

Towards the Space Qualification of a Bi-Wavelength Quantum Payload for Autonomous Generation and Detection of Entangled Photon Pairs

Gustavo Amaral^a, Nienke ten Haaf^a, David Bakker^a, Mark Boekel^a, Bart Peeters^a, Daniela Birca^a, Daniel van der Velde^a, Zahra Sadre Momtaz^a, Jelle Vonk^a, Glenn van Zalen^a, Yoram Vos^a, Alper Ozulker^b, Muhammed Izcinar^b, Salih Durak^b, Fatih Emin Aslan^b, Sander van Haagen^b, and Kartal Cona^b

^aTNO, Stieltjesweg 1, 2628 CK Delft, The Netherlands

^bQubitrium, Delftechpark 1, 2628 XJ Delft, The Netherlands

ABSTRACT

Quantum communication, the transmission of quantum information encoded onto photons between distant terminals, has attracted substantial investment over the past twenty years. While terrestrial optical fibre networks are inherently limited by transmission losses, satellite-based quantum communication enables global-scale connectivity and constitutes an essential component of future quantum networking infrastructures. Europe is currently investing heavily in this direction through EuroQCI and associated space missions, creating a growing demand for space-qualified quantum hardware. In this work we present the development and environmental qualification of a bi-wavelength autonomous quantum payload developed jointly by TNO and Qubitrium. The payload integrates two complementary entangled photon-pair source technologies operating at near-infrared and telecommunications wavelengths together with dedicated single-photon detection, time-tagging and onboard processing subsystems. Particular emphasis is placed on the qualification campaign performed in preparation for launch aboard the EPIQ mission. The qualification programme comprised mechanical, thermal, contamination and integration activities, including vibration, shock, thermal cycling, bake-out and thermal-vacuum testing. Critical vulnerabilities were identified in fibre-array attachment, wire-bond robustness, thermal management and the accommodation of commercial off-the-shelf optical components. Corrective actions were implemented and verified through iterative subsystem and payload-level testing. The results demonstrate a practical pathway for increasing the Technology Readiness Level of integrated quantum photonic technologies while providing valuable insight into the engineering bottlenecks associated with future quantum communication missions. Beyond qualification of a specific payload, the campaign contributes to emerging discussions regarding interoperability, standardization and hardware architectures for the next generation of space-based quantum networks.

Keywords: Quantum communications, quantum payloads, entangled photon-pair sources, photonic integrated circuits, space qualification, quantum networks

1. INTRODUCTION

Quantum communication has evolved from a predominantly academic discipline into a strategic technological capability attracting substantial worldwide investment. Beyond quantum key distribution, the long-term vision of quantum communications encompasses distributed quantum computing, blind quantum computing, distributed quantum sensing, and ultimately a global quantum internet.^{1,2} The principal challenge faced by terrestrial quantum networks is optical loss. Even with state-of-the-art optical fibre infrastructure and the future development of quantum repeaters,^{3,4} transmission losses limit ground-based quantum links to few hundred kilometres. Space-based quantum communications provide an attractive alternative by exploiting low-loss free-space propagation between orbital and terrestrial terminals.⁵ Consequently, an increasing number of international initiatives, including EuroQCI,⁶ Eagle-1,⁷ SAGA and ESA's QUASAR programme, rely on the availability of space-qualified quantum hardware. A key enabling technology for the next generation of trust-free quantum networks is the

Correspondence: gustavo.castrodoamaral@tno.nl

entangled photon-pair source (EPPS). Despite impressive demonstrations worldwide, very little consensus currently exists regarding the preferred implementation of such systems. Different operating wavelengths, source architectures, encodings and detector technologies are currently being pursued in parallel.^{8,9} For this reason, representative demonstrator missions capable of evaluating multiple technical approaches under realistic space conditions are particularly valuable. Previous in-orbit demonstrations have shown the feasibility of satellite-based quantum key distribution, quantum teleportation and long-distance entanglement distribution, but have relied predominantly on bulk-optical implementations rather than photonic integrated circuits.^{8–10} Photonic Integrated Circuits (PICs) offer a compelling route towards scalable deployment of quantum communication hardware. Their reduced size, weight and power consumption, combined with the possibility of large-scale manufacturing, make them attractive candidates for future satellite payloads. However, demonstrating quantum functionality alone is insufficient. Integrated quantum photonics must also demonstrate survivability under launch loads, thermal cycling, vacuum operation and long-term autonomous operation. The work presented in this paper focuses on this transition from laboratory demonstrators towards flight-ready hardware.

2. PAYLOAD ARCHITECTURE

The EPIQ mission was conceived as a representative demonstrator system capable of autonomously generating and measuring entangled photon pairs in orbit. Rather than evaluating a single source technology, the mission integrates two complementary quantum communication payloads within a common spacecraft platform. The first payload is based on a free-space coupled PPKTP crystal source operating at approximately 810 nm and generating polarisation-entangled photon pairs.¹¹ This wavelength range benefits from comparatively low beam divergence in free-space propagation and highly efficient single-photon detection using silicon avalanche photodiodes. The second payload is based on a silicon-on-insulator photonic integrated circuit containing a micro-ring resonator that generates energy-time entangled photon pairs around 1550 nm through spontaneous four-wave mixing,^{12,13} where waveguide geometry was selected to provide dispersion characteristics compatible with efficient phase matching of the spontaneous four-wave mixing process while maintaining compatibility with available fabrication processes. Operation in the telecommunications C-band provides compatibility with existing optical communications infrastructure and leverages the maturity of integrated photonic manufacturing technologies.¹⁴ Integrated thermal tuning elements are used to stabilize and align resonances, enabling compatibility with dense wavelength-division multiplexing architectures. During the design phase, the source architecture was optimized to balance pair-generation rate, spectral bandwidth, thermal stability and manufacturability. The integrated payload architecture combines the quantum sources with supporting subsystems including tunable lasers, wavelength-division multiplexing filters, polarisation control hardware, single-photon detectors, time-tagging electronics and dedicated processing electronics.

The telecommunications payload, depicted in detail in Fig. 1, contains a tunable pump laser whose output is routed through an optical isolator and polarisation controller before being coupled into the photonic integrated circuit. Photon pairs generated inside the micro-ring resonator are subsequently separated using dense wavelength-division multiplexing filters and directed towards single-photon detectors through a dedicated optical routing architecture. All measurement data are processed using dedicated FPGA-based electronics capable of performing time-stamping and coincidence identification on-board the spacecraft. This architecture enables autonomous evaluation of photon-pair correlations without requiring continuous interaction from the ground segment: photon arrival times are recorded by the FPGA-based timing electronics and used to construct coincidence histograms onboard; the primary mission success metric is the autonomous observation of a statistically significant photon-pair correlation peak in orbit, corresponding to a measured $g_{1,2}^{(2)}$ larger than 2. The resulting payload therefore represents not only a quantum optical experiment but also a complete autonomous quantum communication subsystem. An equally important design driver was compliance with stringent spacecraft constraints. The payload was required to fit within a tightly constrained volume allocation while maintaining acceptable thermal behaviour, optical performance and mechanical robustness. Consequently, system design emphasis was placed on minimizing optical interfaces, reducing fibre routing complexity and maximizing subsystem integration. The resulting architecture can serve as a scalable foundation for future operational quantum payloads.

SAMV71 MCU with
instrument drivers and power supply

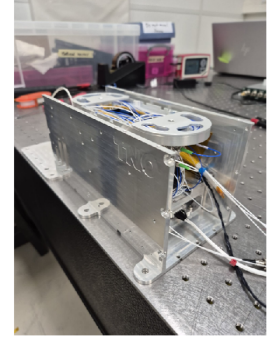
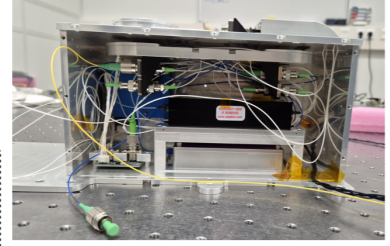
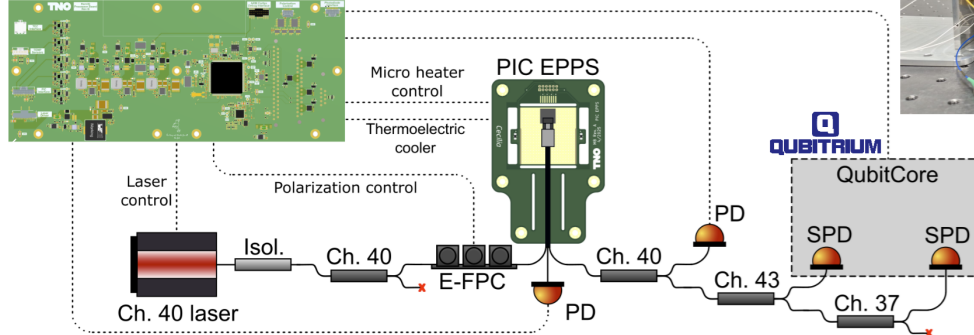


Figure 1. Block diagram of the EPIQ quantum payload, combining TNO’s PIC EPPS with detector and timing electronics developed by Qubitrium. The system integrates a photonic integrated entangled photon-pair source, optical routing components, single-photon detectors, time-tagging electronics and onboard processing hardware to autonomously generate and detect photon-pair correlations in orbit. On the right handside: integrated EPIQ payload prior to full environmental qualification; optical, electronic, and mechanical subsystems are accommodated within a volume compatible with the spacecraft allocation (2U) while preserving thermal and optical accessibility.

2.1 PIC EPPS Design Considerations

The architecture of the photonic integrated entangled photon-pair source was not selected solely based on source brightness requirements. Instead, the final implementation emerged from a broader design trade-off involving optical efficiency, spectral properties, manufacturability, environmental robustness and compatibility with future quantum networking applications. During the design phase, several photonic building blocks were investigated through analytical modeling and numerical simulations. Particular attention was given to fibre-to-chip coupling efficiency, waveguide dispersion engineering, resonator coupling coefficients, achievable quality factors, phase-matching conditions and source spectral purity. These parameters jointly determine key system-level figures of merit including pair-generation rate, coincidence-to-accidental ratio, source fidelity and ultimately the secure-key-rate achievable in a quantum communication link.^{4,12,14} Fig. 2 illustrates the resonantly enhanced SFWM architecture adopted for the PIC EPPS, including pump injection, signal/idler extraction and thermal tuning elements used to stabilize source operation.

The source architecture is based on a silicon-on-insulator micro-ring resonator operating in the telecommunications C-band and generating photon pairs through spontaneous four-wave mixing. Telecommunications-band operation was selected because it benefits from compatibility with mature optical communication infrastructure and wavelength-division multiplexing technologies while enabling future integration with quantum networking architectures. Design studies further demonstrated that waveguide geometry and resonator parameters can be adjusted to achieve favourable phase-matching conditions while maintaining compact device dimensions and compatibility with available fabrication processes. One particularly important outcome of the early modelling activities was the identification of optical coupling efficiency as a dominant system-level parameter. The generated pair rate depends on both efficient pump injection into the resonator and efficient extraction of signal and idler photons. As a result, the detectable photon-pair rate scales approximately with the fourth power of coupling efficiency. Small improvements in fibre-to-chip coupling therefore translate into disproportionately large improvements in source performance. This observation strongly influenced both the packaging strategy adopted for the flight hardware and the future technology developments described in Section 4. The final PIC EPPS architecture therefore represents a compromise between quantum-optical performance, manufacturability, envi-

3.1 Qualification Results for the Photonic Integrated Entangled Photon-Pair Source

The photonic integrated entangled photon-pair source emerged as one of the most critical subsystems of the mission. While the silicon photonic chip itself demonstrated excellent robustness, environmental testing revealed multiple vulnerabilities associated with packaging and optical interfacing.¹⁴ Early modeling activities revealed that the detectable photon-pair rate scales approximately with the fourth power of fibre-to-chip coupling efficiency because coupling losses affect both pump injection and extraction of generated photons. Consequently, packaging robustness and optical interfacing become primary design drivers throughout the qualification campaign. In fact, the most significant issue identified during early shock testing involved the fibre-array attachment. Mechanical loading produced substantial increases in optical losses, in some cases approaching 15 dB per coupler. These observations clearly demonstrated that qualification of integrated photonics¹⁴ extends far beyond qualification of the photonic chip itself. To increase robustness, additional mechanical reinforcement was implemented through dedicated strain-relief structures and revised adhesive strategies. The resulting modifications substantially improved resistance against launch-induced mechanical loads. Wire-bond integrity constituted a second important challenge. Handling activities and environmental exposure created risks of bond deformation and failure. Protective structures and revised assembly procedures were therefore introduced, as detailed in Fig. 3. Thermal testing revealed additional vulnerabilities. The integrated resonance-control heaters were found to be susceptible to degradation under excessive electrical loading; in particular, heater degradation was observed at drive currents exceeding approximately 80 mA. Furthermore, discrepancies between expected and measured thermal behaviour highlighted the importance of system-level thermal modelling. Corrective measures included improved thermal conduction paths, dedicated heat sinks, thermo-electric cooling provisions and specialized wire-bond protection structures.

3.2 Qualification of Supporting Subsystems

The qualification campaign extended beyond the integrated source itself. The polarisation controller required special attention due to uncertainty regarding material composition and vacuum compatibility. Residual-gas analysis performed during thermal-vacuum testing confirmed acceptable contamination behaviour. The tunable pump laser also represented a critical subsystem. Mechanical testing revealed vulnerabilities that would likely have remained undetected in standard laboratory operation. Collaboration with the supplier enabled implementation of corrective actions aimed at improving long-term reliability. Similarly, the dense wavelength-division multiplexing subsystem introduced challenges related to insertion loss, packaging density and fibre routing. Design iterations focused on minimizing splicing and unnecessary optical interfaces, thereby reducing both integration complexity and susceptibility to environmentally induced degradation.

3.3 Integrated Environmental Testing and Systems Engineering Lessons

Environmental qualification incorporated vibration, shock, thermal cycling, bake-out and thermal-vacuum testing. Bake-out activities produced favourable contamination metrics (2.3% to 0.89%) and confirmed compatibility with the requirements imposed by spacecraft operation. Thermal-vacuum testing subsequently validated subsystem behaviour under representative combinations of temperature and pressure. Finite-element and modal analyses complemented experimental testing by identifying assemblies vulnerable to dynamic amplification during launch. Perhaps the most significant lesson learned throughout the programme is that future quantum payloads must be treated as systems-of-systems. Although source brightness, entanglement fidelity and detector performance remain critical performance indicators, qualification results demonstrated that mission success can depend equally on packaging quality, thermal engineering, software orchestration, optical interfaces and manufacturing considerations. The EPIQ programme therefore provides lessons that extend well beyond a single quantum payload and contribute directly to future standardization and interoperability efforts for space-based quantum communications.^{5,6}

4. FUTURE WORK AND TOWARDS OPERATIONAL QUANTUM COMMUNICATION PAYLOADS

The qualification activities described in this paper focused on demonstrating the environmental robustness of a representative quantum payload. Although these efforts substantially increased the Technology Readiness

Shock test showed big vulnerability in array attachment
 -> optical loss increased to 15dB per coupler

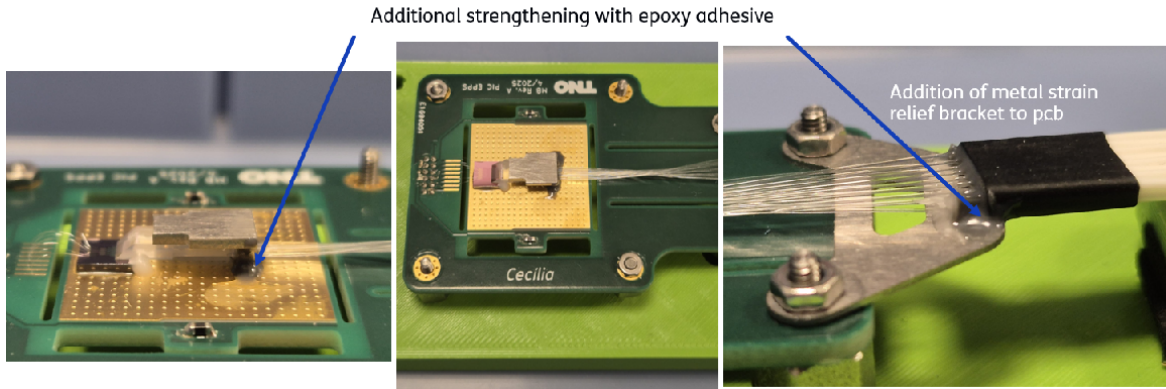
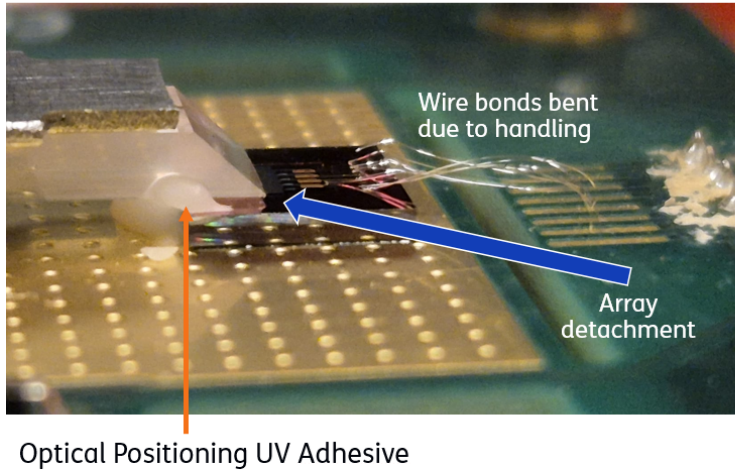


Figure 3. Mechanical qualification of the PIC entangled photon-pair source. Early shock testing revealed vulnerability of the fibre-array attachment (top), motivating reinforcement through strain-relief structures and structural epoxy (bottom).

Level of the system, several developments remain necessary before integrated photonic entangled photon-pair sources can support operational space-to-ground quantum communication links. One of the most significant limitations of the current generation of PIC-based entangled photon-pair sources lies in the optical coupling efficiency between the photonic chip and the fibre network. The current implementation employs grating-coupler interfaces exhibiting losses on the order of several decibels per coupler, resulting in approximately 7.5 dB coupling loss at both the input and output interfaces of the chip. Since every photon lost at the source directly impacts the achievable coincidence rate and heralding efficiency, coupling losses currently represent one of the dominant system-level limitations.

Current development efforts therefore focus on a next-generation photonic integrated platform combining silicon, silicon dioxide and silicon nitride layers within a multi-layer architecture. The approach, further detailed in Fig. 4, exploits simultaneous refractive-index engineering, mode-field matching and diffraction control to improve the overlap between guided modes inside the photonic circuit and the optical mode supported by a standard telecommunications fibre. Simulation results indicate that coupling losses could potentially be reduced from approximately 7 dB per coupler to values approaching 0.5 dB per coupler while maintaining compatibility with standard packaging approaches. Beyond the direct reduction in insertion loss, such improvements would have a multiplicative effect on overall system performance. Higher coupling efficiencies translate directly into larger detected photon-pair rates, higher heralding efficiencies and improved coincidence-to-accidental ratios. Furthermore, they enable operation with a larger number of wavelength channels and therefore support the

spectral multiplexing strategies required by future quantum networking architectures.^{2,3} The envisioned platform targets operation with more than ten channel pairs while maintaining pair generation rates approaching the MHz regime and fidelities suitable for advanced quantum communication protocols.

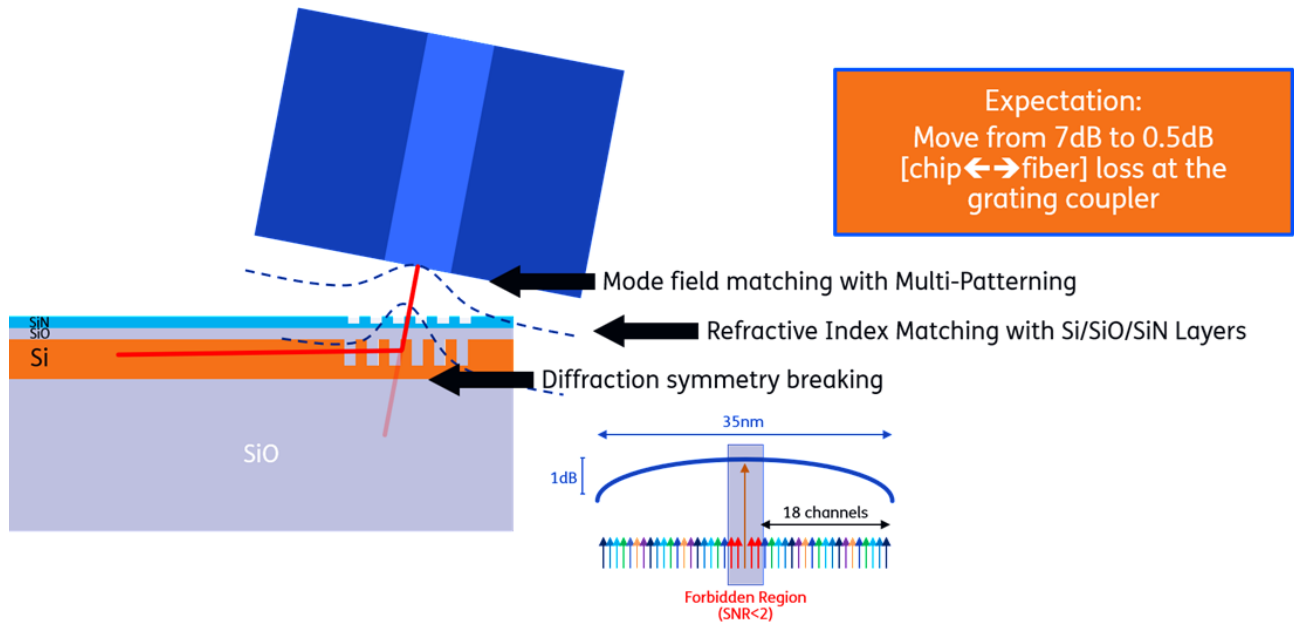


Figure 4. Concept for next-generation SiN-on-SOI grating couplers targeting ultra-low loss fibre-to-chip interfaces. Numerical simulations indicate a potential reduction of coupling losses from approximately 7 dB to below 0.5 dB per coupler through refractive-index engineering and mode matching in a multilayer Si/SiO₂/SiN platform.

These developments are particularly relevant for space-based applications. Link-budget analyses performed for future satellite quantum communication missions indicate that the losses associated with the source payload constitute a critical parameter in determining whether entanglement distribution between space and ground can be achieved with practical aperture sizes and detector technologies.^{5,8} Consequently, reducing chip-to-fibre coupling losses is expected to provide one of the largest performance gains available within the source subsystem. The transition from qualification-focused demonstrators toward operational payloads will therefore require not only environmental robustness but also substantial improvements in optical efficiency. In parallel with coupling-efficiency improvements, future developments aim to increase resonator finesse, integrate filtering and wavelength-routing functionalities directly on-chip, expand automated control capabilities and further reduce overall system size, weight and power consumption. Taken together, these developments outline a roadmap from the present EPIQ demonstrator towards a new generation of highly efficient and fully integrated quantum communication payloads capable of supporting direct space-to-ground entanglement distribution.

5. CONCLUSIONS

This work presented the development and qualification of one of the first Dutch quantum payloads intended for autonomous operation in space. Through an extensive environmental qualification campaign, vulnerabilities associated with fibre-array attachment, thermal management, wire-bond protection and supporting optical assemblies were identified and mitigated. The resulting payload combines multiple quantum communication technologies within a compact architecture compatible with satellite integration. Beyond the immediate mission objectives, the work contributes to European efforts towards quantum communication standardization, interoperability and future trust-free satellite quantum networks. The qualification campaign demonstrates that integrated quantum photonics can successfully transition from laboratory demonstrations towards flight-ready hardware through a systematic engineering approach. The most significant outcome of the campaign is the observation that packaging, thermal management and interface engineering dominate the qualification risk of integrated quantum photonic systems. Addressing these challenges is therefore as important as improving source

brightness or entanglement fidelity for future operational missions. As future missions increasingly depend on entanglement distribution capabilities in orbit, the lessons learned during EPIQ will help guide the development of the next generation of quantum communication payloads.

ACKNOWLEDGMENTS

EPIQ-in-Space and *Qubitcore in Space* projects are funded by Holland High Tech — TKI HSTM via the PPP Innovation Scheme (PPP-I) for public-private partnerships. The authors acknowledge the contributions of the EPIQ mission team, TNO, Qubitrium and all supporting partners involved in payload development, environmental testing and integration activities.

REFERENCES

- [1] Kimble, H. J., “The quantum internet,” *Nature* **453**, 1023–1030 (2008).
- [2] Wehner, S., Elkouss, D., and Hanson, R., “Quantum internet: A vision for the road ahead,” *Science* **362**(6412) (2018).
- [3] Sangouard, N., Simon, C., de Riedmatten, H., and Gisin, N., “Quantum repeaters based on atomic ensembles and linear optics,” *Reviews of Modern Physics* **83**, 33–80 (2011).
- [4] Amaral, G. et al., “Towards the integration of a PIC-based entangled photon-pair source and an ensemble-based quantum memory compatible with the telecommunication C-band,” in [*International Conference on Space Optics — ICSO 2024*], **13699**, 1369942, International Society for Optics and Photonics, SPIE (2025).
- [5] Aspelmeyer, M. et al., “Long-distance quantum communication with entangled photons using satellites,” *IEEE Journal of Selected Topics in Quantum Electronics* **9**(6), 1541–1551 (2003).
- [6] European Commission, “European quantum communication infrastructure (euroqci),” (2025). <https://digital-strategy.ec.europa.eu/en/policies/euroqci>.
- [7] European Space Agency, “Eagle-1 quantum key distribution mission,” (2025). <https://www.esa.int>.
- [8] Yin, J. et al., “Satellite-based entanglement distribution over 1200 kilometers,” *Science* **356**(6343), 1140–1144 (2017).
- [9] Liao, S.-K. et al., “Satellite-to-ground quantum key distribution,” *Nature* **549**, 43–47 (2017).
- [10] Ren, J.-G. et al., “Ground-to-satellite quantum teleportation,” *Nature* **549**, 70–73 (2017).
- [11] Kwiat, P. et al., “New high-intensity source of polarization-entangled photon pairs,” *Physical Review Letters* **75**, 4337–4341 (1995).
- [12] Helt, L. G., Yang, Z., Liscidini, M., and Sipe, J. E., “Spontaneous four-wave mixing in microring resonators,” *Optics Letters* **35**(18), 3006–3008 (2010).
- [13] Silverstone, J. W. et al., “On-chip quantum interference between silicon photon-pair sources,” *Nature Photonics* **8**, 104–108 (2014).
- [14] Wang, J. et al., “Integrated photonic quantum technologies,” *Nature Photonics* **14**, 273–284 (2020).
- [15] European Cooperation for Space Standardization, “Ecss-e-st-10-03c mechanical testing standard,” (2022).
- [16] NASA, “General environmental verification standard gsfc-std-7000,” (2021).