ADQOGS: Versatile Optical Ground Station for Satellite-based Quantum Key Distribution

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The project Abu Dhabi Quantum Optical Ground Station (ADQOGS) for Secure Free-Space Optical Communications has a main goal to connect Abu Dhabi, and thereby the United Arab Emirates as a whole, to the global Quantum-secure Communication Network. Quantum Key Distribution (QKD) is the most mature quantum communications technology, enabling secure, private communication even in the presence of adversaries with unlimited computing power. QKD is used to exchange secure encryption keys using single photons. In this paper, we present the role of ADQOGS in facilitating long-distance QKD-secure communication channels and its impact on the development of Free-space optical communications in general. The paper also showcases new applications the ADQOGS facility can provide in different space-related domains.

I. INTRODUCTION

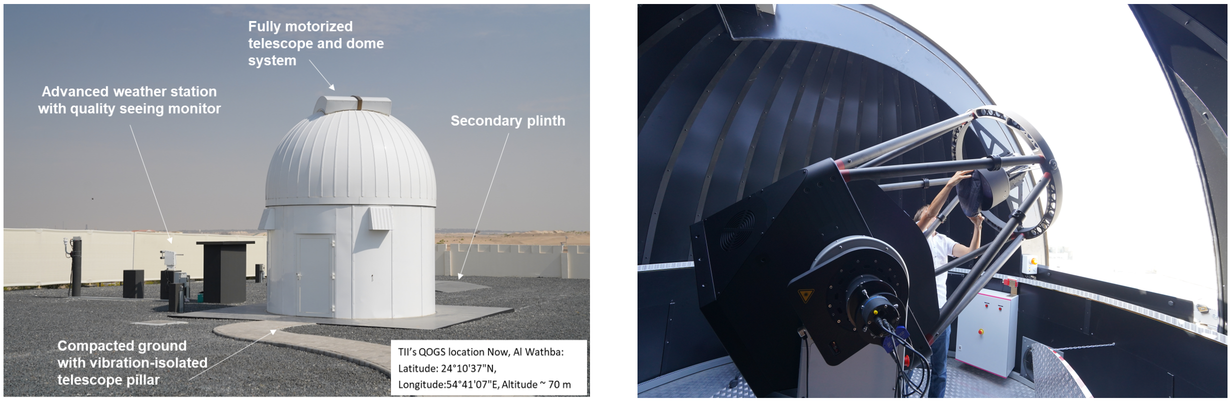
With cyberattacks growing increasingly sophisticated, with potential breaches compromising sensitive data and critical infrastructure, secure communication has never been more crucial. Around the world, various initiatives are working on quantum-secure solutions allowing them to be prepared against any damaging cyber attacks using quantum computers. From national defence projects to global collaborations like the European Union's EuroQCI [1] and China's quantum satellite network [2–4], all aimed at ensuring unbreakable encryption for the future. Recently QATAR has announced building an innovative quantum communication link in collaboration between Hamad Bin Khalifa University's Quantum Research Center QC2 and the telecommunication provider Ooredoo [5]. The use of Quantum Key Distribution (QKD) is presented as the ultimate solution for quantum-proof encryption keys. QKD accomplishes this by using single photons to generate and transmit quantum signals, allowing the creation of symmetric encryption keys between two parties. This key is then used to secure a communication channel between them. The quantum nature of the photons makes any eavesdropping attempt along the quantum channel detectable. Over metropolitan distances (less than 50km), existing optical fibre infrastructure offers an attractive target for establishing QKD-secure communication channels. However, when connecting distant networks, intrinsic fibre losses make deployment over fibre links unfeasible. For this task, an architecture based on free-space optical transmission between satellites and ground-based receivers is the only present solution. In this paper, we present the development of a unique quantum Optical ground station equipped with a versatile multi-wavelength Quantum Acquisition and Tracking System (QATS) tailored to support various upcoming space-based QKD missions. The versatility is crucial for the practical implementation of global quantum communication networks. Moreover, this paper presents several use cases for ADQOGS complementing its initial quantum goals.

II. QUANTUM OPTICAL GROUND STATION

Abu Dhabi Quantum Optical Ground Station (ADQOGS) is mainly an optical ground station with a large 0.8 m diameter Ritchey–Chrétien telescope with an Alt-Az precise tracking mount, hosted inside a fully automated observatory dome. The UAE Space Agency is a strategic partner in the realization of this facility and has issued a No Objection Certificate (NOC) to ensure the project's regulatory compliance. The facility is equipped with a world-class weather station for highly accurate and high-resolution meteorological data, as well as a secondary plinth for hosting transportable ground stations. The system telescope system has 2 Nasmyth outputs that can be selected with a tertiary flip mirror. Figure 1 is a photograph of the current ADQOGS site.

For active tracking of the QKD satellite, a downlink beacon from a satellite to the ground will be used to enable fine pointing to the OGS. Another uplink beacon from the OGS to the satellite is then used to precisely localize the satellite's position for accurate pointing. Once the satellite and the OGS know each other's position precisely, the quantum channel will be activated to transmit the single photons from the satellite to the ground station.

To receive the downlink beacon, a Quantum Acquisition and Tracking System (QATS) will be placed on one of the Nasmyth outputs of the telescope. The QATS is a multi-wavelength tip/tilt stabilized optical receiver system for QKD signals and associated classical downlink beacons. An interface module is a fixed broadband module with a Fine Pointing Mirror (FPM) assuring a first-order correction of the incoming optical wavefront in the wavelength range from 600 nm to 1560 nm. A multi-band dichroic splitter is then used to separate the Quantum signal band between 740 nm - 900 nm from the rest of the optical spectrum which covers the Visible spectrum (VIS) between 400 nm and 740 nm and the SWIR band from 1530 to 1560 nm.



(a) (b)

FIG. 1: Overview of the ADQOGS site layout. ADQOGS is hosted by Al Sadeem Observatory, Alwathba, Abu Dhabi. (a) ADQOGS Site description. (b) The telescope AltAz 800 f6.85.

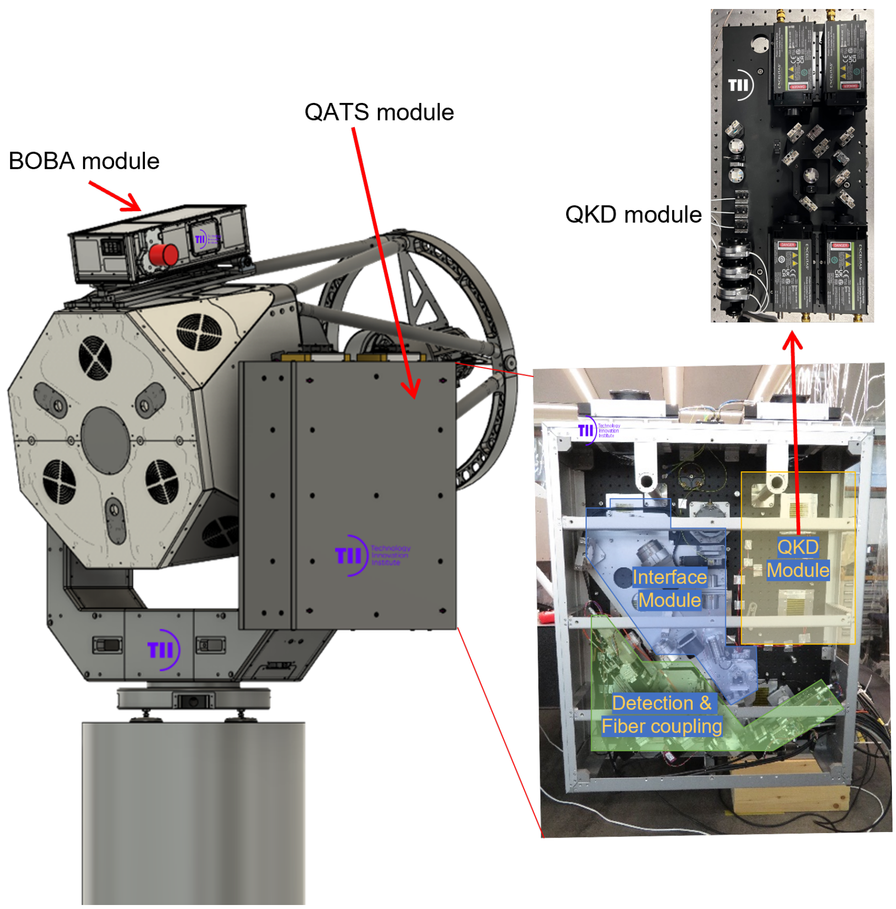


FIG. 2: Construction model of ADQOGS's telescope and its sub-systems. QATS: Quantum Acquisition and Tracking System. BOBA: Beacon Optical Bench Assembly. QKD module: free-space receiver module for polarization-encoded Quantum Key Distribution. We are publishing the technical details of this design in a proceeding at SPIE for International Conference on Space Optics - ICSO 2024 [6].

The free-space QKD module is adequate to detect QKD signals at 780±10 nm and 850±3 nm. It offers spatial and spectral filtering capabilities along with a motorized polarization correction system.

A compact Beacon Optical Bench Assembly (BOBA) for the transmission of the uplink beacon is placed on the side of the telescope. It allows fine pointing of the uplink beacon beam with the configurable point-ahead and other pointing corrections. The module is compatible with lasers ranging from 1530 nm to 1610 nm, and laser power for up to 10 W. Figure 2 shows the construction model of ADQOGS's telescope and its sub-systems QATS and BOBA.

In addition to the active tracking of the satellite, the optical beacons can be used as a classical free-space optical communication channel between the ADQOGS and the satellite. A multimode fibre coupling stage is implemented in the QATS SWIR band, allowing the QATS box to be used also in LEO-DTE scenarios. Downlink data rates of up to 2.5 Gbps can be achieved with the implemented fibre. An optical modem is used for the high data rate modulation of the uplink beacon laser. This bidirectional classical communication channel will be used for an active QKD connection with the satellite [7].

The unique multi-wavelength design will allow ADQOGS to adapt to the upcoming QKD satellite missions. Moreover, this will overcome the challenge of relying on a single satellite as a trusted node, particularly if it's owned by a third party, which raises significant security concerns. By supporting redundant satellite key routing across multiple satellite providers, we are enabling a parallel trusted node approach to space QKD as published recently by our group [8].

III. MULTI-MISSION ADQOGS: APPLICATIONS AND POTENTIAL USE-CASES

The strategic location of ADQOGS opens doors to new space optical applications. The modular design of the QATS and the broadband feature of the BOBA described above is developed with the key idea of versatility, allowing the OGS to communicate with a vast and different number of satellites. This ability implies that we are not restricted to implementing one particular type of activity. In this section, we highlight key areas where our ADQOGS can foster potential collaborations, encouraging partnerships and joint efforts to advance shared goals.

A. Quantum communication networks

ADQOGS contains a QKD receiver and will be able to collect Quantum Keys from partnering QKD satellites. Once connected with a dark fiber to other Quantum receivers, it will become a trusted node within the UAE's future quantum communication infrastructure. In Figure 3 illustrates potential sites for building an initial Quantum Secure network in the UAE, where dark fiber links between these locations do not yet exist but are speculatively chosen as trusted nodes for their relevance to future developments. By connecting ADQOGS to international Optical Ground stations, we would enable the UAE to connect to international quantum-secure communication networks, providing a highly secure platform for various sectors. These include financial institutions, pharmaceutical companies, embassies, harbors, free zone commercial areas, and other entities that require top-tier security for their communications. Additionally, quantum networks can be leveraged for secure data storage solutions, ensuring the safe transfer of sensitive information between big data centers.

B. Free-Space High-data Rate Optical Communication

Free-space optical (FSO) communication uses laser beams to transmit data through the atmosphere or space, offering much higher bandwidth than traditional Radio Frequency (RF) communications. FSO systems benefit from narrow, highly focused beams, which reduce signal interference, and also reduce the signal footprint on the ground, thus provide an enhanced data security, and make interception more difficult. Moreover Satellite communication (SatCom) systems are compact and use less power as optical systems are more energy-efficient, while still supporting high-speed, reliable data transmission. Additionally, FSO is less affected by spectrum congestion, making it a superior choice for satellite and ground station communications [9]. This makes FSO especially advantageous for applications requiring high-speed, low-latency communications such as optical feeders, and earth observation, and NexGen networks.

Optical feeders: In some systems, such as Intelsat EpicNG [10], optical feeders are used to transmit high-speed data from ground stations to satellites, where the signal is then redistributed via RF (Radio Frequency) to cover broader areas. Combining optical feeder links with high-throughput satellites (HTS) offers flexibility and high data rates across global regions.

Earth Observation: Free-space optical communication is crucial for real-time video, high-resolution imaging, and large-scale data exchanges, especially for missions requiring precise, reliable, and long-distance communications. Its ability to support long-distance communication without the need for traditional radio frequencies makes FSO particularly valuable in scenarios such as environmental monitoring, disaster response, and crisis management. The low latency and high data throughput offered by FSO enhance the efficiency of Earth observation missions, providing crucial insights for timely decision-making and improving the accuracy of remote sensing applications [11].

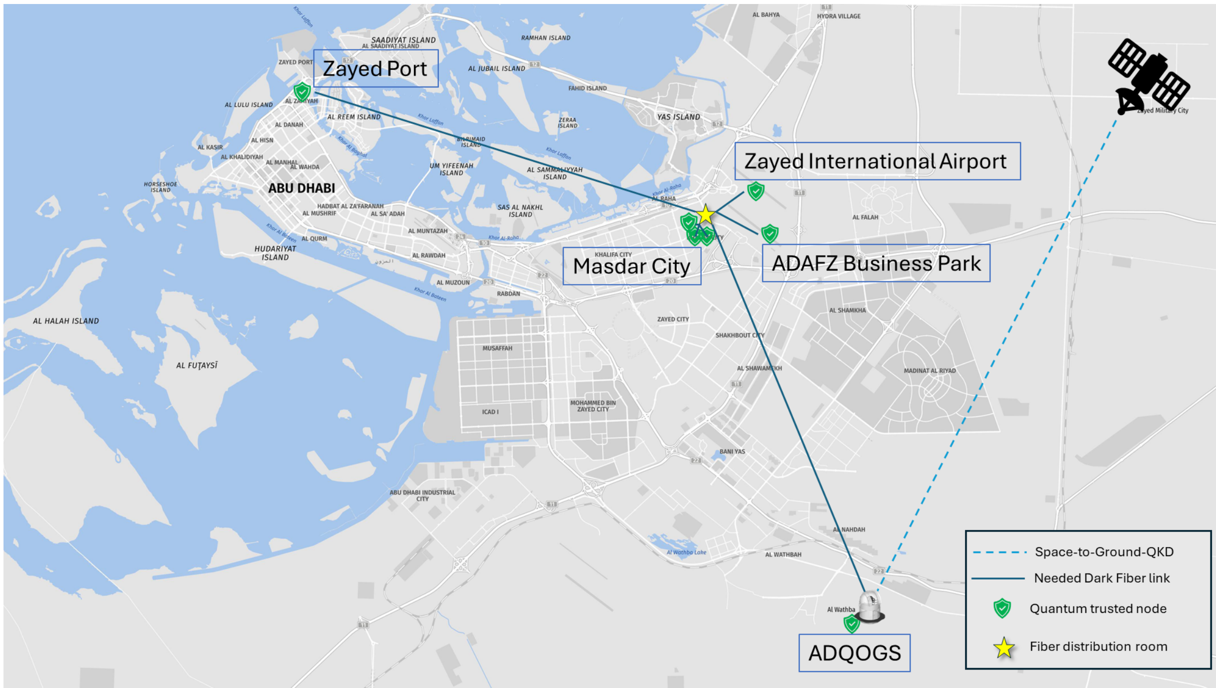


FIG. 3: Speculative locations for establishing an initial Quantum Secure network in the UAE, highlighting potential sites where dark fiber links could be developed in the future.

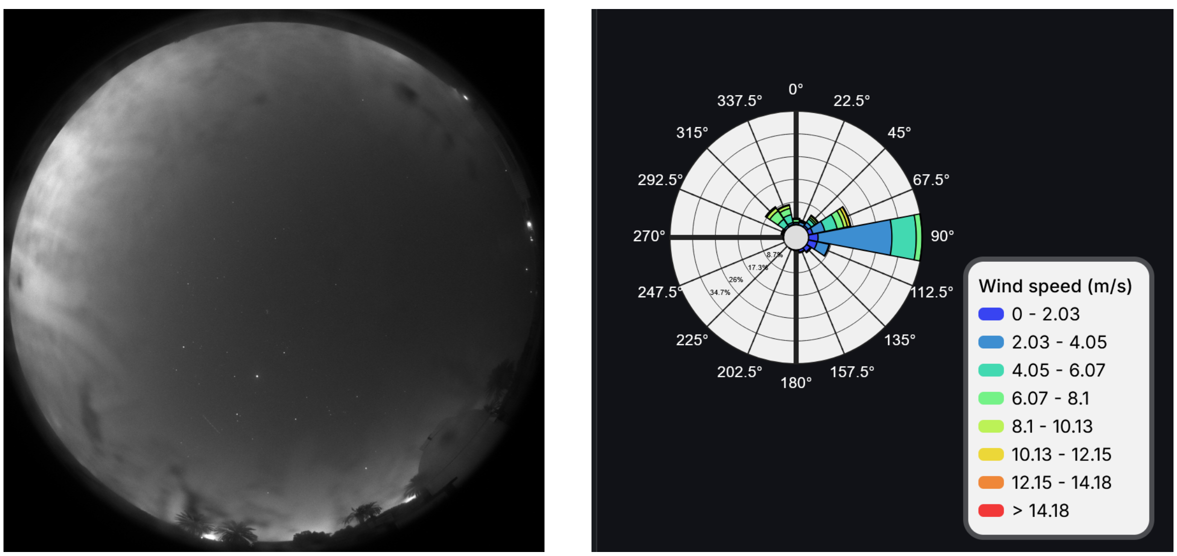
C. Deep Space optical communication

For deep space missions like the Lunar Gateway, Free-Space Optical (FSO) communication systems are crucial for high data rate transmissions over vast distances. The second Nasmyth output of the ADQOGS telescope can be equipped with single-photon detectors, such as superconducting nanowire single-photon detectors (SNSPDs), that can capture ultra-low power signals from lunar spacecraft. These systems enable reliable communication by detecting faint optical signals, allowing for efficient data transfer even under strict power limitations. The UAE's strategic geographic location makes it ideal for enhancing global coverage and connectivity for deep space communication, which supports real-time data transmission and large-scale data exchange compared to traditional radio frequency systems.

D. Weather station and sky monitors

Having complete information on the atmospheric conditions during the establishment of an optical communication channel is of crucial importance for the beam front correction at the level of the fine-pointing mirror and the optical receivers. For this reason, the facility is equipped with a weather station that is part of an international weather station network for the global availability of FSO and QKD signals. The weather station has an all-sky camera to monitor clouds, wind speed, rain and other sky conditions as can be seen on Figure 5. In addition, the station is equipped with a Differential Image Motion Monitor (DIMM) that delivers the seeing parameters (i.e.Fried parameter r_0), proportional to the atmospheric scintillation, and crucial for the optimization of the optical links. All the obtained data is stored and available for further meteorological applications. A long-term recording of the atmospheric variations allows the prediction of the optical channel availability for communication satellites throughout the year. We noticed that, despite being almost at sea level, the measured atmospheric seeing parameters defining the beam distortions at ADQOGS are favourable to low-losses optical communications. On the other hand, high humidity and poor visibility due to haze or fog in the summer season remain more challenging. Figure 4 shows exemplary data from the weather station measured in March 2024.

FIG. 4: Example of data from the weather station dashboard: Zenithal temperature, irradiance, atmospheric seeing resolution, and Fried parameter r_0.



(a) (b)

FIG. 5: Weather station dashboard. (a) All-sky camera view on 16/09/2024 at 03:00 am. (b) Wind speed data on 16/09/2024 09:00 am

E. Space Situational Awareness

ADQOGS has a strategic position in the Arabian Peninsula, offering a unique vantage point for space situational awareness (SSA), particularly in tracking key geostationary (GEO) satellites visible from this region. With the increasing density of satellites and space debris in GEO orbits, ADQOGS can play a critical role in monitoring and maintaining the operational integrity of these assets. By integrating advanced laser ranging technologies, the station can accurately determine the positions and movements of GEO satellites, providing real-time data that enhances collision avoidance, orbital analysis, and overall space security. This capability would offer significant contributions to both regional and global space sustainability and infrastructure management[12].

FIG. 6: The secondary plinth at ADQOGS facility.

F. Fundamental research and metrology

Long-distance optical links via satellites and FSO optical networks will positively influence fundamental research, particularly in areas like quantum sensing and metrology, where sensors operate at the fundamental limits of precision. Among these applications are remote optical atomic clock synchronisation via satellite[13–15], testing the quantum theory on curved space-time with quantum networks[16, 17], and advancing the studies of atmospheric propagation effects relevant to optical communications[18–20]. The secondary plinth shown in Figure **??** in ADQOGS is built to host transportable optical ground stations and other transportable experiments such as quantum sensors and gravimeters or laser rangers. These advancements pave the way to novel experimental tests and technologies

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IV. CONCLUSION

In this paper, we presented the Abu Dhabi Quantum Optical Ground Station (ADQOGS). This project is collaborative by design to maximize the impact of homegrown UAE technologies. Applications such as Quantum Key Distribution, free-space communications, and space situational awareness were discussed. The station's design is unique for its multi-mission capability and is the first of its kind in the region. Our goal is to integrate ADQOGS into a broader quantum communication infrastructure within the UAE and to an international quantum-secure communication network.

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