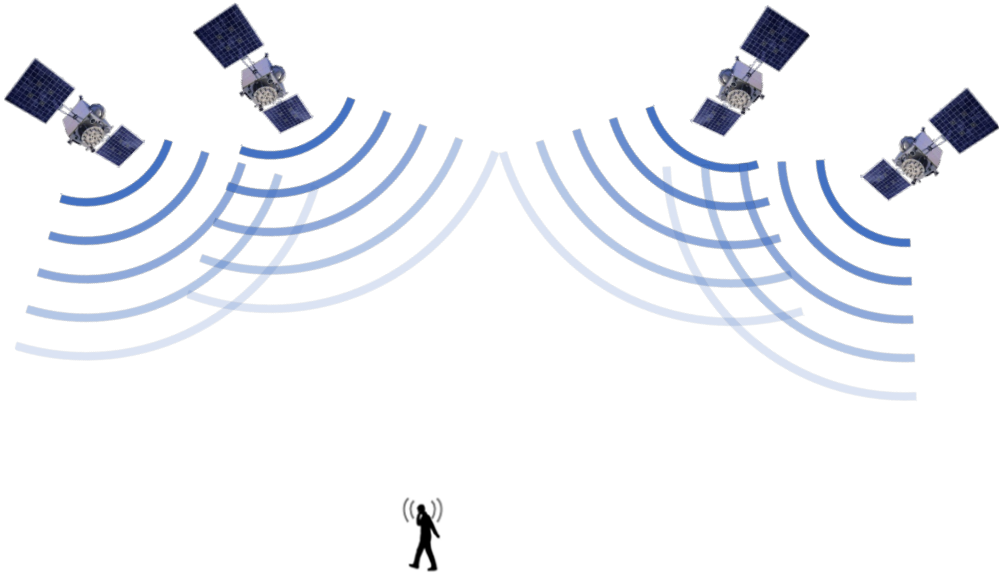
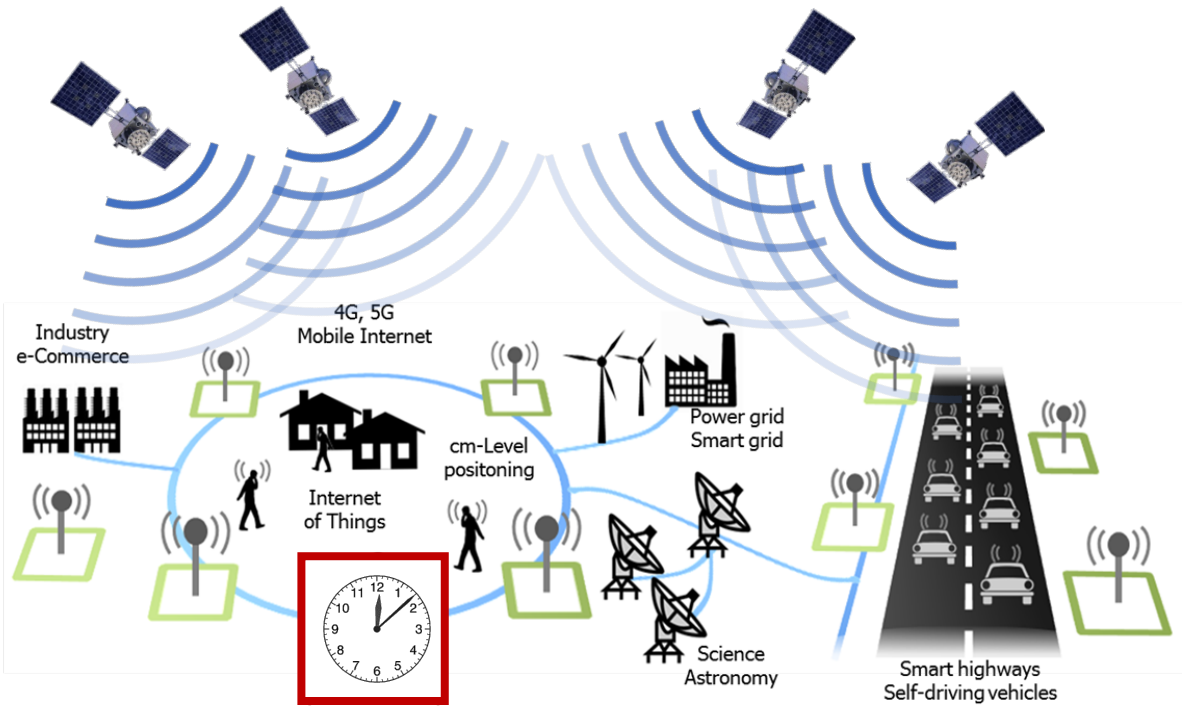
An Integrated Quantum + Optical Terminal for Resilient PNT

Presented by: David Mitlyng, CEO, Xairos

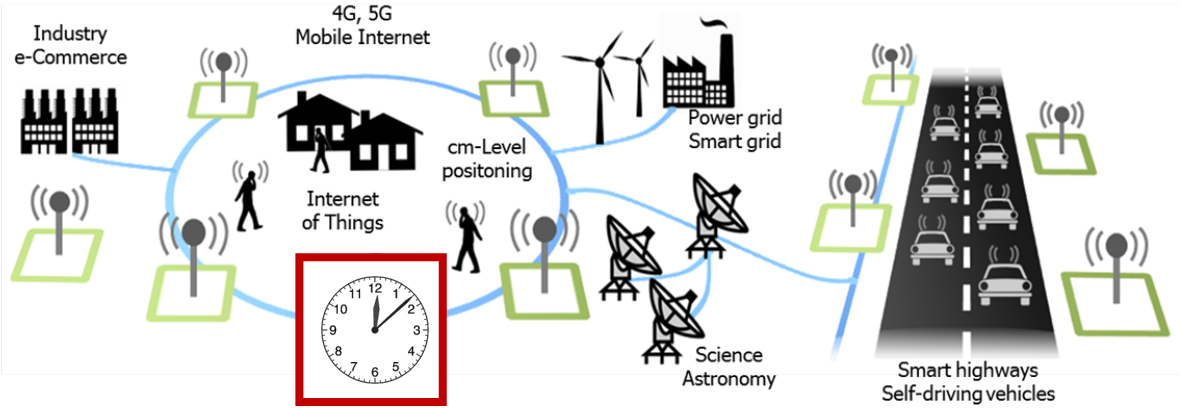
GPS



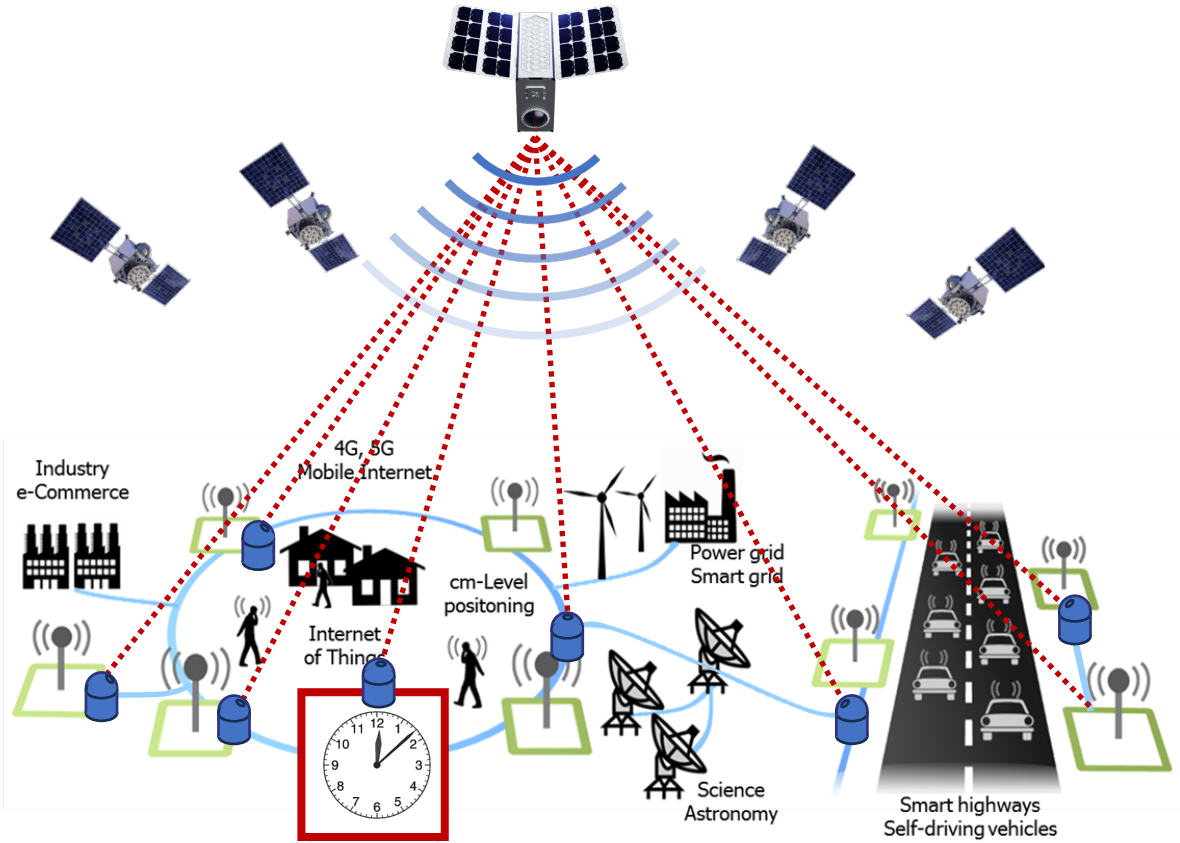
GPS Timing Architecture



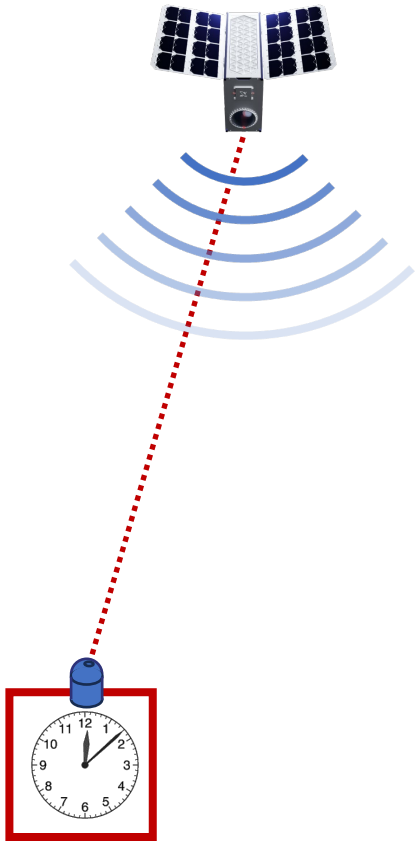
SuperGPS Architecture



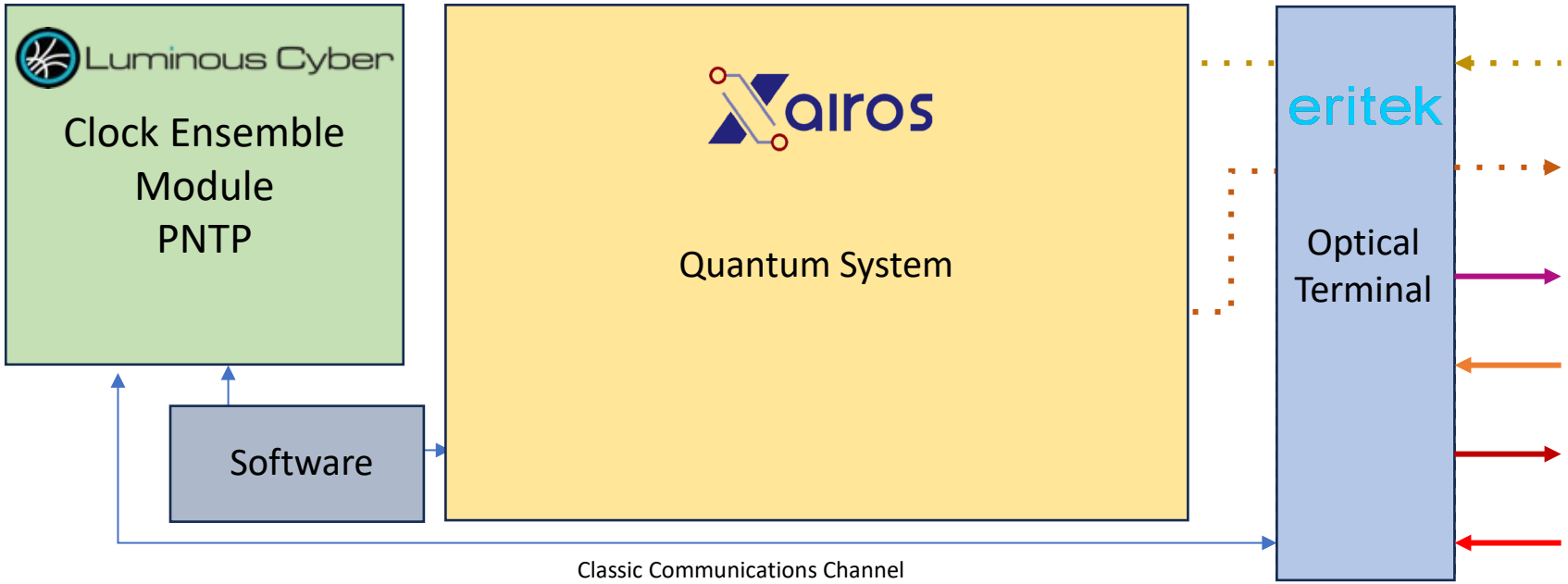
SuperGPS Architecture



Quantum Timing Development

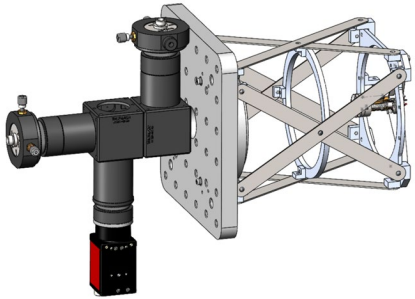


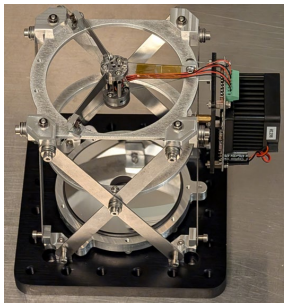
Quantum + Optical Terminal Design



Optical Communications Terminal

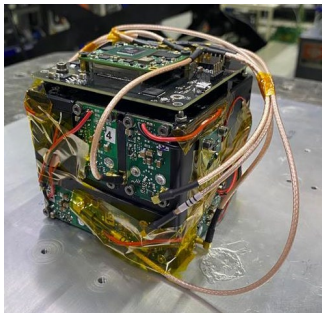
- 10 Gbps high-data-rate communications channel and low-power quantum channel
- Closed loop feedback beacon steering to maintain tight pointing
- Compact Afocal dual reflector Cassegrain design
- 86 mm diameter primary reflector
- Secondary reflector with Fast Steering Mirror (FSM)

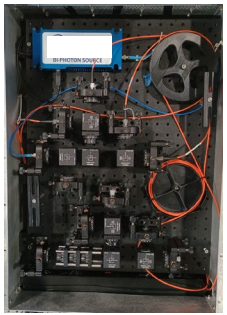


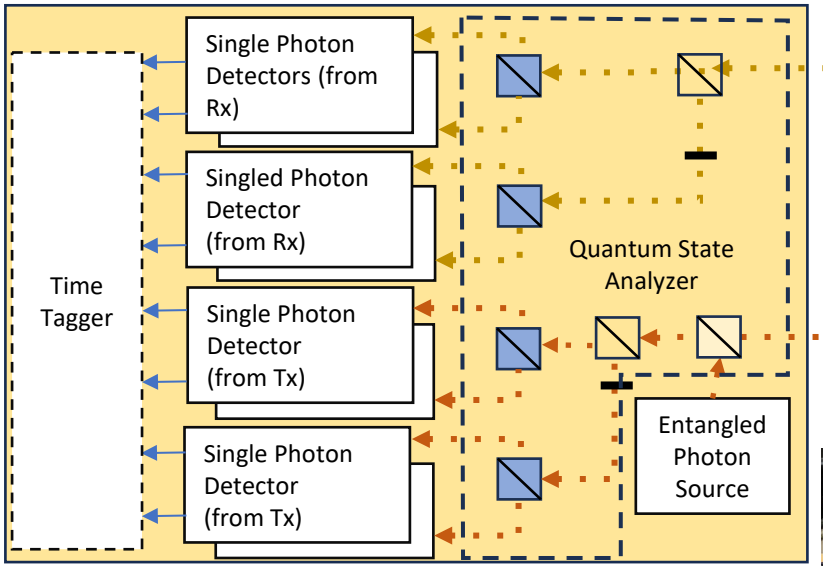


Quantum System

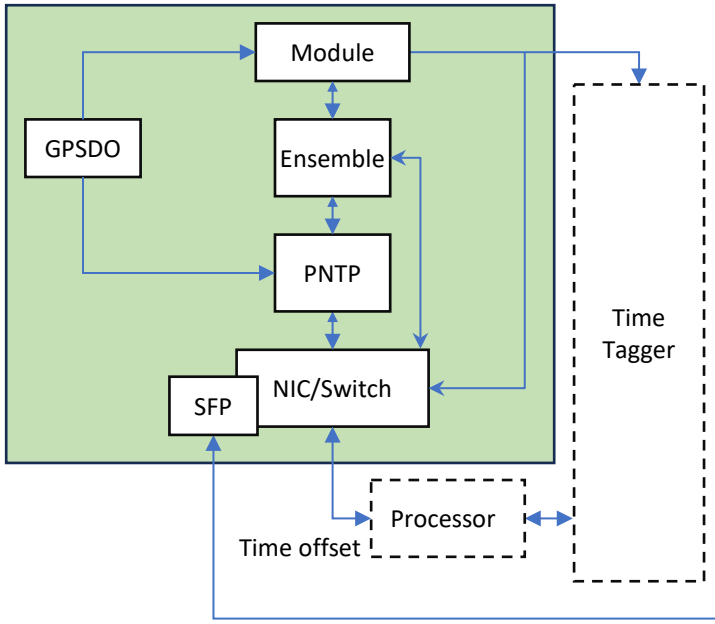
- Entangled photons distributed through optical terminal to provide quantum time transfer (QTT)
- Leverages off-the-shelf entangled photon hardware
- Interface to the optical terminal and detected photon events for the QTT algorithm



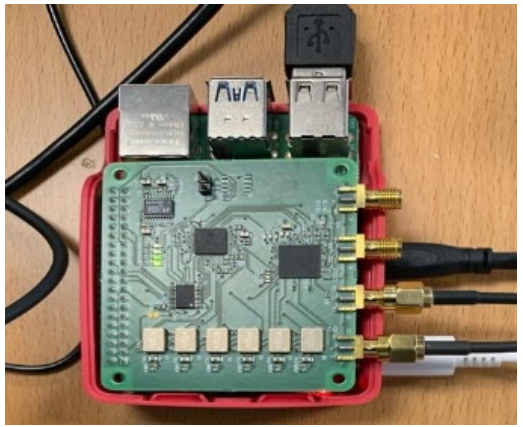




Clock and Timing

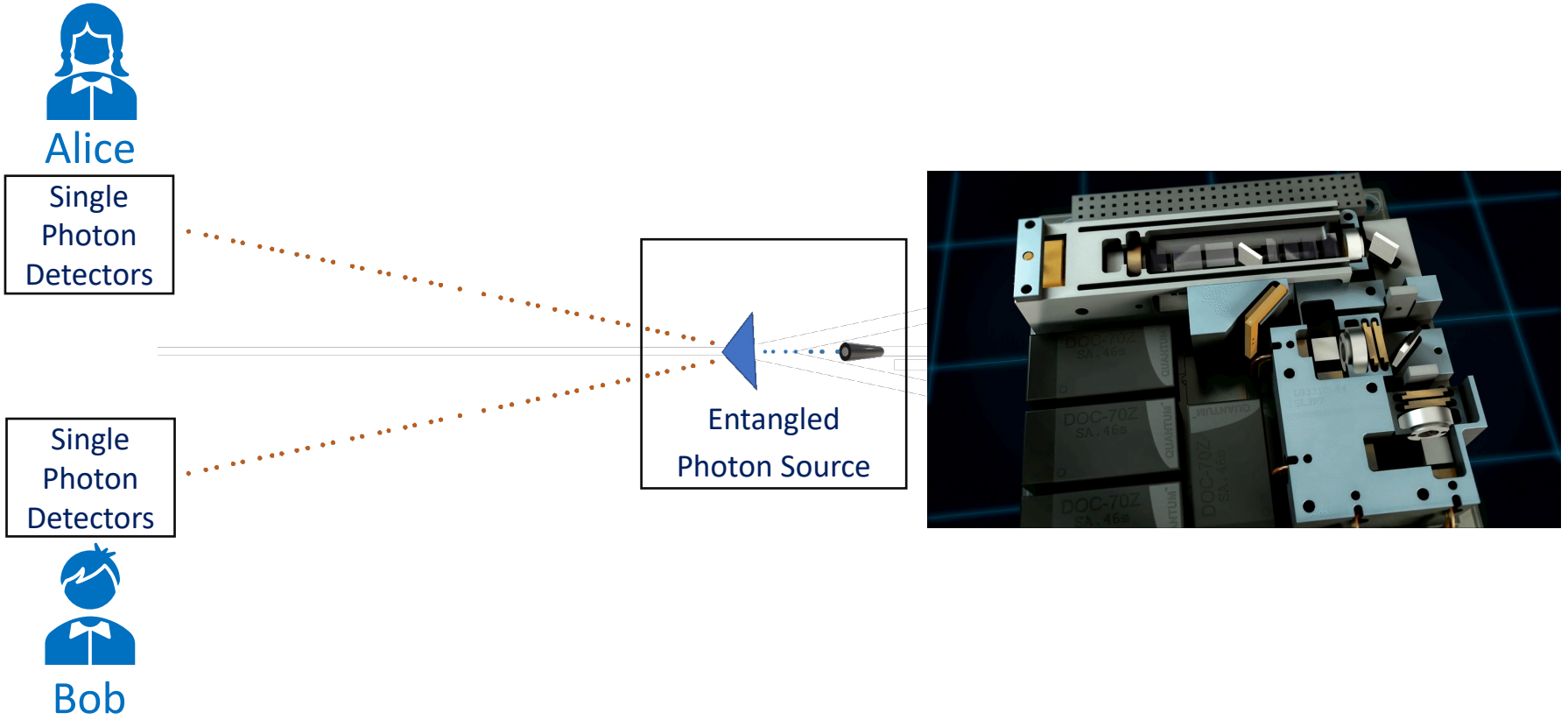


- Stable timing provided by a clock ensemble algorithm
- Novel QTT information for sub-nanosecond phase
- PNTP protocol to provide RF and optical position and timing information
- AI/ML algorithm to compensate for temperature, aging
- Target Holdover of 10 ns at 3600 seconds

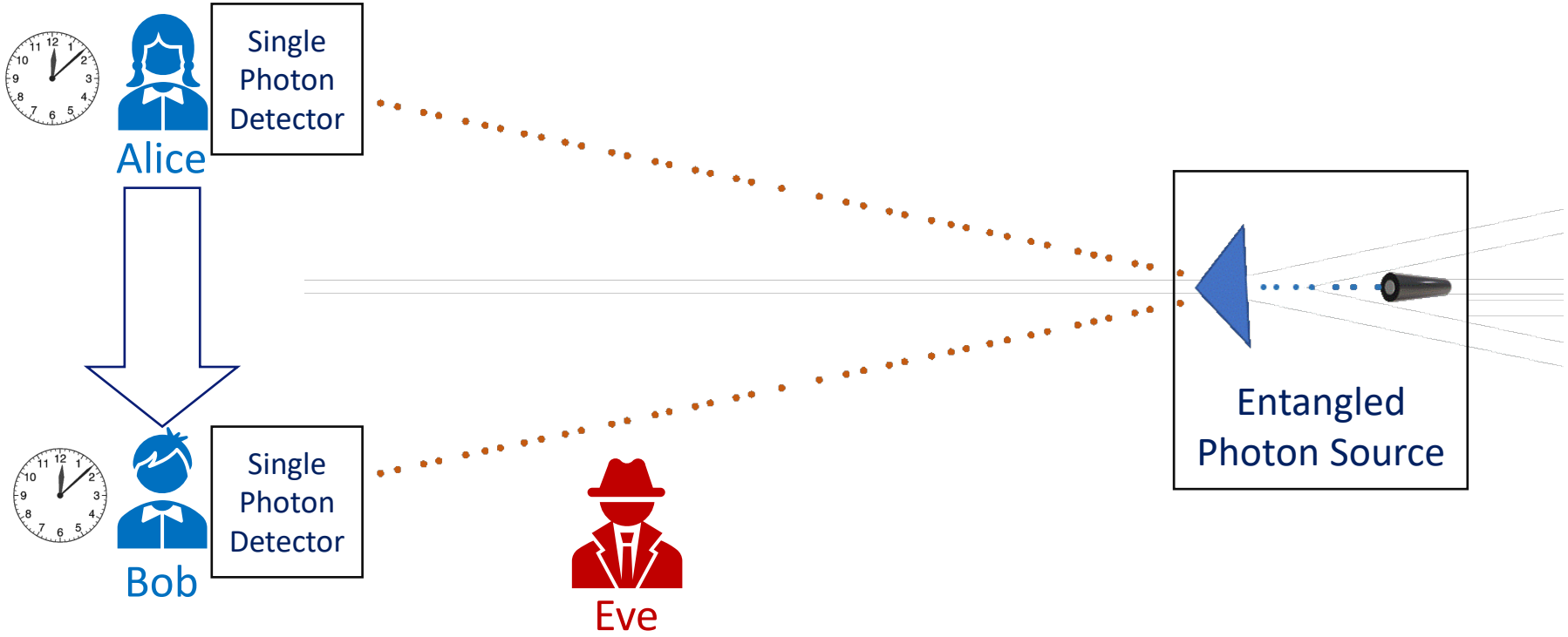


Quantum Time Transfer

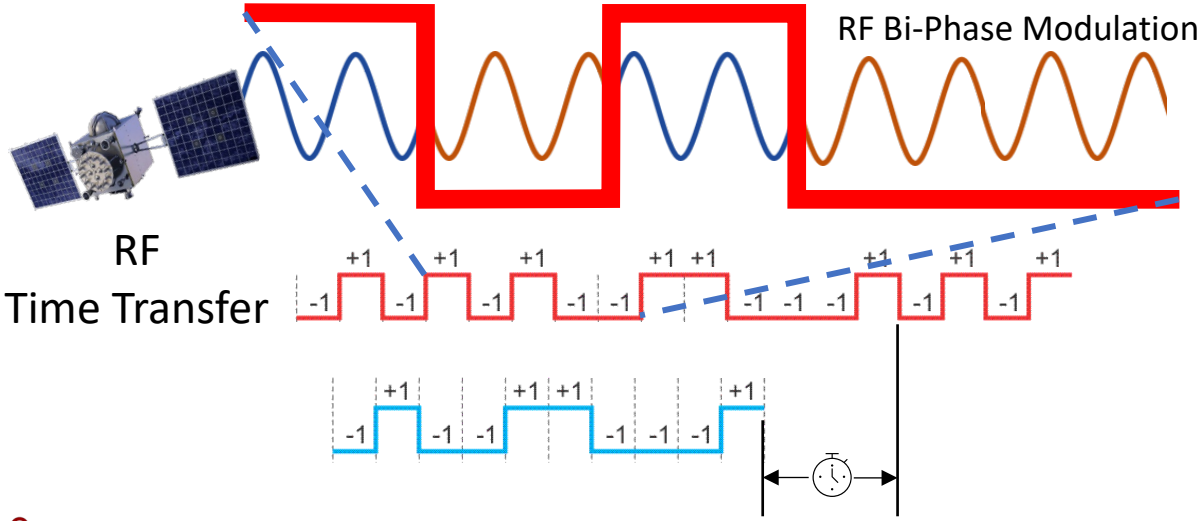
Quantum Time Transfer

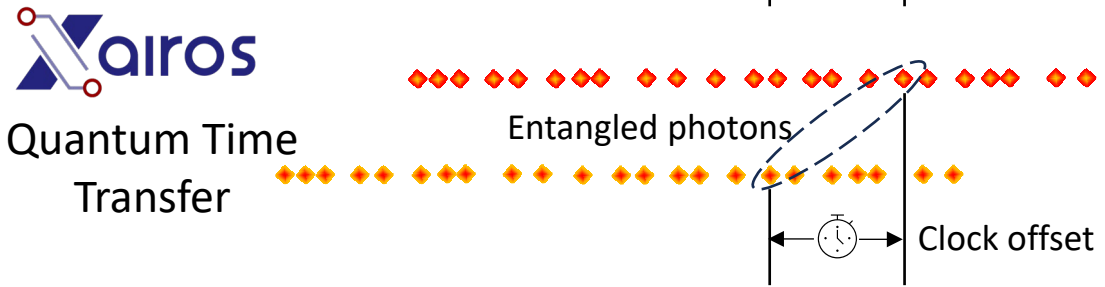


Quantum Time Transfer



Quantum vs RF and Optical Time Transfer





Correlation peaks will be located at:

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

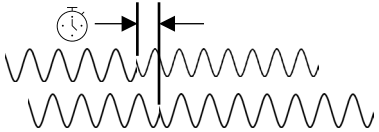
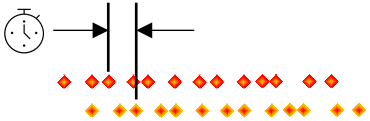
Average propagation time between Alice and Bob:

$\Delta T = ½ (\Delta t_{AB} + \Delta t_{BA}) = ½ (\tau_{AB} - \tau_{BA})$

or simply

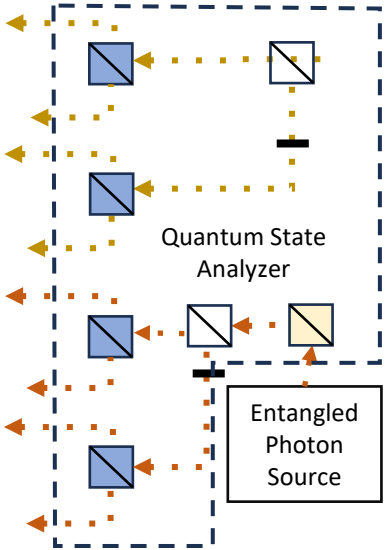
$\delta = ½ (\tau_{AB} + \tau_{BA})$ for reciprocal distance

Advantages of Quantum Time Transfer

	 RF Time Transfer	Xairos Quantum Time Transfer	Difference
How it Works			
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

Security

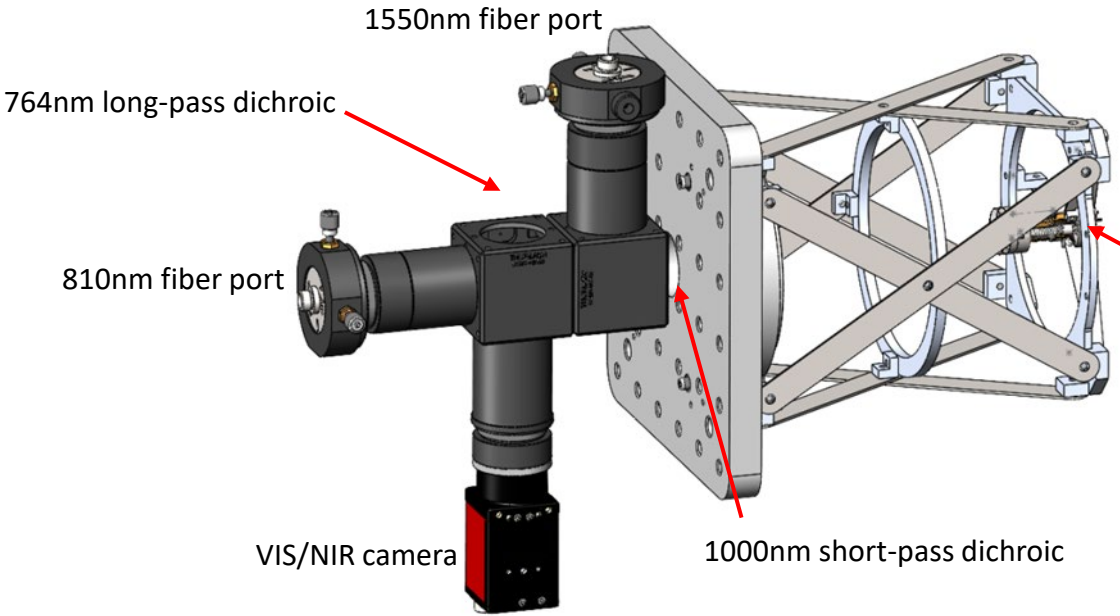
- QKD security tests and proofs for authenticated time transfer
  - Authentication with entanglement
  - Randomness
  - No-cloning theorem
  - Resilient to spoofing
  - More robust than QKD
- Side channel, resend/asymmetric delay, denial-of-service/saturation and other attacks
- Polarization is detected with a Quantum State Analyzer

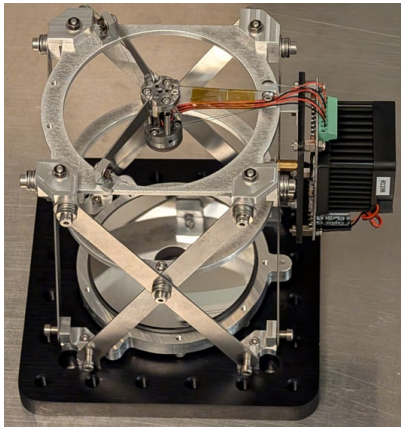


Optical Terminal

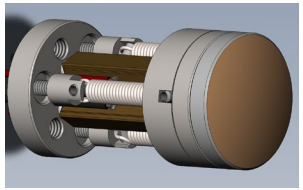
Optical Terminal Design

Approximate dimensions: 13” x 6” x 9” (excluding connectors)



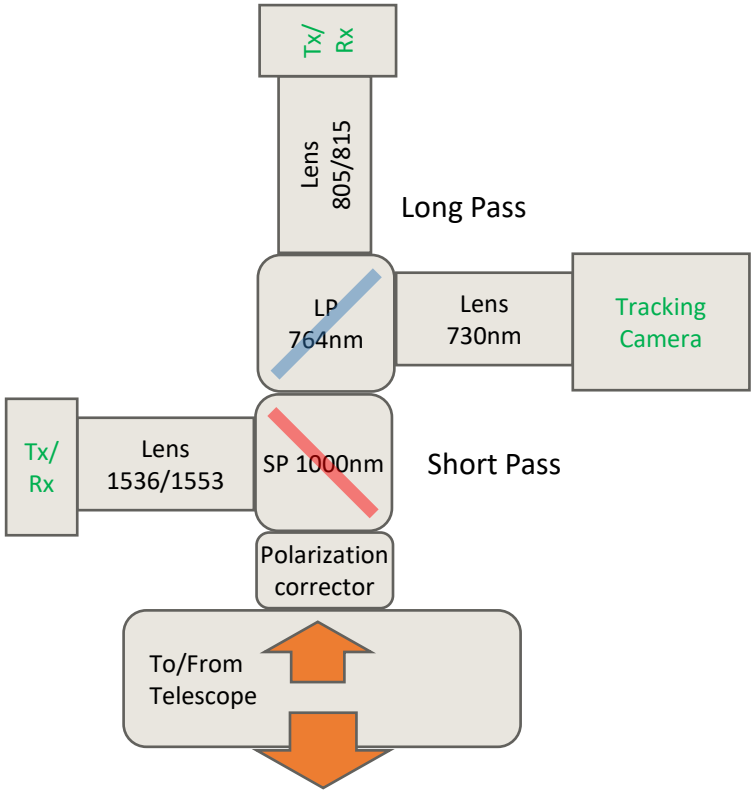


FSM-mounted secondary mirror



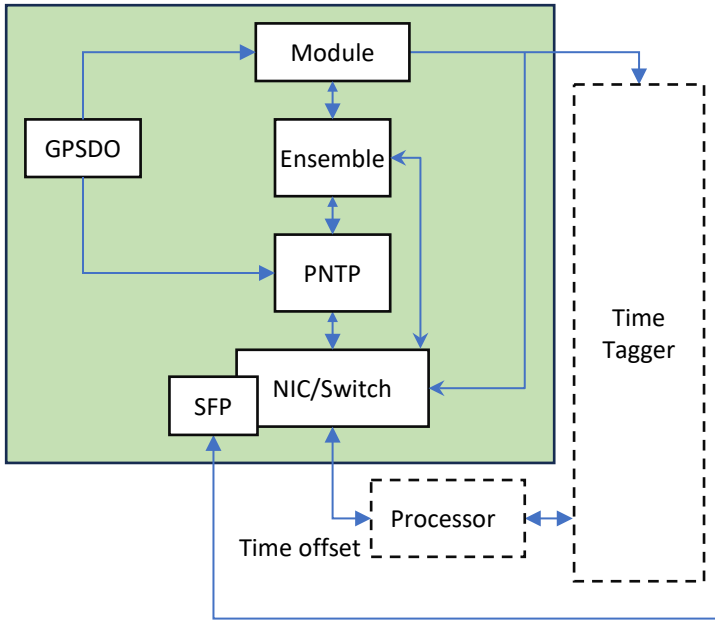
Telescope Back-End

- Dichroic filters separate color channels:
  - <760nm = tracking camera (beacon)
  - ~810nm = entangled communications
  - ~1550nm = conventional lasercom
- Lens sets are diffraction-limited
  - High optical efficiency
  - Made for coupling to the telescope
- Polarization corrector



Clock and Timing

Clock Ensemble



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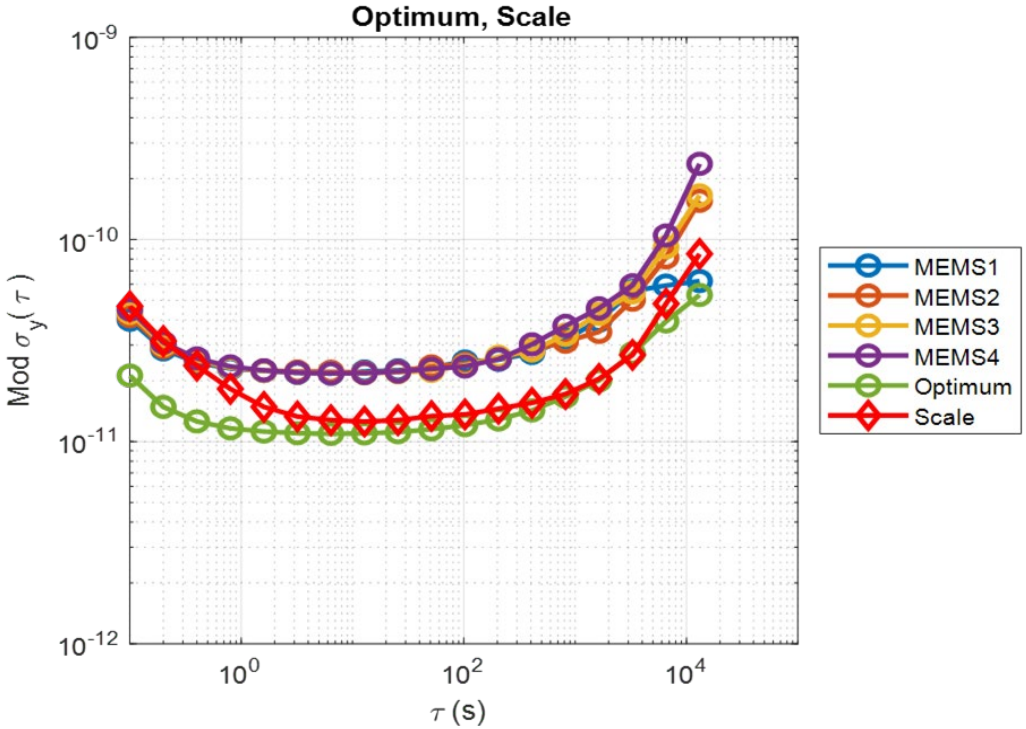
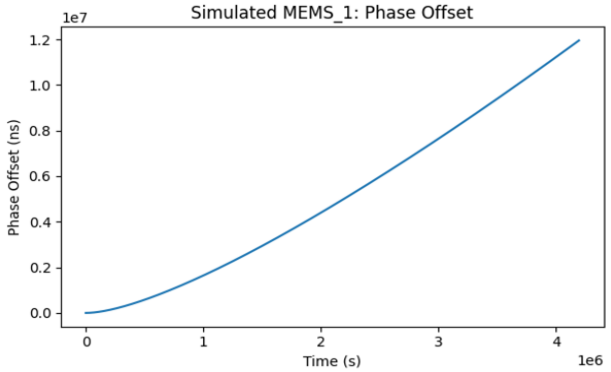
Clock Ensemble

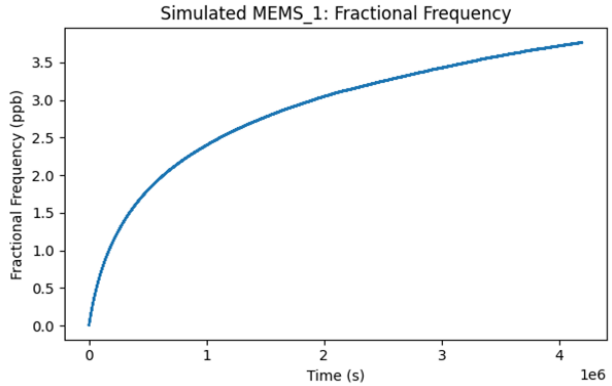
Simulated MEMS Oscillator Ensemble (4)



AI/ML for Aging and Temperature Compensation

- Apply AI/ML techniques for system identification and time series prediction
- Filter data to smooth noise
- Implement time series prediction models that forecast future values based on historical data patterns
- Aging
  - Train using a) simulated clocks; b) physical clocks (unlocked); c) physical clocks (locked)
  - Compare deep-learning techniques versus classical regression techniques
  - Update simulation models from physical data
- Temperature
  - Repeat the process for LEO temperature environment
  - Measure MDEV, Holdover as functions of time and temperature



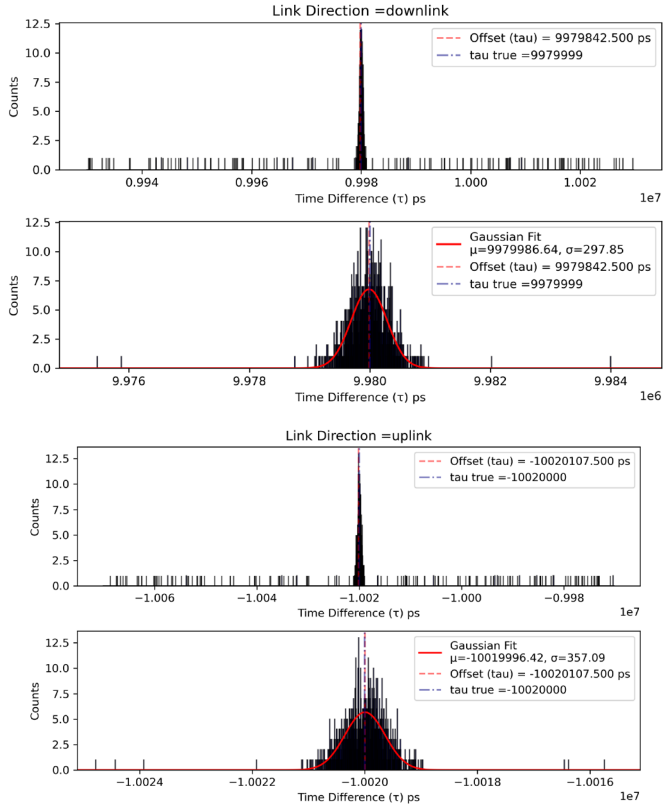


Software and Processing

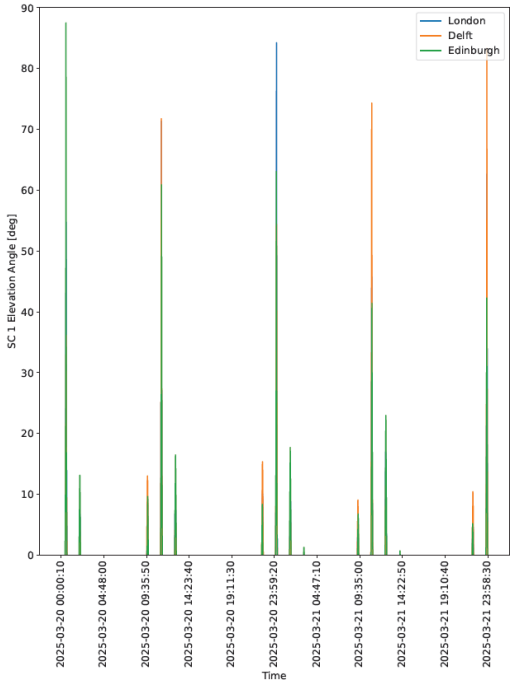
PNTP (w/o QTT)

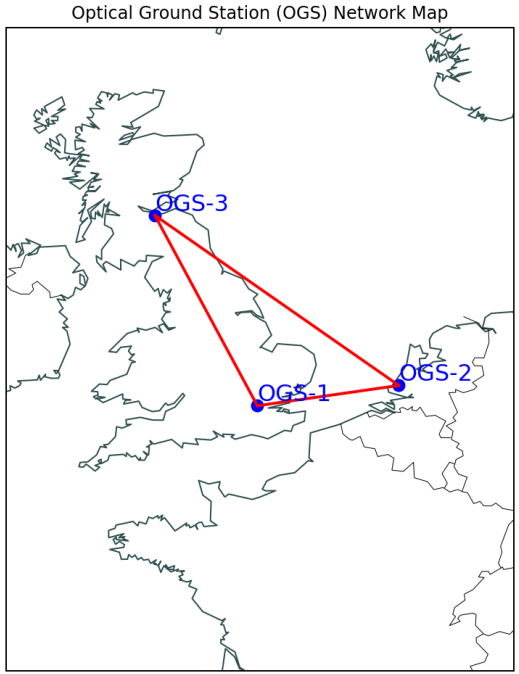
- Position, Navigation & Timing Protocol
  - Add Position, Velocity & Acceleration to PTP
  - Enables PTP across moving platforms
  - TLV on PTP
- Early results before QTT are +/- 2.5ns rms jitter
- QTT is expected achieve ~10 ps

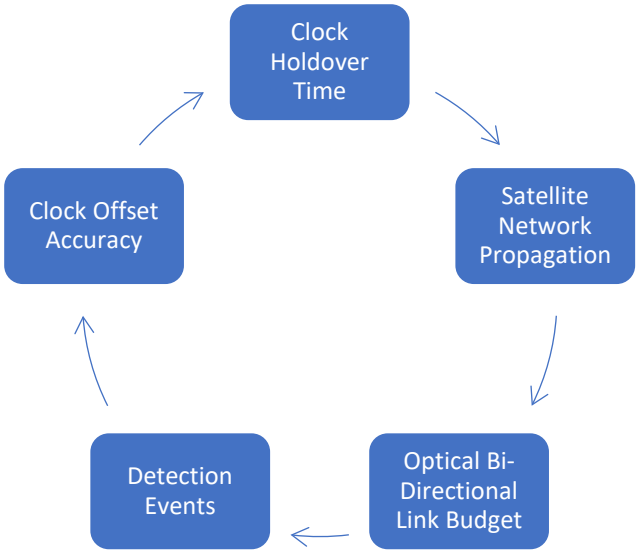
QTT Algorithm



Simulation Model







Thank You!

Contact: david@xairos.com