
Precision Synchronization for Long-distance Free-space Quantum Networking

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Quantum 2.0

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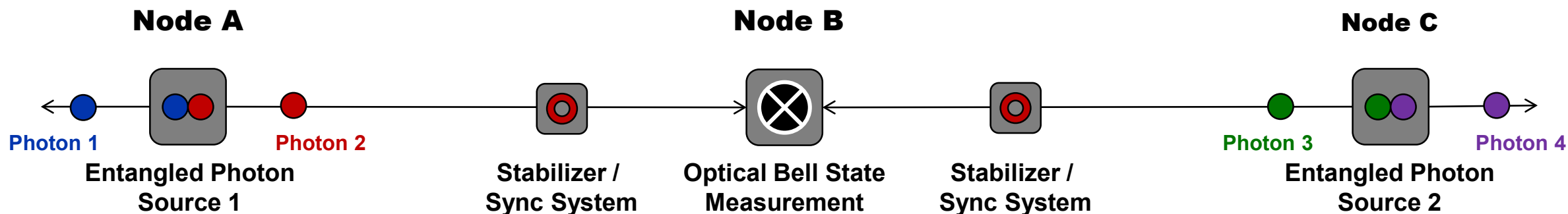
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Multi-Span Entanglement Distribution

Synchronization Considerations



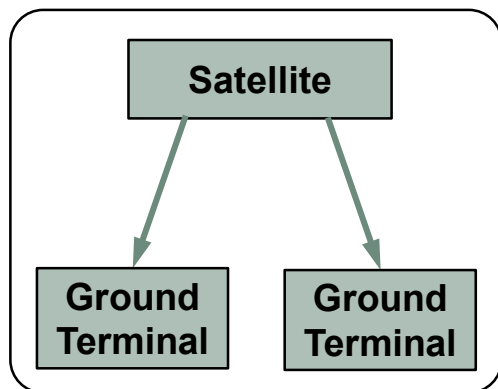
- Entangled Photon Sources produce pairs of entangled photons
- Photons 2 and 3 sent to Optical Bell State Measurement (OBSM)
- OBSM concatenates links, resulting in entanglement between Photons 1 and 4
- Channel stabilizers synchronize photon arrivals at OBSM (ps-class sync required)

Synchronization techniques are critical to realizing efficient high-rate entanglement distribution



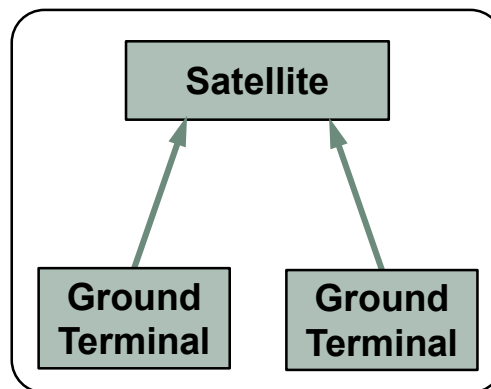
Quantum Network Link Topologies

Dual Downlink



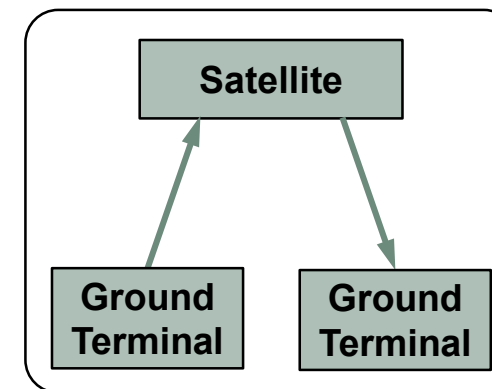
- Entanglement source on satellite
- Photonic qubits sent to different ground stations
- Space-ground synchronization is independent for each downlink

Dual Uplink



- Entanglement sources at both ground stations send qubits to satellite
- Optical Bell state measurement on satellite entangles remaining qubits at ground stations
- Both uplinked qubits must be synchronized at satellite

Uplink / Downlink

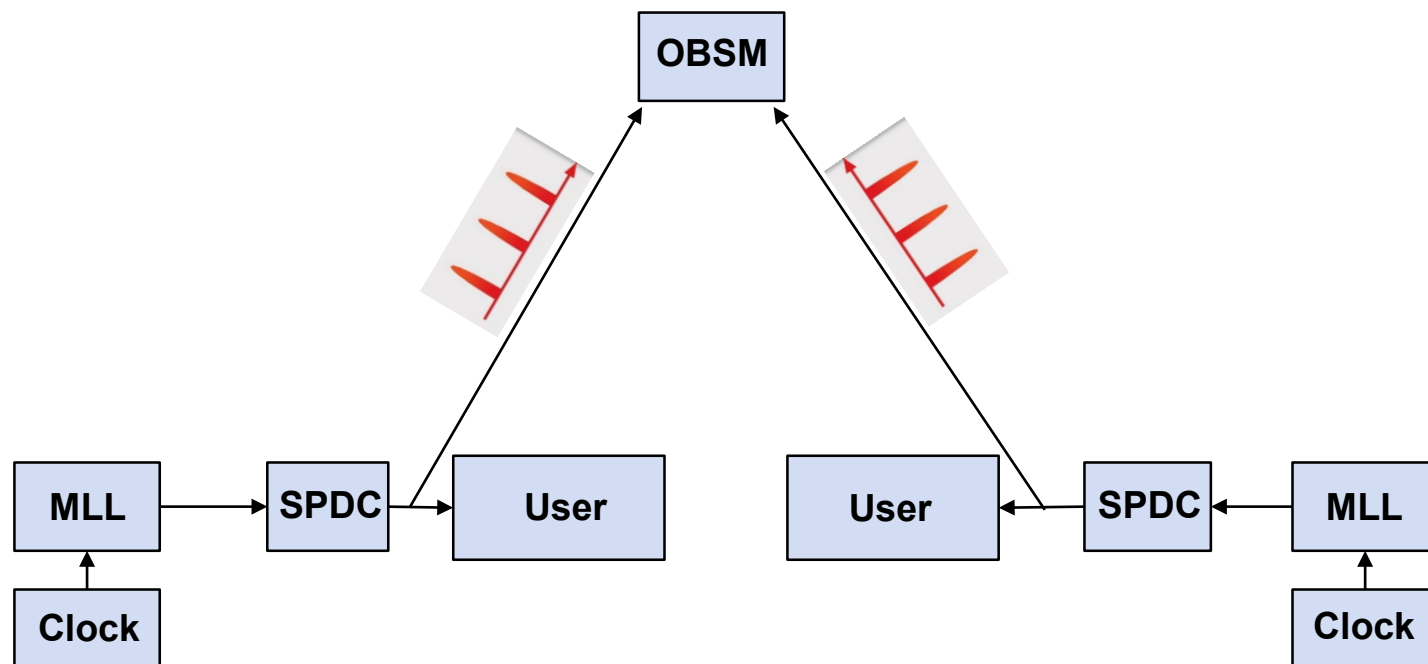


- Entanglement source at one ground station
- Photonic qubit sent via satellite-based passive relay to second ground station
- No space-ground synchronization required

Synchronization techniques are critical to realizing efficient high-rate entanglement distribution



Uplink-Uplink Synchronization Challenges



- **Pulse duration**
 - 1 ps pulse is 300 microns in length
- **Low flux**
 - $\sim 10^4$ to 10^6 pulses per second
 - ~ 1 -100 coincidences per second
- **Timing variations due to:**
 - **Spacecraft Motion (Doppler, jitter)**
 - ~ 7 km/s motion
 - **Channel effects**
 - **Tx and Rx path length**
 - **Source jitter**
 - ...
- **Needs to be robust in fading**

Architecture likely requires strong supplementary sync signals with a hierarchy of time alignment mechanisms



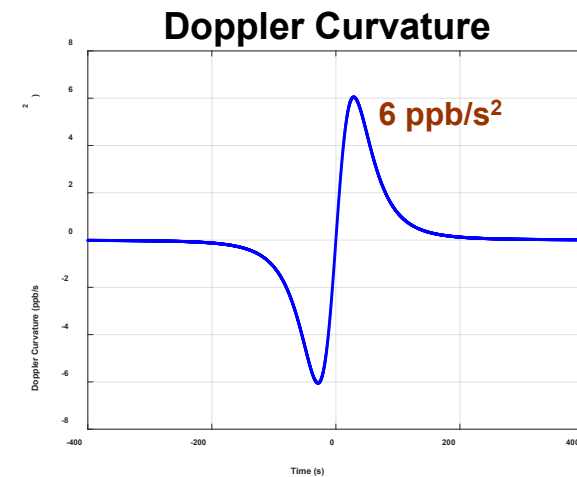
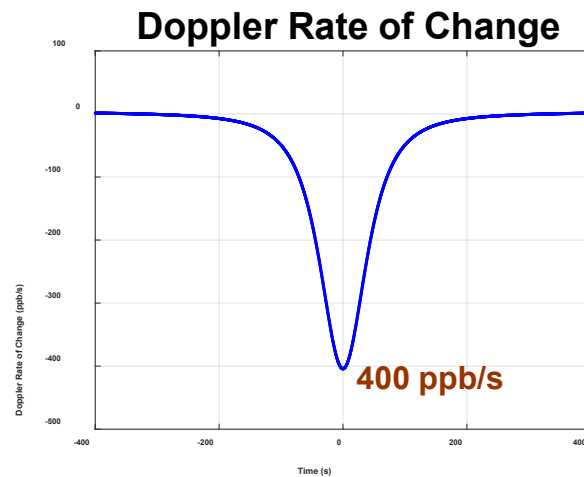
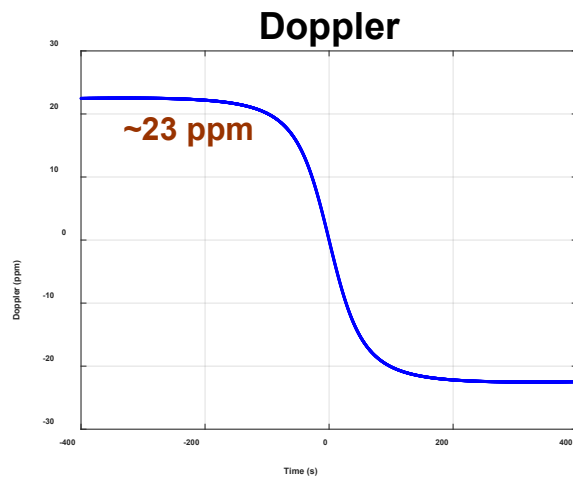
- **Provide strong synchronization signal on each uplink for high SNR measurement at space terminal**
- **Timing measurement on space terminal**
 - **Comparison of received sync signals (via mixer, cross correlation): challenging to measure to ~ 0.1 ps**
 - **HOM alignment signal via BSM**
- **Path length control methods**
 - **Ground source repetition rate**
 - **Path length (space and ground)**
 - **Adjustable optical delay line (mechanical/ piezo-electric)**
 - **Thermal**
 - **Phase modulator (fast but limited throw)**
- **Control methodologies**
 - **Precompensation**
 - **Phased locked loop**

Synchronization capability determined by fundamentals and technologies

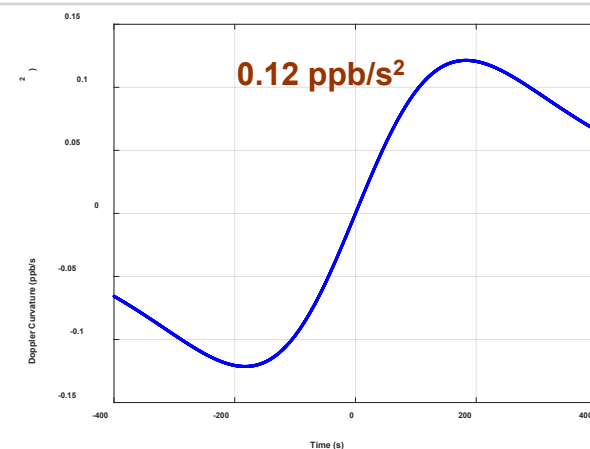
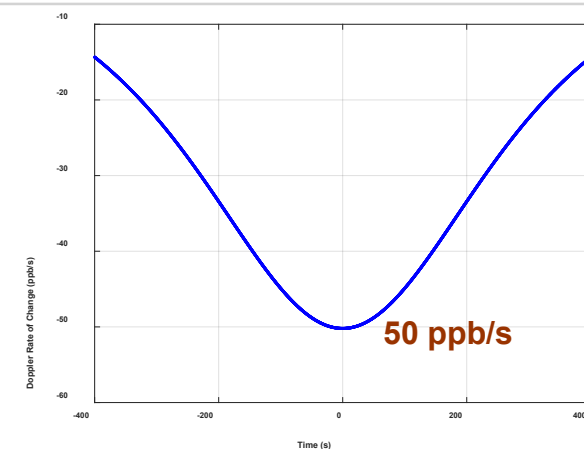
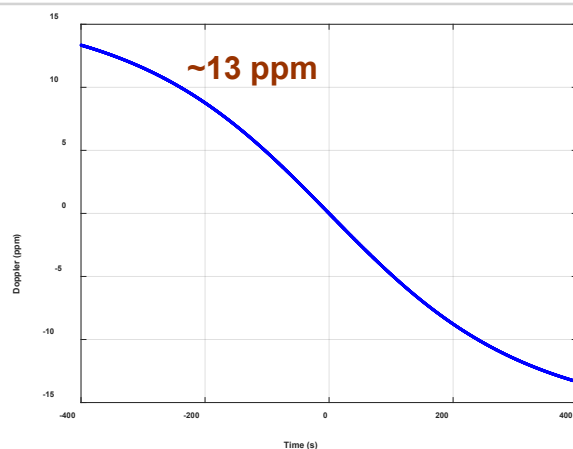


Orbital Motion

LEO (400 km)
7.7 km/s
~1.3-9 ms
propagation delay



MEO (2000 km)
6.9 km/s
~6-10 ms
propagation delay



• Doppler sets control
loop throw requirement

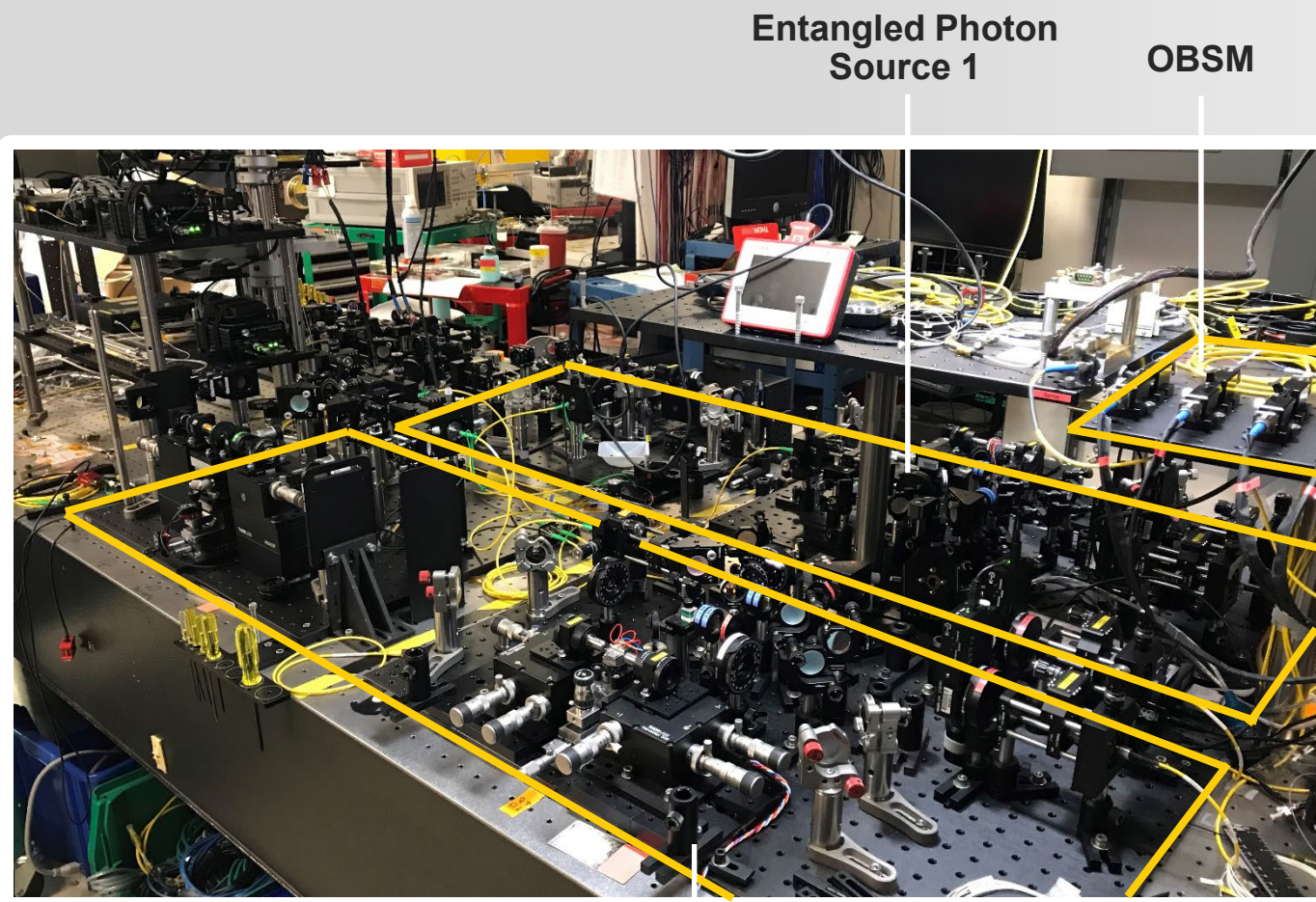
• Doppler rate of change sets
loop bandwidth requirement

Link architecture puts fundamental constraints on synchronization



Space-Ground Entanglement Distribution Test Bed

Entangled Photon
Source Pump
Subsystems
(off photo)



Entangled Photon
Source 1

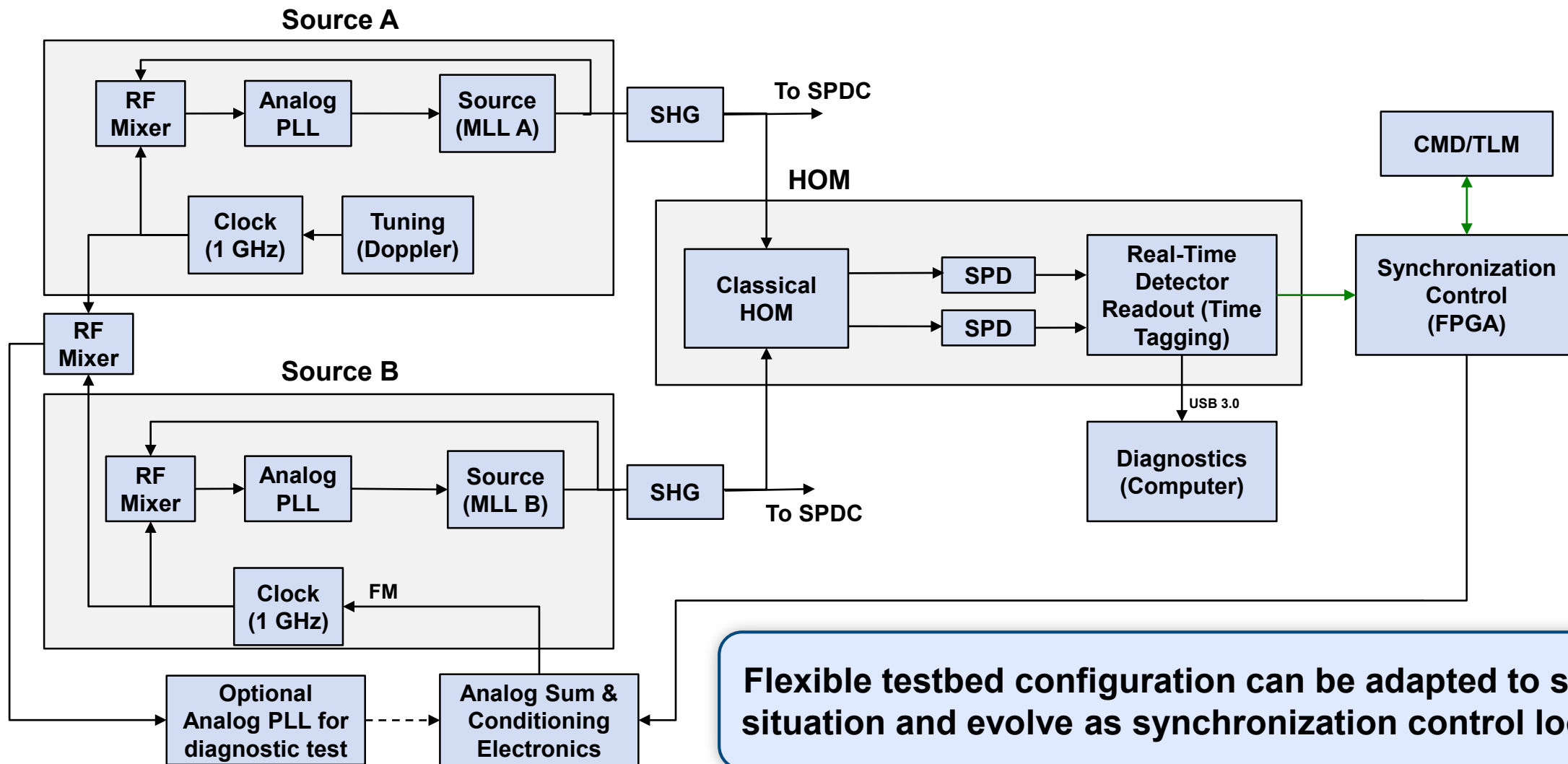
OBSM

Entangled Photon
Source 2

- Two Entangled Photon Sources
- Optical Bell State Measurement (OBSM) with fiber connections to single-photon detectors
- Fiber connections to free-space link across Hanscom AFB
- Rolling integration test approach
 - Table-top testing
 - Free-space link testing



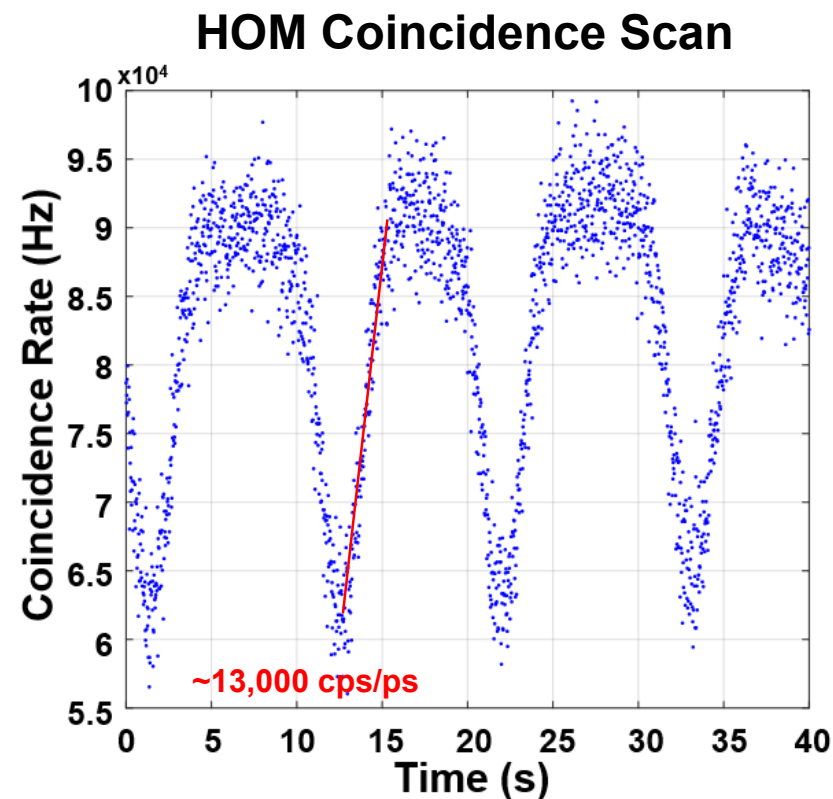
Testbed Configuration





Control Loop Timing Discriminant

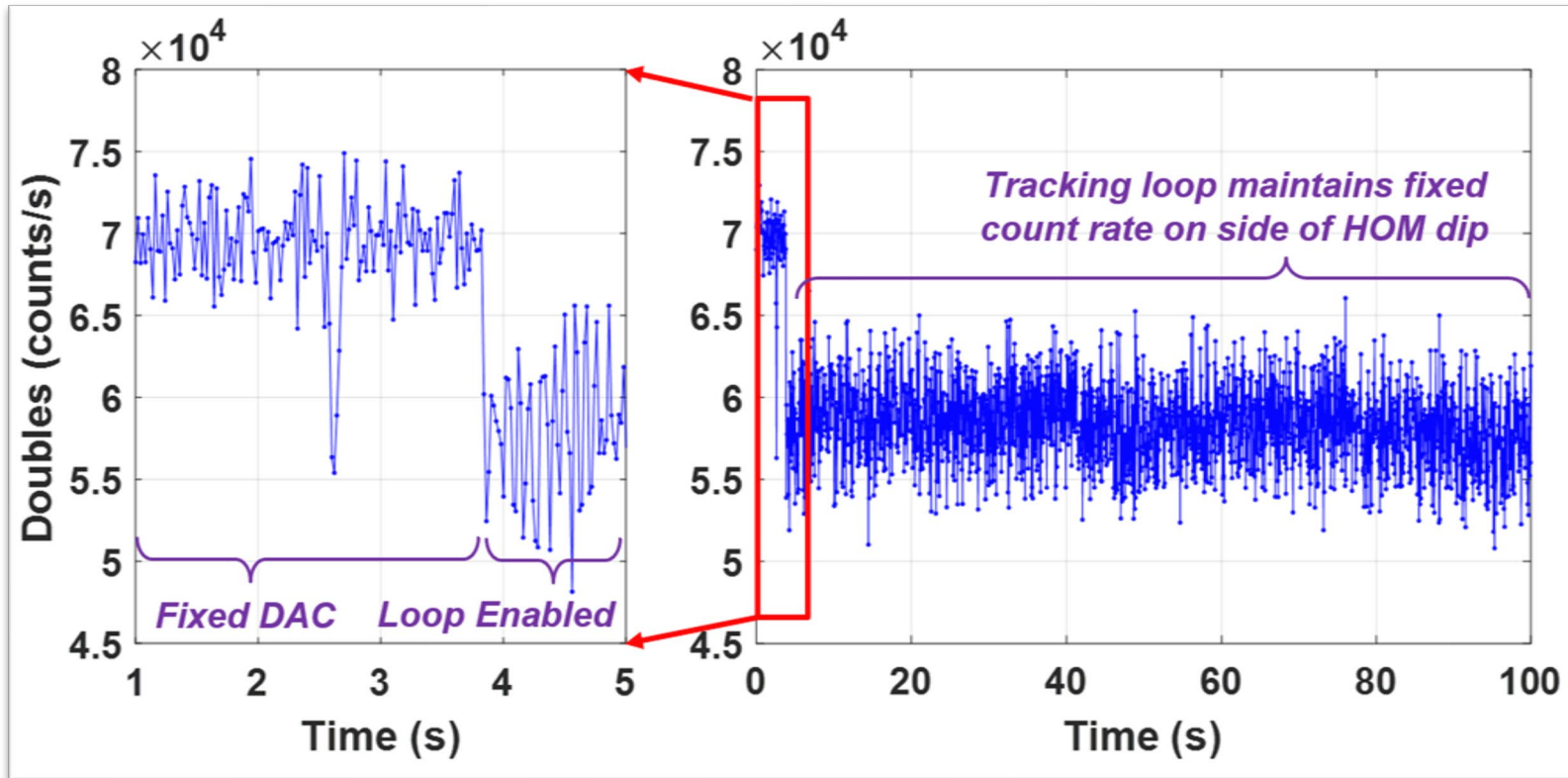
- ~13,000 cps/ps HOM slope
- For 100 Hz (10 ms) averaging time at operating point (75,000 cps), see 750 counts and ~27 count uncertainty
 - For 130 counts/(10 ms-ps) slope, this means $27/130 \sim 0.2$ ps timing uncertainty
- For 1 kHz (1 ms) averaging time at operating point (75,000 cps), see 75 counts and ~8 count uncertainty
 - For 13 counts/(1 ms-ps) slope, this means $8/13 \sim 0.6$ ps timing uncertainty
- This work is informing best values for design parameters (control bandwidth, count rates, allowable timing deviations)



Simple analysis supports basic control loop feasibility; requires laboratory validation



Demonstrating Synchronization

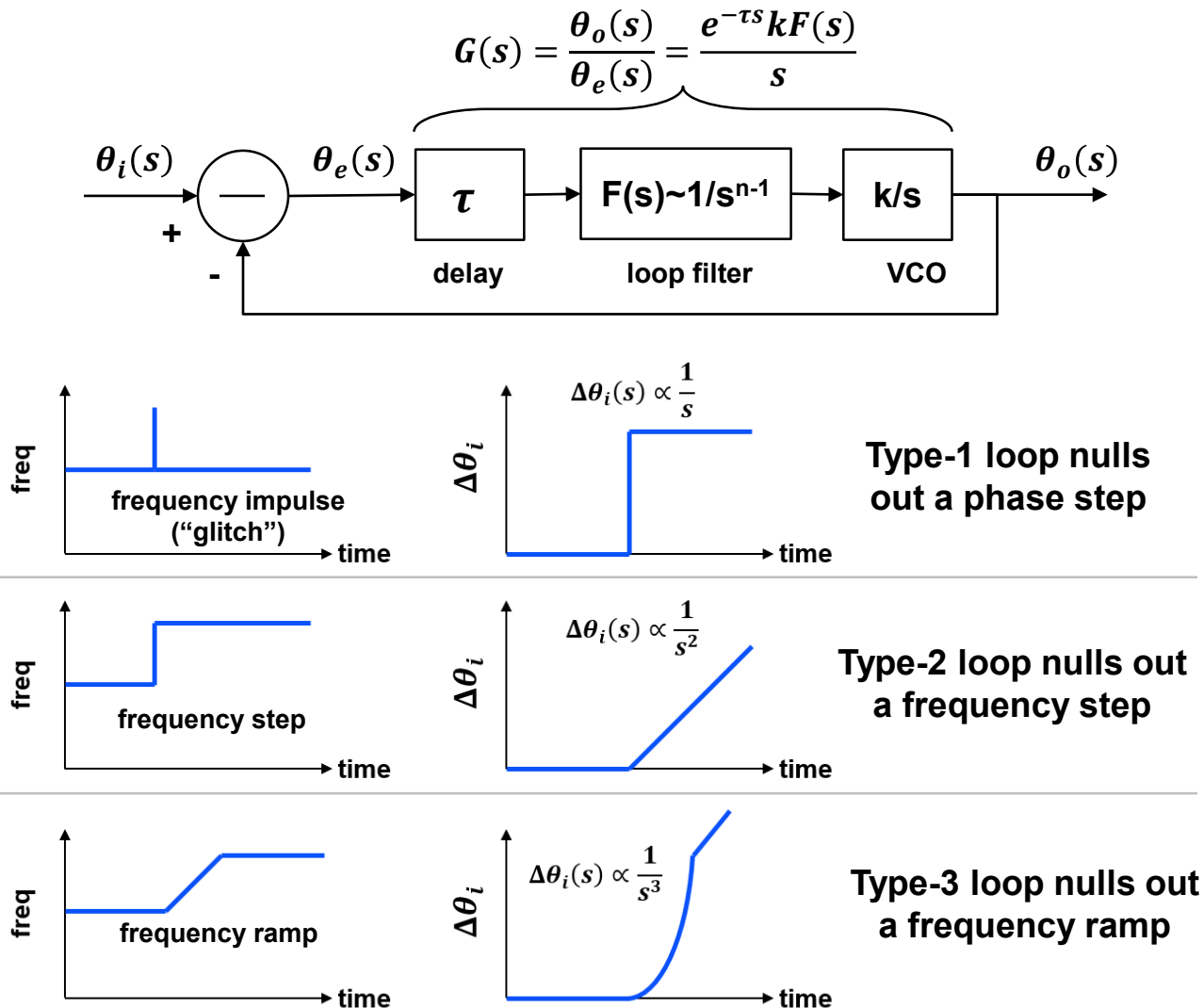


- Simple control algorithm used coincidence-count linear feedback to adjust DAC to phase align the tracking source to the primary source
 - Type 1 control loop
- Subsequent work done to extend loop capability
 - Type-2: null out a frequency offset
 - Type-3: null out a frequency rate of change

First demonstration of locking is important first step that validates many aspects of the method (e.g. SNR)



Phase-Locked Loop Overview

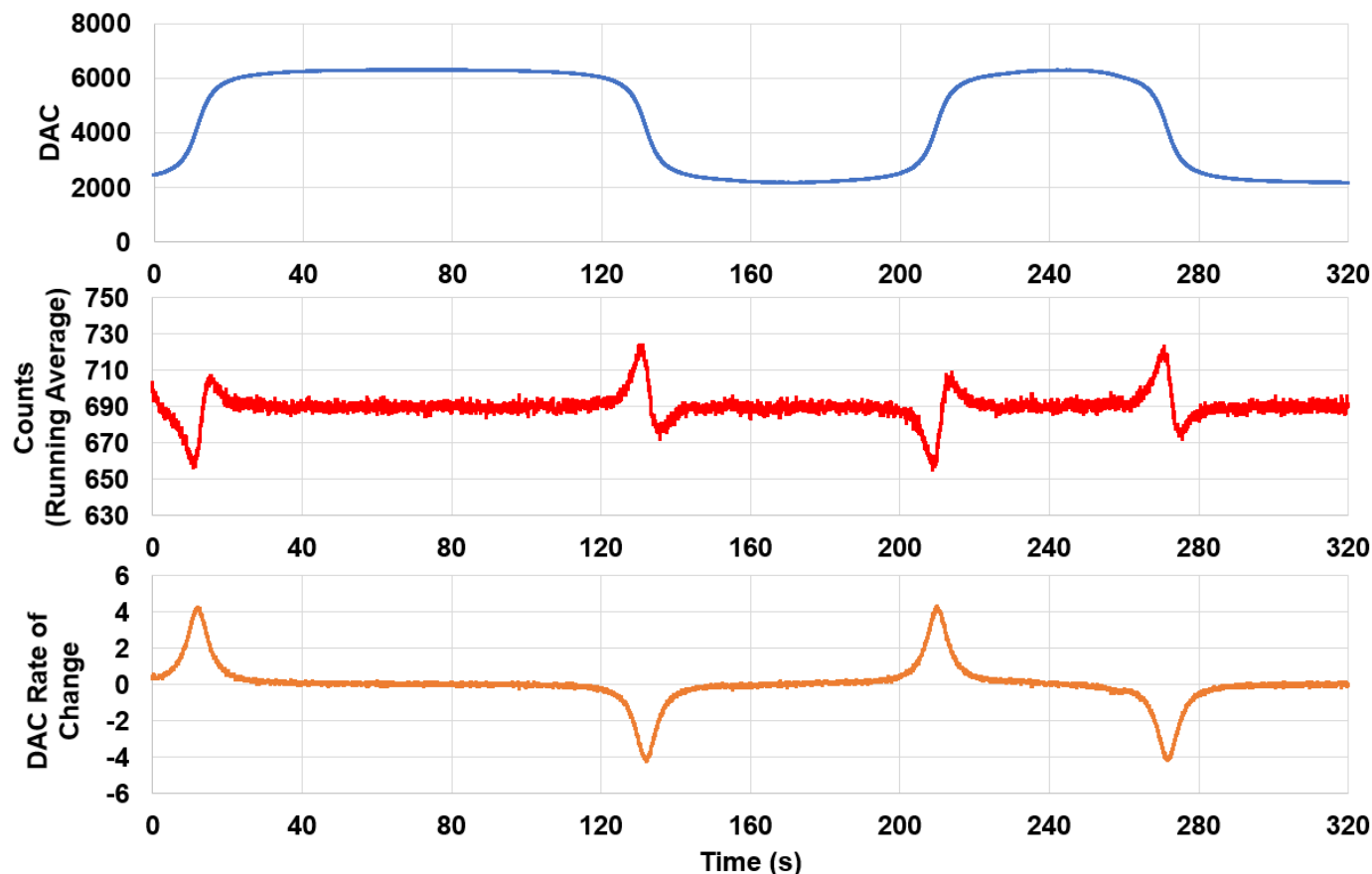


- PLL uses feedback to control a voltage controlled oscillator (VCO) frequency to null the residual error
- Analog loops analyzed by Laplace transform analysis of VCO tuning and feedback loop filter
 - $F(s) = \int_0^\infty f(t)e^{-st}dt$, with $s = \sigma + i\omega$
- PLL categorized by number of open loop transfer function poles at origin (n poles for type-n loop)
- Time delay τ determines maximum stable tracking loop bandwidth

Analysis indicates that type-3 loop is needed for dual uplink scenario



Type-3 Control Loop: Tracking over extended ranges and rate

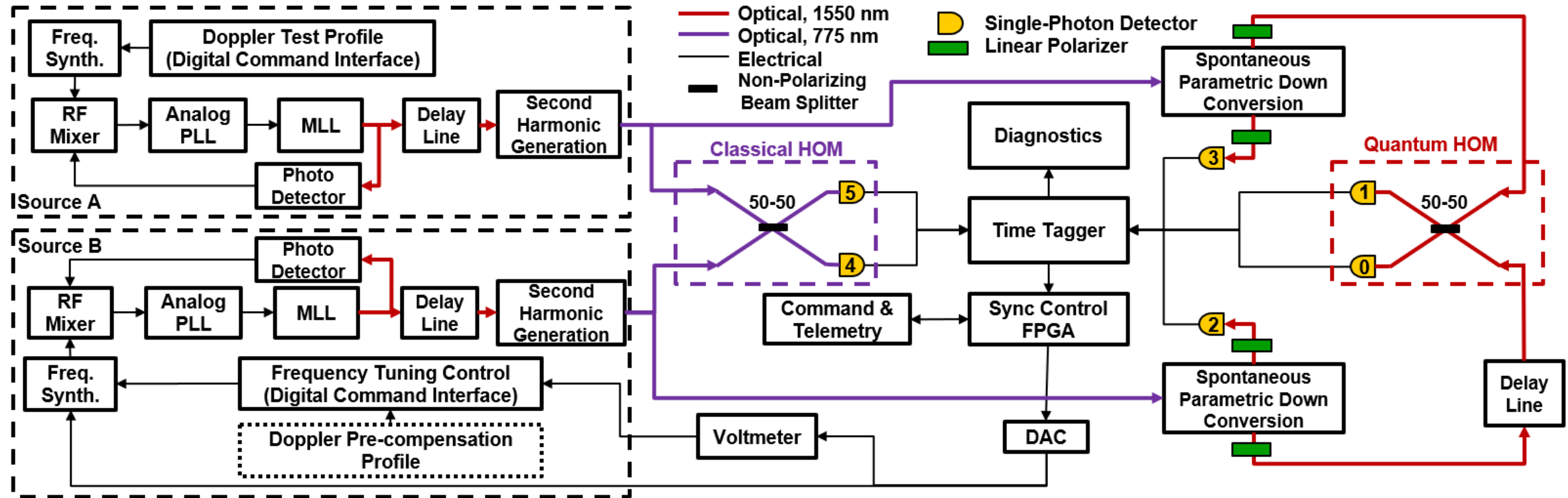


- Type-3 control loop tracks the frequency and frequency rate of change to maintain synchronization with a primary source whose frequency is ramping
- Control approach compatible with the space-to-ground delay
- Tested over modest ranges
 - ~16 ppb frequency range
 - ~1.5 ppb/s peak rate of change
 - ~0.3 ppb/s² curvature

Demonstrated type-3 loop operation appropriate for space-to-ground synchronization; working to extend range and rate capability



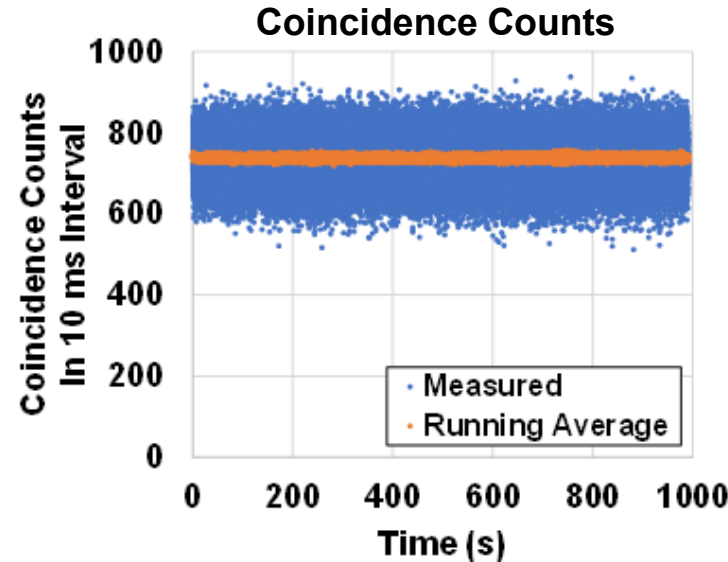
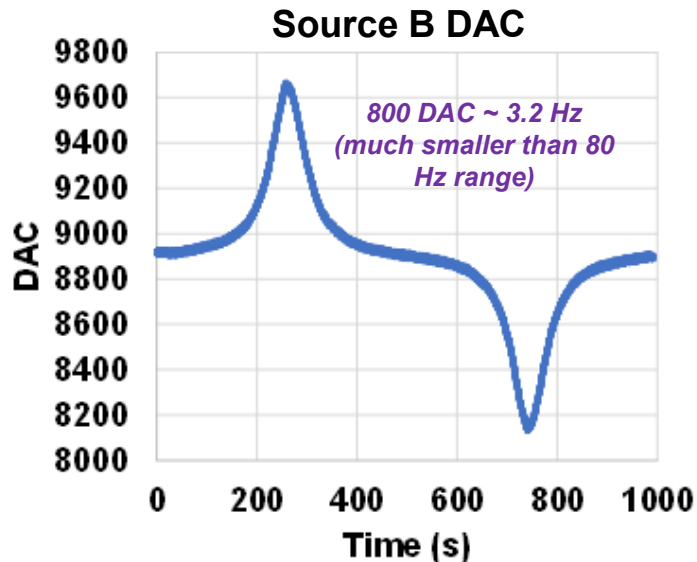
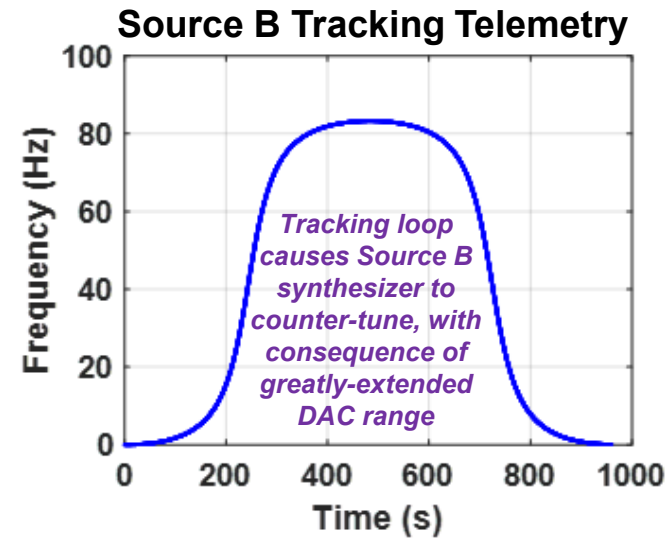
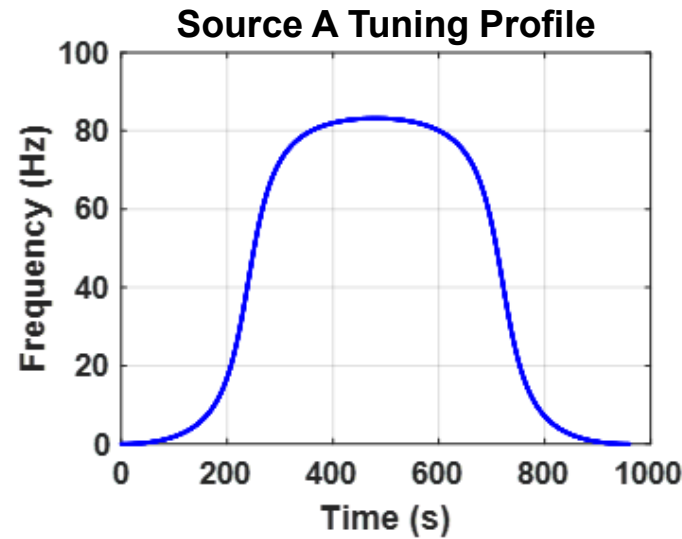
Testbed Configuration: DAC Relaxation for Extended Range Operation



Flexible testbed configured to relax DAC by observing rate of change and counter-tuning the Source-B synthesizer



DAC Relaxation Test Results



- Source A tuned over 80 Hz (80 ppb) range
- Source B synthesizer counter-tuned by tracking loop that observes DAC rate of change
- Required DAC tuning range much smaller (successful DAC relaxation)
- Coincidence count telemetry confirms good synchronization control

DAC relaxation technique allows operation over much larger Doppler ranges than otherwise possible



Summary

- **Robust synchronization is critical for enabling emerging high-rate long-distance quantum networking**
- **Dual-uplink and uplink-downlink architectures may enable near term entanglement distribution demonstrations using available lower-SWaP methods**
- **Presented a method for achieving precision synchronization for wideband situation**
- **Laboratory testbed provides thorough test capability**
- **Demonstrations have shown feasibility of key elements**
- **Working to extend techniques in range and rate to cover full range of space-to-ground motion**