Optical Ground Stations & Quantum Advancements in Timing and Encryption in Contested and Congested Environments

Ground System Architecture Workshop (GSAW) 2025

Presented by David Mitlyng, Xairos CEO, 25 February 2025

Quantum Communications

- The Second Quantum Revolution is leveraging advancements in quantum hardware and systems
- Quantum Communications developments have been the most advanced of the quantum technology
    - Primary use case: secure communications and time transfer
    - Two flavors of quantum communications
        - Single photon – quantum key distribution (QKD), quantum random number generation (QRNG)
        - Bi-Photon Entanglement – QKD, quantum time transfer (QTT), quantum networking

Quantum Computing

Quantum Communications

Quantum Sensing

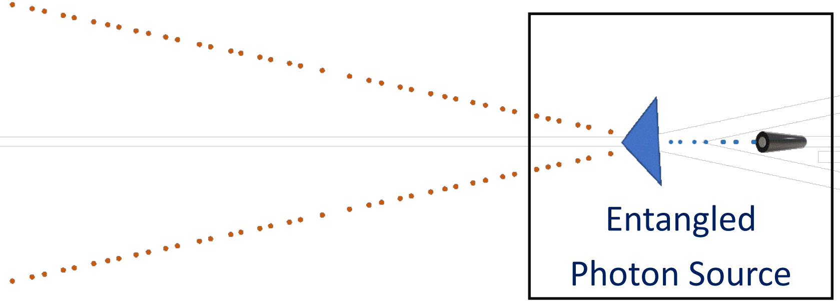
Quantum Communications Entanglement Distribution

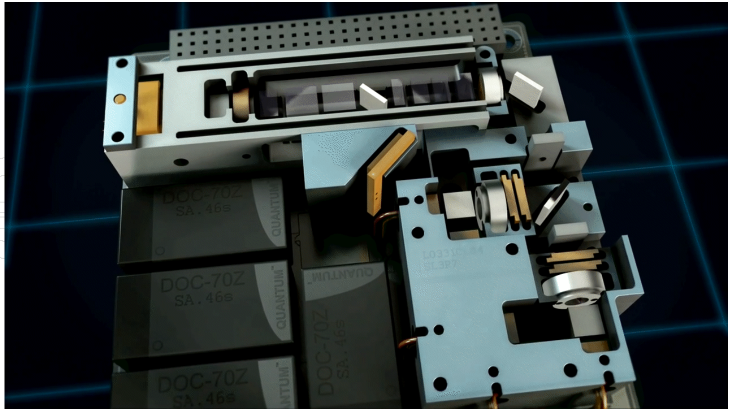
Alice

Single Photon Detectors

- Entanglement-type quantum communications enabled by key hardware developments

- Entangled photon source (EPS) - typically based on spontaneous parametric down-conversion (SPDC) using bulk nonlinear crystals





Single Photon Detectors

Bob

- Single Photon Detectors (SPDs)
  - Single-photon avalanche photodiodes (SPADs) using avalanche effect in reverse-biased semiconductors, room-temperature, low-cost, but limited to ~900 nm wavelength
  - Superconducting nanowire single-photon detector (SNSPD) have higher efficiency, lower dark count and timing jitter, and support broad range of wavelengths but require cryo-cooling

Entanglement-Type Quantum Key Distribution

- Entangled photons create random string of bits between Alice (sender) and Bob (receiver)
- Eve (eavesdropper) cannot measure without breaking quantum properties
- All QKD protocols require an authenticated classical communication channel
  - Protocol assumes Eve can access communications but won't be able to distill the shared key
  - Can be an optical comms layer for a free-space system

Quantum Time Transfer

- QTT builds upon known QKD hardware but instead used to synchronize Bob's clock to Alice's reference clock
- One-way QTT (shown) when distance between Alice and Bob is known, two-way QTT solves for distance
- For Alice's and Bob's photon pairs respectively, the correlation peaks will be located at

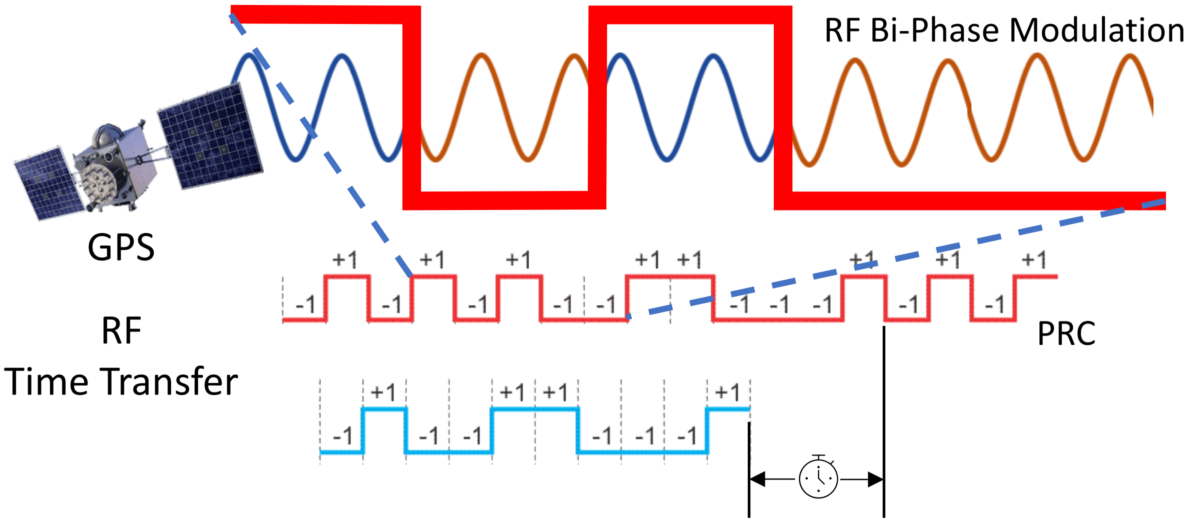
$$\tau_{AB} = \delta + \Delta t_{AB} \quad \text{and} \quad \tau_{BA} = \delta - \Delta t_{BA}$$

- This yields a measurement the average propagation time between Alice and Bob

$$\Delta T = ½\,(\Delta t_{AB} + \Delta t_{BA}) = ½\,(\tau_{AB} - \tau_{BA}) \text{ or simply } \delta = ½\,(\tau_{AB} + \tau_{BA}) \text{ for reciprocal distance}$$

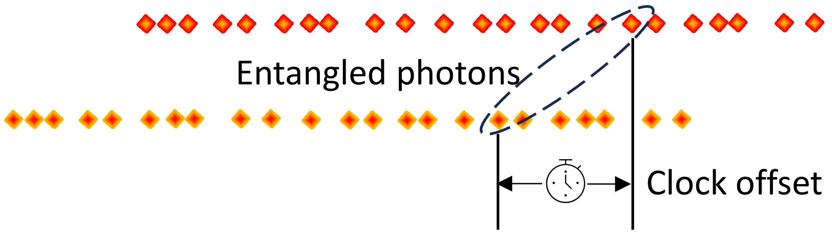
Xairos' Quantum Time Transfer compared to RF Time Transfer

RF
Time Transfer



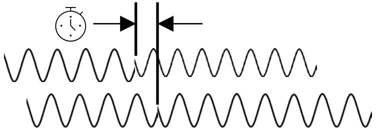
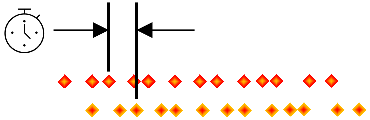
- GPS uses RF one-way time transfer
- Clock offset found from change in bi-phase modulation
- Information is transmitted with a code overlay

Quantum
Time Transfer



- QTT uses entangled photons for security and to find clock offset
- Information is transmitted over classical communications channel

Advantages of Quantum Time Transfer

	 RF Time Transfer	Quantum Time Transfer	Difference
How it Works			Measures the offset of individual photons vs. offset in phase
Accuracy	40 nanoseconds	10 picoseconds (>1000x more accurate)	• Tight time correlation of entanglement • Direct detection vs. analog-to-digital conversion • Resistant to link loss, dispersion, and noise
Resiliency	Easy to jam	Difficult to jam	• Resilience due to directional optical links • LPI/LPD of the entangled photons
Security	Easy to spoof	Unspoofable	• Entanglement prevents eavesdropping and spoofing, and provides true randomness • Bell's test authenticates the timing source

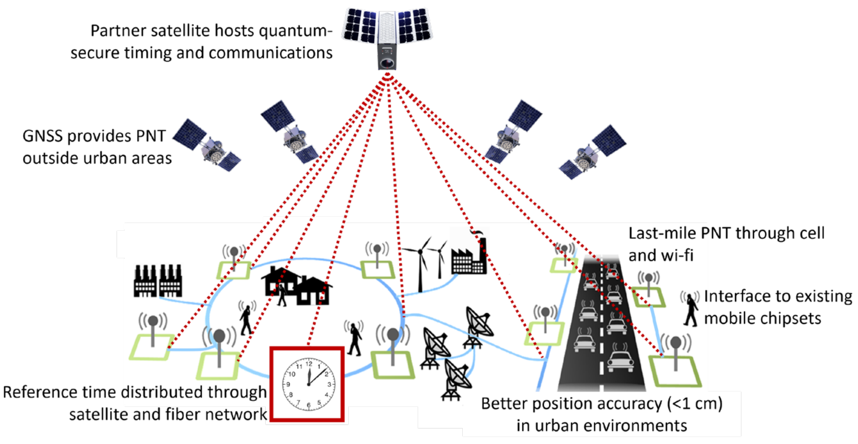
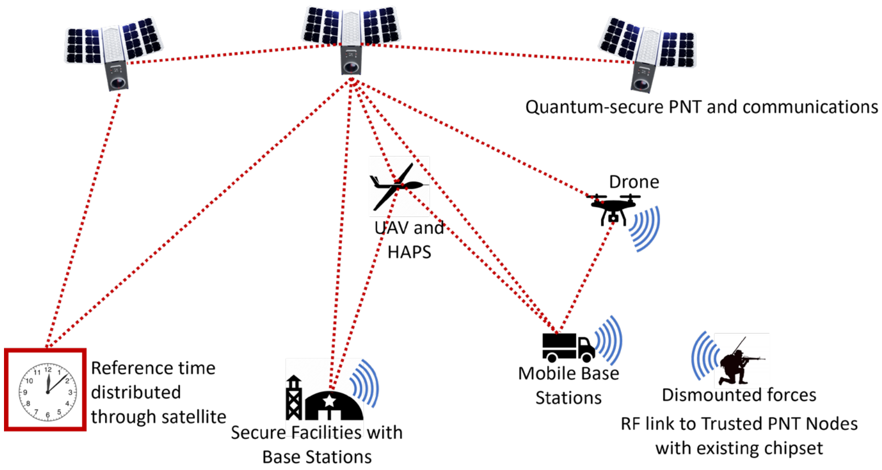
Quantum Communications Security

- Quantum communications leverages the No-Cloning Theorem and entanglement for security
- QKD entanglement type protocols include the E91 protocol with Bell's test and BBM92 without Bell's Theorem
- QTT leverages the decades of QKD security tests and proofs for authenticated time transfer
    - Photon pairs are entangled in polarization to authenticate the photons used to carry the timing information
    - The pattern of their temporal correlations is fundamentally unpredictable due to quantum nature of SPDC pair production
    - The polarization state of the photons cannot be perfectly copied during transmission
    - An adversary attempting to control the measured clock differences by faking the timing photon signal will be detected due to their disturbance of the polarization state of the detected photons — the same method used to detect eavesdropping in QKD
    - Unlike QKD, the shared random bits encoded into polarization do not need to be corrected and distilled into secure key or significant post-processing due to decoy-state weak coherent pulse implementations
    - This makes QTT more robust to loss and background noise as compared to entanglement based QKD
- Detailed security assessment underway including side channel, resend/asymmetric delay, denial-of-service/saturation and other attacks

Quantum Capabilities to Address Contested and Congested Environments

- Optical Ground Stations have advanced to provide FSOC capabilities
    - Resilience of optical links are already established in contested and congested environments
- The addition of a quantum layer adds additional timing and encryption capabilities
    - Resilient and accurate synchronization of the satellite constellation to a ground-based UTC source, enabling distributed sensing and comms and removing the need for expensive satellite clocks
    - A GPS-independent solution by providing an accurate timing reference and satellite position knowledge through accurate quantum ranging using time-of-flight measurements of entangled photons
    - Accurate timestamps for sensor data that enables data fusion
    - Quantum encryption keys that provide an extra layer of resiliency to the sensing and data transport capability
    - An authenticated ground truth reference that will help identify and assess any external threats to the PNT architecture from sources of spoofing and jamming

Quantum-Secure Timing and Communications Architecture

Commercial Architecture	Alt PNT Architecture
	

Commercial Architecture

Space-based constellation for global reach

Fiber-based network security for local networks

Leverages existing terrestrial infrastructure for timing and last-mile RF PNT delivery to mobile users

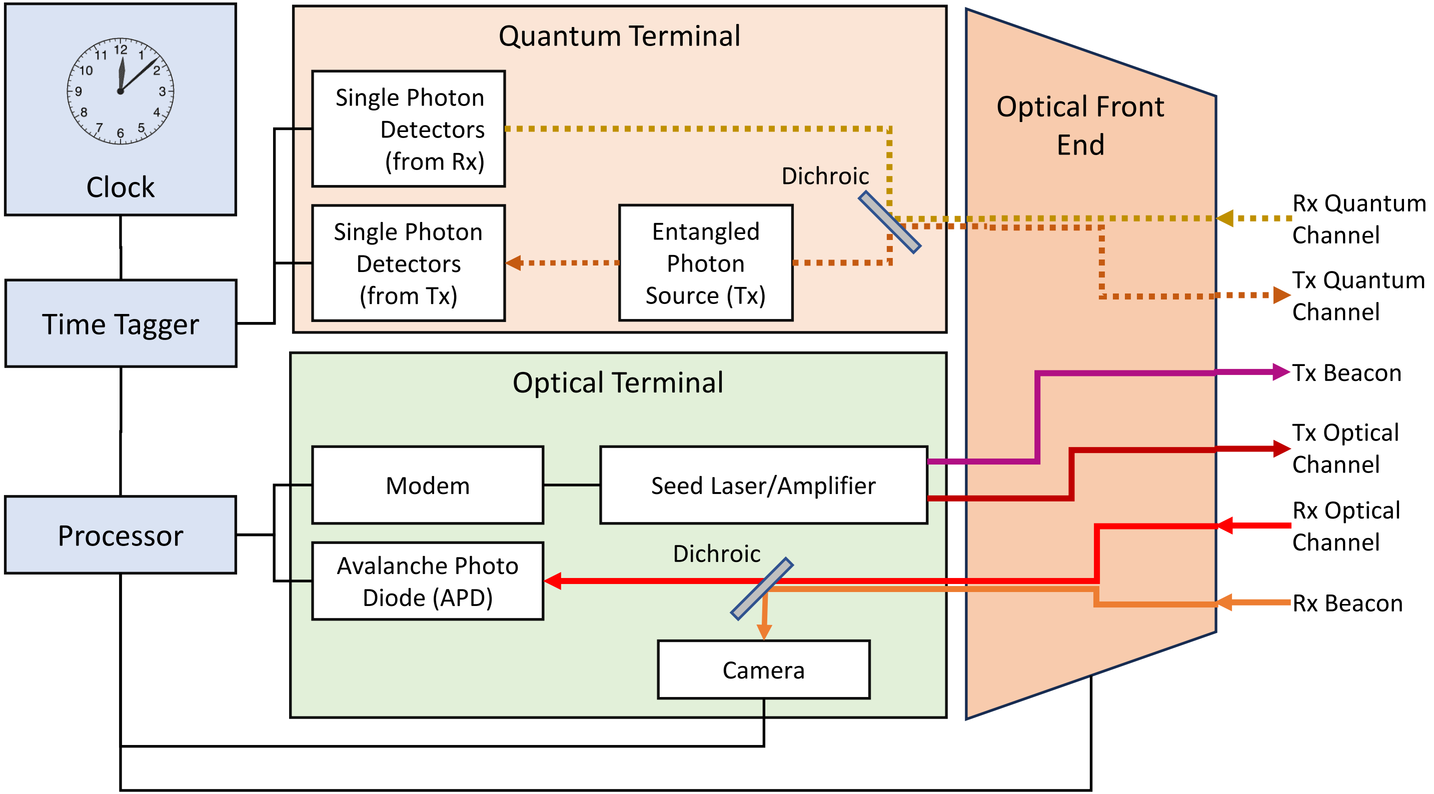
Alt PNT Architecture

Free-space quantum links for secure network of drones, HAPS, ships, and other mobile vehicles

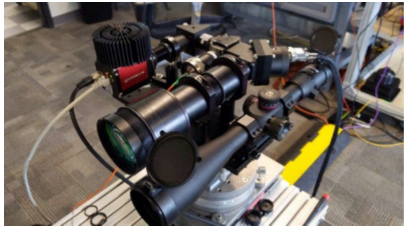
Deployed in a RF congested and denied environment to provide Trusted nodes for last-mile RF PNT

Quantum + Optical Terminals and Ground Station Block Diagram

- Quantum interface to a free-space optical comms (FSOC) terminal and ground stations are under development
- Goal is a system that can deliver time and keys via the quantum layer and comms via the optical layer



Xairos’ Development of Terminals and Ground Stations

US Space Force Phase II SBIR	**European Space Agency** Navigation Innovation and Support Program (NAVISP)	**Space Development Agency** Proliferated Warfighter Space Architecture (PWSA)	**European Space Agency** Greek Optical Ground Station
			
Develops terminal with clock ensemble and optical and quantum links	Develops quantum payload, simulation model, and commercialisation plan	Develops transportable optical ground station	Develops quantum receiver for large fixed optical ground stations

Xairos

Xairos’ Future Development Plans

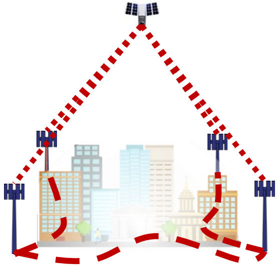
- Xairos invented and patented the QTT protocol in 2018, prototype completed
- Plans for field tests of integrated quantum + optical terminals and optical ground station in 2025
- Goal is to work with industry partners to develop a resilient global timing service at sub-nanosecond accuracy

Prototype Complete

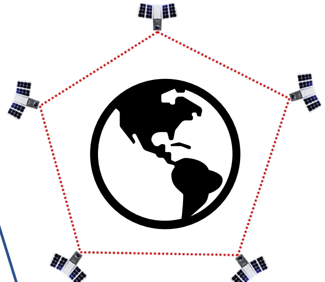
Quantum + Optical Terminal

Quantum + Optical Ground Station

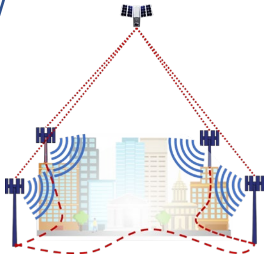
Demo Satellite



Regional Service



Global Service

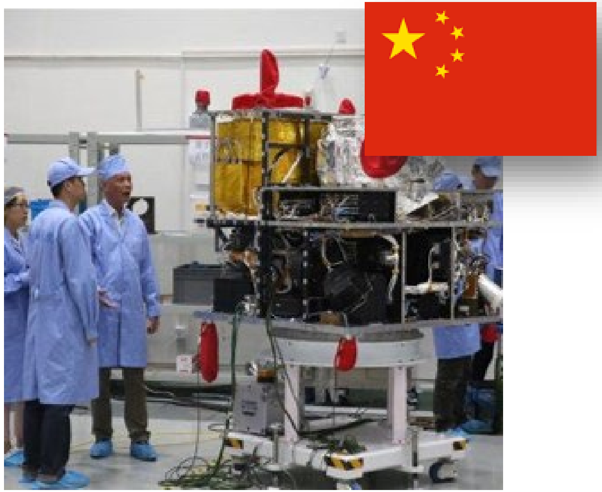


Last-Mile PNT

Quantum Satellite Global Development

Chinese Academy of Sciences		Micius QKD demonstration satellite (launched 17 Aug 2016)
		Space Lab Tiangong-2 quantum payload (launched 15 Sept 2016)
		Jinan 1 (launched 29 July 2022)
		LEO satellites (2025), MEO and GEO satellites (2026)
European Space Agency		Eagle-1 QKD satellite led by SES (2026)
		QKD-GEO satellite led by Thales and Hispasat (2027)
		IRIS^2 Secure Satellite Constellation with QKD links (2027)
		QKDSat private partnership with Honeywell UK (2027)
Canadian Space Agency		Quantum Encryption and Science Satellite (QEYSSat) (2026)
SpeQtral and CQT		SpooQy-1 (launched 17 June 2019), SPEQTRE (2025), SpeQtral-1 (2025)
UK Space Agency		QUARC, NANOBOB, ROKS
DLR		QUBE (launched 16 Aug 2024), QUBE-II (2025)
NASA, Boeing		SEAQUE (launched 27 June 2024), Q4S led by Boeing (2027)

China’s Quantum Satellite and Ground Station Development



- $100M Micius satellite launched August 2016 demonstrated:
    - BB84 “decoy state” QKD
    - Entanglement-based QKD
    - Quantum teleportation using entanglement-based QKD
    - Quantum-safe conference call between China and Vienna
    - Demonstration of “Quantum-Secure Time Transfer”
- 100 kg mobile quantum ground station developed with 280 mm aperture, 300W power consumption, and less than 1 m^3
- Chinese Academy of Sciences (CAS) announced new MEO and GEO quantum satellites October 2023

China's Quantum Time Transfer Developments

- Demonstrated QTT over fiber as part of their "High-Precision Ground-Based Timing System Project" to provide 100 picosecond timing accuracy across 20,000 km of fiber optics and 295 timing sites across China
- Demonstrated QSTT from Micius with plans to include on future MEO and GEO quantum satellites

Towards satellite-based quantum-secure time transfer

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High-precision time synchron... an important role in fundam... applications[4,5]. However, curr... niques[6,7] have been shown to... adversaries[8]. There is a com... new methods to distribute h... securely. Here, we propose a... time transfer (QSTT) schem... key distribution in free spa... the key technologies of the s... satellite. In QSTT, a quantum... photon) is used as the carr...

Quantum two-way time synchronization over a 103 km urban fiber

Huibo Hong, Runai Quan, Xiao Xiang, Yuting Liu, Tao Liu, Mingtao Cao, Ruifang Dong, and Shougang Zhang

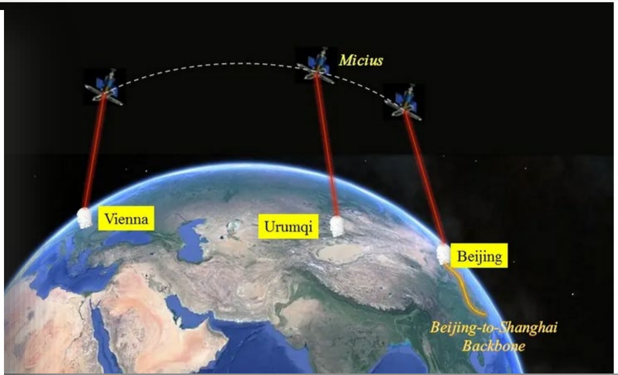
***Abstract*—As a new approach to realizing high-precision time synchronization between remote time scales, quantum two-way time synchronization via laboratory fiber link has shown significant enhancement of the synchronization stability to several tens of femtoseconds. To verify its great potential in practical systems, the field test in long-haul installed fiber optic infrastructure is required to be demonstrated. In this paper, we implement the two-way quantum time synchronization over a 103 km urban fiber link. A time synchronization stability of 3.67 ps at 10 s and 0.28 ps at 40000 s has been achieved, despite the large attenuation of 38 dB leading to fewer than 40 correlated events per second. This achievement marks the first successful step of quantum two-way time synchronization in the task of high-**

shown that the Q-TWTT setup is robust against symmetric channel delay attacks [18]. Shortly afterward, the experimental demonstration was extended to a 50 km coiled fiber with the TDEV stability reaching 2.6 ps at 7 s, and a minimum of 54.6 fs at 57300 s [19]. In comparison with its classical counterpart [20], the Q-TWTT result has shown significant improvement in the time synchronization performance, especially in the long-term averaging time. Its verification in metropolitan urban fiber links is urgently expected to pave the way for the field applications of Q-TWTT in long-haul fiber-optic timing systems.

China plans to take 'hack-proof' quantum satellite technology to new heights

By Andrew Jones published October 30, 2023

The country aims to build on a pioneering 2016 mission with a new medium Earth orbit satellite.



Questions?

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