

Enabling Free-Space QKD and High-Rate Optical Communications from the UAE

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Abstract

Cybersecurity and quantum communications are becoming central pillars of optical space links as satellite-based Quantum Key Distribution (QKD) missions continue to expand worldwide. However, the lack of consensus on payload architectures and operational wavelengths has created a fragmented landscape, posing challenges for long-term interoperability and scalability. This situation underscores the need for flexible, multi-mission optical ground stations capable of supporting a wide range of quantum and classical optical communication links. In this context, the Abu Dhabi Quantum Optical Ground Station (ADQOGS) has been designed and built as a versatile platform to accommodate heterogeneous mission requirements and evolving technological standards. Following the presentation of the station's technical architecture at ICSO 2024 [1], this proceeding reports the first experimental results obtained after ADQOGS's successful commissioning. We demonstrate ground-to-ground free-space QKD over an approximately 1.8 km atmospheric channel using an entanglement-based QKD payload, achieving a secure key rate in the kbps range. In parallel, we present an on-site characterization of atmospheric and seeing conditions, including turbulence and background illumination, which validate the station's operational margins for future satellite-to-ground QKD services.

1 Introduction

Quantum communication relies on the fundamental properties of quantum mechanics to offer unprecedented levels of cybersecurity, allowing theoretically unconditionally secure data transmission [2]. While terrestrial fiber networks are currently limited by exponential photon loss over long distances, satellites provide a critical solution by establishing free-space line-of-sight links that bypass these terrestrial constraints. Consequently, implementing a global quantum internet depends heavily on deploying multiple, resilient satellite-based entanglement distribution links [3, 4]. In the broader concept of the satellite quantum network, space-based nodes will act as global relays, linking isolated metropolitan networks across continents to form a continuous web of secure communication. As space-based QKD architectures mature, optical ground stations (OGSs) act as the critical bridge connecting the space segment to terrestrial networks. To ensure practical integration, these stations must balance proximity to urban centers with manageable atmospheric and optical noise conditions. Currently, the industry faces significant hurdles due to severe technological fragmentation. The lack of consensus on payload architectures, communication protocols, and operational wavelengths has created a fragmented landscape, challenging long-term interoperability and scalability. This underscores the critical importance of standardization to unify hardware and software interfaces and ensure disparate

global networks can communicate seamlessly. This situation simultaneously underscores the need for flexible, multi-mission optical ground stations capable of supporting a wide range of quantum and classical optical communication links. In this context, the Abu Dhabi Quantum Optical Ground Station (ADQOGS) has been designed and built as a versatile platform to accommodate heterogeneous mission requirements and evolving technological standards. This paper outlines the station’s modular architecture, presents the results of an end-to-end terrestrial QKD transmission experiment, and characterizes the local atmospheric turbulence and background light conditions affecting optical link performance.

2 Abu Dhabi Quantum Optical Ground Station

The Abu Dhabi Quantum Optical Ground Station was designed as a fully automated and versatile facility for optical and quantum communications [1]. Situated in Al Wathba, Abu Dhabi, at an altitude of roughly 50 m above sea level, the site provides a highly relevant low-altitude coastal-desert testing environment. The station hosts an 80 cm Ritchey-Chrétien telescope equipped with a Quantum Acquisition and Tracking System (QATS): the optical signal collected by the primary mirror is routed towards different paths according to the wavelength; see Figure 1. The QATS can detect a classical beacon in two wavelength bands (visible: [600 – 700] nm; infrared: [900 – 1565] nm); it also includes a multimode fiber output port for receiving amplitude-modulated communication at [1530 – 1565] nm. Visible and infrared beacons are detected using Silicon and InGaAs detectors, respectively. Inside the QATS, the signal in the [770 – 850] nm range is routed to a QKD receiver module; equipped with four Silicon Single Photon Detectors (SPDs). The module implements a QKD passive basis receiver for two mutually unbiased polarization bases. Three motorized wave plates are placed at the module input to implement a generic rotation of the quantum signal polarization, achieving the same polarization reference frame between the satellite and the station. In addition, spectral filters are mounted in translation stages so that the desired spectral background selection can be implemented according to the satellite’s specific mission. A Fast Steering Mirror (FSM) is placed at the input of the QATS to implement first-order wavefront correction (tip-tilt). An uplink beacon is required to establish accurate OGS positioning. Therefore, the station is also equipped with a high-power beacon laser emitter (BOBA) operating in the wavelength range of [1500 – 1600] nm, with up to 10 W output. It is installed as a “sidecar” to the telescope structure, and it is equipped with a fast-steering mirror and a point-ahead mechanism. Different wavelengths can be provided by different master oscillators and amplifiers.

ADQOGS site uses a GPS-synchronized Rubidium master clock as the timebase reference for all internal processes. Moreover, a Miratlas weather station records macroscopic weather parameters and optical turbulence measurements.

3 Terrestrial free-space QKD experiment

To validate the end-to-end performance of the quantum receiver chain under realistic environmental conditions, a horizontal free-space BBM92 QKD experiment was conducted [5]. The line-of-sight link spanned 1.8 km across a semi-urban desert environment approximately 40 km from the city center of Abu Dhabi. The experiment was performed at night under moderate atmospheric conditions using two static outdoor terminals, providing a representative field validation of the complete optical architecture intended for future satellite-to-ground quantum communications. The campaign was designed not as a proof-of-principle quantum optics experiment, but as a system-level validation of the compatibility between a space-qualified quantum payload and a fully automated optical ground station.

The transmitter node (Alice) utilized space-qualified engineering models of both the quantum light source and a quantum receiver developed for the SpeQtre satellite payload; see Figure 2. The entangled source is based on a Type-0 spontaneous parametric down-conversion process implemented in a linear

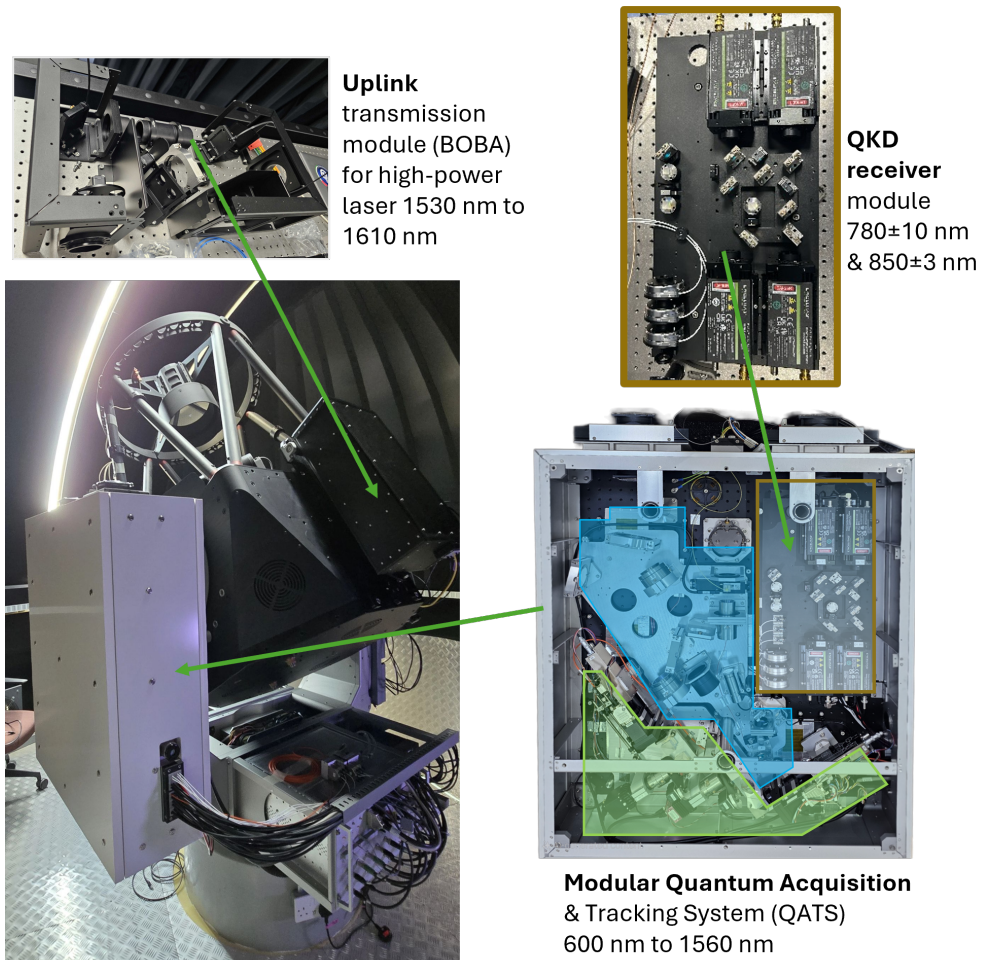


Figure 1: Modular design of the Quantum Acquisition and Tracking System of the ADQOGS station.

displacement interferometer. Polarization-entangled photon pairs were generated at wavelengths of 780 nm (signal) and 842 nm (idler), targeting the Bell state $|\Phi^-\rangle$. The experiment emulated the operational single-downlink architecture foreseen for SpeQtre, in which the idler photon is measured locally within the payload while the signal photon is transmitted through free space toward the ground station. The transmitted beam was launched through a 135 mm aperture telescope, producing an optical spot approximately 100 mm in diameter at the receiver plane. Bob’s receiver is the QKD measurement module of ADQOGS. To reproduce the operational conditions expected during satellite passes, we employed identical background-rejection techniques: spectral filtering used a 16.6 nm FWHM interference filter centered at 785 nm, while spatial filtering restricted the field of view to 0.0028° (10 arcsec). Synchronization between Alice and Bob was achieved through timestamp cross-correlation using GPS-disciplined clocks, while classical communication was established through long-range radio links. The initial acquisition employed a dedicated alignment laser before switching to the quantum signal, after which the received count rate was optimized through fine alignment. During data collection, the QATS continuously compensated residual pointing drifts using closed-loop tracking based on a classical beacon and a fast steering mirror, maintaining stable optical coupling throughout the experiment.



Figure 2: Photos of the two deployed nodes.

A continuous 20-minute acquisition demonstrated stable system operation without measurable degradation in either coincidence rate or quantum bit error rate (QBER). A mean sifted coincidence rate of 24,665 photon pairs per second was measured together with an average QBER of $4.8\% \pm 0.24\%$. The temporal evolution of both quantities, shown in Figure 3, confirms the stability of the complete optical and tracking chain during field operation. The finite-key analysis was performed within a composable security framework using the recently introduced Sharp statistical bound [6], with a total security parameter of $\epsilon = 4 \times 10^{-16}$. Since finite-size effects dominate for short acquisition intervals, the raw data were aggregated over increasing integration times. Using 5-minute acquisition blocks, the finite-size secret key rate reached 7.6 kbps, approaching the asymptotic performance limit of the system. These results demonstrate that the integrated SpeQtre payload and ADQOGS architecture can sustain stable entanglement-based QKD operation under realistic outdoor conditions while validating the optical interfaces, background rejection strategy, synchronization procedures and post-processing pipeline required for future satellite deployments.

Although the experiment was conducted over a relatively low-loss terrestrial link, it verified several key operational elements required for future LEO demonstrations, including compatibility between the space-qualified quantum payload and the optical ground station, closed-loop optical tracking, stable polarization analysis, synchronization, and the complete quantum post-processing chain. These results therefore establish an important intermediate technology-readiness milestone prior to full satellite deployment, where additional challenges such as high link losses, dynamic polarization rotation,

Doppler compensation and autonomous orbital tracking will have to be addressed.

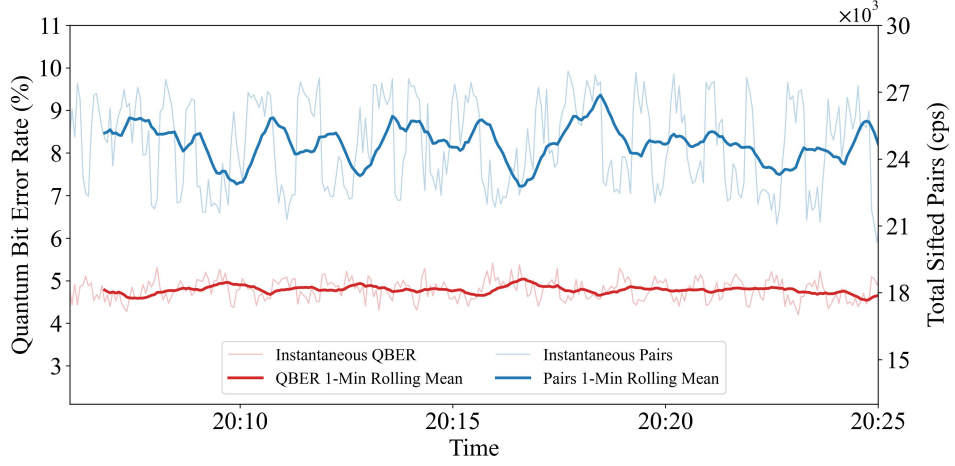


Figure 3: Temporal evolution of system performance metrics. The left axis shows the quantum bit error rate, with instantaneous 1-second-resolution data plotted in light red and the corresponding 1-minute rolling mean in dark red. The right axis denotes the detected sifted pair rate in counts per second, scaled by 10^3 . The instantaneous sifted pair rate is depicted in light blue and its 1-minute rolling mean in dark blue. The system’s performance remained stable over the whole measurement session. Image taken from [5].

4 Site Characterization: Turbulence and Background Light

The transition to operational satellite networks requires a precise understanding of the free-space channel's atmospheric constraints; hence we studied the level of turbulence and background noise at the station's location [7]. Two of the most used metrics to evaluate optical turbulence is the Fried parameter r_0 and the isoplanatic angle θ_0 , which can be expressed as [8]:

$$r_0 = \left[0.423 k^2 \sec(\xi) \int_0^h C_n^2(z) dz \right]^{-\frac{3}{5}}, \quad \theta_0 = \left[2.91 k^2 \sec^{8/3}(\xi) \int_0^h C_n^2(z) z^{5/3} dz \right]^{-\frac{3}{5}} \quad (1)$$

where $k = 2\pi/\lambda$ is the optical wave number and ξ is the zenith angle (valid up to $\approx 70^\circ$). This equation holds for a downlink scenario. ADQOGS continuously monitors this parameter via a c-DIMM system. Analysis of a 19-month dataset revealed a median Fried parameter of approximately 7.5 cm at 500 nm. Scaling this to near-infrared wavelengths typically used for QKD yields an $r_0 \approx 12.8$ cm at 780 nm and $r_0 \approx 14.2$ cm at 850 nm; see Figure 4. These moderate turbulence levels validate the viability of robust acquisition and tracking utilizing the current fast tip-tilt correction system.

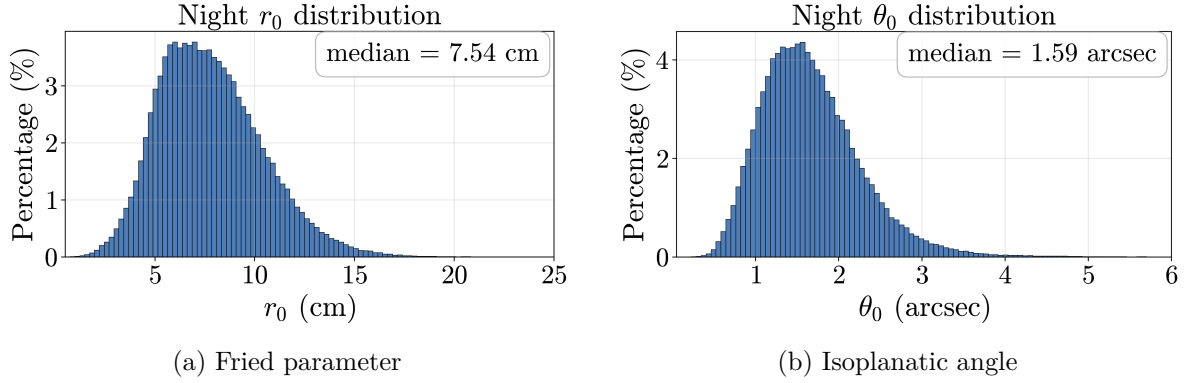


Figure 4: Percentage of optical turbulences expressed in Fried parameter r_0 and the isoplanatic angle θ_0 recorded at 500 nm.

In addition, we performed sky background measurements during both no-moon and full-moon conditions; see Figure 5. During no-moon nights, we observed a few hundred counts per second per detector; the background was dominated by anthropogenic sky-glow, which showed a pronounced azimuthal asymmetry toward the city of Abu Dhabi. During no-moon nights, single counts per detector oscillated up to 1600 cps; the background was heavily localized according to the position of the moon. All these measurements were performed with spatial and spectral filtering. Overall, the long-term turbulence statistics and background-light survey demonstrate that the ADQOGS site provides favorable conditions for free-space quantum communications. These measurements directly informed the receiver design and operational strategy adopted in the terrestrial QKD demonstration presented in the previous section, while simultaneously establishing an environmental baseline for future satellite-to-ground quantum communication experiments.

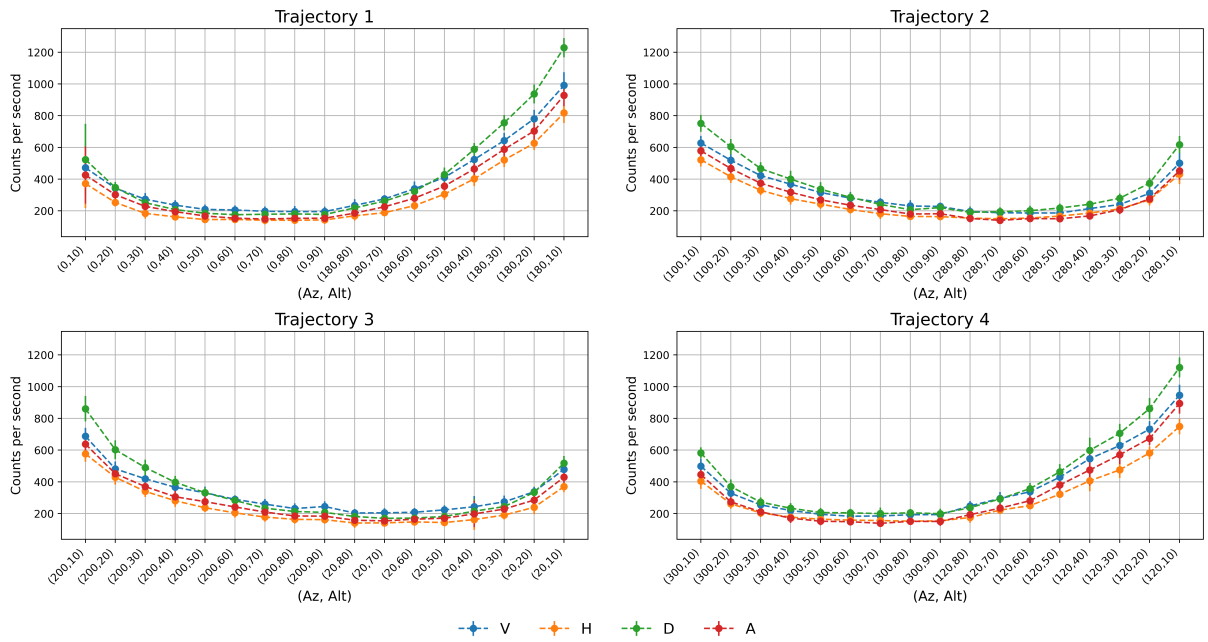
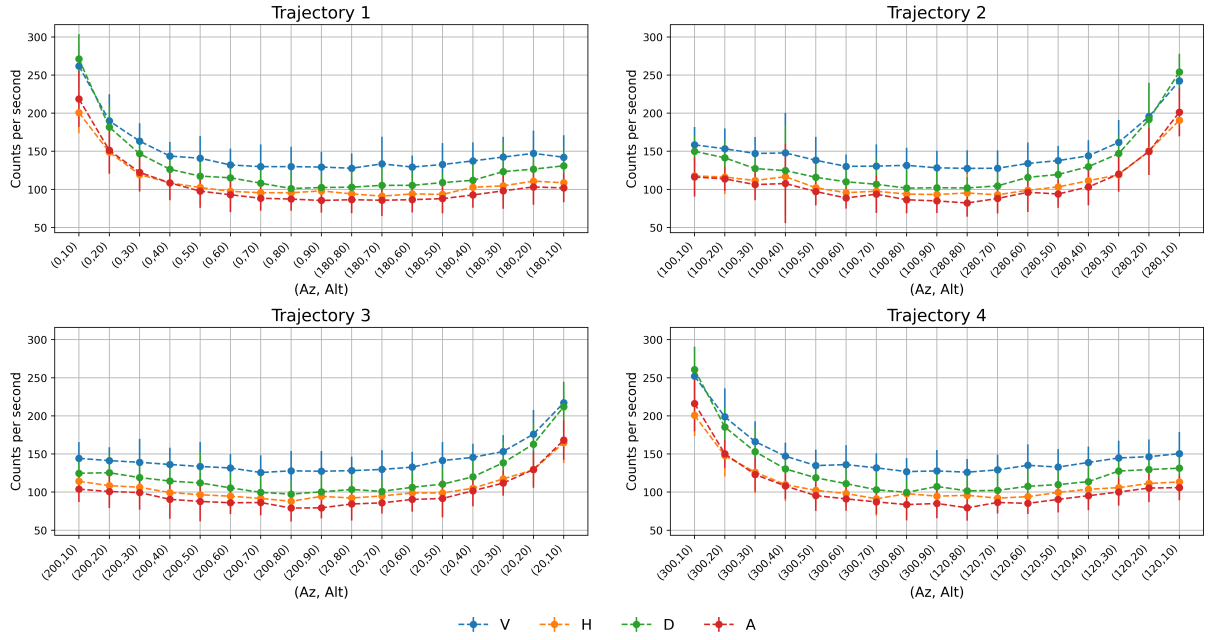


Figure 5: Background radiation for four different trajectories with a spectral filter of 16.6 nm FWHM centered at 780 nm [7].

5 Conclusions

In this work, we have demonstrated the successful commissioning and experimental validation of the Abu Dhabi Quantum Optical Ground Station. Built to address growing fragmentation in satellite quantum communication architectures, ADQOGS is a highly versatile, multi-mission platform capable of adapting to diverse and evolving payload standards. Through a terrestrial free-space BBM92 QKD experiment spanning a 1.8 km line-of-sight channel, we validated the end-to-end performance of the station’s quantum receiver chain. The system achieved a finite-size secure key rate of 7.6 kbps with a mean QBER of 4.8%, using a space-qualified entanglement-based source. Furthermore, extensive site characterization revealed a median Fried parameter of approximately 12.8 cm at 780 nm, confirming that the moderate optical turbulence in this coastal-desert environment is well within the correction capabilities of the station’s fast tip-tilt tracking systems. Background illumination measurements highlight the necessity of robust spatial and spectral filtering to mitigate localized anthropogenic sky-glow and lunar background noise. Ultimately, these results confirm ADQOGS’s operational readiness to support high-throughput classical links and secure satellite-to-ground quantum communications. The facility now stands as a critical experimental testbed in the Arabian Peninsula, ready to contribute to the global standardization and deployment of the future quantum internet.

References

- [1] Sana Amairi-Pyka, Christoph Fischer, Konstantin Kravtsov, Gianluca De Santis, Alessandro Grosso, Edgar Fischer, Klaus Kudiella, and James A Grieve. Versatile optical ground station for satellite-based quantum key distribution in abu dhabi. *arXiv preprint arXiv:2412.03872*, 2024.
- [2] Nicolas Gisin and Rob Thew. Quantum communication. *Nature photonics*, 1(3):165–171, 2007.
- [3] Robert Bedington, Juan Miguel Arrazola, and Alexander Ling. Progress in satellite quantum key distribution. *npj Quantum Information*, 3(1):30, 2017.
- [4] Gianluca De Santis, Konstantin Kravtsov, Sana Amairi-Pyka, and James A Grieve. Parallel trusted node approach for satellite quantum key distribution. *EPJ Quantum Technology*, 12(1):50, 2025.
- [5] Gianluca De Santis, Jia Boon Chin, Srihari Sivasankaran, Konstantin Kravtsov, Chin Chean Lim, Aitor Villar, Robert Bedington, Sana Amairi-Pyka, Eleni Diamanti, Alexander Ling, et al. Terrestrial readiness campaign for space-to-ground quantum communications with a space-qualified entangled photon-pair system. *arXiv preprint arXiv:2605.19689*, 2026.
- [6] Vaisakh Mannalath, Víctor Zapatero, and Marcos Curty. Sharp finite statistics for quantum key distribution. *Physical Review Letters*, 135(2):020803, 2025.
- [7] Gianluca De Santis, Konstantin Kravtsov, Ozan Kara, Sana Amairi Pyka, and James A. Grieve. Site characterization for satellite quantum key distribution at the abu dhabi quantum optical ground station. In *IAF Space Communications and Navigation Symposium*, pages 318–326. International Astronautical Federation (IAF), 2025.
- [8] Larry C Andrews and Ronald L Phillips. Laser beam propagation through random media. *Laser Beam Propagation Through Random Media: Second Edition*, 2005.