Quantum Satellites:

Topologies, Demonstrations, and Design Considerations

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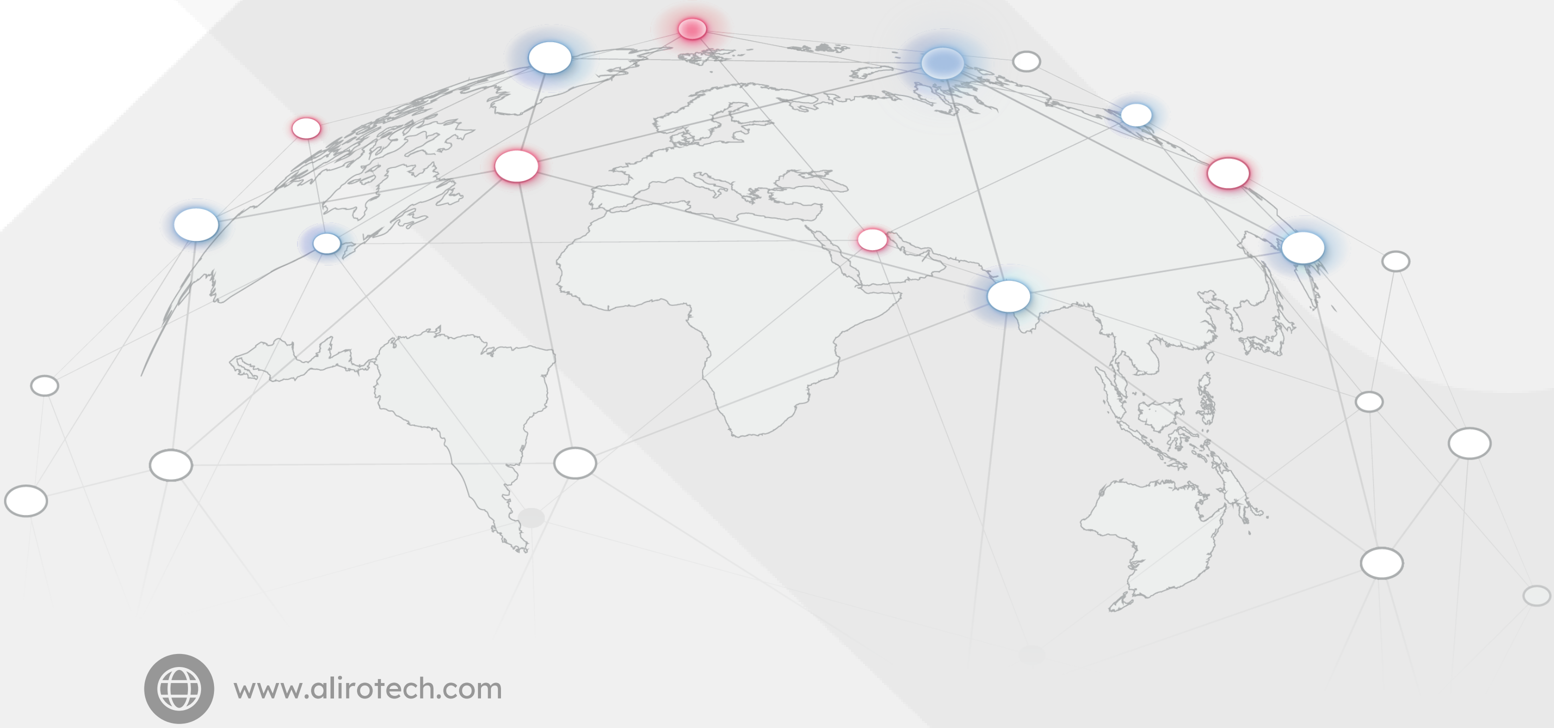

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Quantum Satellites

Topologies, Demonstrations, and Design Considerations

Summary

This white paper examines the design considerations and trade-offs of implementing quantum satellite systems that enable the long-range quantum communications links required for expanding the coverage of quantum networks.

Introduction

Building on the previous **Quantum Networking with Satellites webinar**, which introduced satellite communications and their role in digital infrastructure, this white paper examines topologies and architectures of quantum satellites, elements of design, and gives a brief comparison of satellite quantum communication missions. Traditional satellite networks enable services such as global positioning systems (GPS), Internet communications, and geospatial mapping and imaging. Quantum satellite communications will enable this same kind of global connectivity for applications in quantum secure communication, quantum sensing, computing, astronomy, and fundamental physics research.

The Motivation for Quantum Satellites

This widespread global coverage of quantum networks cannot be achieved with terrestrial fiber networks alone.

Quantum communication experiences loss differently in fiber channels than in free-space channels. In fiber, photon loss scales exponentially with distance due to photon absorption, which limits the distances at which effective communication can be achieved. While fiber-based networks can support local, metro, and limited wide-area coverage, they are impractical for extending quantum communication over global distances.

Quantum photons experience only quadratic loss over free-space channels, making them a more efficient choice for long-range quantum communication. Satellites provide a solution for connecting quantum devices over several hundreds or thousands of kilometers, a regime where fiber-based repeaters become inefficient vehicles for quantum communication. The main source of loss in free-space links, such as earth-to-satellite quantum transmission, is due to beam diffraction, resulting in beam divergence. Other sources of loss such as scattering, absorption through the atmosphere occur only within the first ten kilometers above the Earth's crust. Beyond this, in the vacuum of space, photon loss is much less impacted by atmospheric factors. In addition to loss, there exists the more practical challenge for free-space quantum links which is the line-of-sight requirement between the transmitter and the receiver. This same constraint also applies to classical free-space optical (FSO) communication links.

Satellite-Based Quantum Key Distribution (QKD) Architectures

The majority of quantum satellite missions have focused on QKD applications. Satellite-based quantum key distribution (QKD) relies on two types of protocols: prepare-and-measure (BB84) and entanglement-based (Ekert-91, BBM92, or device-independent protocols). Prepare-and-measure protocols rely on single-qubit superposition whereas entanglement-based protocols rely on multi-qubit entanglement and superposition to extract a secure key. Thus, the type of protocol used greatly influences the network topology and architecture.

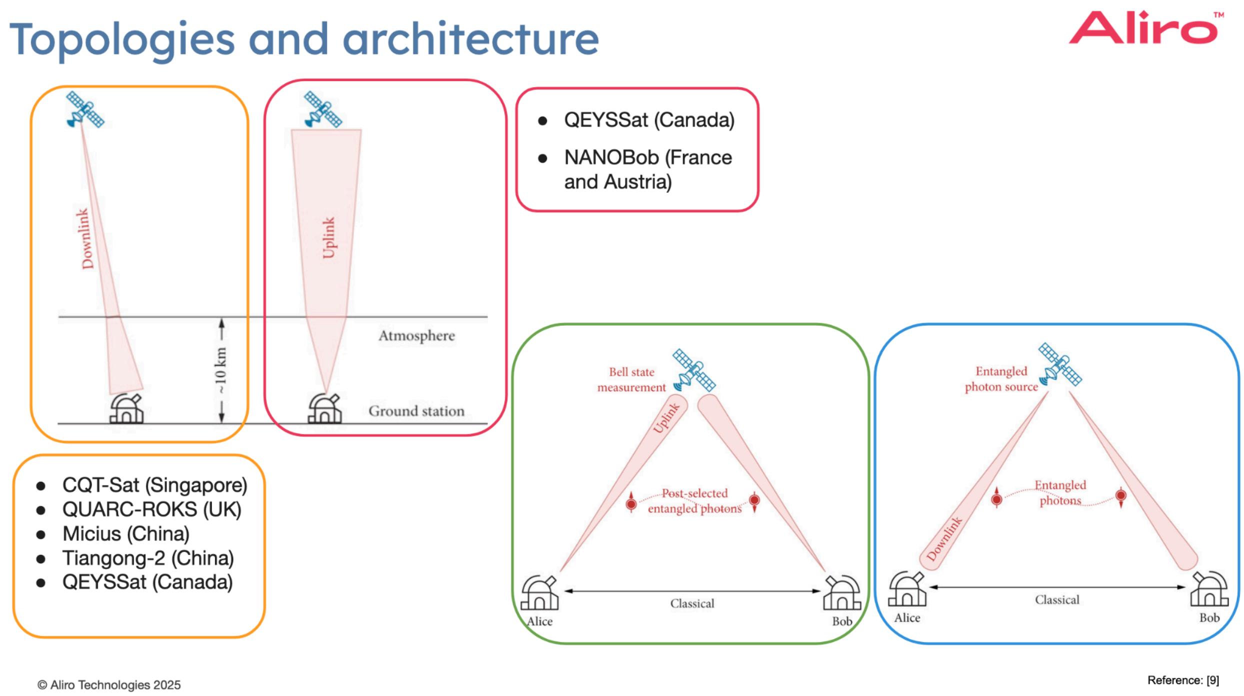

Image reference [9]

Prepare-and-measure QKD typically uses a single direct link between a satellite and a ground station, either in a downlink or uplink configuration. Many existing satellite QKD missions have adopted a downlink approach, where the satellite transmits quantum signals to the ground station. Entanglement-based protocols, on the other hand, enable entangled photon distribution. This can be achieved either by the transmission of entangled photon pairs from the satellite to distant ground stations, or by transmitting single photons from independent ground stations to the satellite, such that they interfere at a Bell-state measurement apparatus on the satellite which facilitates heralded entanglement generation.

A few examples of quantum satellite missions that have implemented different QKD topologies and architectures include:

Micius. The first satellite to demonstrate free-space QKD, supporting both prepare-and-measure and entanglement-based QKD in a single downlink configuration, enabling secure quantum communications over large distances. The entanglement-based QKD is demonstrated by measuring one of the entangled photons locally at the satellite and transmitting the other entangled photon to the ground station.

Tiangong-2. Hosted a compact QKD payload and performed downlink to several ground stations.
Jinan 1. China's first test satellite for QKD in a Low Earth Orbit (LEO) network of satellites, aimed towards development of a satellite-based quantum communications system spanning low to medium-to-high Earth orbits.
QEYSSat. A planned mission that will implement both the BB84 and BBM92 protocols using an uplink configuration rather than the typical downlink approach.
QUBE-I (launched) & QUBE-II (planned). CubeSats with QKD implementations at two wavelengths: 850 nm and 1550nm.

Hybrid Terrestrial-Space Quantum Networks

Hybrid terrestrial-space quantum networks leverage free-space links at different altitudes. Relatively close to Earth's surface, there will be ground stations, as well as mobile assets, and airborne assets such as aircraft, drones and high-altitude platform stations (HAPs) that could be part of this infrastructure. Free-space quantum communication will rely on Low-Earth Orbit (LEO) resources like constellations of CubeSats, as well as Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO) satellite links. This infrastructure will serve as the backbone needed to achieve a global Quantum Internet.

While most free-space Quantum Key Distribution (QKD) implementations focus on links between satellites and ground stations, satellite-to-satellite connectivity is essential for extending the coverage area and enabling quantum networks to scale beyond what's possible with fiber-based links alone. Satellite-to-satellite quantum links facilitate the secure communication between orbiting nodes, increasing coverage and reducing reliance on expensive terrestrial ground station networks for global quantum communication. However, satellite-to-satellite QKD presents technical challenges, including maintaining quantum coherence over long distances in space, mitigating signal loss, as well as ensuring precise pointing, tracking and synchronization between satellites.

There are some advancements in intra-satellite technologies to look forward to in the near-term. There are already projects underway that are developing and testing space-grade quantum hardware. Recent work encompassing implemented projects and those under development include: NASA's atom interferometry experiments conducted on the International Space Station; planned satellite launches by a consortium composed of Q.ANT, Bosch, TRUMPF, and the German Aerospace Center (DLR) for testing miniaturized, quantum-based gyroscopes to provide high-precision attitude control for satellites; and HRL and Boeing's planned entanglement swapping demonstrations in a satellite. Advancing these intra-satellite quantum technologies lays the foundation for interconnected space-based quantum networks, ultimately moving toward a hybrid terrestrial-space Quantum Internet.

Considerations & Trade-offs in Quantum Satellite Design

Designing a quantum satellite network requires careful evaluation of multiple factors that impact performance, scalability, and security. Unlike classical satellite communication, where signals can be amplified and regenerated, quantum signals are constrained by the no-cloning theorem and are highly sensitive to loss and noise. As a result, design decisions involve trade-offs that must balance feasibility, efficiency, and long-term viability.

The key considerations in quantum satellite design, include:

- **Satellite Orbit Selection.** The selection of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geostationary Orbit (GEO) affects signal loss, transmission latency, and network coverage.
- **QKD Protocol Selection.** The selection of either a prepare-and-measure (BB84), an entanglement-based (Ekert-91, BBM92), or a measurement-device-independent (MDI-QKD) protocol affects security and complexity of network operations.
- **Selecting Quantum Link Direction.** The transmission of quantum signals, whether via uplink (ground-to-satellite) or downlink (satellite-to-ground), is affected differently by atmospheric signal distortion. This, in turn, influences the required distortion compensation scheme as well as impacts detection efficiency.
- **Wavelength Selection and Photon Detectors.** The chosen operational wavelength (e.g., C-band vs. Si-band) influences transmission loss, capability for daytime operation, detector sensitivity, and compatibility with existing quantum hardware.

Each of these design elements contribute to the efficiency and effectiveness of a quantum satellite network. In the following sections, we explore these trade-offs in detail, outlining their implications for global quantum communication and the future quantum internet.

Satellite Orbit Selection

The orbit of a satellite impacts quantum link performance, network scalability, and how the satellite operates. Each orbit offers different advantages and challenges, leading to trade-offs that must be carefully evaluated for quantum key distribution (QKD) and other quantum applications.

Trade-offs in the selection of Satellite orbit

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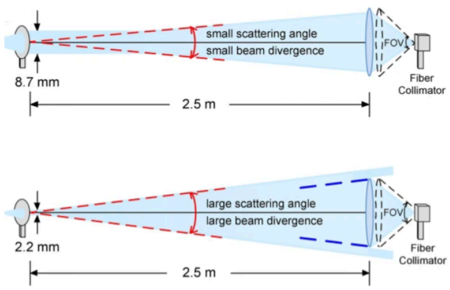
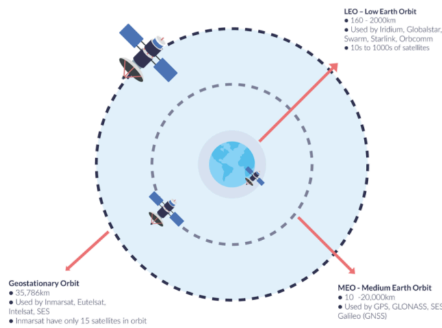
Options	Advantages	Challenges
LEO	• High key rates due to shorter distances • Supports larger beam divergence with smaller, cheaper terminals • Lower telescope aperture reduces size and cost	• Limited coverage and short pass durations • Requires rapid ground station adjustments and high pointing agility. Correcting for Beam wandering is nontrivial.
MEO/GEO	• Wider coverage and improved availability • Enables inter-satellite communication across altitudes • Easier tracking. Beam wandering can be corrected by tracking the counter-propagating beacon signal	• Lower key rates to the ground • Adversely affected by beam divergence • Larger, costlier telescopes





Reference: [23],[24]

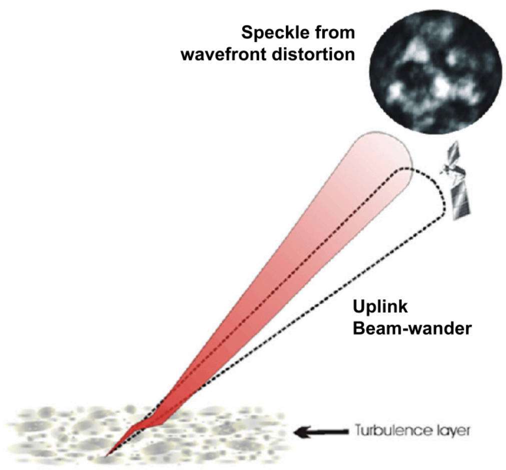
Image reference [23], [24]

LEO satellites, positioned at altitudes between 160 km and 2,000 km, provide higher key generation rates due to shorter transmission distances, which reduce signal loss. The short link distance can tolerate larger beam divergence while maintaining good collection efficiency, allowing for the use of smaller, more cost-effective ground terminals. Additionally, smaller telescope apertures lower the overall size and cost of the satellite. However, the limited coverage of LEO satellites requires frequent satellite handovers, making continuous communication more complex. Furthermore, rapid ground station adjustments and high pointing agility are necessary to maintain alignment.

MEO and GEO satellites are positioned at higher altitudes, with MEO at 2,000–35,786 km, and GEO at over 35,786 km, offer wider coverage and longer visibility durations, reducing the need for frequent satellite handovers. These higher orbits enable inter-satellite communication across different altitudes, supporting a more interconnected network. Additionally, tracking stability is improved in MEO/GEO using counter-propagating beacon signals. However, as the transmission distance increases, key generation rates decrease due to reduced quantum signal collection efficiency caused by beam divergence. This makes high-altitude QKD transmissions more challenging than those at lower altitudes. To minimize beam divergence at the transmitter and enhance collection efficiency at the receiver, larger and more expensive telescopes are necessary for successful quantum communication over these distances.

Ultimately, the trade-offs between LEO and MEO/GEO involve balancing key rate efficiency, coverage area, tracking complexity, and infrastructure costs. While LEO is optimal for high-fidelity quantum links, GEO and MEO provide greater coverage. The challenges of different orbits are due to distance from the Earth, as well as Earth's atmosphere.

Effects of Atmosphere and Free-space propagation



Cause	Effect
Atmospheric channel	• Wavefront distortions • Beam wandering
Link distance	• Beam divergence

Beam wandering refers to the random lateral displacement of the beam's center, caused by large-scale atmospheric turbulence that tilts the wavefront.

Wavefront distortion describes irregularities in the wavefront shape due to small-scale refractive index variations, leading to intensity and phase fluctuations across the beam.

Beam divergence measures the angular increase in beam diameter or radius as the beam propagates from its source.

Reference: [21],[22]

Image reference [21], [22]

Quantum signals propagating through free-space channels are impacted by several atmospheric effects that influence their stability and detectability. These effects have a direct impact on the design of effective quantum communication systems and optimization of satellite orbits for Quantum Key Distribution (QKD). There are three main challenges associated with atmospheric interference are: beam wandering, wavefront distortion, and beam divergence.

Beam Wandering. Beam wandering refers to the random lateral displacement of the beam's center due to large-scale atmospheric turbulence. As quantum signals pass through the atmosphere, turbulence cells larger than the beam diameter will tilt the beam direction, causing the beam's center to shift unpredictably at the receiver site. Calibration techniques such as using a beacon laser can compensate for these displacements. Correcting this effect becomes nontrivial as satellites move faster in lower orbits, making it harder for the beacon laser's beam path in the atmosphere to overlap with the quantum signal that requires correction.

Wavefront Distortion. Wavefront distortion refers to irregularities in the wavefront caused by small-scale variations in the refractive index, which result in fluctuations in both intensity and phase across the beam. These variations ultimately degrade the collection efficiency of the quantum signal. This effect can be largely corrected using adaptive optics, which will be discussed in greater detail later.

Beam Divergence. Beam divergence describes the gradual increase in beam diameter as the quantum signal propagates through free space. The longer the transmission distance, the wider the beam spreads, leading to increased signal loss. A larger beam size at the transmitter ensures a slower rate of beam divergence. Additionally, the choice of receiver aperture size plays a crucial role in mitigating the effect of beam divergence—larger telescopes can collect more photons, improving the signal-to-noise ratio and enhancing detection fidelity.

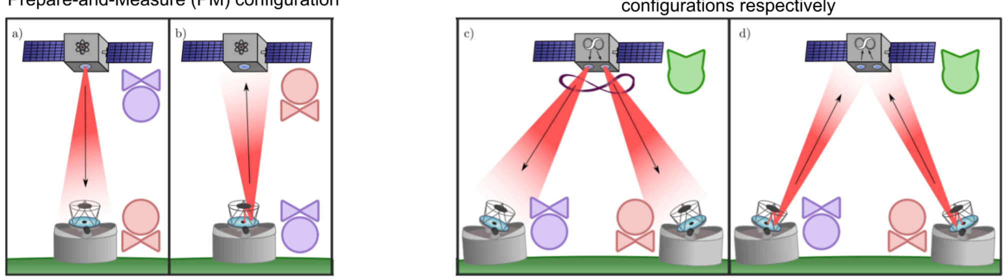
These atmospheric effects play a key role in determining optimal satellite orbits for quantum communication. By understanding and addressing these atmospheric challenges, quantum networks can be optimized for higher efficiency, better signal integrity, and improved scalability across different orbit regimes.

QKD Protocol Selection

After determining the optimal satellite orbit, the next design decision involves selecting the communication protocol. Most satellite quantum communication missions have focused on Quantum Key Distribution (QKD) for secure communications. The choice of QKD protocol influences network security, operational complexity, and system performance.

Trade-offs in the selection of QKD configuration

Options	Advantages	Challenges
Prepare-and-Measure (PM)	• Single line of sight link, high key rates, simple setup	• Relies on secure trusted nodes
Entanglement-Based (EB) / Measurement-Device Independent (MDI) QKD	• Higher security • Satellite can be an untrusted node	• Requires simultaneous dual-line visibility, dual-line efficiency impacts key rates, therefore complex pointing systems in the satellite needed.



Reference: [10]

Image reference [10]

Prepare-and-Measure Protocols

Prepare-and-measure protocols, such as BB84, utilize single qubits in superposition to distribute cryptographic keys. This approach offers several advantages:

- Only a single line of sight link is needed, simplifying tracking and alignment.
- Because transmission relies on a direct single link, these protocols achieve higher key rates, as the rate depends only on the loss experienced by that link.
- The hardware setup for prepare-and-measure protocols is less complex.

However, there are security trade-offs to consider. Because these protocols require the satellite to be a trusted node (which may or may not be truly trustworthy), prepare-and-measure QKD protocols like BB84 introduce security vulnerabilities.

Entanglement-Based Protocols

Entanglement-based protocols, such as BBM92, E91, and Measurement Device-Independent QKD (MDI-QKD), offer higher security by distributing entangled photon pairs between ground stations. That is, unlike prepare-and-measure protocols, entanglement-based QKD does not require trusting the satellite, making it more suitable for high-security applications. The same entanglement distribution infrastructure may also be used to support a variety of other quantum applications beyond security. However, this approach does have its challenges:

- Entanglement-based QKD requires the satellite to maintain continuous visibility of two or more ground stations to distribute entangled photons. The uplink and downlink configurations for both links demand precise pointing, acquisition, and tracking systems to sustain entanglement distribution rates.
- The key rate of entanglement-based QKD depends on the product of the transmission efficiencies of both links, thus resulting in lower rates compared to prepare-and-measure protocols.
- Since both end users must establish a simultaneous direct line of sight with the satellite, this imposes a constraint on the maximum allowable distance between them, determined by the satellite's orbital altitude.

Selecting Quantum Link Direction

The choice of quantum link direction, uplink (ground-to-satellite) or downlink (satellite-to-ground), also impacts the performance and feasibility of satellite-based quantum communication systems. Each approach presents distinct advantages and challenges due to factors such as wavefront distortion, beam wandering, and the ability to correct for these atmospheric effects.

There are two metrics that help to quantify the trade-offs between uplink and downlink configurations:

> **Point Ahead Angle (PAA).** Point Ahead Angle refers to the angular difference between the direction a transmitter needs to point its beam and the direction of the intended receiver; essentially, it's the angle at which the transmitter needs to aim slightly ahead of the receiver's current position to ensure the signal reaches it properly. Misalignment of PAA reduces efficiency at the receiver.
>
> **Isoplanatic Angle.** Isoplanatic angle refers to the separation of two optical beams in the sky that overlap enough that one of these beams can be used to correct the effects of atmospheric turbulence on the other beam.

Downlink Example

In a downlink configuration, where quantum signals are transmitted from the satellite to the ground station, the primary challenge is wavefront distortion. This distortion occurs due to turbulence in the lower 10 km of the atmosphere, where fluctuations in the refractive index alter the shape of the wavefront and introduce phase errors.

In this configuration, adaptive optics can be used to compensate for wavefront distortions. Downlink configurations also experience negligible beam wandering compared to uplink configurations. Most existing and planned quantum satellite missions use downlink, and use established ground-based technologies for signal correction.

Uplink Example

In an uplink configuration, where the quantum signal is transmitted from a ground station to a satellite, beam wandering is the main issue that hinders a stable link with a moving satellite. The tilt experienced by the uplink beam while propagating through the atmosphere leads to a significant shift in the beam center as it continues traveling through free space, severely degrading signal collection efficiency. When the point-ahead angle is less than or comparable to the isoplanatic angle, beam wandering can be corrected using a downlink beacon, as the propagation paths of both beams sufficiently overlap. However, for low Earth orbits, this correction becomes more difficult because the high orbital speeds can cause the point-ahead angle to exceed the isoplanatic angle, making a downlink beacon an invalid reference for correction.

Wavefront distortion has a lesser impact on signal quality in an uplink configuration compared to a downlink configuration. This is because, in an uplink setup, most wavefront distortion occurs within the first 10 km of atmospheric propagation, before the beam undergoes significant divergence in free space. As the beam expands, the fast irregularities introduced by the atmosphere remain nearly unchanged and are further stretched out, reducing their degrading effect on the signal.

Choosing the Right Link Direction

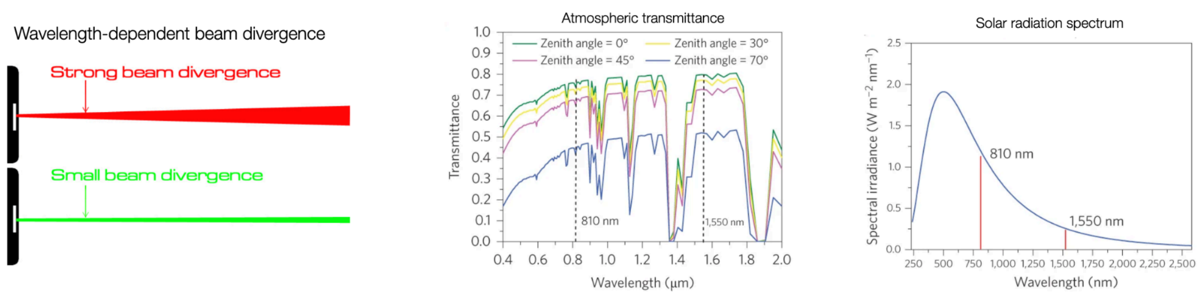
Many quantum satellite missions have opted for downlink QKD, benefiting from adaptive optics correction and reduced beam wandering in this configuration. Upcoming quantum missions are planned to explore uplink configurations and further improve this configuration for quantum communications. As quantum satellite technology progresses, hybrid configurations that combine both uplink and downlink topologies for the quantum links could offer a more robust and resilient global quantum network.

Selecting Wavelength and Single Photon Detectors

The selection of wavelength for quantum satellite communication is a design choice that impacts several parameters including transmission efficiency, compatibility with terrestrial networks, detector performance, and resilience to atmospheric noise. There are two wavelength bands that are considered for most satellite-to-ground quantum communication: the telecommunications band, or C-band (1530–1565 nm), and the silicon band, or Si-band (700 - 900 nm). As with the other design considerations discussed so far, the choice between these bands have benefits and trade-offs that make them more suitable or less suitable for particular satellite missions.

Trade-offs in selection of wavelength

Options	Advantages	Challenges
C-band (~1550 nm)	• Lowest fiber loss • Wide tech adoption; easy interfacing with fiber network • Good atmospheric transparency • Low solar radiation; could support day-time operation.	• Higher beam divergence. • SPADs have low efficiency • SNSPDs have high efficiency but need cryocooling.
Si-band (~800 nm)	• Higher antenna gain for equally sized equally-sized terminal due to lower beam divergence. • Silicon detector support	• Less fiber compatible • Higher solar radiation



The choice of the quantum channel wavelength is also closely tied to available technologies for single-photon detection.

Reference: [10], [27], [28]

Image reference [10], [27], [28]

The C-band is widely used in terrestrial fiber networks, making it a natural choice for integrating free-space quantum links with those on the ground. This band experiences less interference from solar radiation than the Si-band, making it more suited to daytime QKD operations. It is better to use superconducting nanowire single photon detectors (SNSPDs) at the C-band as opposed to the avalanche photodiodes because they operate at a higher efficiency for detection at the C-band and improve the key generation rate. However, SNSPDs require cryogenic temperatures and this requirement adds to the size, weight, power, and cost (SWaP-C) constraints, which may not be ideal for satellite payloads. Longer wavelengths like 1550 nm also result in greater beam divergence, which reduces efficiency at the receiver. Larger telescope apertures can compensate for this.

Trade-offs in wavelength: Single Photon detectors

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Options	Features
SNSPDs at C-Band (1550 nm)	• High efficiency (~90%) • Low dark counts (~100 Hz) • Cryogenic operation (<2 K) • High cost & complexity • Fiber-coupled systems
InGaAs SPAD at C-Band (1550 nm)	• Moderate cooling (~-40°C) • Lower efficiency (~20%) • Higher dark counts (~1 kHz) • Affordable & simple • Afterpulse mitigation needed
Silicon SPAD in Si-Band (750 nm)	• Good efficiency (~60%) • Room-temp operation possible • Low dark counts (~100 Hz) • Low cost & mature • Short dead time (~20 ns)

Image reference [10], [29], [30], [31]

The Si-band is frequently used in quantum satellite missions because the single-photon detection technology that is compatible at this wavelength has fewer hardware constraints. Silicon Avalanche Photodiodes (Si-SPADs) have good detection efficiency, they are compact, power-efficient, and lightweight compared to SNSPDs. They operate at room temperature, eliminating the need for cryogenic cooling. Shorter wavelengths also experience less beam divergence. This boosts the efficiency at the receiver and enables better signal detection in some cases. However, the Si-band is more susceptible to noise during daytime operations and this wavelength is not compatible with terrestrial fiber networks. Additional signal conversion is necessary to integrate the Si-band with existing infrastructure on the ground.

There are planned satellite missions that aim to explore the C-band with downlink configurations, where detection occurs at ground stations. In addition, advancements in SNSPD technology could lead to lower size, weight, power, and cost constraints that make the C-band even more viable as satellite payloads.

Selecting Photon Sources

The choice of photon sources is dependent on the QKD protocol being implemented, with different requirements for prepare-and-measure protocols like BB84 and entanglement-based protocols like BBM92 and Ekert91 (E91). Practical considerations such as temperature stability, power fluctuations, and integration with satellite-to-ground and satellite-to-satellite links are important when selecting the best photon source for a quantum payload.

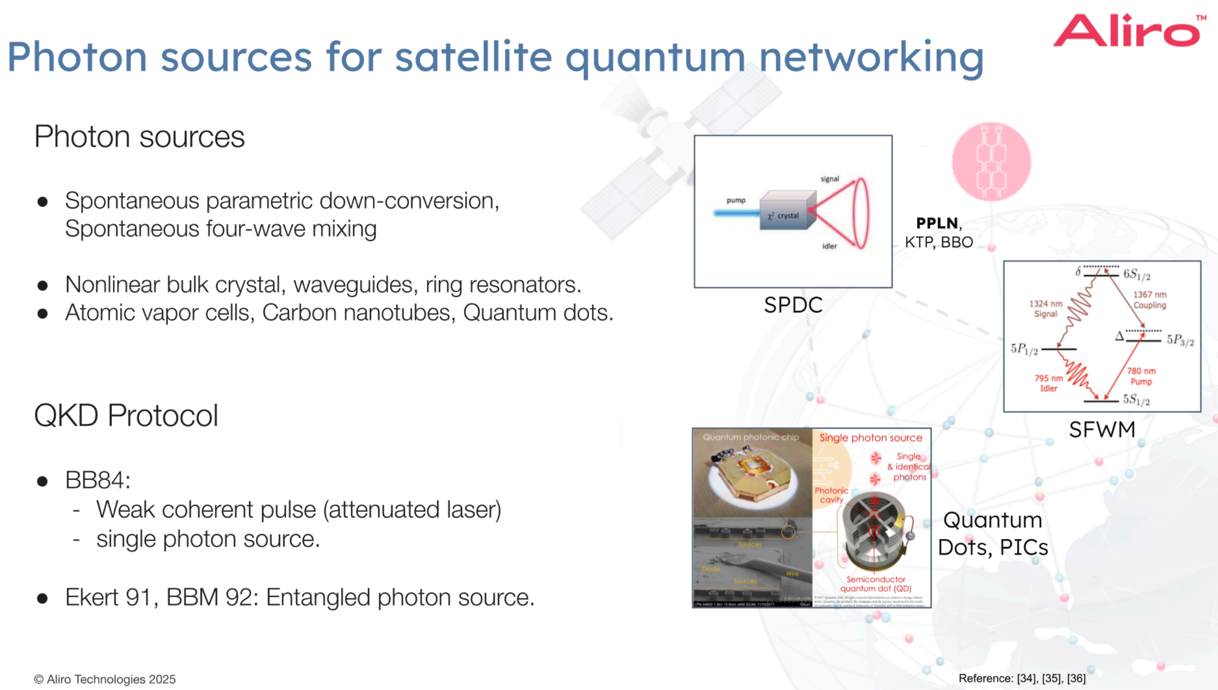

Image reference [34], [35], [36]

Photon Sources for Prepare-and-Measure QKD (BB84)

For BB84-based QKD, the commonly used photon source is the weak coherent pulse. Weak coherent pulses are generated using attenuated laser pulses and are able to approximate single-photon sources by reducing the intensity of laser emissions. One advantage of using this type of source is that it produces higher key rates.

Single photon sources using quantum dots and other emitters are another photon source used in BB84. These sources have lower key rates, but are maturing for space-based deployment.

Photon Sources for Entanglement-based QKD (BBM92 and E91)

For entanglement-based QKD, photon sources must generate entangled photon pairs that are then distributed between nodes, whether those nodes are ground stations or satellites. Entangled photon sources are discussed in detail in the white paper **Entangled Photon Sources**. The two primary nonlinear processes used for this are:

Spontaneous Parametric Down-Conversion (SPDC). Spontaneous parametric down conversion occurs when one high-energy photon interacts with a nonlinear material and splits into two lower-energy (or down converted) entangled photons.

Spontaneous Four-Wave Mixing (SFWM). In Spontaneous Four-Wave Mixing, two pump photons interact with a nonlinear medium to generate an entangled photon pair.

In either case, the nonlinear medium could be nonlinear bulk crystals, waveguides, or ring resonator sources. SFWM has also been demonstrated in atomic vapor cells. Some single photon sources have been implemented using quantum dots or defects in carbon nanotubes. Many of these entangled photon sources are available for utility, but when placing them in a payload, there are constraints to consider such as:

- Is the source durable enough to withstand the harsh launch conditions?
- Can the source maintain stable operation despite temperature fluctuations in space?
- How does the pump laser affect power stability and photon generation rates?
- How does link configuration impact the selection of photon sources?

Optical Ground Stations

Optical Ground Stations (OGS) are the interface between space-based and terrestrial networks. While some ground stations are equipped with photon sources and lasers for uplink transmission, we focus in this section on OGS receivers, which are responsible for detecting and processing quantum signals transmitted from satellites.

There are a number of subsystems required for OGS, the first being the receiving subsystem for the quantum signals: the receiving telescope, the adaptive optics module that corrects for atmospheric turbulence, and a coupling to single mode fiber that is routed to detectors allowing this system to be integrated with terrestrial fiber networks. Additionally, an auxiliary optical module for receiving the synchronizing signal coming from the transmission beacon laser is used to ensure precise timing.

Next are pointing, acquisition, and tracking (PAT) subsystems. These are involved in optimizing link stability and in physically orienting the telescope to the satellite path based on the satellite's laser beacon and a guiding camera. These are software- and control-oriented subsystems.

There is also the electronic control subsystem, which is used in detecting, synchronizing, and processing the quantum signal. This subsystem analyzes received quantum states, corrects for errors, and facilitates secure key extraction for cryptographic applications.

Optical ground station (OGS)

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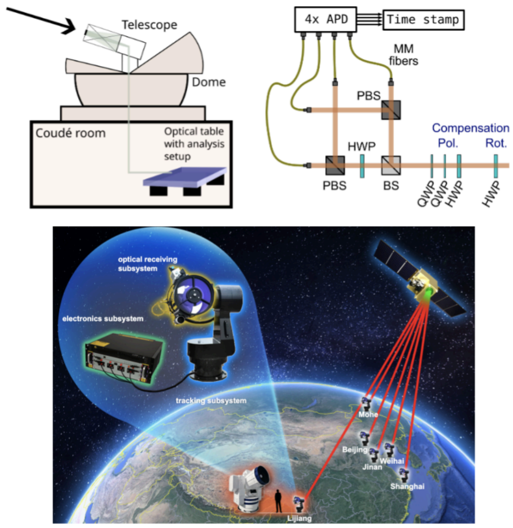

For example, subsystems in a receiving OGS:

Optical receiving subsystem
- receiving telescope
- adaptive optics module
- a coupling and measuring optical module
- auxiliary optical module for receiving synchronizing beacon laser

Tracking subsystem
- control computer with software
- Servo-controlled direct drive mount.

Electronics subsystem
- single-photon avalanche diodes (SPADs)
- Time to digital converter (FPGA-based)
- Quantum signals and synchronization signals routed to the electronics subsystem.

Other considerations:
Portable OGS, Integration with Fiber networks.

Reference: [37], [38]

Image reference [37], [38]

There is growing interest in mobile, portable optical ground stations that can be installed in remote locations, ships, or other airborne platforms. These portable optical ground stations must be built to meet size, weight, and power (SWaP) constraints while maintaining high-precision tracking and signal acquisition capabilities.

Layers of a Satellite Quantum Key Distribution (QKD) Mission

A satellite-based QKD mission has several layers, each contributing to secure quantum communication. These layers can be broadly categorized into hardware-centric layers and software-centric layers.

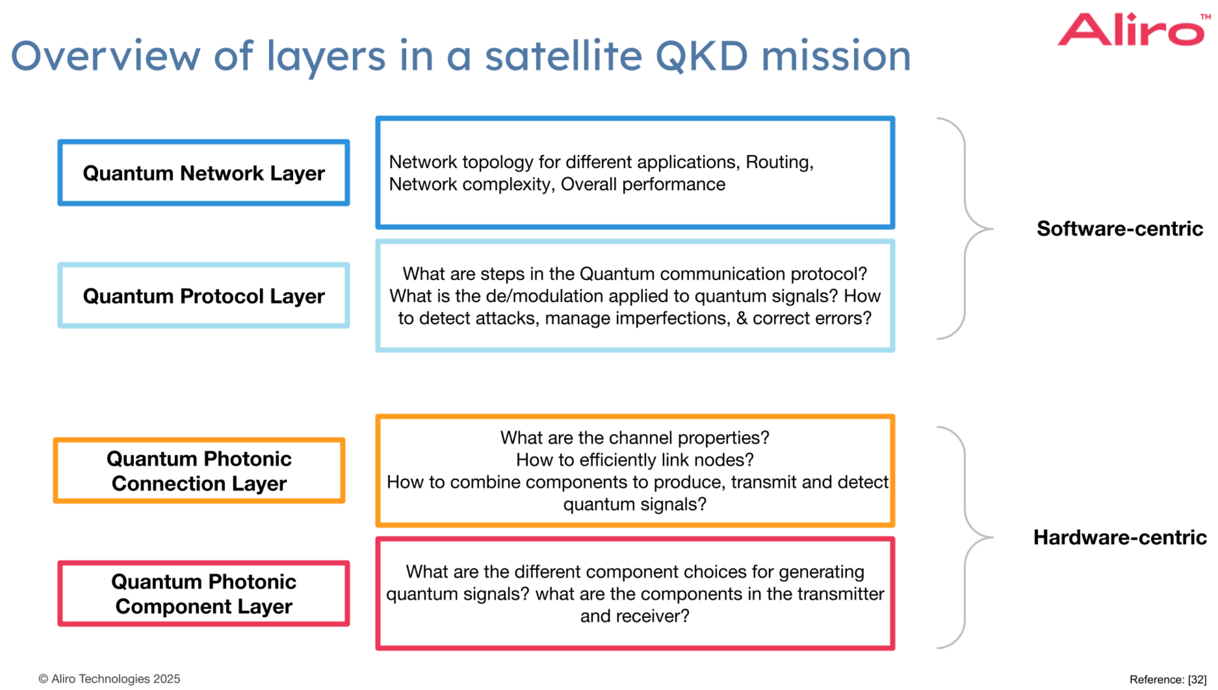

Image reference [32]

Hardware-centric Layers

The hardware layers are the physical components of the system, including the Quantum Photonic Component Layer and the Quantum Photonic Connection Layer. These layers encompass the component choices for generating quantum signals, and the components selected for the transmitter and receiver. These layers address the physical generation, transmission, and detection of quantum signals and determine how photons are produced, manipulated, and transmitted through free space while mitigating atmospheric effects. Key considerations for hardware-centric layers include optical component selection, link properties, and channel stability. Many of these considerations have been discussed already.

Software-centric Layers

The software-centric layers operate at a higher level, ensuring the effective implementation and management of QKD protocols and network routing. The Quantum Protocol Layer defines the communication steps, error correction mechanisms, and security measures required to establish and maintain quantum links. The Quantum Network Layer manages topology, routing strategies, and network performance, and includes optimizing how quantum keys are distributed across the network. Software plays an important role in designing, testing, and operating quantum satellite missions.

Software Requirements

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Software tools for space-based quantum communications:

- Simulation
  - System design
  - Terrestrial experiments, testing
- Orchestration
  - Device configuration
  - Metrics & monitoring
  - Integration with fiber networks
- Control & comms.
  - Low-latency protocol execution
  - Calibration
  - Timing & synchronization
  - Data aggregation & real-time processing

Simulation Software

Before deployment, software-based simulation tools are essential for designing an effective and efficient quantum satellite mission. Simulations can model performance under real-world constraints (e.g., orbital path, temperature fluctuations). Optical ground station subsystems can be simulated for better performance, including pointing, acquisition, and tracking systems. The effects of atmospheric conditions on quantum signals (e.g., turbulence, beam wandering) and corrections to these effects can also be simulated before any hardware is purchased. These simulations ensure that hardware selection, wavelength choices, and mission parameters are optimized before launch. Simulation-driven insights will also inform emulation tests on payload prototypes, drastically accelerating the iterative design process for payload manufacturers.

Orchestration Software

Once launched, quantum satellites benefit greatly from software-defined orchestration systems. Orchestration can aid in device configuration and remote operation, essential to these systems because direct human intervention is not typically possible in space. Software-defined orchestrations also allow for continuous system monitoring and telemetry analysis to ensure stable operation and can simplify the integration of satellite systems with terrestrial fiber networks.

Control & Communications Software

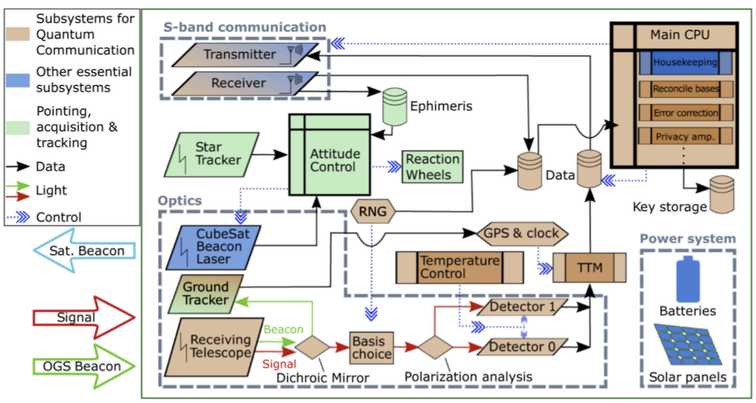
At the lowest software level, real-time control systems are needed to enable orchestration. Control and communications software enable low-latency protocol execution. They are important for dynamic calibration and error correction, enabling hardware components to be controlled and adapted to changing atmospheric conditions. This type of software and firmware enables the precise timing and synchronization required for QKD protocols.

Together, the hardware-centric and software-centric layers of a quantum satellite mission create a reliable quantum communication infrastructure that enables scalable and secure quantum networking via satellites.

Designing and Measuring Successful Quantum Satellite Missions

Successful quantum satellite missions are defined by metrics that describe how well these systems distribute quantum keys, including key rate, fidelity of quantum states, and the reliability / durability of the satellite itself in real-world conditions. Achieving these objectives requires careful consideration of system design parameters.

Key metrics



Goal is to jointly optimize:

- Key rate
- Quantum state fidelity
- Reliability and durability
- Coverage
- Precise time synchronization
- Dynamical polarization compensation
- High-bandwidth acquiring, pointing and tracking (APT)

Other factors to care about:
size, weight, power, cost, radiation, heat sensitivity, vibration.

Reference: [33]

Image reference [33]

Key Rate. The rate at which secure keys are generated between the satellite and ground stations.

Quantum State Fidelity. Measures how accurately transmitted quantum states are received. Affected by atmospheric disturbances, photon loss, and system imperfections.

Reliability and Durability. The ability of the satellite system to maintain stable performance over its mission lifetime. Factors include radiation resistance, temperature stability, and mechanical durability in orbit.

Coverage. Defines the geographic reach of the satellite.

Time Synchronization and Stability. Essential for QKD protocols, where the timing reference for analyzing quantum measurements and establishing communication must be highly accurate to generate a shared secure key.

Polarization Compensation and Optimization. Adjusts for changes in photon polarization and other signal properties caused by atmospheric conditions and satellite motion.

High-Bandwidth Pointing, Acquisition, and Tracking. Measures how well the satellite and optical ground station align and maintain connection. Precise tracking compensates for beam wandering and reduces transmission loss, improving overall signal integrity.

Beyond performance metrics, engineering constraints impact mission feasibility:

Size, Weight, and Power (SWaP). Hardware must be as compact, lightweight, and power-efficient as possible for satellite deployment.

Cost. Budget constraints affect technology selection and mission scalability.

Radiation & Heat Sensitivity. Quantum hardware must withstand space radiation and temperature fluctuations.

Vibration & Mechanical Stability. Systems must survive launch vibrations and maintain alignment in orbit.

Effective Quantum Satellite Programs

An effective quantum satellite program will address the system design parameters outlined in this paper. It also requires strong partnerships across multiple sectors including payload manufacturers, quantum satellite mission sponsors, hardware and software suppliers, and satellite companies.

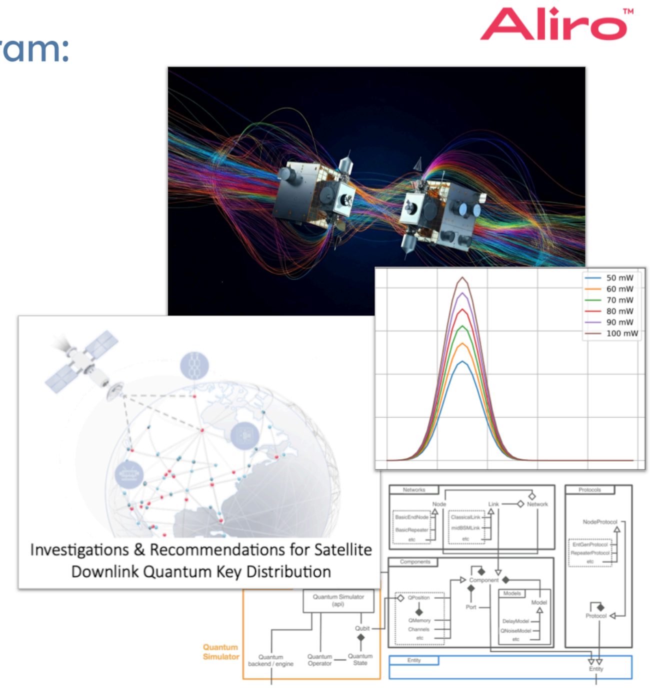
Aliro's Quantum Satellite Program: Design Considerations

System Design:

- Hardware selection
- Wavelength selection
- Maximize performance under SWaP-C constraints
- Ground station design
- Operational parameters
- Experimental data validation

Engagements:

- Payload manufacturers
- Quantum satellite mission sponsors
- Hardware suppliers & Aliro partners
- Satellite companies



The Future is Entanglement-based Quantum Networks

As we look to the future of secure communications, entanglement-based quantum networks are at the forefront. Building these networks for global connectivity requires incorporating free-space communications.

Entanglement-based quantum networks are being built today by a variety of organizations for a variety of use cases – benefiting organizations internally, as well as providing great value to an organization's customers. Telecommunications companies, national research labs, and systems integrators are just a few examples of the organizations Aliro is helping to leverage the capabilities of quantum secure communications, including building quantum satellites. Aliro's quantum satellite program aids organizations in designing and deploying quantum satellite systems efficiently and effectively.

AliroNet™, the world's first full-stack entanglement-based network solution, consists of the software and services necessary to ensure customers will fully meet their secure networking goals. Each component within AliroNet™ is built from the ground up to be compatible and optimal with entanglement-based networks of any scale and architecture. AliroNet™ is used to simulate, design, run, and manage quantum networks as well as test, verify, and optimize quantum hardware for network performance. AliroNet™ leverages the expertise of Aliro personnel in order to ensure that customers get the most value out of the software and their investment.

Depending on where customers are in their quantum networking journeys, AliroNet™ is available in three modes that create a clear path toward building full-scale entanglement-based secure networks: (1) Emulation Mode, for emulating, designing, and validating entanglement-based quantum networks, (2) Pilot Mode for implementing a small-scale entanglement-based quantum network testbed, and (3) Deployment Mode for scaling entanglement-based quantum networks and integrating end-to-end applications. AliroNet™ has been developed by a team of world-class experts.

To get started on your Quantum Networking journey, reach out to the Aliro team for additional information on how AliroNet™ can enable secure communications.

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