

Development and Integration of a 2 km Free-Space-to-Fiber Quantum Communication Testbed for Satellite Downlink Emulation

Breno Perlingeiro^a, Alexandros Sousanis^a, Aristeidis Stathis^b, Argiris Ntanos^b, David Bakker^a, Giorgos Mazarakis^a, Giannis Giannoulis^b, Hercules Avramopoulos^b, Gustavo Castro do Amaral^a, Lukas Achatz^c, Johannes Pseiner^c, Mark Boekel^a, Nienke Ten Haaf^a, Yoram Vos^a, Philip Menz^d, Emmanuel M. Xilouris^e, and Athanasios Marousis^e

^aTNO High Tech Industry, Stieltjesweg 1, 2628 CK Delft, The Netherlands

^bInstitute of Communication and Computer Systems (ICCS), 9 Iroon Polytechniou Street, Zografou 15780, Athens, Greece

^cqtlabs – Quantum Technology Laboratories GmbH, Vienna, Austria

^dqssys – Quantum Space Systems GmbH, Munich, Germany

^eNational Observatory of Athens (NOA), Athens, Greece

ABSTRACT

The Leap in Advancing Critical Quantum Key Distribution Space Components (LaiQa) project addresses key technological challenges associated with future space-based quantum communication networks. As quantum payloads mature and quantum communication architectures increasingly rely on existing terrestrial fiber infrastructures, the free-space-to-fiber interface becomes a critical element in the overall system performance. Efficient transfer of received quantum states from atmospheric free-space channels into single-mode telecommunications fibers is therefore a necessary step towards scalable satellite-to-ground quantum networks. Within LaiQa, TNO is developing an ultra-low-loss free-space-to-fiber coupling platform designed to emulate a satellite-to-ground quantum communication downlink over a 2 km terrestrial free-space link. The system integrates pointing control, clock synchronization, adaptive optics correction, and free-space-to-single-mode-fiber coupling within a unified receiver architecture operating entirely in the telecommunications C-band. The design objective is to maximize fiber-coupling efficiency under realistic atmospheric conditions while maintaining interoperability with different quantum source technologies and terrestrial optical network infrastructures. The estimated loss for the system under development is -18 dB from fiber to fiber under low-turbulence conditions. The presented architecture follows a systems-engineering approach in which wavefront correction, beam stabilization, synchronization, and quantum signal transport are jointly optimized to reduce end-to-end link losses. Particular emphasis is placed on the integration of adaptive optics within the receiver chain, the preservation of common pupil planes throughout the optical architecture, and the implementation of calibration and alignment strategies that enable stable operation in realistic deployment scenarios. At the time of writing, the free-space-to-fiber coupling system is undergoing final assembly, integration, and alignment in the laboratory. The forthcoming field campaign in Delft will validate the complete architecture over a 2 km free-space link using quantum sources developed by LaiQa partners qssys and qtlabs. In addition, the developed coupling approach is being prepared for future deployment in larger-aperture infrastructures, including validation activities involving the 2.3 m Aristarchos telescope at Helmos Observatory. This paper presents the architectural development, design rationale, subsystem integration strategy, and verification methodology of the low-loss free-space-to-fiber coupling system. Initial laboratory results and, where available at the time of final submission, field-demonstration results will also be presented.

Keywords: Quantum Communication, Quantum Network, Satellite Communication, QKD

Further author information: (Send correspondence to Breno Perlingeiro)

Breno Perlingeiro: E-mail: breno.perlingeirocorrea@tno.nl , Telephone: +31 6 43510123

1. INTRODUCTION

The emergence of space-based quantum communication is gradually shifting the performance bottleneck of quantum key distribution (QKD) systems from quantum state generation towards the optical interface between free-space channels and terrestrial fiber networks.^{1,2} Satellite platforms can provide global coverage and overcome the distance limitations imposed by direct fiber transmission, but the practical realization of a scalable quantum network depends equally on the ability of ground infrastructures to deliver the received quantum states into low-loss fiber systems where detection, processing, and networking equipment are located. As a consequence, free-space-to-fiber coupling is evolving from a subsystem-level concern into a system-level architectural requirement.³

This transition becomes particularly relevant as quantum communication architectures move away from isolated demonstrations and towards interconnected network deployments. In such architectures, the optical ground segment is no longer expected to host all processing functions locally. Instead, quantum receivers, synchronization systems, and future quantum networking equipment are expected to be distributed across existing fiber infrastructures.⁴⁻⁶ This evolution creates a direct dependency between the performance of the free-space optical interface and the achievable end-to-end network performance.

A major challenge arises from atmospheric turbulence. Although geometric losses are minimized through accurate pointing and appropriately sized telescope apertures, atmospheric propagation introduces wavefront distortions that degrade coupling into single-mode fibers.^{7,8} Since single-mode fibers effectively act as spatial mode filters, phase distortions translate directly into coupling losses, reducing photon detection probability and limiting the achievable secret-key rate. Previous studies have shown that adaptive optics correction can significantly improve coupling efficiency under realistic atmospheric conditions by compensating higher-order aberrations before fiber injection.⁹⁻¹¹ These observations motivate the development of integrated optical architectures in which pointing control, synchronization, adaptive optics and fiber-coupling functions operate as a single coordinated system rather than as independent subsystems.

Within the Horizon Europe LaiQa project, TNO is developing an ultra-low-loss free-space-to-fiber coupling platform intended to emulate the reception chain of future satellite-to-ground quantum communication systems.¹² The objective is not only to improve fiber-coupling efficiency, but also to establish a deployable architecture capable of interfacing quantum payloads operating in the telecommunication bands with terrestrial optical networks. The work presented in this paper describes the architectural evolution, subsystem integration strategy, and on-going implementation of this platform. Since the field campaign is planned to October 2026, the paper focuses on the design rationale, system development, laboratory integration activities, and verification methodology that precede operational testing.

2. MOTIVATION AND DEVELOPMENT OF THE LOW-LOSS FREE-SPACE-TO-FIBER INTERFACE

The design of the ultra-low-loss coupling system was driven by a fundamental architectural observation: improvements in photon source performance alone no longer guarantee proportional improvements in end-to-end quantum communication throughput. As source brightness and detector efficiency continue to increase, losses introduced at the free-space-to-fiber interface constitute an increasingly dominant contribution to the overall link budget.¹³⁻¹⁵

For quantum communication links operating in the C-band, the ability to transport received photons through standard telecommunications infrastructure creates significant deployment advantages. However, this benefit can only be realized if coupling efficiencies remain sufficiently high under realistic atmospheric conditions. Consequently, free-space-to-fiber coupling must be treated as a dynamic process rather than a static optical alignment problem.

Atmospheric turbulence introduces both beam wander and higher-order wavefront aberrations. These effects occur on different temporal and spatial scales and therefore require different control mechanisms. A single correction mechanism is generally unable to address both phenomena efficiently. This constraint directly leads to an architecture in which coarse and fine pointing functions are separated from higher-order wavefront correction. The resulting design combines a fast steering loop responsible for beam stabilization with an adaptive optics

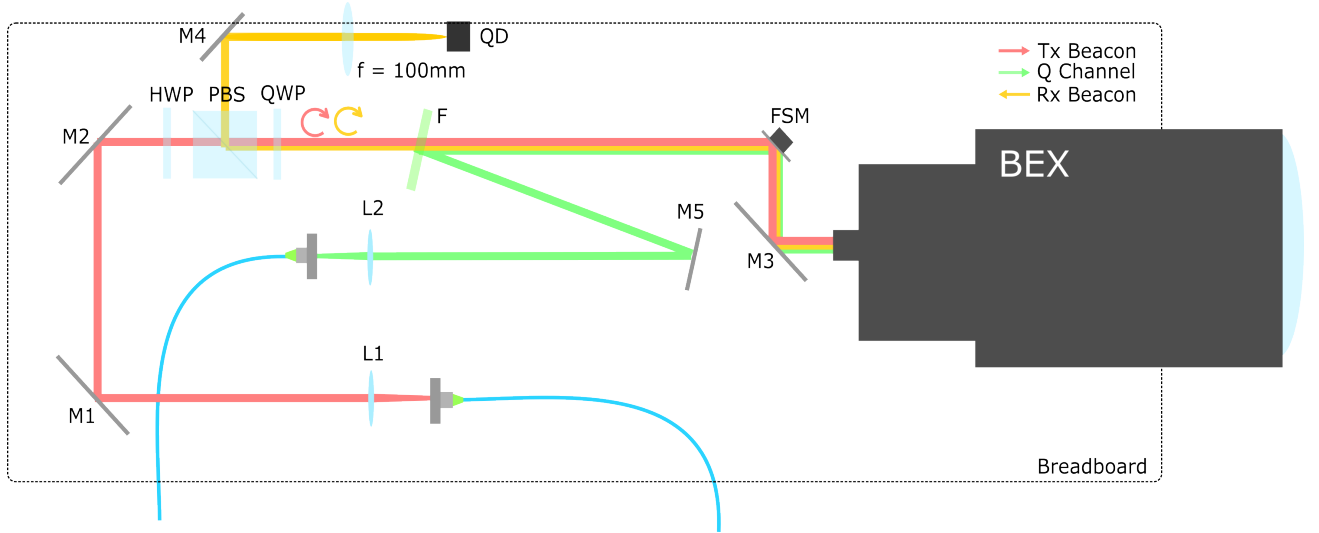


Figure 1. Sketch of the LaiQa Transmitter Breadboard (LTBB). L1 and L2 are plano-convex lenses with a focal length of 50 mm, used to collimate the beams. The half-wave plate (HWP) adjusts the linear polarization of the transmitter (Tx) beacon to maximize transmission through the polarization beam splitter (PBS). After the PBS, the quarter-wave plate (QWP) converts the beacon into circular polarization. The filter (F) combines the quantum channel and the Tx beacon. Both beams are reflected by the fine steering mirror (FSM) and mirror M3 before being transmitted through the beam expander (BEX). The receiver (Rx) beacon passes back through the QWP, which converts it to linear polarization orthogonal to that of the Tx beacon, causing it to be reflected by the PBS. The Rx beacon is then focused by a 100 mm focal-length plano-convex lens onto the quadrant detector (QD), which provides feedback to the FSM for the pointing-control loop. The Rx beacon is modulated with a 10 MHz square wave used for synchronization between the nodes. The quantum-channel fiber can be connected either to the entangled photon-pair source developed by qtlabs or to the prepare-and-measure source developed by qssys.

loop dedicated to phase compensation. Such separation allows each subsystem to be optimized according to its dominant disturbance frequencies while maintaining overall system stability.

The resulting requirements were derived from analytical turbulence models and previous adaptive-optics field experiments. The design targets correction of the first higher-order Zernike modes beyond tip and tilt, operation across the telecommunications S, C and L bands, and adaptive-optics control bandwidths sufficient to compensate atmospheric dynamics observed in terrestrial links representative of satellite downlink conditions. Particular emphasis was placed on ensuring that the adaptive optics control objective can be optimized directly for fiber-coupling efficiency rather than solely for wavefront error minimization.

The receiver architecture evolved through successive design iterations informed by laboratory experimentation and system-level trade-off analyses. Early development efforts focused on investigating custom adaptive optics solutions assembled from commercial off-the-shelf components.^{16–18} Building upon the knowledge and infrastructure inherited from these previous projects, the current system adopts a free-space optical architecture comprising a 100 mm aperture transmitting telescope and a 150 mm aperture receiving telescope, both with a magnification factor of 10. The system achieves a pointing accuracy of approximately $10\ \mu\text{rad}$. The transmitted beam divergence is nominally set to $70\ \mu\text{rad}$ on the sky and can be adjusted via a calibrated mechanical mechanism down to approximately $10\ \mu\text{rad}$. The transmitter optical power is limited to a maximum of 100 mW, ensuring eye-safe operation under all configurations. For synchronization, the classical communication channel supports recovery from interruptions of up to $12\ \mu\text{s}$, while the estimated distributed clock jitter remains below 600 ps.

These experimental activities provided valuable insight into the practical constraints associated with adaptive optics implementation, including deformable mirror incidence angles, pupil-plane registration, control-loop bandwidth limitations, and alignment sensitivities. Although the studies successfully demonstrated the feasibility of a custom adaptive optics solution, they also revealed that comparable performance could be achieved using

commercially available adaptive optics platforms, thereby reducing integration risk, implementation complexity, and development time.

This finding motivated a strategic shift from subsystem development toward system-level architectural integration. Rather than prioritizing novelty at the component level, the design effort focused on ensuring that all optical functions required for quantum key distribution (QKD) could operate cohesively within a unified receiver architecture. As a result, the receiver breadboard was conceived as a common platform integrating multiple interacting subsystems, including pointing and tracking, wavefront correction, wavelength multiplexing, clock recovery, polarization monitoring, and efficient single-mode fiber coupling.

3. ADAPTIVE OPTICS SYSTEM DESIGN AND INTEGRATION

Table 1. Comparison of the adaptive optics (AO) system requirements for the LaiQa project, the specifications of the procured system, and the results of the Site Acceptance Test (SAT). In addition to the requirements listed in the table, several project requirements are implicit and therefore not explicitly included. These include operation in the C-band, compatibility with beam diameters of at least 10 mm, and minimal impact on the polarization state of the transmitted signals. The evaluated AO system satisfies all of these requirements.

Property	Requirements	Procured AO system Specifications	SAT Result
Minimum number of modes correction	>8 modes	>60 modes	67 modes
Rejection bandwidth	>100 Hz	>200 Hz	236 Hz
Control loop frequency	>2000 Hz	5000 Hz	5038 Hz

The adaptive optics subsystem integrates a deformable mirror, a Shack-Hartmann wavefront sensor, and a real-time control platform operating at kilohertz rates. The selection process was guided primarily by architectural compatibility with the receiver breadboard rather than isolated component performance.

A critical lesson learned during preliminary investigations concerned the sensitivity of adaptive-optics performance to mechanical and optical alignment. Small deviations in mirror incidence angles or pupil-plane positioning were observed to generate significant reductions in correction effectiveness. As a result, the integration strategy prioritized alignment robustness and repeatability from the earliest stages of development.

The final optical layout implements a sequence of relay stages that distribute the overall magnification required between the deformable mirror and wavefront sensor. This approach reduces beam-size sensitivity, simplifies alignment activities and preserves correction performance throughout the optical chain. The architecture furthermore introduces a dedicated calibration channel that enables regular adaptive-optics recalibration without disturbing the operational optical path. Such capability becomes increasingly important when considering future deployable ground stations that must maintain performance over extended operational periods and changing environmental conditions.

An equally important design choice concerns the optimization criterion itself. Rather than minimizing the residual wavefront error measured by the sensor, the adaptive-optics control loop is designed to maximize coupling into the receiving single-mode fiber. This distinction reflects the system objective of preserving quantum-channel performance and aligns the adaptive-optics operation directly with end-to-end communication metrics. Based on the simulations and field test experience, the estimated loss for the system under development is -18 dB fiber-to-fiber.

4. RECEIVER BREADBOARD IMPLEMENTATION

The receiver breadboard serves as the physical implementation of the architectural principles described above. The design combines wavefront correction, pointing stabilization, synchronization and wavelength management within a unified optical platform operating entirely in the telecommunications bands.

The optical configuration separates classical and quantum channels through wavelength-selective filtering while preserving common alignment references. This architecture allows classical beacon signals to support

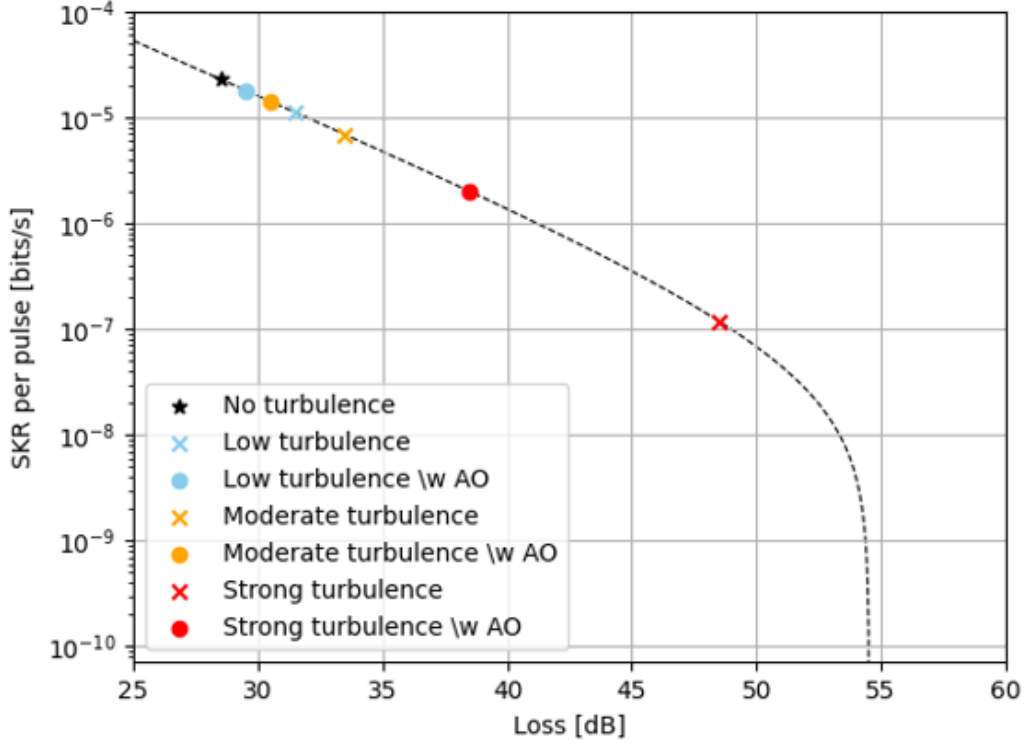


Figure 2. Simulation of the Secret Key Rate (SKR) for different configuration based on the turbulence and Adaptive optics data from¹¹ and considering the system developed in.¹⁸

several operational functions simultaneously, including synchronization, pointing control and adaptive-optics sensing, thereby reducing system complexity and enabling tighter integration between subsystems.

Particular attention was given to ensuring interoperability with quantum sources developed by different consortium partners. By standardizing optical interfaces at the fiber level, the system can accommodate both prepare-and-measure source, developed by qssys, and entanglement-based, developed by qtlabs without fundamental modifications to the free-space receiver chain. This capability is essential for technology validation activities, where the objective is to evaluate optical transport performance independently of specific source implementations.

5. INTEGRATION AND VERIFICATION STRATEGY

The development approach follows a progressive verification test in which subsystem validation precedes full system deployment. Factory and site acceptance tests of the adaptive optics subsystem have already demonstrated compliance with the principal performance requirements related to bandwidth, modal correction capability and closed-loop operation, see table 1. Laboratory verification campaigns are now focused on completing optical integration, calibration procedures and interoperability testing between transmitter and receiver breadboards.

The next phase consists of a field campaign over a 2 km free-space link in Delft. The campaign is intended to validate the complete optical architecture under realistic atmospheric conditions and to quantify the interaction between atmospheric turbulence, adaptive-optics correction and single-mode fiber coupling. Due to project scheduling adjustments, this campaign is currently planned for October 2026. The measurements obtained during that campaign will form the basis of future performance-oriented publications.

6. FUTURE FIELD DEMONSTRATION CAMPAIGNS

Beyond the Delft deployment, the developed coupling architecture has been designed to support its integration into larger-aperture optical infrastructures. A future validation activity within the LaiQa roadmap foresees

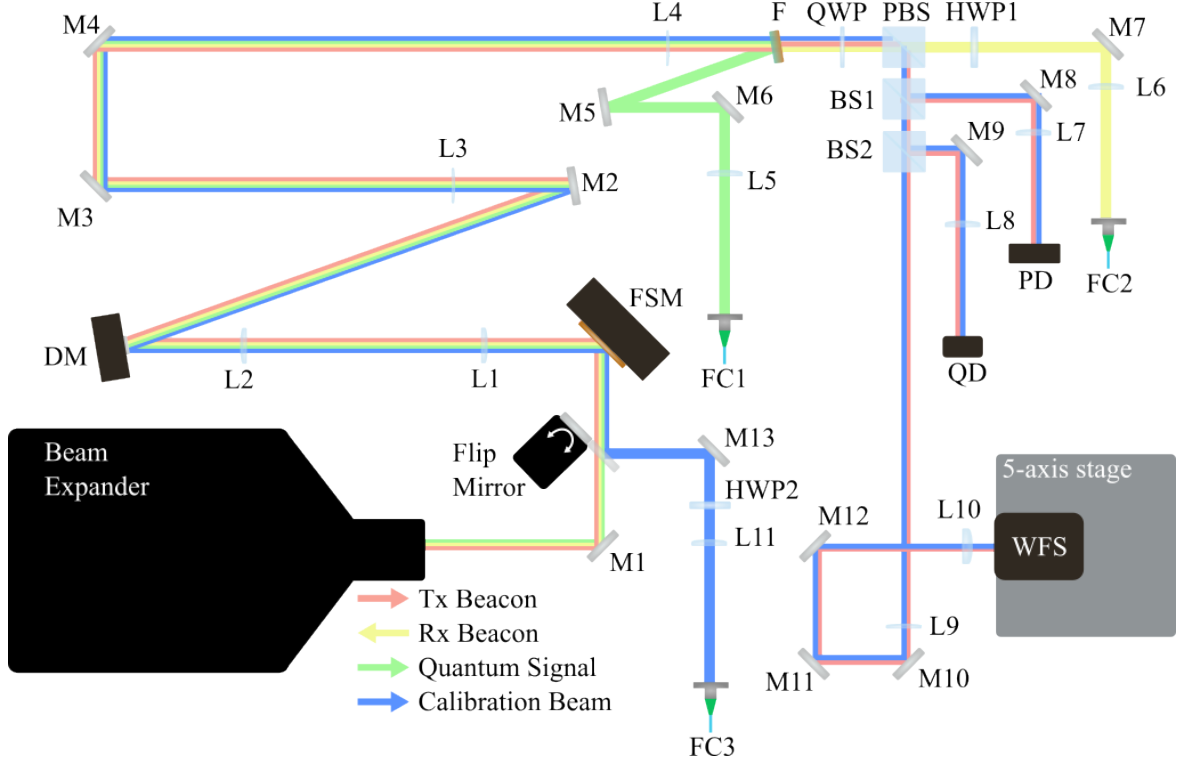


Figure 3. Illustration of the LaiQa Receiver Breadboard (LRBB). The red and green lines represent the incoming beams from the transmitter: the beacon and quantum signal, respectively. The blue line indicates the beam path used for adaptive optics (AO) loop calibration, while the yellow line denotes the receiver (Rx) beacon path. All components labeled M# are broadband dielectric mirrors designed for the C-band. L1, L2, L7, and L8 are plano-convex lenses with a focal length of 100 mm. L1 and L2 form the first optical relay between the fine steering mirror (FSM) and the deformable mirror (DM). L3 and L4 are plano-convex lenses with focal lengths of 500 mm and 400 mm, respectively, and relay the DM pupil to a plane located after the second beam splitter (BS2). The filter (F) separates the classical channel (1540-1545 nm) from the quantum channel. The polarization beam splitter (PBS) separates the Rx beacon path from the incoming beam paths. The half wave plate (HWP) on the rx beacon path is adjusted for maximum transmission at the PBS. BS1 and BS2 are beam splitters with reflection-to-transmission (R:T) ratios of 70:30 and 90:10, respectively. L7 and L8 focus the incoming beam onto the photodetector (PD) for clock recovery and onto the quadrant detector (QD) for the FSM pointing-control loop. L9 and L10 are plano-convex lenses with focal lengths of 300 mm and 30 mm, respectively, used to match the DM pupil to the wavefront sensor (WFS) pupil while reducing the beam diameter. L5, L6, and L11 are plano-convex lenses with focal lengths of 50 mm, used for collimating light from the fiber or coupling light into it.

the deployment of the receiver concept on the 2.3 m Aristarchos telescope at Helmos Observatory. In that configuration, the free-space-to-fiber interface will provide the technological bridge between large-aperture photon collection and telecommunications-grade fiber transport.

From a systems perspective, this evolution represents a natural progression from terrestrial link validation towards architectures that increasingly resemble operational satellite-ground quantum communication systems. The Delft campaign therefore serves as an intermediate step whose primary value lies not only in demonstrating performance, but also in reducing integration risk prior to deployment on large astronomical infrastructures.

7. CONCLUSIONS

This work presented the development and ongoing integration of a low-loss free-space-to-fiber coupling system within the LaiQa project. The architecture was conceived to address one of the key challenges of satellite-based quantum communications: the efficient transfer of atmospheric free-space optical signals into telecommunications-grade single-mode fiber networks. Through successive design iterations, the system evolved into an integrated platform combining pointing control, adaptive optics, synchronization, and wavelength management within a

common receiver architecture operating in the C-band. Moreover, the optical system allows the integration with different types sources operating on the telecommunications wavelength providing TNO a testbed facility for QKD in the Netherlands.

At the time of writing, the transmitter and receiver breadboards are undergoing final alignment in the laboratory. The adaptive optics subsystem has successfully completed factory and site acceptance activities, while ongoing integration efforts are focused on validating the interoperability of the complete system with multiple quantum source architectures. The forthcoming Delft field campaign, scheduled for October 2026, will provide the first end-to-end evaluation of the integrated free-space-to-fiber interface over a 2 km atmospheric link.

Beyond the Delft demonstration, the same architectural approach is intended to support future integration with larger-aperture optical infrastructures, including the Aristarchos telescope at Helmos Observatory. In this sense, the work reported here represents an intermediate but necessary step toward deployable satellite-to-ground quantum communication systems capable of interfacing directly with terrestrial optical fiber networks.

8. ACKNOWLEDGMENTS

This research was funded from the European’s Union Horizon Europe Research and Innovation programme under the project “Leap in Advancing of crItical Quantum key distribution-spAce components (LaiQa, Grant Agreement No. 101135245).

REFERENCES

- [1] Aspelmeyer, M., Jennewein, T., Pfennigbauer, M., Leeb, W., and Zeilinger, A., “Long-distance quantum communication with entangled photons using satellites,” *IEEE Journal of Selected Topics in Quantum Electronics* **9**(6), 1541–1551 (2003).
- [2] Lu, C.-Y., Cao, Y., Peng, C.-Z., and Pan, J.-W., “Micius Quantum Experiments in Space,” *Reviews of Modern Physics* **94**, 035001 (2022).
- [3] Yin, J., Peng, C.-Z., Villoresi, P., and Jian-Wei, P., “Free-space quantum communication toward a global quantum network,” *Optica* **13**, 1469–1487 (Aug 2026).
- [4] Wehner, S., Elkouss, D., and Hanson, R., “Quantum internet: A vision for the road ahead,” *Science* **362**(6412), eaam9288 (2018).
- [5] Askarani, M. F., Chakraborty, K., and Castro do Amaral, G., “Entanglement distribution in multi-platform buffered-router-assisted frequency-multiplexed automated repeater chains,” *New Journal of Physics* **23**, 063078 (jun 2021).
- [6] Lukens, J. M., Peters, N. A., and Qi, B., “Hybrid classical-quantum communication networks,” *Progress in Quantum Electronics* **103**, 100586 (2025).
- [7] Capraro, I., Tomaello, A., Dall’Arche, A., Gerlin, F., Ursin, R., Vallone, G., and Villoresi, P., “Impact of turbulence in long range quantum and classical communications,” *Phys. Rev. Lett.* **109**, 200502 (Nov 2012).
- [8] Vallone, G., Marangon, D. G., Canale, M., Savorgnan, I., Bacco, D., Barbieri, M., Calimani, S., Barbieri, C., Laurenti, N., and Villoresi, P., “Adaptive real time selection for quantum key distribution in lossy and turbulent free-space channels,” *Phys. Rev. A* **91**, 042320 (Apr 2015).
- [9] Noll, R. J., “Zernike Polynomials and Atmospheric Turbulence,” *Journal of the Optical Society of America* **66**(3), 207–211 (1976).
- [10] Saathof, R. et al., “Adaptive Optics Pre-correction for Optical Feeder Links: Breadboard Performance,” in *[International Conference on Space Optics (ICSO)]*, (2018).
- [11] Broekens, K. A., Doelman, N. J., Klop, W. A., Silvestri, F., Amaral, G. C., et al., “Field Test Demonstration of Adaptive Optics Pre-correction for a Terabit Optical Communication Feeder Link,” in *[International Conference on Space Optics (ICSO)]*, (2023). Available via IEEE Xplore.
- [12] Giannoulis, G., Lyras, N. K., Ntanos, A., Stathis, A., et al., “LAIQA: shaping the quantum satellite communications beyond Eagle-1,” in *[International Conference on Space Optics — ICSO 2024]*, Bernard, F., Karafolas, N., Kubik, P., and Minoglou, K., eds., **13699**, 1369940, International Society for Optics and Photonics, SPIE (2025).

- [13] Pirandola, S., “Satellite quantum communications: Fundamental bounds and practical security,” *Phys. Rev. Res.* **3**, 023130 (May 2021).
- [14] Bulla, L., Pivoluska, M., Hjorth, K., Kohout, O., Lang, J., Ecker, S., Neumann, S. P., Bittermann, J., Kindler, R., Huber, M., Bohmann, M., and Ursin, R., “Nonlocal temporal interferometry for highly resilient free-space quantum communication,” *Phys. Rev. X* **13**, 021001 (Apr 2023).
- [15] Rozenman, G. G., Maslennikov, A., Gandelman, S. P., Reches, Y., Delfan, S., Kundu, N. K., Zhang, L., and Liu, R., “Free-space and satellite-based quantum communication: Principles, implementations, and challenges,” (2026).
- [16] Dirks, B., Ferrario, I., Pera, A. L., Finocchiaro, D. V., Desmons, M., de Lange, D., de Man, H., Meskers, A. J. H., Morits, J., Neumann, N. M. M., Saathof, R., and Witvoet, G., “GEOQKD: quantum key distribution from a geostationary satellite,” in [*International Conference on Space Optics — ICSO 2020*], Cugny, B., Sodnik, Z., and Karafolas, N., eds., **11852**, 118520J, International Society for Optics and Photonics, SPIE (2021).
- [17] Dirks, B. P., do Amaral, G. C., Bakker, D., Mazzarella, L., Ferrario, I., Kossen, S., Marcus, M., Corrêa, B. P., Sharma, H., Pera, A. L., Finocchiaro, D. V., Ottavi, M., Scaiella, N., and Riccardi, G., “Hybrid BBM92 approach for GEOQKD: lab implementation and future perspectives,” in [*International Conference on Space Optics — ICSO 2022*], Minoglou, K., Karafolas, N., and Cugny, B., eds., **12777**, 1277724, International Society for Optics and Photonics, SPIE (2023).
- [18] Amaral, G. C. et al., “Hybrid Fiber-Free-Space Entanglement Distribution Using Off-the-Shelf Quantum Devices.” <https://arxiv.org/abs/2508.11023> (2025). arXiv preprint, Accessed: August 2026.