA's National Space Quantum Laboratory Program

Scott A. Hamilton[a]*, Don M. Boroson[a], P. Ben Dixon[a], Matthew E. Grein[a], Nicholas D. Hardy[a], Thomas R. Howe[a], Catherine Lee[a], Ryan P. Murphy[a], Hemonth G. Rao[a], Neal W. Spellmeyer[a], Donald M. Cornwell[b], Nasser Barghouty[b], Barry J. Geldzahler[b], and Badri A. Younes[b]

[a] *MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420*
[b] *NASA Space Communications and Navigation (SCaN) Program, NASA Headquarters, 300 E Street Southwest Washington, DC, 20546 USA*
* Corresponding Author: shamilton@ll.mit.edu

Abstract

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.

In FY18, NASA initiated a hardware development program at MIT Lincoln Laboratory (MIT-LL) to enable a series of near-term space-based quantum communication demonstrations that leverage the agency's significant investment in classical lasercom hardware pathfinders. Our program is focused on developing technology to enable entanglement-based quantum network demonstrations over satellite-based downlinks and crosslinks. Critical technology development underway today includes: precision synchronization, high-rate heralded entanglement sources and variable storage-time quantum memory. The ultimate goal of the program is to deploy this quantum communication infrastructure on the International Space Station to provide a National Space Quantum Laboratory (NSQL) that can be used collaboratively by the quantum information science research community to characterize new quantum technologies and evaluate new quantum system applications enabled by quantum states distributed over long distances.

Quantum free-space communication links also require beam pointing, acquisition and tracking and a classical communication channel provided by RF or lasercom terminal technology. Today, MIT-LL is developing next-generation lasercom terminal hardware for NASA that will be used to demonstrate LEO-to-GEO bi-directional crosslinks and high-rate communications for Lunar downlinks. We envision that a near-term NASA free-space lasercom pathfinder will be leveraged to demonstrate NASA's first space quantum communication links. The Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) program will host a next-generation lasercom terminal developed by MIT-LL on the International Space Station in the 2022 timeframe. The ILLUMA-T lasercom terminal integrated with a quantum modem can also be used to demonstrate high-rate space-to-ground entanglement distribution and explore the feasibility of dual-span ground-to-ground links and smallsat quantum crosslinks.

In this presentation, we describe the objectives of NASA's NSQL quantum communications program and discuss key technologies employed in the space and ground terminals.

Keywords: Quantum Communication, Quantum Network, Entanglement Swap, Free-Space Optical Communication, Lasercom, and International Space Station)

Nomenclature

λ_{GB}: Ground terminal beacon broadened beam wavelength, λ_{SB}: Space terminal beacon broadened beam wavelength, and λ_{SQ}: Space terminal quantum communication and synchronization signal wavelength.

Acronyms/Abbreviations

Quantum Key Distribution (QKD), Quantum Experiments at Space Scale (QUESS), International Space Station (ISS), Low Earth Orbit (LEO), Pointing, Acquisition and Tracking (PAT), Quantum State Analyzer (QSA), Modular, Agile Scalable Optical Terminal (MAScOT), Spontaneous Parametric Down-Conversion (SPDC), Superconducting Nanowire Single-Photon Detector (SNSPD), Lunar Laser Communication Demonstration (LLCD), Laser Communication Relay Demonstration (LCRD), Optical Communications Terminal Laboratory (OCTL), Ground Station 2 (GS2), Advanced Maui Optical and Space Surveillance

Technologies (AMOS), and Advanced Electro-Optical System (AEOS).

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 finally systems that are enabled by connecting two non-classical systems.

Distributing and measuring weak pulses enables BB84 type QKD [1] 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 demonstrated 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 [2] 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 onboard their SOCRATES satellite [3]. 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 [4]. 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 [5]. 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 coutns) to two different ground terminals separated by ~1200 km [6] and Singapore's successful demonstration of entanglement source deployment and operation in space [7]. Micius also went a step further and achieved a preliminary feasibility demonstration of low-rate space-to-ground entanglement-based QKD [8] for use in future space-based architectures.

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 which 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 [9], 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.

2. System Overview

In FY18, MIT-LL began working with NASA to develop a plan for deploying quantum optical terminal technology on the ISS and demonstrating a scalable quantum network architecture that provides space-to-ground entanglement distribution and entanglement swap [10] functionality. Here, we use the term "scalable quantum network architecture" to describe a system where entanglement distribution is achieved with heralded photon pairs after a high-loss channel that arrive at their receivers in known time slots such that entanglement swap and/or quantum teleportation can be achieved with a single arbitrary quantum state. Critical quantum technology for enabling this architecture includes high-rate entanglement sources, efficient high-rate single-photon detectors and precision synchronization for efficient "flying qubit" photon-photon operations (e.g. entanglement swap). We believe that our demonstration of entanglement-based quantum communications from the ISS can be accomplished in the next few years by: 1) leveraging NASA's investment in space lasercom terminal technology development for near-Earth and Lunar applications and 2) utilizing a space-to-ground quantum downlink architecture where quantum technology complexity is biased toward the ground terminal (vs. the space terminal).

2.1 System Architecture

NASA's vision for enabling a scalable quantum network architecture is called the NSQL. The system architecture ultimately targets development of an integrated space and ground quantum network where the space segment comprises quantum downlinks, uplinks and crosslinks and the ground segment comprises fiber-connected ground stations and laboratories as shown in Figure 1. In this architecture, on-demand multi-node entanglement is ultimately enabled by quantum memory. High-rate entanglement distribution is also a goal for enabling development of non-classical distributed timing, sensing and computing applications. To achieve these goals, the NSQL architecture must provide a straightforward path for integrating new quantum communication technology, e.g. quantum repeaters, and new quantum-enabled applications/protocols. We believe these goals can be met by deploying the primary space quantum node on the ISS since significant payload size, weight and power is readily available. In addition, the ISS space node will also accommodate technology with varying levels of flight maturity due to the moderate radiation environment and availability of special-purpose flight packaging structures designed to enable simple integration of lab-grade equipment on the ISS [11]. The ground terminals will accommodate integration of new technology by utilizing research facilities that enable laboratory-grade technology to be straightforwardly coupled to the optical aperture. The NSQL architecture will enable new quantum communication applications

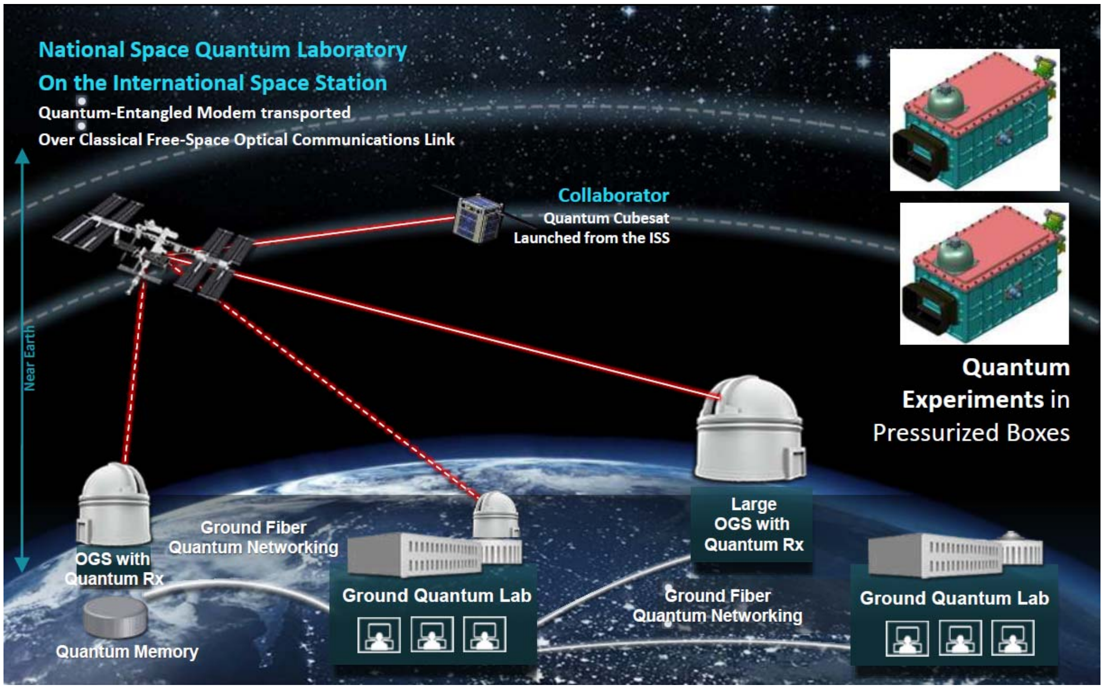

Fig. 1. NASA National Space Quantum Laboratory targets development of an entanglement-based quantum network research environment. The system architecture includes integrated space and ground quantum network where the space segment comprises quantum downlinks, uplinks and crosslinks and the ground segment comprises fiber-connected ground stations and laboratories.

and protocols by locating primary system functionality and processing complexity at the system edge, i.e. ground terminals.

The first phase of NASA's NSQL development will target the demonstration of space-to-ground quantum downlinks between a LEO spacecraft and one, or possibly two, ground terminals. The ISS will host the quantum payload which is comprised of one, or possibly two interconnected, fully-gimballed quantum terminals instrumented with a high-rate entanglement source, precision clock and quantum state analysis hardware for projecting the measured photon onto two orthogonal basis states, measuring which time slots are filled with entangled-photon pairs, and performing tomographic entanglement-source self-test functionality. Ground terminals will be instrumented with entanglement source, clock regeneration, quantum state analysis and entanglement swap hardware. The primary quantum communication protocols, e.g. entanglement distribution and swap, will be processed at the ground terminal. The system architecture for the NSQL first phase demonstration is shown in Figure 2.

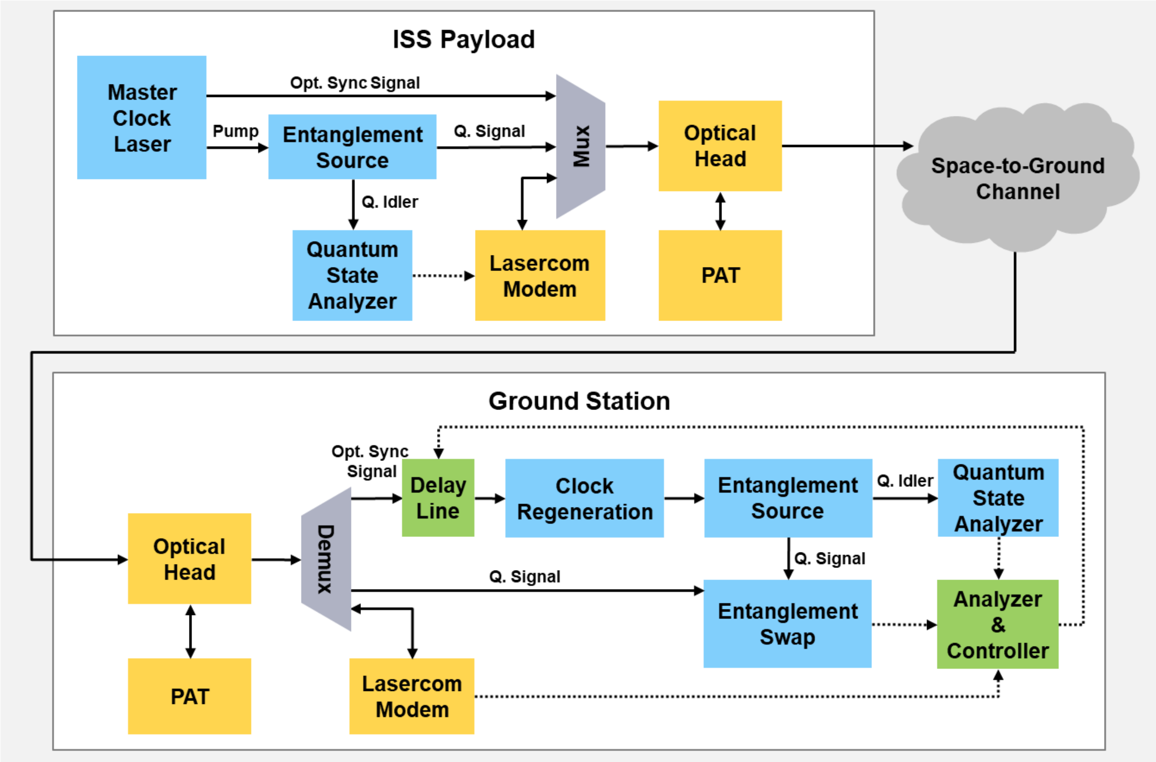

Fig. 2. NSQL space-to-ground entanglement swap quantum downlink system architecture.

2.2 Quantum Link Initiation

In order to maximize link efficiency, narrow optical beams with precise optical beam control will be used to reduce pointing jitter to a fraction of a beamwidth. The space and ground quantum terminals will utilize the following PAT process derived from previously demonstrated lasercom systems: i) the ground terminal will scan a broadened beam at wavelength, λ_{GB}, toward the space terminal; ii) the space terminal detects light from the ground terminal on its acquisition sensor and directs a broadened beam at wavelength, λ_{SB}, toward the ground terminal; iii) the ground terminal detects light from the space terminal on its acquisition sensor and also uses a portion of this light to begin tracking/compensating atmospheric fluctuations via adaptive optics; and iv) the space terminal begins transmitting a diffraction-limited beam to the space terminal at wavelength, λ_{SQ}, which includes the quantum communications signal and a classical synchronization and lasercom signaling waveform. At the beginning of the acquisition process, pointing errors are caused by imprecise knowledge of ground terminal orientation and the initial position and orientation of the space terminal. At the end, tracking errors are caused by residual loop error (i.e. noise equivalent angle) and uncorrected line-of-sight jitter. Our goal will be to maintain residual tracking errors to a fraction of the diffraction-limited signal beamwidth. Such performance has been demonstrated in previous lasercom flight programs, c.f. [12].

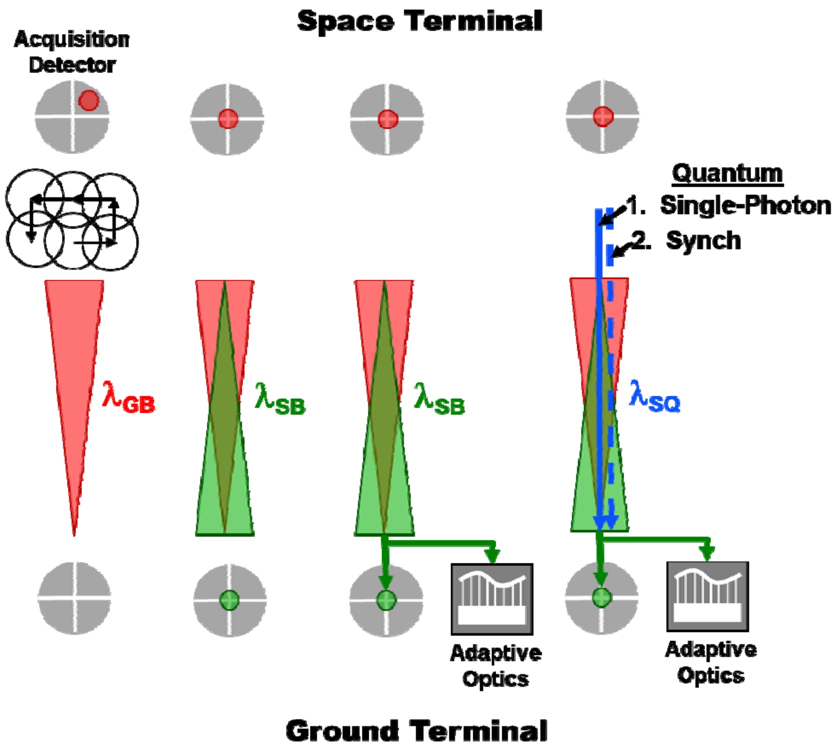

Fig. 3. NSQL Optical Link Acquisition and Quantum Signaling Initiation Process

2.3 Single-Span Space-to-Ground Entanglement Swap

After optical tracking has been established between the space and ground terminals, quantum communications can be initiated. For the single space terminal quantum downlink case, the primary goal will be to achieve kHz-class, or higher, entanglement swap rates. Demonstration of this capability requires pulsed high-rate entanglement sources located at the space and ground terminals that each generate two independent pairs of entangled photons S1-S2 (space source) and G1-G2 (ground source). Entanglement swap begins when one half of the space pair, S1, is transmitted to the ground terminal and a joint Bell-state measurement [13] is made at the gate in Figure 4 with one half of the ground pair, G1. During the Bell-state measurement, photons S1 and G1 are projected onto one of four Bell states and the remaining photons, S2 and G2, also collapse into a Bell state and are entangled even though these two remaining photons have never directly interacted. Single-span entanglement swap verification will be achieved by heralded measurements of entangled photons S2 and G2 with their respective QSA subsystems at the space and ground terminals.

Because photonically-adressable quantum memory is unlikely to be fully developed in time for the first phase of the NSQL flight demonstration, precision synchronization of the space and ground entanglement sources is critical. This is challenging to achieve due to the high-velocity and large optical link dynamic range imposed by the spacecraft orbit. The NSQL precision synchronization architecture is its own topic and will be further developed in a future publication. Here, we note that our architecture will utilize source heralding and leverage optical comb-based precision time-frequency transfer techniques. This approach will enable efficient joint measurements on photons S1 and G1 which must maximally overlap their temporal coherence envelopes for efficient interferometric interaction at the Bell-state measurement gate.

2.4 Dual-Span Ground-to-Ground Entanglement Swap

If two quantum terminals are deployed with the spacecraft quantum payload, the space-to-ground entanglement swap downlink capability described above can be extended to enable dual-span ground-to-ground entanglement swap functionality. To demonstrate this capability, the two quantum terminals each point to a unique ground terminal and establish independent optical links where the range between the ground terminals is determined by the satellite's field of regard, i.e. orbit altitude. Dual-span entanglement swap is initiated when one half of an entangled photon pair generated at the spacecraft is transmitted from each space terminal to their respective ground terminals. At

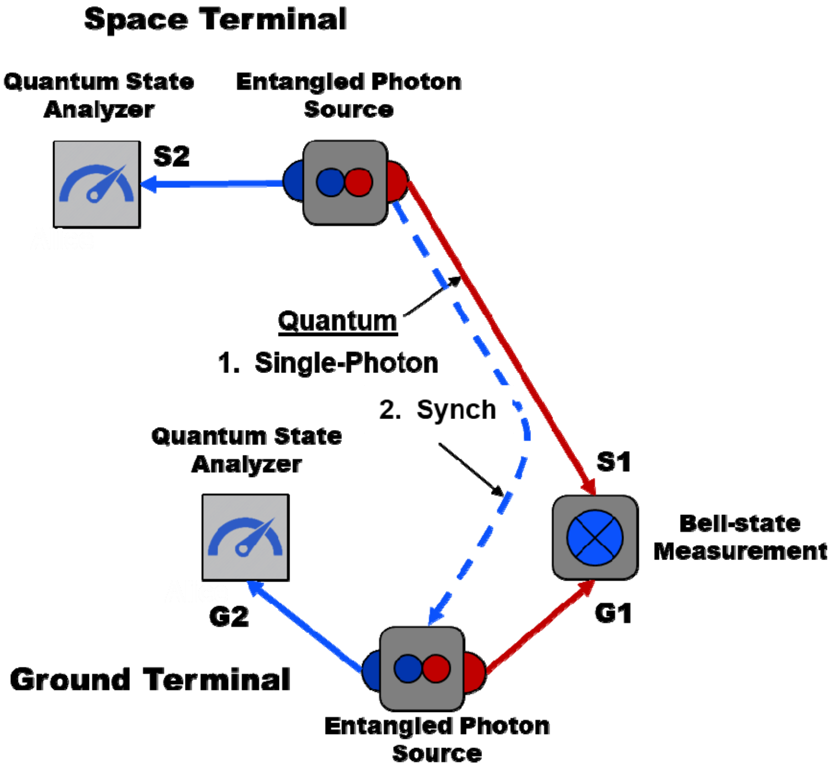

Fig. 4. Single-span space-to-ground entanglement swap operation.

each ground terminal, a joint Bell-state measurement is made between the received space photon and half of a photon pair independently generated at the ground terminal. After successful Bell-state measurements at each ground terminal, the remaining photons at each ground terminal will thus be entangled. In order to demonstrate interesting dual-span entanglement swap rates over useful ground terminal separation distances, significant technology development is required including photonically-adressable quantum memory, very high-rate entanglement sources and large-aperture space and ground terminals. A dual-span entanglement swap capability enhances NASA's overall goal for NSQL of providing a unique laboratory for enabling distributed quantum information science collaborations, and will facilitate ground terminal and quantum technology partnering between research groups separated by, potentially, trans-oceanic distances.

3. Optical Terminal Technology

The NSQL architecture requires development of high-performance quantum technology to enable entanglement-based quantum communications over space-to-ground or dual-span ground-to-ground links. To enable a flight demonstration in 3-5 years, NSQL will leverage NASA's substantial investment in classical lasercom space and ground terminal development over the past decade [14]. Generally, the NSQL system achieves space-to-ground links using classical lasercom terminal technology and quantum communications functionality largely resides in a quantum modem that is fiber-coupled to a lasercom terminal.

3.1 Optical Terminal Design Drivers

Multiple considerations drive the design of lasercom terminal technology. For NSQL, 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. 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 inhomogeneities 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 [15]. A point receiver in the far field will see time varying irradiance that can vary as surges of several dB and fades of several 10's of dB [16]. 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 [17]. To minimize optical loss due to the atmospheric channel, NSQL space and ground terminals will employ active tracking beam control via a fast-steering mirror to compensate beam tilt [18], and adaptive optics at the ground terminal to compensate higher-order turbulence-induced aberrations [19].

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 [20], 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 NSQL, 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 NSQL ground terminals) is described in [21].

The space environment presents multiple challenges that drive optical terminal hardware design. First, the terminal subsystems must survive large random vibration and shock loads imposed by the rocket during the launch and space deployment phase. Once deployed on the space platform, the terminal must survive and successfully operate through an aggressive thermal environment during different points in the spacecraft orbit that see direct solar illumination and Earth shadow. Depending on the orbit, the terminal hardware may also need to survive a challenging radiation environment. While developing the first US high-rate space lasercom terminal more than 25 years ago, MIT-LL established a process for designing, building and verifying lasercom terminal prototype hardware for reliable operation in the space environment [22]. NSQL will leverage NASA-developed space lasercom terminal hardware and apply the same best-practice design principles to the quantum communication technology that will be integrated with the space lasercom terminal to make up the quantum flight payload.

3.2 Space Terminal Optical Module

Today, NASA is developing an evolved lasercom terminal that will find its first use deployed on the ISS for the ILLUMA-T program and the Orion crew vehicle as part of the Orion EM-2 Optical communications demonstration (O2O) program [23]. The ILLUMA-T lasercom terminal provides the basis for NASA's NSQL quantum communications terminal because the optical module, or beam director, architecture is flexible to accommodate design modifications required to meet quantum communication performance requirements and the terminal hardware is already designed for integration with the ISS.

The optical module developed for the ILLUMA-T program is referred to as the MAScOT [24]. The MAScOT is under developed to support a wide range of space missions. MAScOT is also attractive for quantum communications since the modular architecture allows leveraging of subassemblies, i.e. telescope, latch and gimbal, and back-end optics, developed for lasercom with straightforward modifications as required for the quantum communication mission. Because the architecture is scalable, the prototype optical module 10-cm telescope aperture can be increased to enhance the quantum communications performance without significant changes to other subassemblies. The architecture provides greater than hemispherical field-of-regard and PAT capability for a fast moving LEO spacecraft. The MAScOT beam director provides a straightforward modem interface via optical fibers connected to the back-end optics assembly.

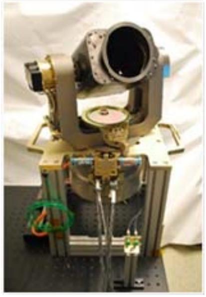

Fig. 5. MAScOT optical module engineering unit prototype.

3.3 Space Terminal Quantum Modem

The NSQL quantum communications terminal will be comprised of a MAScOT optical module that provides transmit and receive optical beam conditioning and opto-mechanical beam pointing functionality. The optical module will interface with the Controller Electronics, Quantum Modem, and Power Converter Unit subsystems. The Controller Electronics subsystem is responsible for processing terminal command, control and telemetry signaling as well as integrating spacecraft attitude determination and control information with terminal pointing information to provide precision optical beam PAT control. The Quantum Modem is responsible for generating quantum and classical transmitted waveforms. The Power Converter Unit converts 120 V bus power to 28 V conditioned power for the lasercom terminal subsystems.

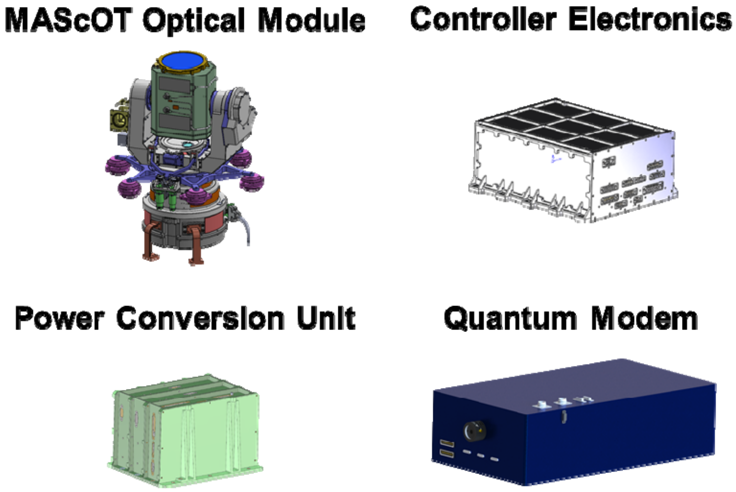

Fig. 6. Space terminal quantum communication subsystems.

3.3.1 High-Rate Entanglement Source Technology

Entangled photon pairs will be generated at the space and ground terminal using SPDC. For the NSQL system architecture shown in Figure 2, our SPDC source is comprised of two blocks: the Master Clock Laser block incorporates a mode-locked laser that pumps the Entanglement Source block which is composed of a nonlinear crystal waveguide and entanglement generation optics. For NSQL, the SPDC sources must enable high-fidelity, high-rate entanglement swap performance at the ground terminal. To achieve this goal, entangled pairs must be generated using GHz laser-pump clock rates in spectrally-pure states. Previously, we have demonstrated that near-unity spectral purity can be achieved with an SPDC source employing Gaussian phase-matching by varying the duty cycle of each poling period along the length of a first-order grating in a nonlinear bulk crystal [25]. We have also demonstrated near-unity fiber coupling efficiency for entangled photon pairs output from an SPDC bulk nonlinear crystal [26]. For NSQL, our SPDC sources will utilize bandwidth matching of the modelocked laser pump and nonlinear crystal bandwidth for generation of entangled photon pairs into spectrally-pure modes without losses due to filtering. Waveguide nonlinear crystals will be used in our SPDC sources to maximize entanglement generation rate with practical pump laser power.

3.3.2. Single-Photon Detector Technology

Characterization of entangled photon pairs at the space and ground terminals will be accomplished using the QSA block in the NSQL system architecture show in Figure 2. Primary functions required for this subsystem include projection of the measured photon onto two orthogonal basis states, measurement of time slots filled with entangled-photon pairs, and tomographic self-test of the terminal's local entanglement-source. Efficient single-photon sensitive detector technology is the critical technology element in the QSA. Previously, we have demonstrated SNSPD array technology using niobium nitride nanowires cooled to approximately 2.5K that achieves high efficiency, high count rate, low dark count, and low jitter single-photon detection [27]. We have also developed a robust SNSPD receiver system shown in Figure 7 for the Lunar Laser Communication Demonstration that was built at MIT-LL and deployed to the ground terminal site at White Sands, NM where it operated for the duration of the mission without interruption [28]. For NSQL, an interesting challenge for the space terminal QSA will be to develop a high-efficiency SNSPD receiver array and cryocooler assembly that efficiently detects photons at GHz rates and is compatible with the space environment. The NSQL ground terminal QSA requires development of a high-rate robust SNSPD array and cryocooler system that operates during day and night background conditions with high single-photon detection efficiency. We plan to leverage our considerable SNSPD detector array and deployable receiver system experience to successfully accomplish this task.

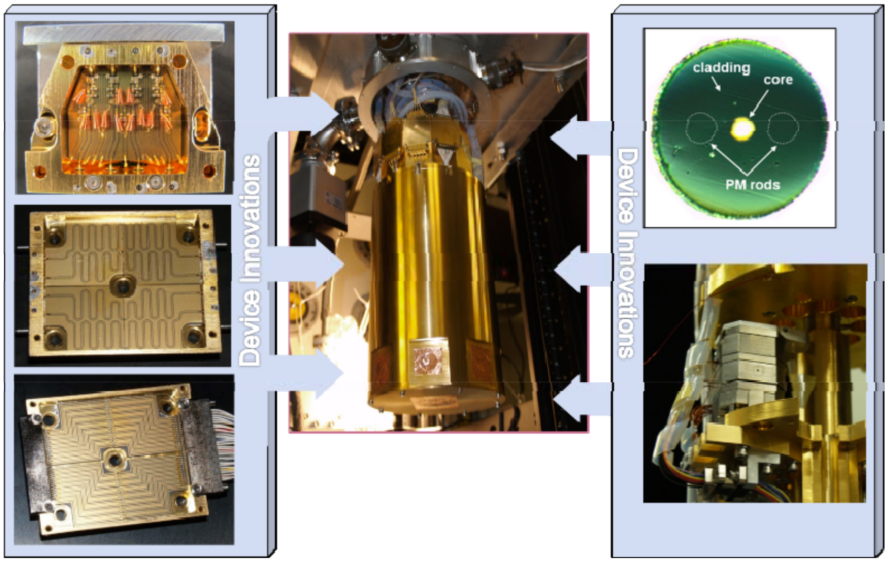

Fig. 7. High-rate superconducting nanowire single-photon detector array receiver used for day/night photon-counting during the LLCD.

3.4. *Quantum Space Payload Integration*

For deployment on the ISS, the quantum payload will be integrated into an approximately “refrigerator-sized” payload structure as shown in Figure 8. The structure will be delivered via rocket to the ISS and robotic arms will extract the quantum payload structure from the rocket and connect it to Japanese Expansion Module Exposed Facility. The quantum payload can also be packaged for integration with a medium-sized satellite where the optical module is likely to be externally integrated to provide maximum field-of-regard and the other quantum payload subsystem boxes are integrated inside the spacecraft.

3.5 *Ground Terminal*

Today, NASA is developing two ground terminals for the LCRD program [29]. The two ground terminals are designed to support multi-rate Gbps-class lasercom links from a geosynchronous relay satellite and both terminals are under consideration for NSQL ground terminal use. Two additional ground terminals are being considered for NSQL, the third due to its large aperture and the fourth due to its East Coast location and connectivity with deployed optical fiber with designated research wavebands.

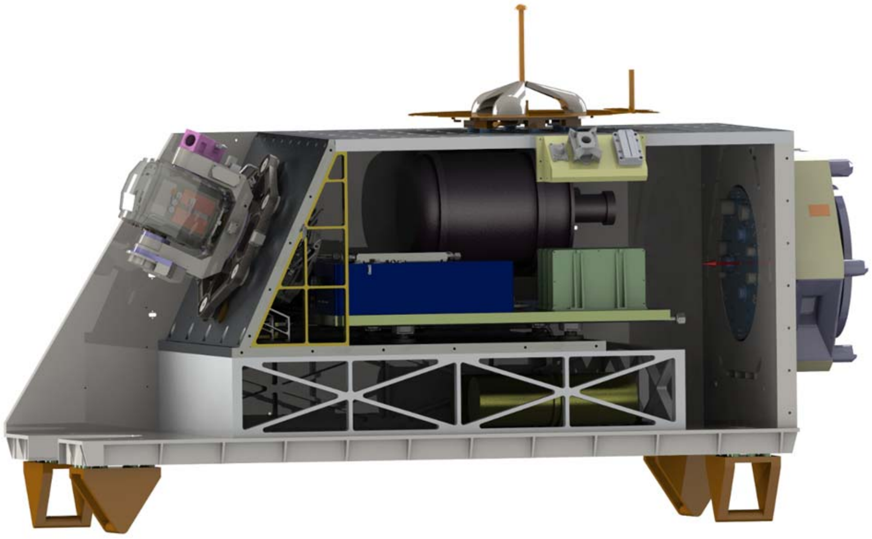

Figure 8. Quantum space terminal flight payload configuration for deployment on the ISS Japanese Expansion Module Exposed Facility.

The first LCRD ground terminal will utilize the Jet Propulsion Laboratory's OCTL at their Table Mountain Facility near Wrightwood, CA. OCTL provides a large 1-m aperture integrated on a mount capable of tracking satellites in a wide range of orbits. OCTL is currently developing a 1550-nm adaptive optics system for the LCRD program which could provide compatibility with an NSQL quantum receiver fiber interface. The OCTL telescope is coupled via Coudé path to an optical laboratory with sufficient space to provide a laboratory environment supporting investigation of newly developed quantum communication technology.

The second LCRD ground terminal will utilize MIT-LL's GS2 terminal located at the AMOS site on Mt. Haleakala, Maui. GS2 provides a 0.6-m telescope aperture and is capable of acquiring the LCRD spacecraft and supporting a duplex lasercom link. GS2 was deployed with a 1550-nm adaptive optics system and supports compatibility with an NSQL quantum receiver fiber interface. GS2 was designed to explore autonomous operations of key subsystems and does not provide flexible laboratory space that may be required for new quantum communications technology.

Two additional ground terminals not currently under development for supporting upcoming lasercom flight demonstrations have also received consideration for NSQL use. The third terminal is termed the AEOS and operated by the Air Force Research Laboratory at the AMOS site on Mt. Haleakala, Maui. AEOS provides the largest aperture telescope at 3.67 m and is integrated on a mount capable of tracking satellites in a wide range of orbits. AEOS does provide a Coudé path that couples an optical research laboratory to the aperture, but does not currently have a 1550-nm adaptive optics system.

The fourth facility that has received consideration for supporting NSQL quantum downlinks is the Firepond telescope facility operated by MIT-LL at the Haystack Observatory in Westford, MA. Firepond provides a large 1.2-m aperture and is integrated on a mount capable of tracking satellites in a wide range of orbits. Firepond also utilizes a Coudé path that interconnects the aperture with an optical research laboratory. Like AEOS, the terminal does not currently have a 1550-nm adaptive optics capability integrated with the telescope. A unique feature of Firepond is that the telescope facility is connected to a pair of optical fibers with optical research wavebands that can be utilized to support integrated free-space and fiber-optic multi-hop quantum network research during the NSQL program.

4. Conclusion

NASA has initiated an effort to develop a National Space Quantum Laboratory that provides a space-based entanglement distribution and swap capability from the International Space Station in low Earth orbit. A near-term flight demonstration can be achieved by leveraging NASA's substantial investment in space- and ground-terminal development for near-Earth and Lunar applications. A primary goal for the system is to accommodate integration of new quantum technologies and exploration of new quantum communication applications and protocols that could lead to distributed quantum network entanglement-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.

Acknowledgements

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

This material is based upon work supported by the National Aeronautics and Space Agency under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Agency.

Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work.

References

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

[2] S.-K. Liao, et al., “Satellite-to-ground quantum key distribution,” Nature, vol. 549, pp. 43–47, 2017.

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

[4] K. Günthner, et al., “Quantum-limited measurements of optical signals from a geostationary satellite,” Optica, vol. 4, Issue 6, pp. 611-616, 2017.

[5] A. K. Ekert, “Quantum cryptography based on Bell’s theorem,” Physical Review Letters, vol. 67, Issue 6, pp. 661–663, 1991.

[6] J. Yin, et al., “Satellite-based entanglement distribution over 1200 kilometers,” Science, vol. 356, pp. 1140-1144, 2017.

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

[8] J. Yin, et al., “Satellite-to-Ground Entanglement-Based Quantum Key Distribution,” Phys. Rev. Lett., vol. 119, pp. 200501, 2017.

[9] J.-G. Ren, et al., “Ground-to-satellite quantum teleportation,” Nature, vol. 549, pp. 70–73, 2017.

[10] M. Żukowski, et al., ‘‘Event-ready-detectors’’ Bell experiment via entanglement swapping,” Phys. Rev. Lett., vol. 71, pp. 4287, 1993.

[11] P. Roberts, ISS Higher Rate Communications Upgrades, 26 July 2016, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160009326.pdf. *(accessed 03.10.19).*

[12] D. M. Boroson, et al., “Overview and results of the Lunar Laser Communication Demonstration,” Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI; pp. 89710S, 2014.

[13] Christian Schmid, et al., “Quantum teleportation and entanglement swapping with linear optics logic gates,” New J. Phys., vol. 11, p. 033008, 2009.

[14] D. M. Cornwell, “NASA's optical communications program for 2017 and beyond,” 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2017.

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

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

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

[18] G. C. Loney, "Design of a High-Bandwidth Steering Mirror for Space-Based Optical Communications," Proc. of SPIE, vol. 1543, pp. 225-235, 1991.

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

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

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

[22] A. D. Pillsbury, "LITE engineering model-II: the flight-qualified subsystems," Proc. SPIE 1866, Free-Space Laser Communication Technologies V, 1993.

[23] A. Seas, et al., "Optical communications systems for NASA's human space flight missions," Proc.

SPIE 11180, International Conference on Space Optics — ICSO, 2018.

[24] T. Shih, et al., “A modular, agile, scalable optical terminal architecture for space communications,” 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS), 2017.

[25] P. B. Dixon, et al., "Spectral engineering by Gaussian phase-matching for quantum photonics," Opt. Express, vol. 21, pp. 5879-5890, 2013.

[26] P. B. Dixon, et al., “Heralding efficiency and correlated-mode coupling of near-IR fiber-coupled photon pairs,” Phys. Rev. A, vol. 90, pp. 043804, 2014.

[27] D. Rosenberg, et al., "High-speed and high-efficiency superconducting nanowire single photon detector array," Opt. Express, vol. 21, **pp.** 1440-1447, 2013.

[28] M. E. Grein, et al., “An optical receiver for the Lunar Laser Communication Demonstration based on photon-counting superconducting nanowires,” Proc. SPIE 9492, Advanced Photon Counting Techniques IX; 2015.

[29] D. J. Israel, et al., “Laser Communications Relay Demonstration (LCRD) update and the path towards optical relay operations,” 2017 IEEE Aerospace Conference, 2017.