Precision synchronization for free-space quantum networking

Neal W. Spellmeyer, Don M. Boroson, P. Benjamin Dixon, Matthew E. Grein, Nicholas D. Hardy, Catherine Lee, Ryan P. Murphy, Hemonth G. Rao, Marvin Scheinbart, Katia Shtyrkova, Mark L. Stevens, and Scott A. Hamilton

SPIE Quantum West

31 January 2023

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

This material is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

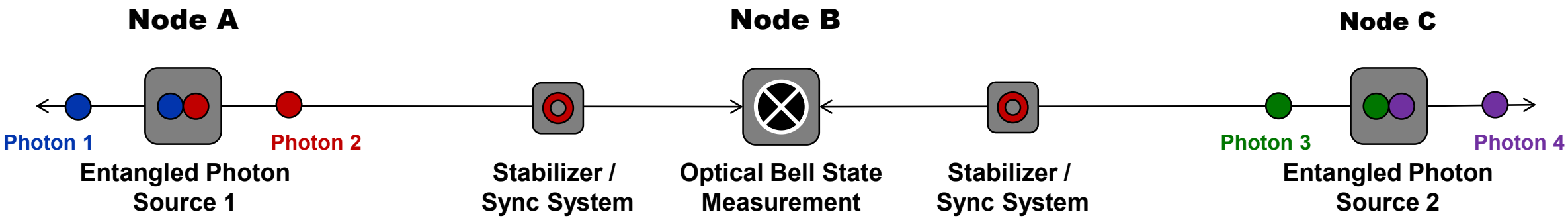


© 2023 Massachusetts Institute of Technology.

Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work.

Multi-Span Entanglement Distribution

Synchronization Considerations

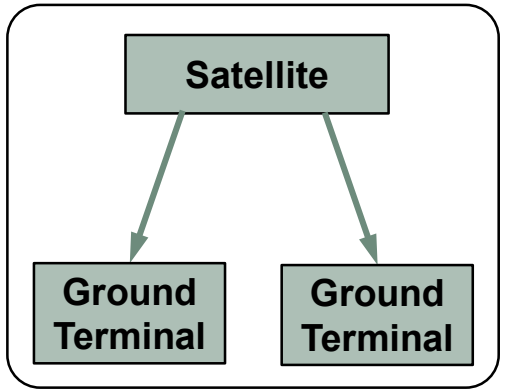


- Entangled Photon Sources produce pairs of entangled photons
- Photons 2 and 3 sent to Optical Bell State Measurement (OBSM)
- OBSM concatenates links, resulting in entanglement between Photons 1 and 4
- Channel stabilizers synchronize photon arrivals at OBSM (ps-class sync required)

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

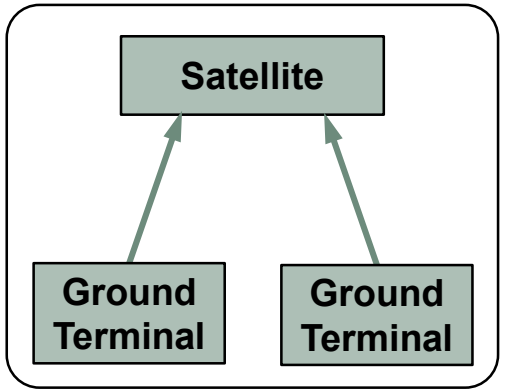
Quantum Network Link Topologies

Dual Downlink



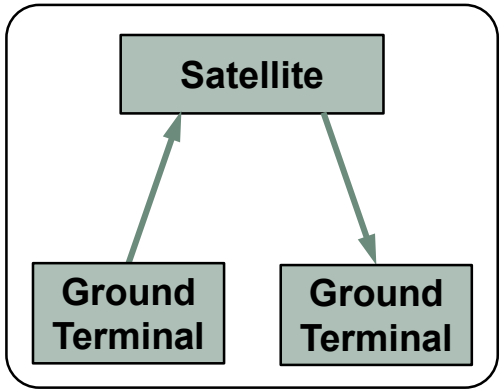
- Entanglement source on satellite
- Photonic qubits sent to different ground stations
- Space-ground synchronization is independent for each downlink

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

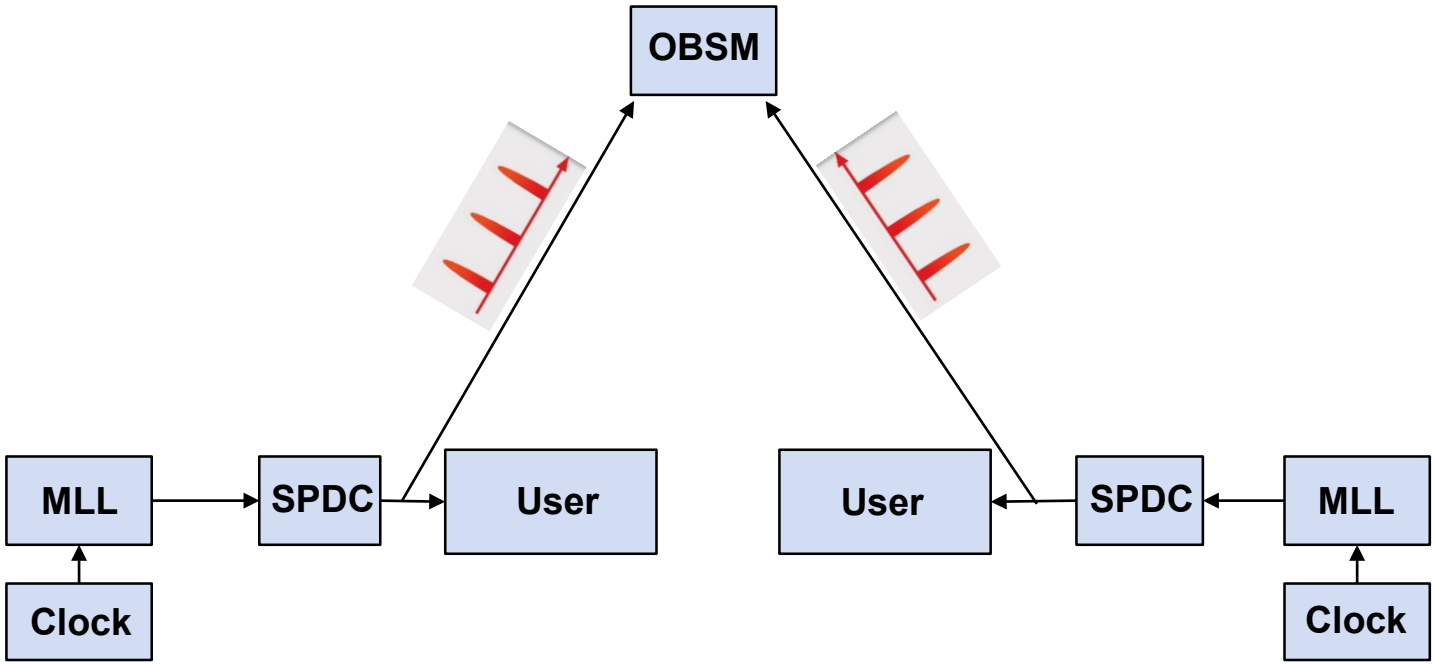
Uplink / Downlink



- 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**
  - ~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**

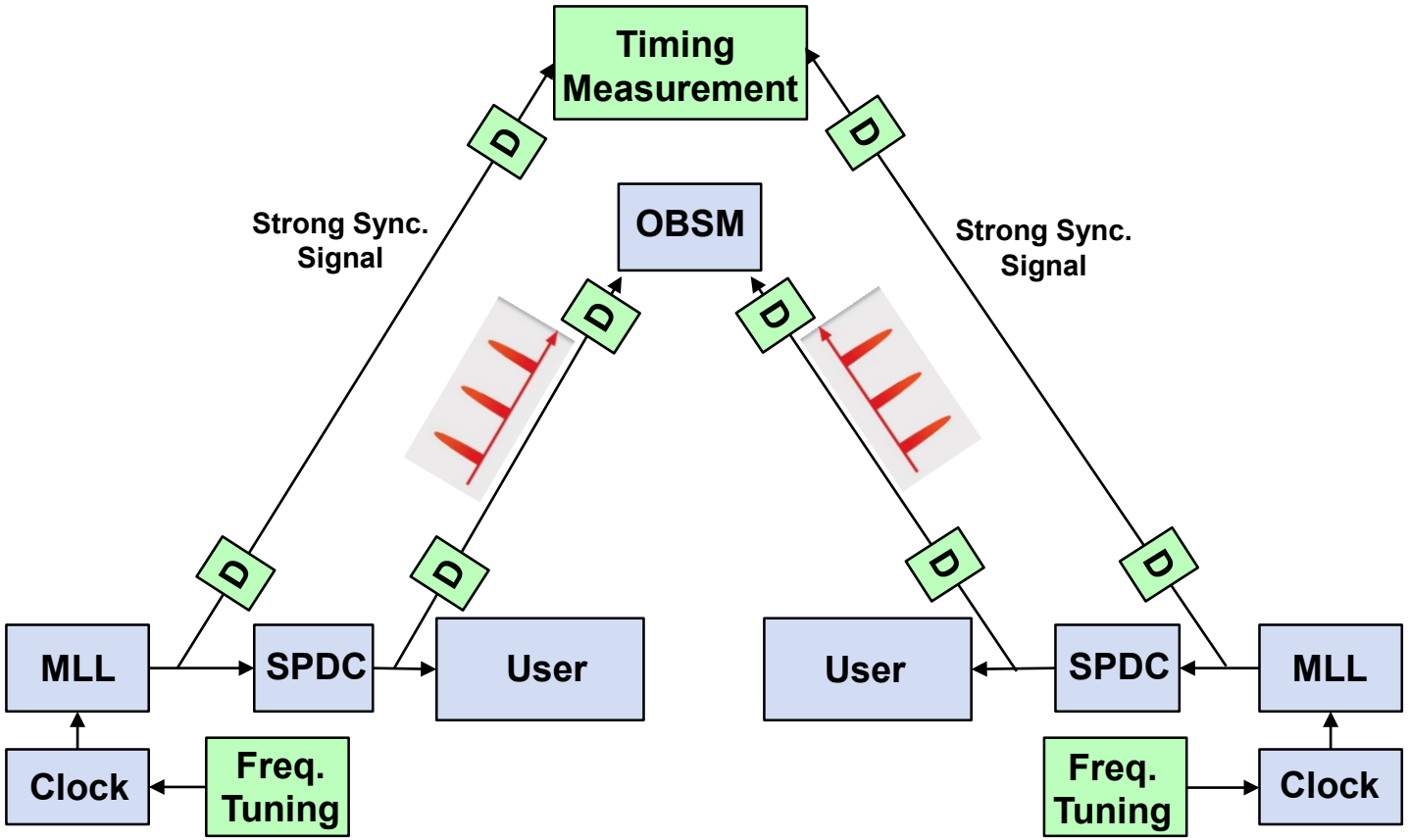
Architecture likely requires strong supplementary sync signals with a hierarchy of time alignment mechanisms

MLL=Mode Locked Laser

OBSM=Optical Bell State Measurement

SPDC=Spontaneous Parametric Down Conversion

Uplink-Uplink Synchronization Architecture



- 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

MLL=Mode Locked Laser
D=Path Length Delay

OBSM=Optical Bell State Measurement

SPDC=Spontaneous Parametric Down Conversion

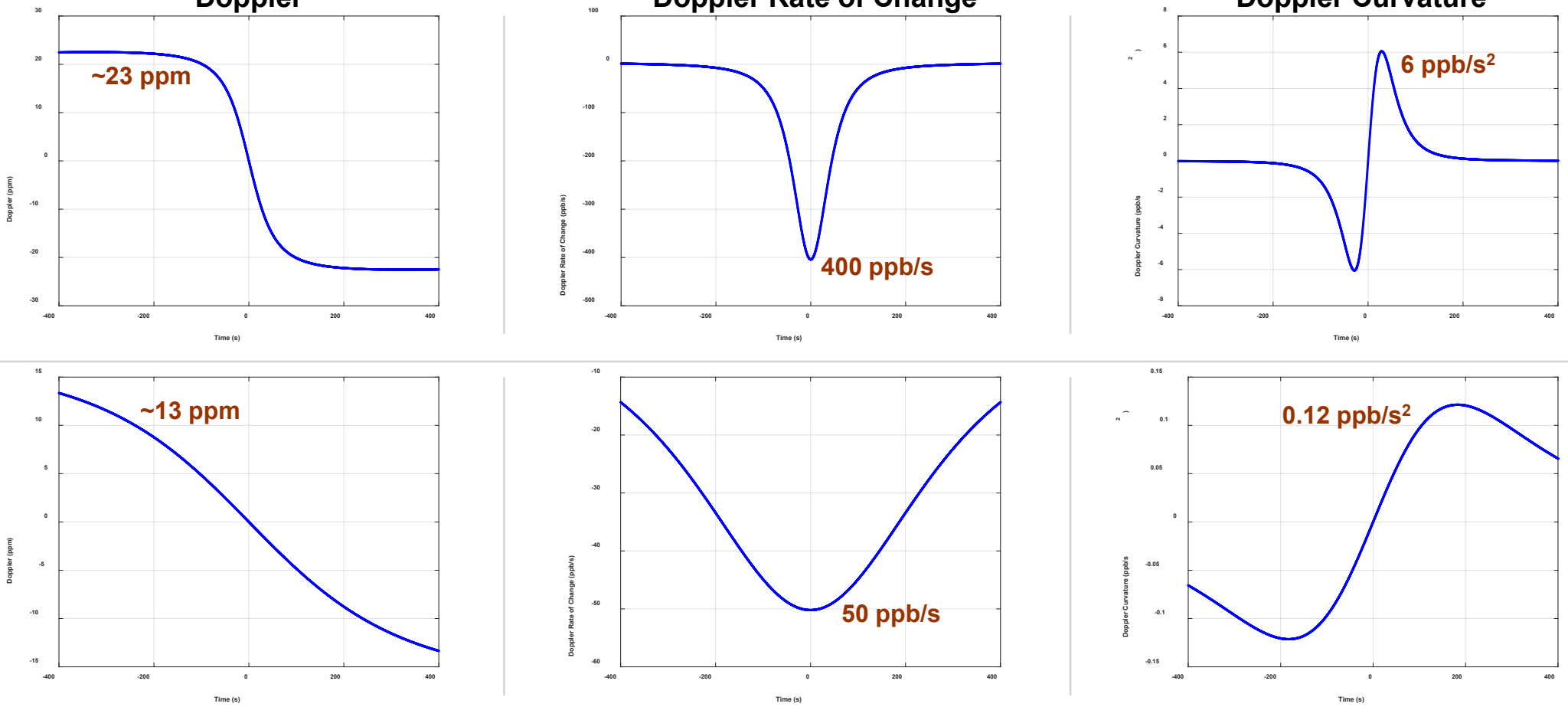
Orbital Motion

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

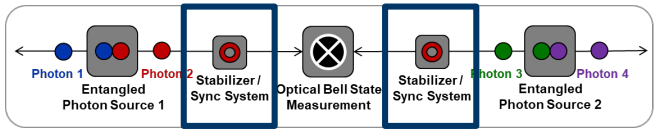


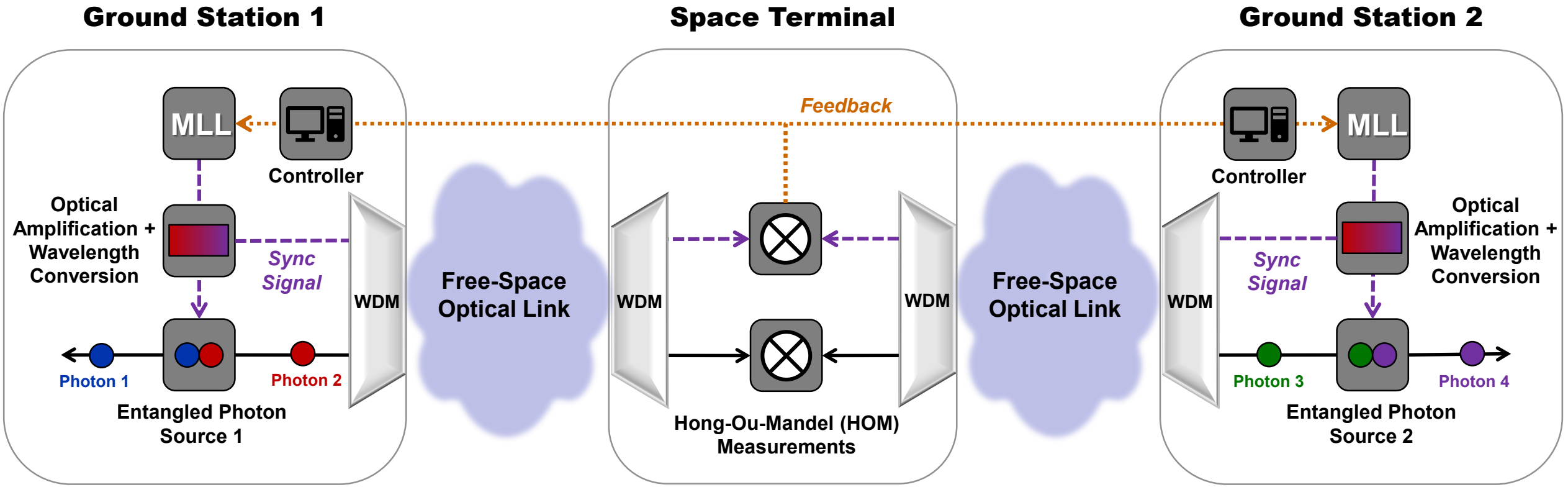
- *Doppler sets control loop throw requirement*
- *Doppler rate of change sets loop bandwidth requirement*

Link architecture puts fundamental constraints on synchronization

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Dual Uplink Synchronization Test Bed Architecture





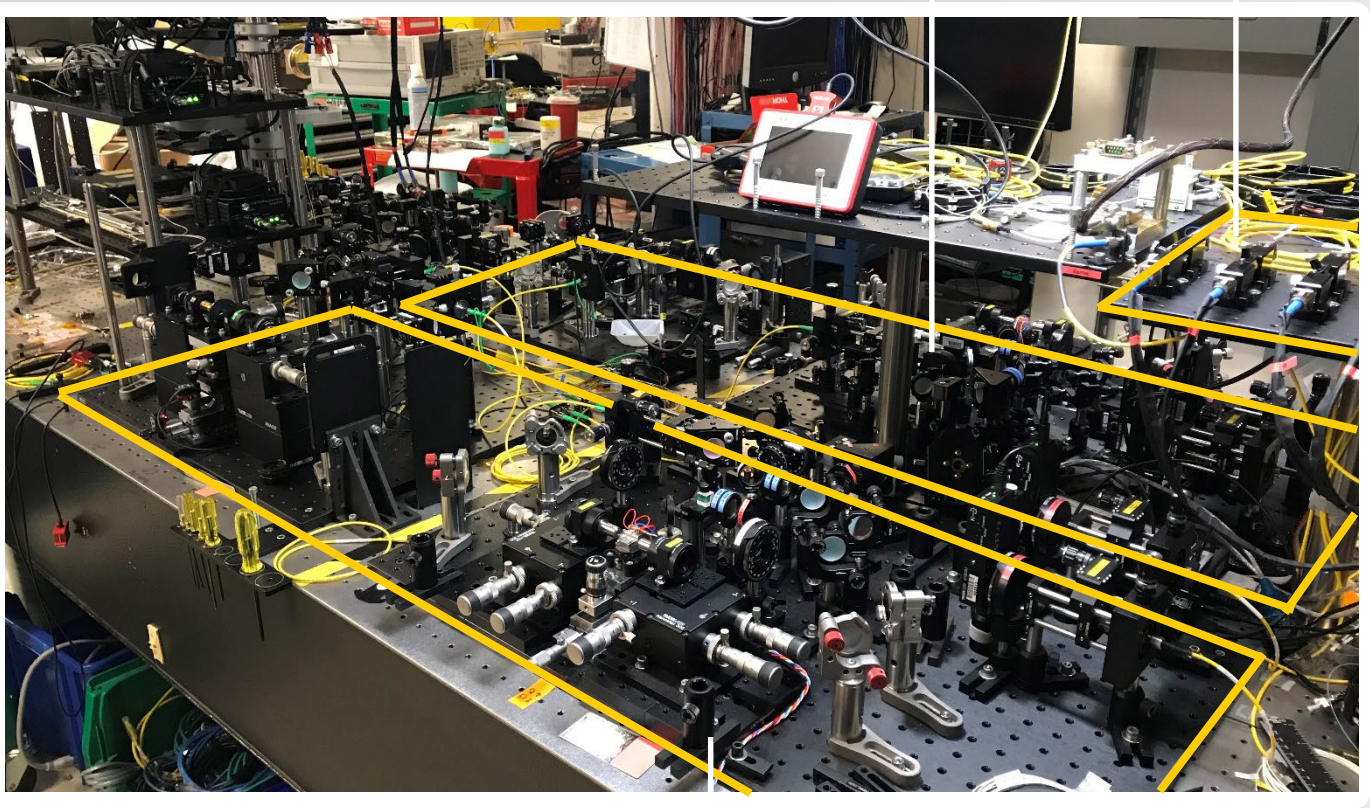
- Provide strong synchronization signal on each uplink for high-SNR HOM measurement at space terminal
- Feedback to ground stations to maintain photon timing alignment

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Space-Ground Entanglement Distribution Test Bed

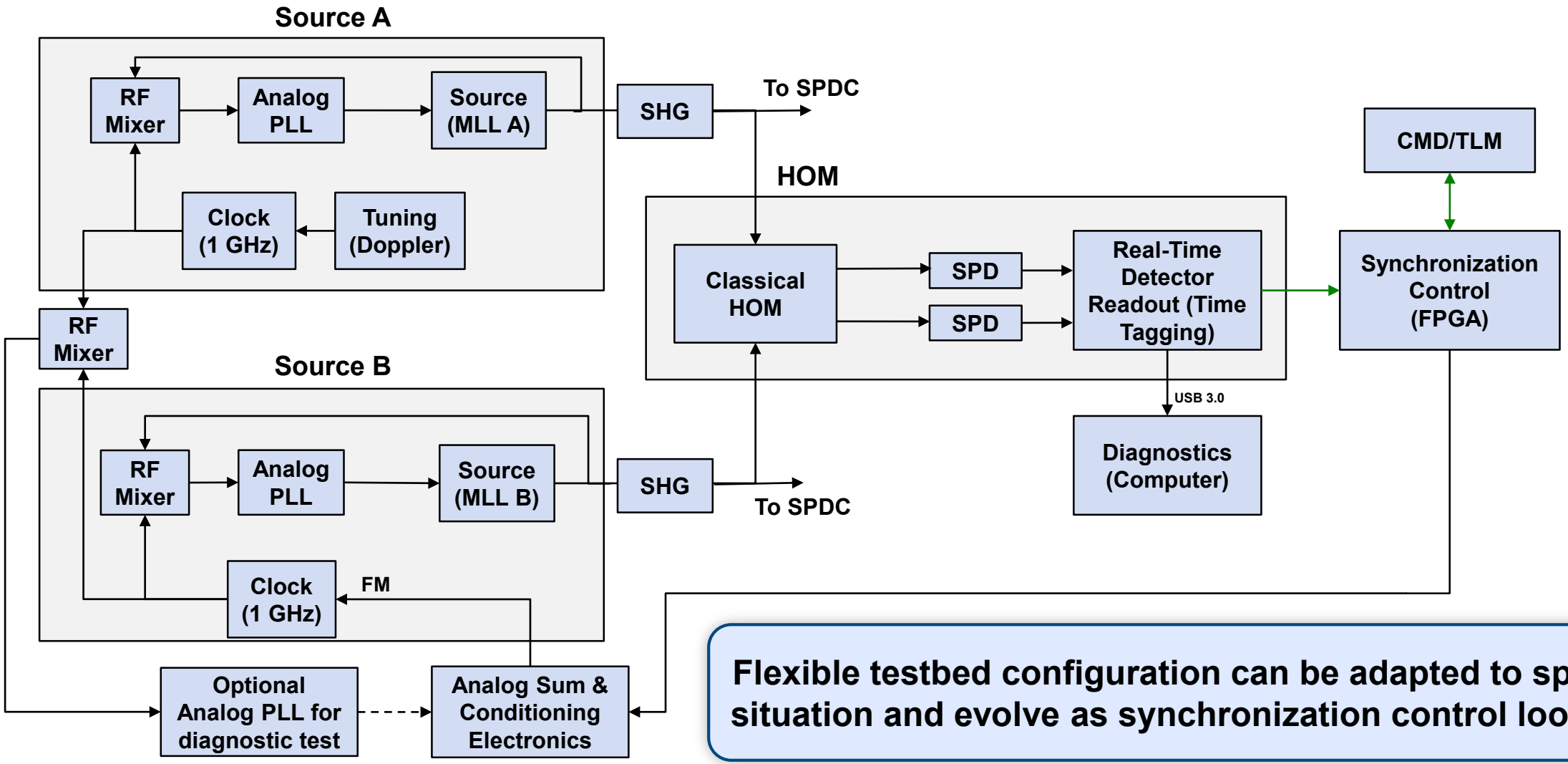
Entangled Photon Source Pump Subsystems
(off photo)





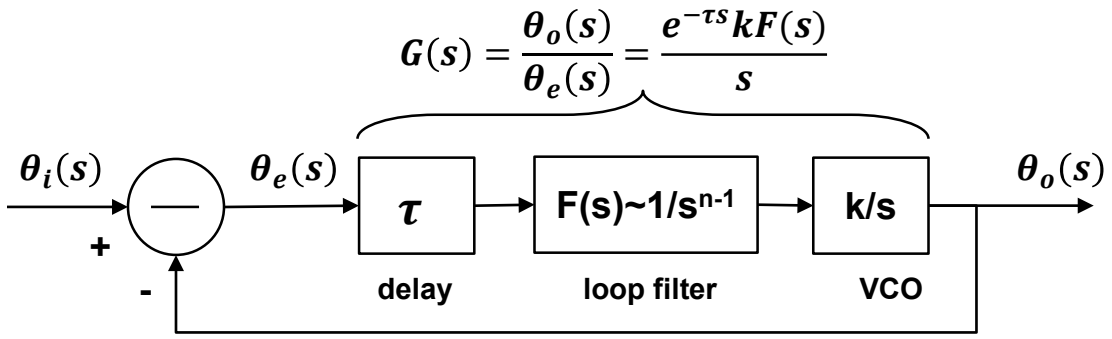
- Two Entangled Photon Sources
- Optical Bell State Measurement (OBSM) with fiber connections to single-photon detectors
- Fiber connections to free-space link across Hanscom AFB
- Rolling integration test approach
  - Table-top testing
  - Free-space link testing

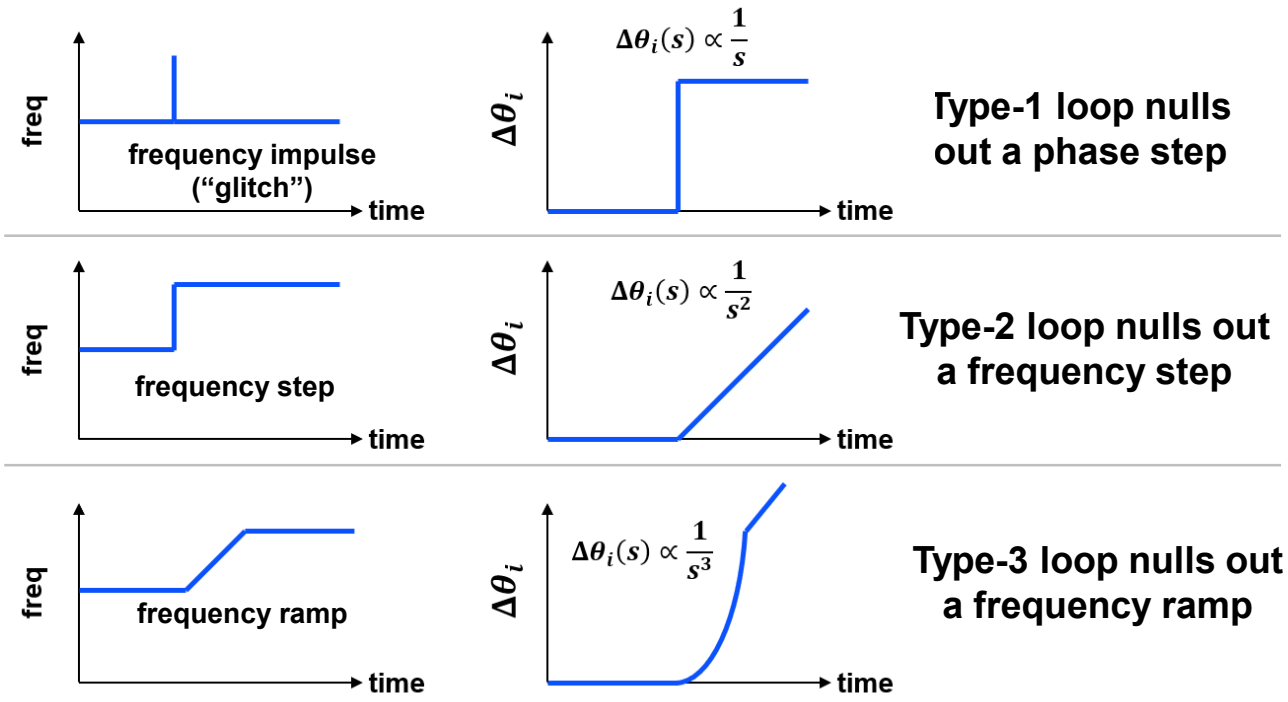
Testbed Configuration



Flexible testbed configuration can be adapted to specific test situation and evolve as synchronization control loop matures

Phase-Locked Loop Overview





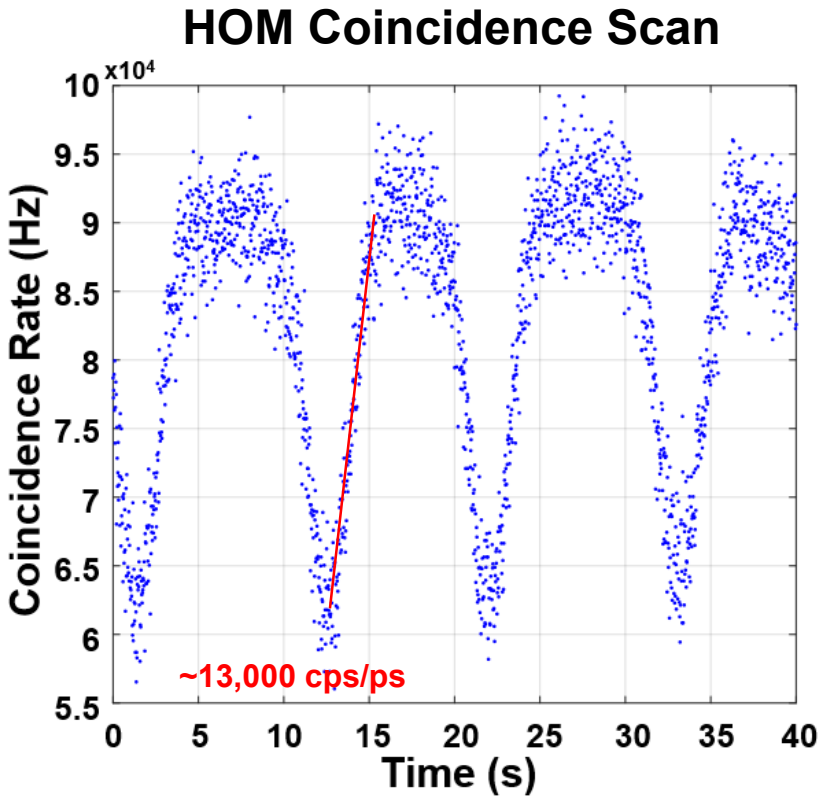
- PLL uses feedback to control a voltage controlled oscillator (VCO) frequency to null the residual error
- Analog loops analyzed by Laplace transform analysis of VCO tuning and feedback loop filter
  - $F(s) = \int_0^\infty f(t)e^{-st}dt$, with $s = \sigma + i\omega$
- PLL categorized by number of open 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

- F. Gardner, Phaselock Techniques, Wiley, 2005
- S. Golestan, et al., IEEE Trans. Power Electronics, vol. 28, no. 11, Nov. 2013

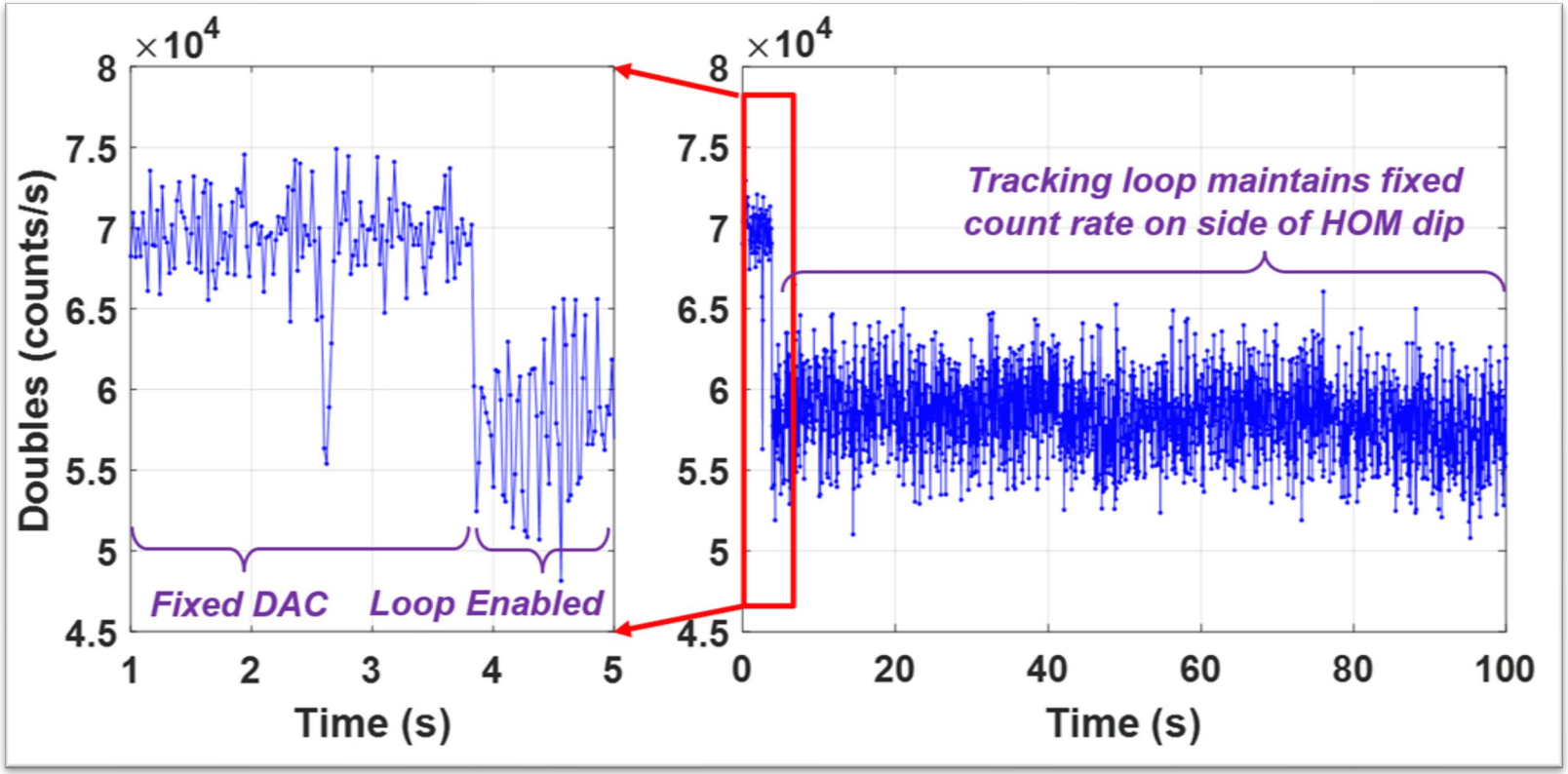
Control Loop Timing Discriminant

- ~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 27/130~0.2 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 8/13~0.6 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

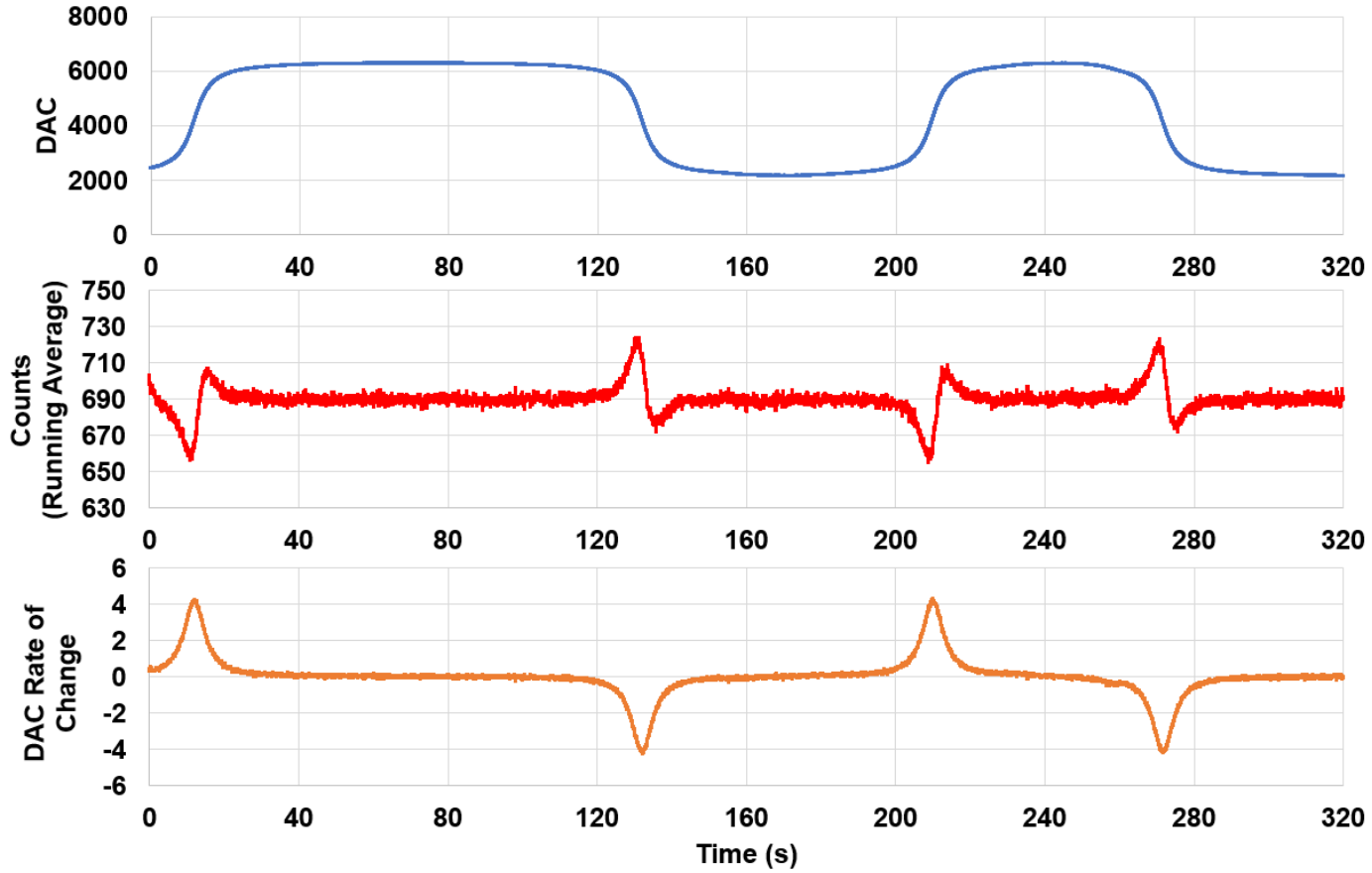
Demonstrating Synchronization



- 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)

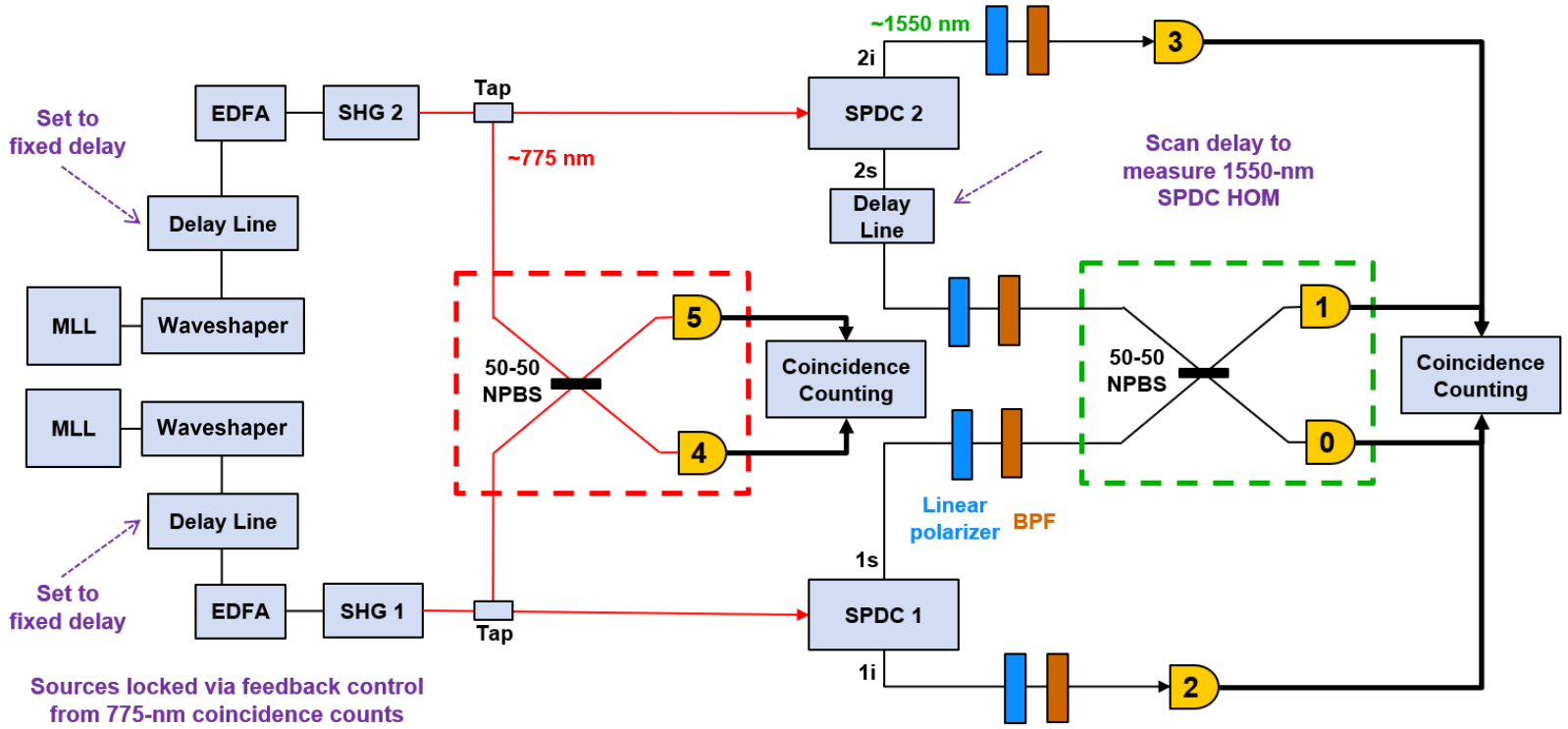
Type-3 Control Loop: Tracking over extended ranges and rate

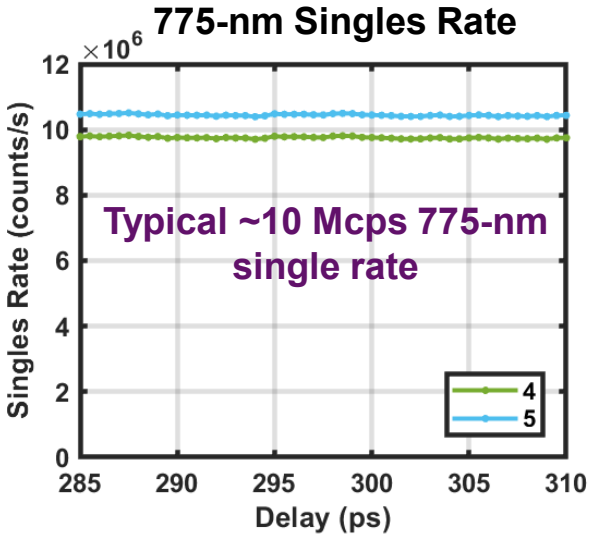


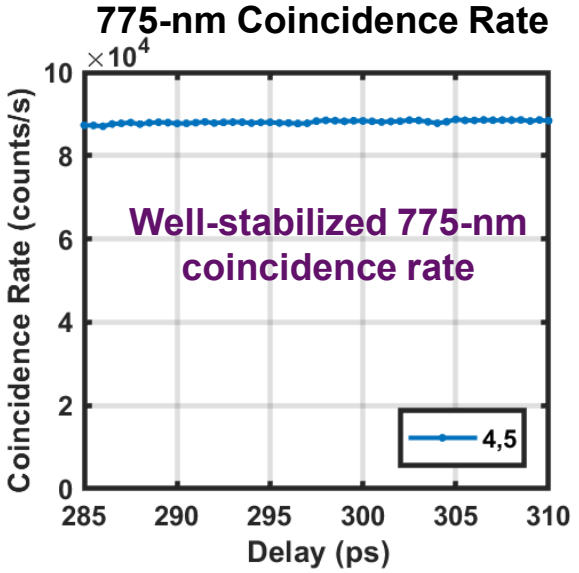
- Type-3 control loop tracks the frequency and frequency rate of change to maintain synchronization with a primary source whose frequency is ramping
- Control approach compatible with the space-to-ground delay
- Testing over modest ranges
  - ~16 ppb frequency range
  - ~1.5 ppb/s peak rate of change
  - ~0.3 ppb/s^2 curvature

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

Quantum HOM Scan Using Classical Synchronization (1/2)



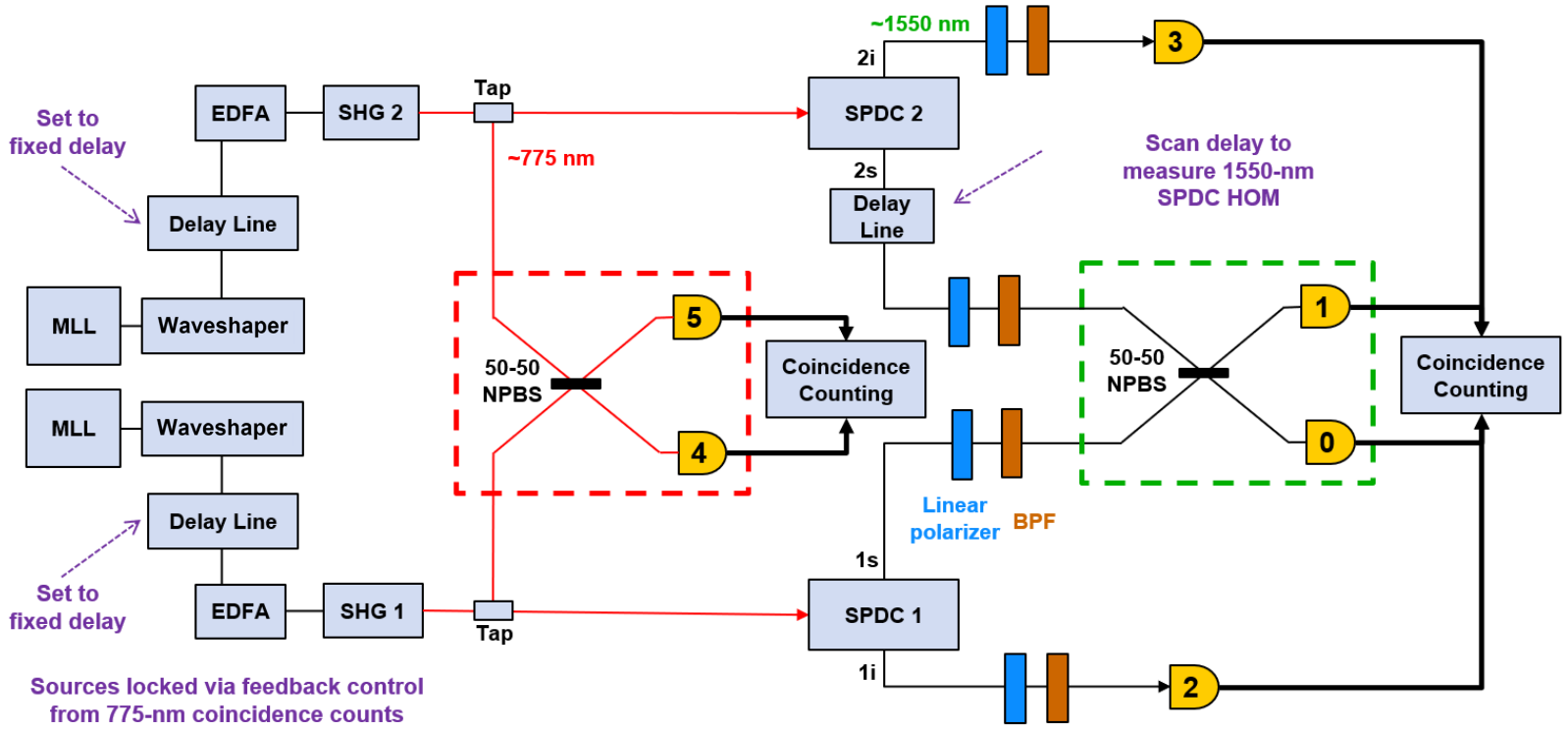


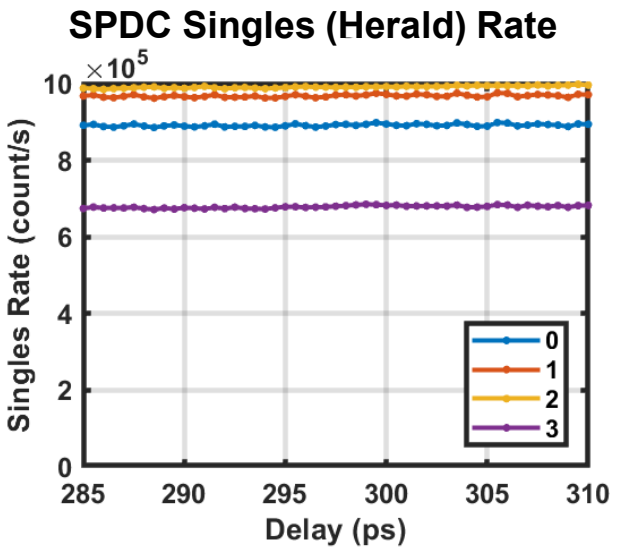


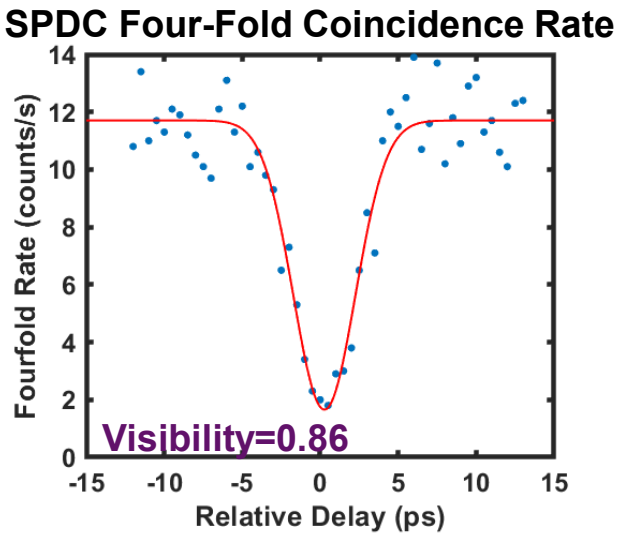
- Use classical 775-nm HOM synchronization to control sources
- Can tune optical delay line to measure SPDC quantum HOM profile

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Quantum HOM Scan Using Classical Synchronization (2/2)







- Clear SPDC quantum HOM dip shows good timing control
- Long (10 s) averaging possible given higher flux timing signal

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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