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ADQOGS: ENABLING FREE-SPACE QKD AND HIGH DATA RATE OPTICAL COMMUNICATIONS FROM THE ARABIAN PENINSULA

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The Abu Dhabi Quantum Optical Ground Station (ADQOGS), developed by the Quantum Research Centre at the Technology Innovation Institute (TII), is a technological facility designed to address future threats to secure communications. As the first quantum optical ground station in the MENA region, ADQOGS is positioned to enable a new era of sovereign, quantum-resilient infrastructure, supporting both free-space Quantum Key Distribution (QKD) and high-data-rate optical satellite links. This paper details the architecture, tested capabilities, and applications of ADQOGS. It outlines its potential in enabling global quantum-secure communication networks, regional cyber defence, and Abu Dhabi's emerging regional leadership in quantum technologies. We include early experimental results from ground-based free-space optical links and site-characterisation data specific to the ADQOGS geographical location.

Keywords
Optical Ground Station, Quantum-Secure Network, Free-Space Optical Communication, Cybersecurity, Defence-in-Depth.

1. Introduction

The rapid evolution of air and space systems has increased the demand for secure, high-capacity communications. As operations become increasingly distributed and dependent on digital connectivity, ensuring the integrity and confidentiality of these communication channels has become a strategic priority. In this context, quantum key distribution (QKD) and high-data-rate optical communications offer transformative capabilities, providing resilience against both conventional and emerging cyber threats.

The strategic need for such capabilities is clear. Cybercrime is projected to cost the world $10.5 trillion in 2025 and is expected to rise further in the coming decade (BD Emerson, 2025). While these numbers represent the amalgamation of a wide range of cybersecurity breaches, they highlight the enormous value intrinsic to our global information economy, and the burden placed upon our cryptographic solutions. Recent estimates indicate that 70-80% of our secure communications rely on algorithms that are expected to be obsolete with the arrival of large-scale quantum computers. Unlike conventional

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algorithmic based cryptography, quantum key distribution (QKD) provides a quantum physics based key generation solution, ensuring that encrypted data remains safe against even the most advanced adversaries.

Around the world, governments and industries are accelerating efforts to deploy quantum-secure solutions. From national defence programs to large-scale initiatives the momentum is clear: building the foundations of an unbreakable encryption era that will safeguard digital trust and resilience in the quantum future. the European Union's EuroQCI initiative has invested nearly €97 million, part of a €1.2 billion quantum budget, to establish a secure pan-European backbone integrating both fiber and satellite-based QKD. This builds on the €1 billion Quantum Flagship, supporting over 5,000 researchers toward creating a continental-scale quantum internet. China, being the leading country in this field counts today over 10,000 km of optical fibre for QKD, 315 pairs of QKD devices in use, 20 metropolitan networks, and 6 Optical ground stations for free-space QKD (Ventures, n.d.).

Free-space QKD plays a foundational role in defence-in-depth architectures, allowing the long-distance secure exchange of cryptographic keys that are immune to interception or decryption, even by quantum computers. By integrating space-based QKD into secure communication networks, we overcome the distance limitation due to optical losses of fibre-based QKD solutions. This comprehensive solution offers a physical-layer security solution capable of securing satellite command and control, defence communications, and critical infrastructure.

With the growing number of satellite-based Quantum Key Distribution (QKD) payload launches, it becomes essential to ensure compatibility across different platforms for satellite tracking and quantum signal acquisition. The Abu Dhabi Quantum Optical Ground Station (ADQOGS), developed by the Quantum Research Centre at the Technology Innovation Institute (TII), represents a significant step forward in realizing these capabilities. As the first quantum optical ground station in the MENA region, ADQOGS enables secure free-space QKD and high-bandwidth optical satellite communications. Its modular architecture supports diverse satellite payloads and a range of missions (De Santis, 2025), bridging the gap between terrestrial networks and space-based communication infrastructures. By integrating advanced optical technologies with strategic foresight, ADQOGS not only enhances secure communications but also positions Abu Dhabi as a key node in emerging global quantum networks.

2. Environmental and technical differentiation

ADQOGS was opened in 2024 at the Al Sadeem Observatory, Al Wathba, Abu Dhabi. The site, shown in Figure 1, is located at 24°11' N, 54°41' E, which is a relatively low altitude of about 70 m above sea level, making it one of the lowest OGSs on Earth and representing an opportunity to explore different atmospheric conditions and scintillation-mitigation techniques. Moreover, the site has a desert climate and an urban-like light-pollution level.

The dome is equipped with a Ritchey–Chrétien telescope mounted on an Alt-Az mount, featuring a primary mirror with an aperture diameter of 80 cm.

A secondary plinth within the OGS premises is reserved for hosting transportable ground stations from around the world. The site is further equipped with a weather station that not only provides accurate and reliable measurements of environmental parameters (e.g., wind, temperature, and sky temperature) but also enables the monitoring of atmospheric seeing parameters through a Differential Image Motion Monitor (DIMM) device. This weather station is connected to a global network of similar stations, helping satellite operators identify the most favourable optical communication links. Weather and seeing data are recorded with timestamps ranging from 30 seconds to 5 minutes. These datasets are of significant value for national and international space research activities and for supporting multiple application partners across the country.

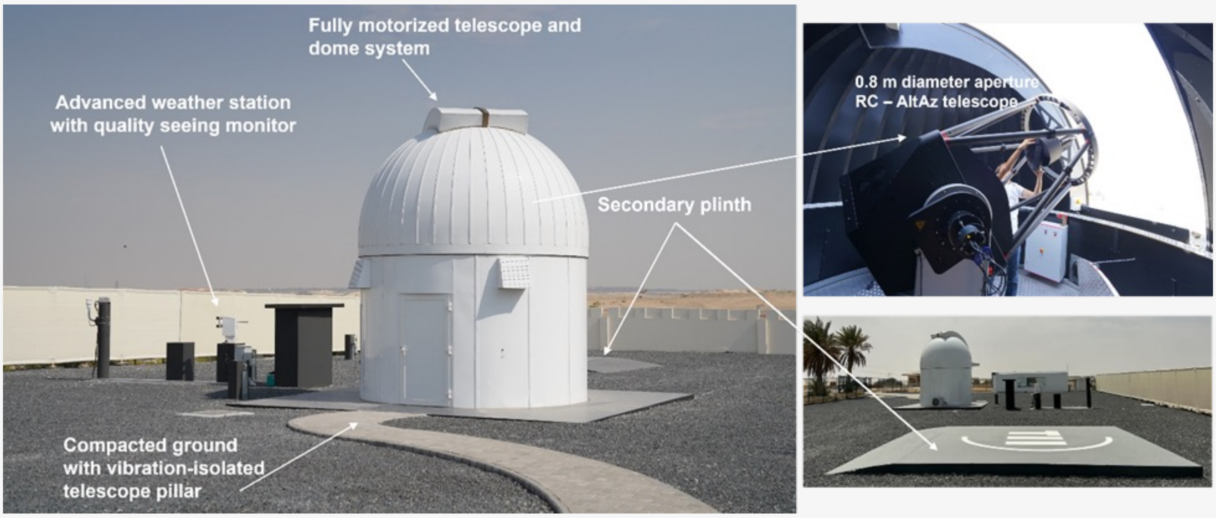

Figure 1 Overview of the ADQOGS site layout. ADQOGS is hosted by Al Sadeem Observatory, AlWathba, Abu Dhabi

The telescope provides two interoperable Nasmyth output ports. One of these hosts the Quantum Acquisition and Tracking System (QATS), which serves as the multi-modular receiver (Rx) and the downlink receiver for short-wave infrared (SWIR) optical communication channels (Figure 2). For uplink operations, the multi-band Beacon Optical Bench Assembly (BOBA) will be employed to transmit the beacon signal and operate as the uplink transmitter (Tx) for guiding satellites to the exact location of the OGS during the tracking and acquisition phase, and for free-space optical communication channels. The second Nasmyth port remains available for other applications, such as Space Situational Awareness (SSA) cameras or future receiver modules.

QATS is a multi-wavelength, tip-tilt-stabilised optical receiver system for QKD signals and associated classical downlink beacons (Amairi-Pyka, 2025). This is mandatory for active optical tracking of satellites. The setup is composed of three main modules. It has wavelength functionality ranging from 600 nm to 1565 nm for downlink beacons. A multimode-fibre output port for 1530–1565 nm amplitudemodulated communication reception is also included to allow downlink on-off-keying free-space optical communication. A dedicated subsystem within QATS features a motorised, polarisation-based QKD receiver module with four free-space single-photon detectors, which supports discrete-variable QKD with polarisation encoding. With the current spectral filters, the QKD detection module can be adjusted remotely to operate for 780 ± 10 nm and 850 ± 3 nm QKD signals. Changing the filters can allow operation at a different wavelength inside the band from 780 nm to 900 nm.

The BOBA OGS subsystem is mounted on the telescope body (Figure 2). It enables ADQOGS to transmit a modulated, high-power uplink beam towards a partner terminal hosted onboard a low-Earth-orbit (LEO) satellite. The module includes a wide-field-of-view camera that will be used for, e.g., initial coarse pointing-model acquisition or large-field-of-view observations. In addition, the system allows the transmission of laser beacons with a power of up to 10 W and a spectral range from 1530 nm to

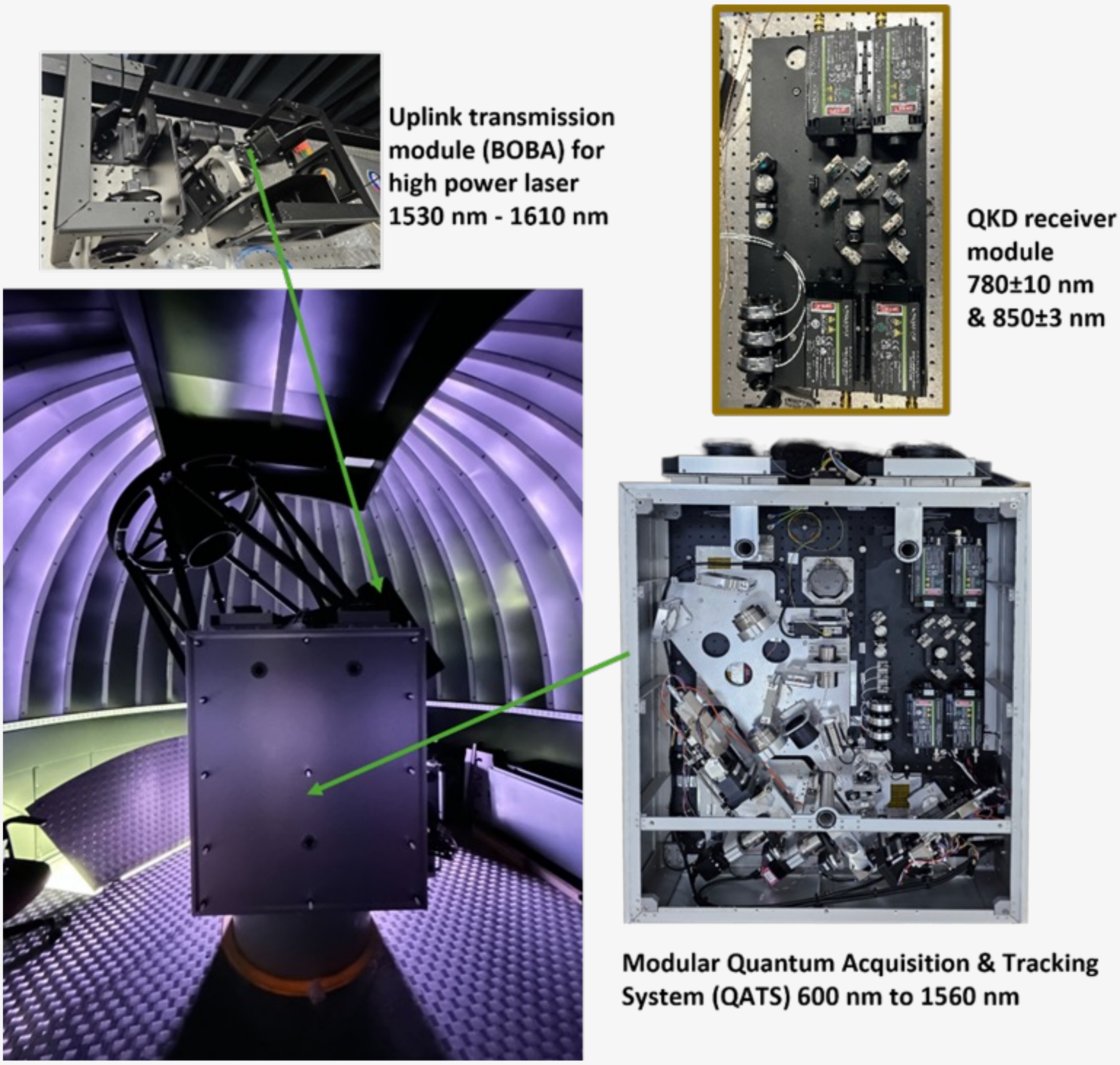

Figure 2 Integrated optical setup of ADQOGS: Modular and multi-mission design.

1610 nm. The BOBA module is equipped with low-frequency tip-tilt correction of the transmitted-beam line of sight, with possible point-ahead-angle-correction capabilities. The co-alignment between the Rx direction (QATS) and the Tx direction (BOBA) is accomplished via simultaneous star imaging.

3. Initial testing results

For the commissioning phase of the OGS, three main tests were performed to ensure the proper functioning of the telescope, the optical alignment, and the anticipated impact of light pollution in the Al Wathba area.

For the telescope-hardware performance testing, we adjusted the focusing parameters of the telescope by observing Saturn, Jupiter, sunlit satellites, and rocket bodies. To evaluate the tracking capabilities for satellites, we found that starting with a sunlit satellite is a valid approach. The most impressive images were obtained from the International Space Station (ISS) and large planets.

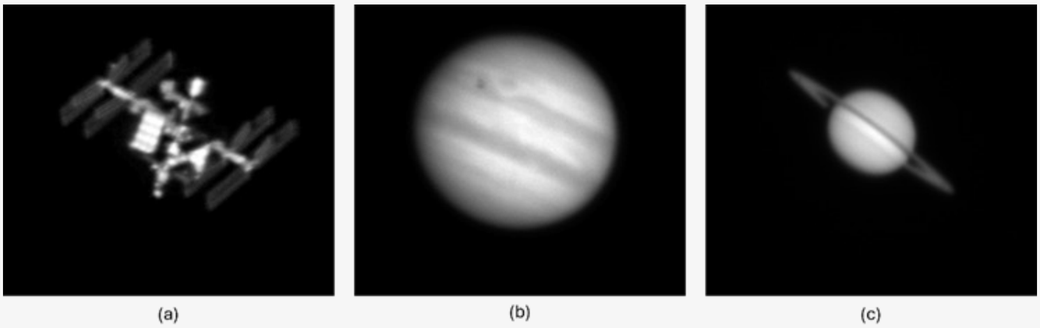

Figure 3 Telescope and satellite tracking performance evaluation: (a) ISS tracking using telemetric trajectory data, (b) Jupiter, and (c) Saturn. Scale bar corresponds to 1' on the sky. Image quality limited by atmospheric seeing conditions.

Figure 3 shows the images captured without any post-processing. The resolution is limited by atmospheric scintillation.

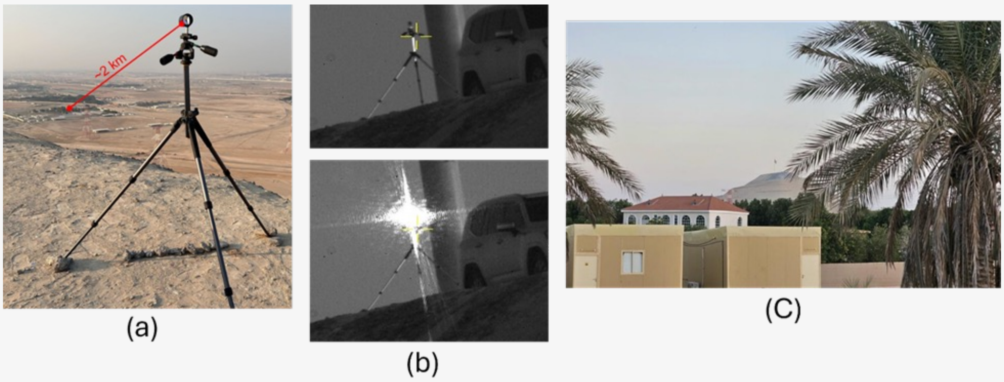

Figure 4 Qualitative tests of free-space ground to ground optical link: images captured by the QATS camera of 1550 nm laser (low power of a few mW) emitted from ADQOGS and retroreflected from Alwathba's hill at a distance of about 2 km. (a) The retroreflector mirror placed on the fill. (b) QATS camera images with the laser off (upper picture) and on (lower picture). (c) Picture of the Alwathba's hill taken from ADQOGS's dome.

For the optical alignment and coupling to the different cameras within QATS, we proceeded by placing a retro-reflective mirror at a far distance, in this case on top of a hill located at about 2 km from the ADQOGS site. We were able to test the free-space communication-links transmission and reception at low laser powers. The experimental setup is shown in Figure 4.

These qualitative tests allowed verification of the different alignments between BOBA and QATS and the coupling efficiency to the cameras and the fibre within QATS.

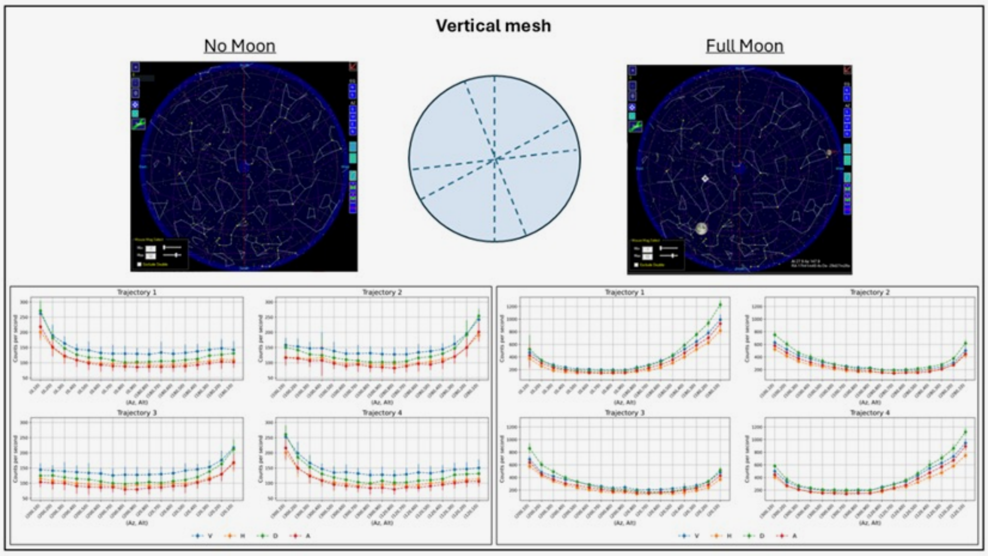

Figure 5 Single-photon detection counts at the four QKD module detectors (V, H, D, A) recorded under different satellite trajectory emulations during a moonless night and a full-moon night.

Light pollution is a critical factor when collecting extremely weak signals such as the QKD signal. To mitigate this issue, specialised spectral filters were integrated into the QATS system. In conditions of high light pollution, such as during a full moon, the background photon counts on the single-photon detectors can significantly increase. For this reason, it is essential to estimate the photon-count rates on the four QKD detectors under both full-moon and moonless conditions. The results are shown in Figure 5.

We estimate that the measured photon counts from light pollution, with and without a full moon, will not limit the performance of a QKD link during a QKD satellite pass, as the anticipated QKD photon-count rate is of the order of millions of photons.

4. Multi-mission capabilities

4.1. Global quantum communication networks:

ADQOGS is envisioned to serve as a trusted QKD node, currently under development for integration with future fibre-based QKD networks in Abu Dhabi with the support of the UAE Space Agency. This dual capability will enable seamless interoperability between space-based and terrestrial quantum communication infrastructures, thereby enhancing the resilience and scalability of secure key distribution. Moreover, quantum communications—and specifically QKD—are gaining international recognition as a defence-in-depth solution, providing an additional layer of enduring protection for sensitive data. In this context, ADQOGS can serve as a model for future facilities deployed to ensure resilient and future-proof communications. Beyond its operational role, ADQOGS is also intended to function as a reference model, providing a benchmark for the design and deployment of similar facilities in other regions.

Likewise, critical-infrastructure facilities, including power plants and energy-distribution networks, demand highly reliable and tamper-proof communication systems to ensure operational safety, protect against cyber threats, and safeguard sensitive industrial data. The health sector—including DNA databanks, biometric data centres, pharmaceutical data repositories, and broader healthcare services—is increasingly recognised as requiring secure communication channels to protect highly sensitive information.

The rapid progress in quantum communication worldwide underscores the importance of creating such hubs early to ensure sovereignty, resilience, and interoperability. International collaborations, particularly in Europe and Asia, are already demonstrating satellite-enabled QKD, highlighting the urgency for the MENA region to secure its position in this emerging field. By linking ground-based and orbital infrastructures, ADQOGS will not only strengthen regional cyber resilience but also position Abu Dhabi as a vital node in a future global quantum-secure network.

4.2. High-data-rate optical communications:

From a technical perspective, ADQOGS, as an optical terminal designed for satellite communication, can be readily adapted to operate as an optical transceiver for high-data-rate free-space optical communications (Amairi-Pyka, 2024).

Free-space optical (FSO) communications offer decisive advantages over radio-frequency (RF) links for next-generation airborne and space systems. Security is stronger because, unlike RF signals that radiate sidelobes and leak power into unintended directions, optical signals are transmitted as tightly focused, narrow beams with an inherently low probability of intercept or detection. When combined with precise pointing, spatial filtering, and modern cryptographic methods (i.e., quantum or post-quantum cryptography), the risk of eavesdropping is reduced to a minimum.

Critically, FSO sidesteps RF-spectrum congestion. Crowded, licensed bands suffer co-channel interference, spectrum sharing, and deconfliction overheads that cap throughput and inflate latency, whereas optical bands are largely unregulated and far less susceptible to electromagnetic interference.

Data rates in FSO scale orders of magnitude higher than in RF systems because optical carriers operate at hundreds of terahertz. This extremely high frequency enables ultra-wide modulation bandwidths and supports advanced techniques such as wavelength-division multiplexing (WDM) and coherent detection, already delivering multi-gigabits per second (Gb/s) today with clear paths toward terabit-per-second (Tb/s) performance (Wang, 2025). A major advantage of FSO is its exceptionally low latency. This is not because light travels faster in optical links, but because they avoid spectrum-access delays that in RF can add several milliseconds. RF systems also rely on heavy media-access control and deep interleaves in congested environments, which further increase delay. In contrast, FSO employs short symbol periods and lean processing stacks, reducing end-to-end latency to just a few microseconds per kilometre.

Beyond low latency and high data rates, FSO also enables two-way optical time transfer with sub-nanosecond to picosecond precision. This level of synchronisation between aircraft, high-altitude platforms, satellites, and ground clocks is essential for distributed apertures, coherent sensing, formation flying, and accurate navigation in GNSS-denied environments. For supersonic and hypersonic vehicles, optical links can take advantage of plasma-transparency windows and off-axis apertures to mitigate RF blackout. At the same time, microsecond-class latency ensures the responsiveness needed for time-critical command, cooperative electronic warfare, and guidance loops.

ADQOGS considers key applications including optical feeder links, which enable high-speed data transfer from ground stations to satellites, and Earth observation (EO), where FSO supports real-time video, high-resolution imaging, and rapid large-scale data delivery from EO satellites to the ground. These functions are particularly valuable for environmental monitoring, disaster response, and other missions that depend on low-latency, high-throughput communications. To further strengthen performance, ADQOGS will be upgraded with adaptive-optics systems that actively correct for atmospheric turbulence. This integration improves signal quality, enhances link stability, and sustains reliable, high-capacity connections even under challenging weather or atmospheric conditions. With adaptive optics in place, ADQOGS will provide a more resilient and scalable platform for current feeder-link and EO services, while ensuring robust availability for future air- and space-based communication needs.

5. Conclusion

In this paper, we presented the Abu Dhabi Quantum Optical Ground Station (ADQOGS). This project is collaborative by design to maximise the impact of home-grown UAE technologies and realise the future space-applications vision of the UAE Space Agency. The station's design is unique for its multi-mission capability and is the first and largest of its kind in the region. Our goal is to integrate ADQOGS into a broader quantum-secured communication infrastructure within the UAE and into an international quantum-secure communication network. By demonstrating both technical feasibility and strategic relevance, the station positions Abu Dhabi as a leading hub in the advancement of global quantum-secure communication networks.

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