

Design and Commissioning of Optical Instrumentation for a Satellite Quantum Communication Ground Station

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ABSTRACT

The design, build, and commissioning of the optical instrumentation for an optical ground station is presented. The ground station supports the SpeQtre quantum communication demonstration mission, which is currently in the commissioning phase. The system comprises of a back focal optics (BFO) assembly and four up-link laser beacons (ULBs), integrated with a ground based optical telescope. The BFO is a modular cage-based instrument designed for the backend of a Cassegrain telescope and has three optical channels: a quantum receiver (QR) path, a polarization control system (PCS) path, and a tracking camera path. The QR and PCS channels are designed to operate at 785 nm and 685 nm, respectively. The primary function of the BFO is to feed the quantum signal into the QR while the PCS measures the incoming polarization state and applies a real-time correction to maintain the required polarization state. Meanwhile, the tracking camera channel is used for continuous monitoring of the target. Finally, the ULB acts as a bidirectional optical system in which the forward path transmits an 860 nm laser beam with a divergence of $\approx 0.48 \pm 0.2$ degrees and the return path images the target, allowing the four ULB telescopes to be co-aligned using a star as a target. In this paper, we discuss the opto-mechanical design of the BFO and ULB subsystems and report the results of their laboratory characterization. Our on-sky results demonstrate that these instruments are suitable for practical satellite-to-ground quantum communication experiments.

Keywords: Quantum communication, beam divergence, up-link laser beacon, back focal optics

1. INTRODUCTION

Free-space optical (FSO) communication has emerged as a transformative technology capable of meeting the growing demand for large bandwidth, low-latency, high-capacity, and spectrum-efficient communication links.¹ The origins of FSO communication can be traced back to 1880, when Alexander Graham Bell and Charles Sumner Tainter invented the photophone, a device that transmitted speech over approximately 213 m by modulating sunlight with sound vibrations.² Although the technology was not commercially deployed at the time, it demonstrated the feasibility of FSO communication and laid the foundations for future developments. Significant advances in FSO communication occurred during the second half of the twentieth century with the invention of the laser and semiconductor laser diode. These technologies provided highly coherent and directional optical sources, enabling substantial improvements in transmission range, data rate, and reliability.³ Despite these advances, atmospheric turbulence, beam divergence, atmospheric attenuation, and the requirement for strict line-of-sight alignment remained major challenges, particularly for long-distance terrestrial FSO communication links.⁴ The development of below 20 dB/km loss optical fibers in the 1970s provided a practical and highly reliable alternative for terrestrial optical communications.^{1,5} As a result, fiber-optic communication rapidly became the dominant technology for high bandwidth data transmission networks. Consequently, the application of FSO communications was largely confined to military communications, inter-satellite links (ISLs), and deep-space optical communication systems.⁶ While fiber-optic networks can deliver high data rates over continental and intercontinental distances, they are inherently constrained by fixed point-to-point infrastructure, limiting

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communication flexibility and global coverage. In contrast, satellite optical communication systems have the potential to overcome these limitations by enabling dynamic, any-to-any connectivity, facilitating information transfer between geographically distant locations.

Over the past few decades, the advantages of FSO communication have driven substantial investment in satellite optical communication systems. Numerous research programs and demonstration missions have successfully validated the feasibility and performance of optical communication links between satellites, as well as between satellites and ground stations, demonstrating data rates far beyond those achievable with conventional RF systems.⁶ Notable examples include the European Data Relay System⁷ (EDRS), NASA's Lunar Laser Communication Demonstration⁸ (LLCD), and various inter-satellite optical link demonstrations that have confirmed the viability of optical communications for future space networks.^{6,8} At the same time, the demand for highly secure communications continues to increase across sectors such as finance, defense, government, and critical infrastructure. Conventional cryptographic methods are becoming increasingly vulnerable due to advances in artificial intelligence and the emergence of practical quantum computing.⁹

Protecting information throughout its entire life-cycle, from generation and transmission to storage and retrieval, therefore requires new approaches that are resilient to future computational threats. Quantum key distribution (QKD) has emerged as a promising solution, offering security based on the fundamental laws of physics rather than computational complexity.¹⁰⁻¹² This enables communicating parties to detect the presence of any eavesdropping attempt on the communication channel through the disturbance introduced to the quantum states being transmitted, thereby providing security that is independent of future advances in computational power.¹⁰ The practical feasibility of quantum cryptography was first demonstrated by Bennet et al.¹⁰ in 1989, marking a significant milestone that stimulated extensive research into the development and deployment of quantum-secure communication technologies. Satellite-enabled quantum communication provides a compelling approach for the secure distribution of cryptographic keys on a global scale.¹³ The ability to distribute keys over intercontinental distances makes satellite QKD a critical technology for future global communication networks, overcoming the distance limitations imposed by fiber-based QKD systems.¹² In such a system, the satellite serves as the platform for quantum key generation and distribution, while the ground station establishes the optical link and securely receives the quantum keys for subsequent communication applications.

Several organizations have either attempted or demonstrated the feasibility of satellite-based quantum communication. Pioneering experiments conducted by the China National Space Administration (CNSA) explored the feasibility of space-based quantum networks.¹² The CNSA's Micius¹³ satellite in low Earth orbit (LEO) achieved a major milestone by demonstrating secure quantum key distribution over 1200 kilometers,¹⁴ including satellite-to-ground QKD, quantum teleportation, and intercontinental quantum-secured communication links. These demonstrations provided the first practical evidence that satellite platforms can support global-scale quantum communication infrastructures, paving the way for future quantum communication networks. While these demonstrations have been highly successful, the systems have relied on large and complex payload infrastructures. In line with the continuing evolution of compact and affordable space technologies, RAL Space*, together with SpeQtral* and CQT*, is undertaking the demonstration of low-Earth orbit satellite-based QKD using the SpeQtre CubeSat mission. The mission was successfully launched on 28 November 2025 and is currently progressing through its commissioning phase*.

In these missions, the ground segment plays a crucial role in the demonstration of quantum communication systems. Ground stations are responsible for establishing the optical link, receiving quantum signals transmitted from the satellite, and validating the integrity of the exchanged quantum keys. Any indication of eavesdropping results in the immediate rejection of the affected key, thereby preserving the security guaranteed by quantum communication protocols. The conceptual operation of a satellite-to-ground optical communication link is illustrated in Figure 1. The Optical Ground Station (OGS) architecture primarily consists of a telescope and tracking system, backend optical instrumentation, and a telescope operations facility. One of the ground stations supporting the SpeQtre mission is located at the Chilbolton Observatory ($51^{\circ}08'40''$ N, $1^{\circ}26'19''$ W), a research

*<https://www.ralspace.stfc.ac.uk/>

*<https://speqtralquantum.com/>

*<https://www.cqt.sg/groups/alexander-ling/>

*<https://www.ralspace.stfc.ac.uk/case-studies/speqtre>

facility in the United Kingdom (UK) operated by RAL Space. The OGS incorporates a PlaneWave CDK24 telescope mounted on an L-600 Direct-Drive Telescope Mount*. A TeleVue-NP101is* guidescope is integrated into the system to support target acquisition and provide accurate pointing and tracking .

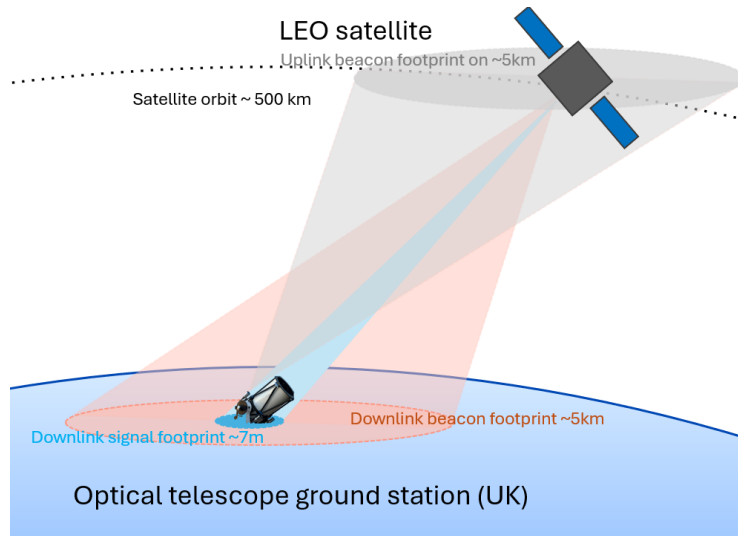


Figure 1. Illustration: Satellite-to-ground optical communication link. The satellite optical payload transmits a downlink beacon and optical signal to the ground station. The down-link beacon is used by the ground station for tracking, while the ground station transmits an up-link beacon that enables the satellite to accurately point toward the ground station. Once bidirectional pointing and tracking are established, the satellite transmits the optical data signal.

The satellite transmits both a beacon signal and a quantum signal to the ground station. The beacon signal enables real-time polarization measurement and compensation, while the quantum signal carries the information required for secure quantum key distribution. In addition, the beacon provides real-time imagery of the target, supporting acquisition, tracking, and operational monitoring functions. The backend instrumentation of the OGS consists of two subsystems namely the Back Focal Optics (BFO) and Up-link Laser Beacon (ULB) subsystems. The BFO subsystem is responsible for capturing, separating, and relaying optical signals received from the satellite payload. The up-link beacon is detected by the active tracking camera within the satellite optical payload. It provides a reference light source for correcting the beam wander and pointing errors induced by satellite dynamics and atmospheric turbulence. Working in conjunction with a fast-steering mirror, the tracking system stabilizes the optical image in real time and maintains the precise pointing accuracy required for reliable optical communication and quantum key distribution.¹⁵

The design, build, and commissioning of BFO and ULB subsystems will be discussed in this paper. The remainder of this paper is organized as follows. Section 2 describes BFO, while section 3 focuses on the ULB. For each subsystem, the opto-mechanical architecture, assembly, integration and testing (AIT) activities, commissioning process, and performance demonstration are presented.

2. BACK FOCAL OPTICS

The BFO subsystem collects and processes optical signals received from the satellite quantum communication payload. In the current implementation, the spacecraft transmits a 685 nm beacon for polarization monitoring and correction, together with a 785 nm quantum signal used for QKD operations. The overview of the BFO operational system is shown in the Figure 2.

The BFO incorporates three independent optical paths: 1. Quantum Receiver (QR) Path – routes the 785 nm quantum signal to the quantum receiver. 2. Polarization Measurement Path – monitors the 685 nm

*<https://planewave.com/products/cdk24-ota/>

*<https://www.televue.com>

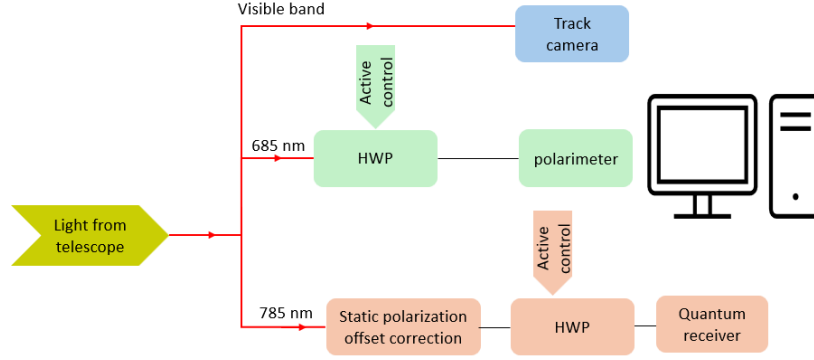


Figure 2. BFO operational system overview. The system performs real-time polarization measurement and correction, compensates for static polarization offsets between the QR and polarimeter paths, and can incorporate an optional camera for continuous target monitoring.

beacon state of polarization and provides feedback for polarization compensation. 3. Tracking Camera Path – provides real-time imaging for target acquisition, and operational verification. The polarization and quantum receiver channels each contain half-wave plates (HWP) for active polarization correction. Collectively, these functions enable simultaneous quantum signal reception, active polarization stabilization, and continuous target monitoring, all of which are critical for maintaining a stable satellite-to-ground quantum communication link.

2.1 Optical and mechanical design

2.1.1 Optical system design

The BFO optical system was designed using ZEMAX ray tracing software and optimized for a compact breadboard implementation at the telescope backend. The opto-mechanical model shown in the Figure 3 is driven by the aperture requirements of the quantum receiver and polarimeter, operational wavelengths, and polarization-control requirements. A fold mirror redirects the telescope beam into the BFO, while spatial filter (≈ 1 mm) suppresses stray light and background. An aspheric lens (L1) collimates the incoming light. A Dichroic beam splitter (DBS1) separates the quantum signal wavelength from the down-link beacon. A beam splitter (BS) enables simultaneous polarization-state monitoring and target acquisition, supporting real-time polarization compensation and optical alignment.

2.1.2 Mechanical system design

The BFO mechanical design consists of a Thorlabs cage system, mounted on a removable breadboard and a stand-alone fold mirror. Both are supported by 1/2 inch stainless steel posts as shown in Figure 3. The design allows the optical chain, excluding the fold mirror, to be aligned in a laboratory environment before installation on the telescope. Following installation, the telescope, fold mirror, and BFO assembly is coarsely aligned using 3D printed tools. Fine adjustments are made to individual elements to align the system to within the required $100\ \mu\text{m}$ accuracy.

Finite element analysis was performed in ANSYS to evaluate gravity-induced deflections for all operational telescope orientations. The maximum predicted displacement of the cage system and breadboard remained below $100\ \mu\text{m}$. The system was validated in the laboratory showing consistent beam coupling when held in different orientations.

2.2 Alignment of the BFO

The BFO optical system was assembled and aligned on a laboratory test bench using a cage-system architecture mounted on a custom breadboard designed to interface with the telescope backend. Height of the optical axis was established using a laser source and spatial filter. Figure 4 presents the laboratory test configuration of the BFO optical system. The optical performance of both the polarimeter and QR paths was characterized

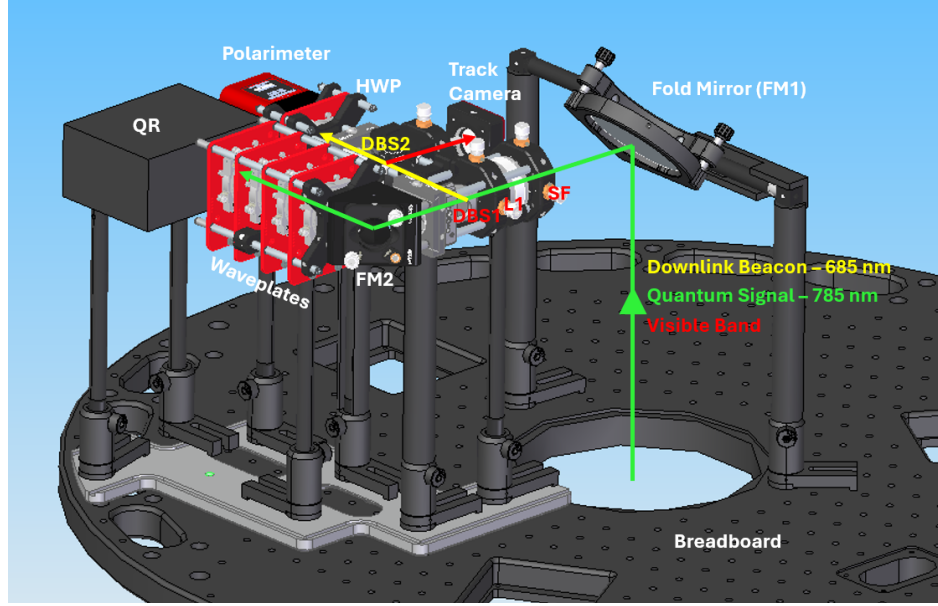


Figure 3. BFO mechanical design. The telescope breadboard is shown in black. The BFO cage removable breadboard is shown in grey. The light entering from telescope breadboard and the beam paths are drawn. Note that the quantum receiver (QR) model is replaced with a black box representation.

using a Shack-Hartmann wavefront sensor. In the QR path, an RMS wavefront error of $\lambda/5.69$ was achieved with a beam size of ≈ 3.4 mm, corresponding to a measured beam divergence of ≈ 0.278 mrad, well within the system requirement of < 1 mrad. Fiber coupling, polarimeter alignment, and polarization offsets between the QR and polarimeter paths were characterized and recorded for static correction. Waveplates mounted on motorized rotation stages enable precise recalibration and real-time polarization control. After successful laboratory testing and verification, the system was deemed ready for telescope integration.

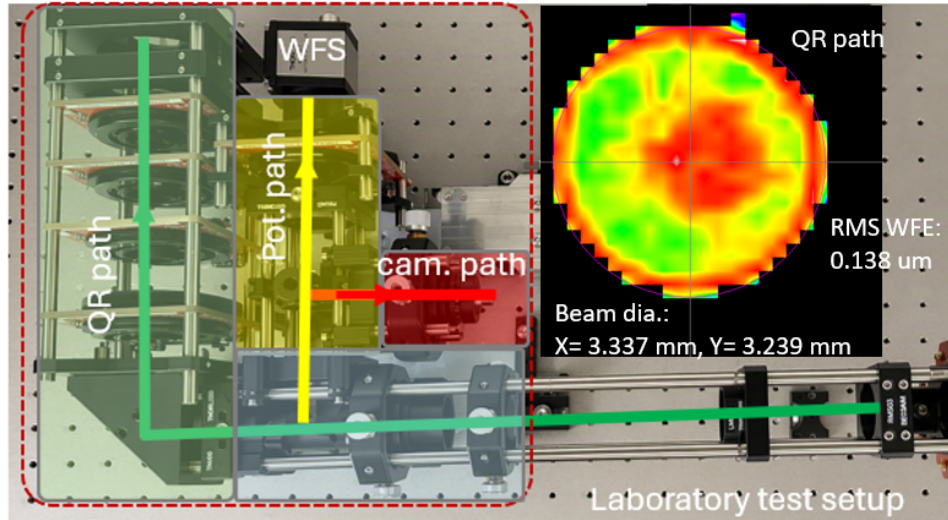


Figure 4. Laboratory setup of the BFO system used for optical alignment and performance verification. Test lasers were employed to establish and confirm alignment of the three optical paths. A Shack-Hartmann wavefront sensor was used to measure the beam size and tilt angle in the polarimeter and QR paths, and to characterize the RMS wavefront error of the QR path. In this figure, the wavefront sensor is shown mounted in the polarimeter path.

2.3 Telescope commissioning

The telescope commissioning of the BFO was performed through four stages: establishment of the correct BFO height, alignment of the polarimeter path, alignment of the tracking camera path, and alignment of the quantum receiver path. The solid model of the BFO integrated with the telescope backend breadboard is shown in Figure 3. The fold mirror redirects the telescope beam by 90° into the BFO assembly. Initial alignment was achieved using custom 3D-printed alignment fixtures and back-propagated test lasers that established the required height and angular orientation of the fold mirror. The telescope focal plane, located approximately 160 mm from the fold mirror, was first characterized using an imaging camera centered on a stellar target. The camera was then replaced by the BFO assembly, and its position was adjusted until the beam propagated through the spatial filter, confirming alignment with the telescope optical axis. To refine the alignment, the BFO system can be translated using a two axes stage and the beam can be tilted using the fold mirror. Fine alignment was performed using observations of bright astronomical targets. Alignment was deemed to have been achieved when a focused image of the target was consistently achieved on the track camera. Owing to the narrow-band filtering centered at 785 nm, the QR path could not be verified using bright stars. Instead, a reverse-propagation alignment technique was employed. A test laser was launched from the QR path aperture and propagated backwards through the optical chain towards the telescope. After referencing the position of spatial filter, the QR fold mirror was finely adjusted to center the back-propagated beam, thereby refining the optical alignment.

The performance of the BFO alignment was subsequently verified using a range of static targets at different elevation angles, as well as several LEO satellites. These validation activities confirmed the optical alignment prior to the successful acquisition of the SpeQtre DLB signal. Figure 5 presents the DLB image acquired by the BFO tracking camera together with the corresponding power measurements obtained from the polarimeter. These results confirm the successful detection of the SpeQtre down-link beacon by both subsystems.

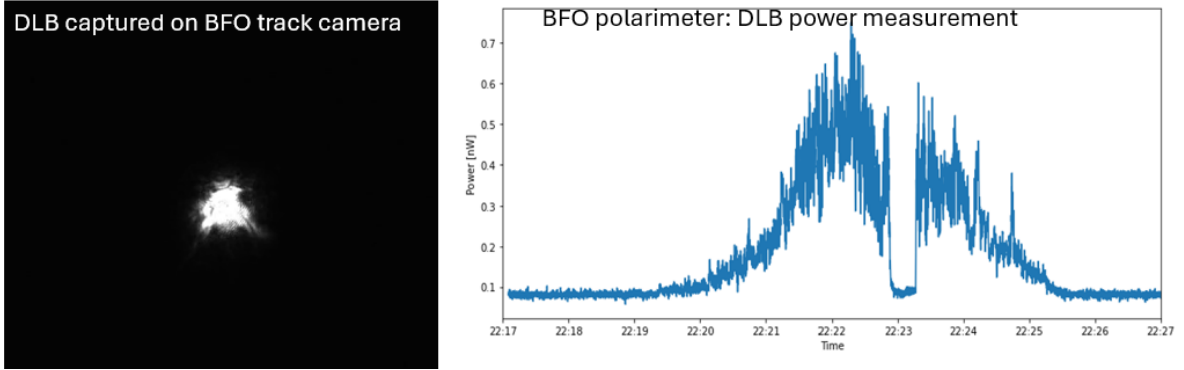


Figure 5. The image on the left shows the down-link beacon (DLB) as captured by the BFO tracking camera, while the plot on the right presents the DLB power measurements recorded using the BFO polarimeter.

The SpeQtre payload is currently in the commissioning phase of its critical QKD delivery subsystems. Concurrently, the ground station quantum receiver and supporting infrastructure are being commissioned to enable satellite-to-ground QKD operations. Results from the end-to-end system demonstration will be reported following completion of the commissioning campaign.

3. UP-LINK LASER BEACON

3.1 System overview

The ULB provides the optical reference signal required by the spacecraft to accurately point the down-link quantum beam toward the ground station. The system comprises four identical beacon units, delivering a combined optical output power of ≈ 2.5 W. The use of multiple independent beacons, rather than a single high-power source, ensures compliance with Civil Aviation Authority (CAA) laser safety regulations while maintaining the required optical performance. All beacon units are mounted directly onto the telescope structure, ensuring that the transmitted beams remain co-aligned throughout satellite tracking operations.

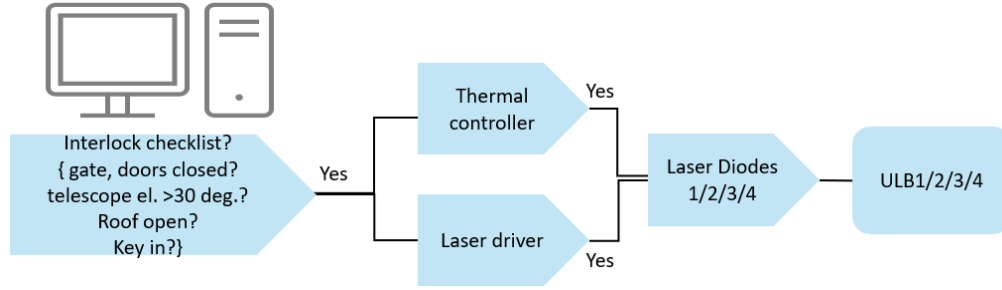


Figure 6. ULB system overview. The interlock system ensures compliance with laser safety requirements prior to enabling the laser transmission.

3.2 Optical and mechanical design

The ULB was designed to transmit an on-orbit beam footprint of approximately 5 km while having an aperture diameter ≈ 100 mm. This corresponds to a beam divergence requirement of 0.5 ± 0.1 mrad.

3.2.1 Optical system

Optical modeling of the ULB system was performed using ZEMAX ray-tracing software. The design was optimized to meet the beam size and beam divergence performance requirements. The opto-mechanical model of the ULB is shown in Figure 7. The design combines a commercial fiber collimator (lenses L1, L2) with a custom beam-expansion assembly (lenses L3, L4, L5) that increases the beam diameter while preserving the required divergence characteristics. The system is designed with a return optical path, enabling it to function as an optical transceiver. This return path operates within the visible spectrum and facilitates the alignment of the ULB with the main telescope as well as with the other three ULBs using a bright reference star. A dichroic beam splitter is used to separate the outgoing beacon laser from the incoming optical signal. To mitigate laser safety risks, an additional optical filter is incorporated to prevent the beacon laser from entering the return path. The laser is delivered through a multi-mode optical fiber (NA ≈ 0.14) using a ruggedized 6 m patch cable suitable for outdoor operation. The resulting system produces a diverging beam, satisfying both aperture and on-orbit footprint requirements.

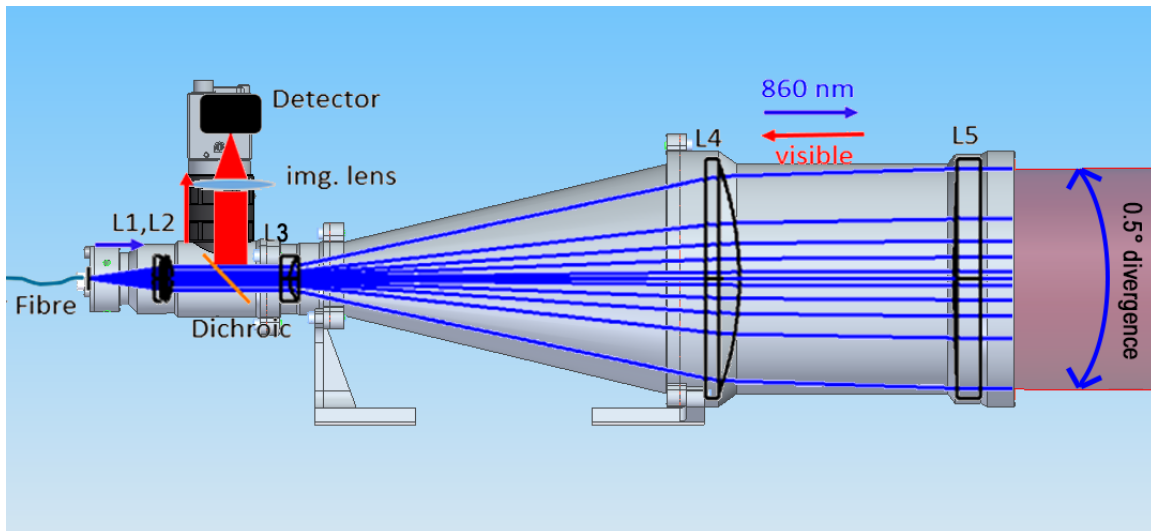


Figure 7. ULB optical model showing the forward and return optical paths. Lenses L1 and L2 collimate the laser beam, while L3, L4, and L5 form the beam-expander assembly. The forward path delivers the 860 nm laser beacon, while the return path operates in the visible wavelength band. Co-alignment of the two beam paths ensures accurate beam pointing.

3.2.2 Mechanical system

Aluminium 6082-T6 was selected as the primary design material due to its high structural efficiency, corrosion resistance and ease of manufacture. Each ULB is assembled from four aluminium beam tubes (Figure 7). Having four sections allows an optical element to be inserted from either end, and adjusted independently. Interfaces between beam tubes have radial clearances below $12.5\text{ }\mu\text{m}$ and angular tolerances of $\pm 0.7\text{ mrad}$ on the largest diameters; these ensure element de-center and tilt remain within allowable tolerances. The beam tube geometry was selected to provide sufficient bending stiffness whilst minimising mass. Each ULB has a mass of approximately 1.5 kg.

Lenses L1 and L2 are contained in the Thorlabs fibre collimation package (F810FC-850). The collimator is offset from the axis of the beam tube to compensate for the beam displacement introduced by the dichroic beam splitter.

Due to the wide operating temperature range, thermal stability was identified as a primary contributor to alignment drift. Therefore, heaters are located around the diameter of the ULB to maintain the assembly above 15°C to avoid condensation and limit thermal expansion/contraction of the beam tube which would change lens separation.

3.3 Alignment and characterization

Each ULB unit underwent laboratory alignment and performance verification prior to installation on the telescope. Beam divergence of $\approx 0.48^\circ \pm 0.02^\circ$ was measured by recording beam diameters at three positions over a propagation distance of $\approx 7.39\text{ m}$. Adjustment of divergence was achieved using precision shims within the beam-expansion assembly. Optical throughput was determined using an apochromatic telescope that reduced the 100 mm output beam to $\approx 3\text{ mm}$ for power measurement. After accounting for measurement-system losses and fiber attenuation, a throughput of $\approx 88\%$ was measured, in close agreement with design predictions. Transceiver beam paths co-alignment was verified using a Shack–Hartmann wavefront sensor configured as a bidirectional alignment system. Propagation of the ULB laser through the beacon optics enabled alignment of the optical axes to within $\pm 0.5\text{ mrad}$ relative to the WFS reference. The corresponding beam position recorded on the ULB return-path camera was subsequently retained as a commissioning reference for future alignment verification. Figure 8 shows the alignment and characterization test setups of ULB.

3.4 Telescope commissioning

After laboratory characterization, the four beacon units were installed on the telescope and aligned using a two-stage commissioning procedure. Initial coarse alignment was performed using a distant terrestrial target. Fine alignment was subsequently carried out using bright stellar targets under closed-loop telescope tracking. Alignment adjustments continued until the observed target centroid coincided with the laboratory reference position. Final verification was performed during tracking of LEO satellites. Throughout these passes, the satellites remained within the ULB camera field of view, confirming stable alignment between the telescope and beacon systems.

Figure 9 shows the ULB on-sky alignment verification. Under hazy sky conditions, long-exposure beacon images acquired with the guidescope confirmed the overlap of all four ULB beams, with the combined beam footprints centered on the tracked target. The measured pointing accuracy was approximately 1.5 arc-min, corresponding to less than 5% of the projected beam diameter at orbital altitude. These results confirm compliance with the pointing and overlap requirements necessary for reliable ULB operations.

4. CONCLUSION

This study presented the design, development, integration, and verification of two critical optical subsystems for a satellite quantum communication ground station: the BFO and the ULB. The BFO provides efficient optical signal routing, polarization analysis, and target acquisition. Its modular cage-based architecture simplifies integration and alignment. The reverse-propagation alignment methodology developed for the quantum receiver path expected to be effective for refining fiber-coupling performance under operational conditions. The ULB was successfully developed as a modular beacon platform capable of rapid deployment and adaptation to different

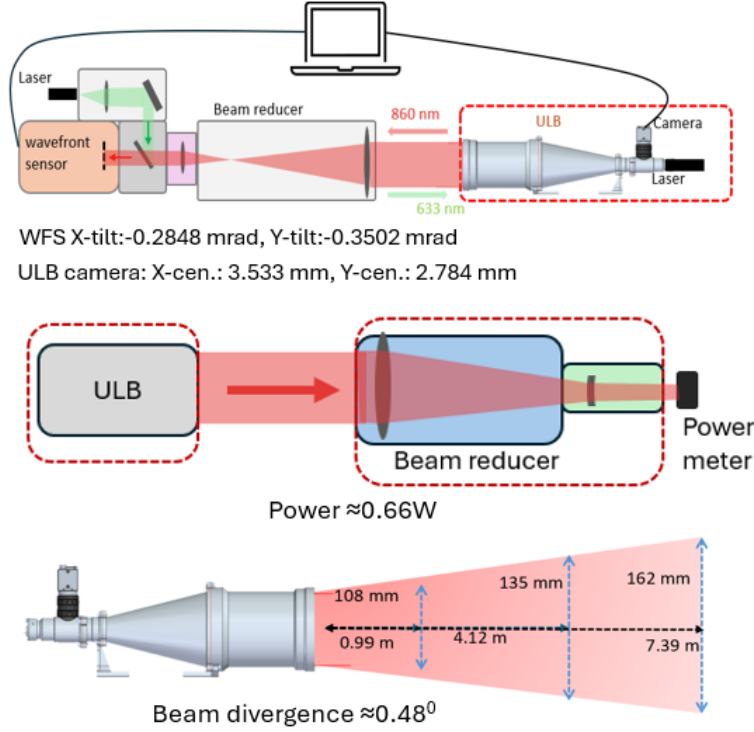


Figure 8. ULB alignment and characterization setup are shown. The top panel shows verification of the transceiver path alignment using a wavefront sensor (WFS), the middle panel illustrates the test setup used for ULB throughput measurements using a power meter, and the bottom panel presents the beam divergence measurement (dimensions are not to scale).

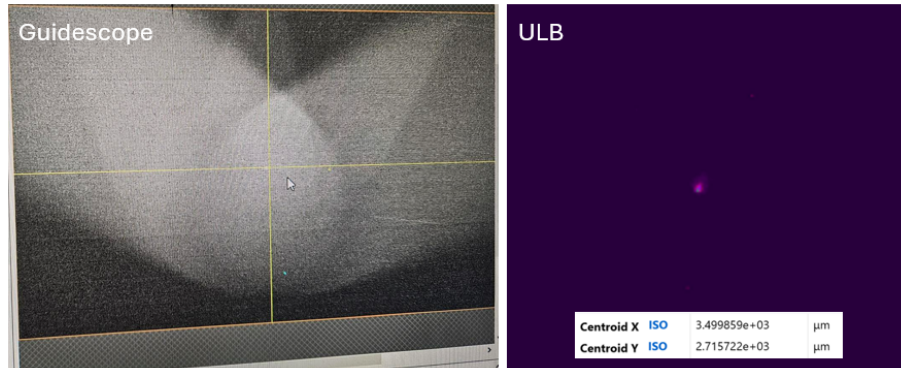


Figure 9. ULB on-sky alignment verification. The image on left shows the overlapping of the four ULB beams captured using the main telescope's guidescope under hazy sky conditions and the image on the right is of a low-Earth orbit object captured using one of the ULB's return camera. The image centroids coincide within 0.025° with laboratory reference shown in Figure 8.

telescope systems. Its architecture supports straightforward alignment of multiple beacon units while maintaining reliable transmit–receive co-alignment and pointing performance during operational satellite tracking. Laboratory testing and on-sky commissioning demonstrated that both subsystems satisfy their primary design objectives. The ULB achieved the required beam divergence, throughput, and pointing accuracy, while the BFO successfully supported target acquisition, and polarization monitoring functions. Although complete end-to-end verification of the quantum communication chain remains ongoing, the results presented here demonstrate that

the developed subsystems provide a foundation for satellite QKD missions and the realization of secure global quantum communication networks.

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