Quantum Satellite Synchronization

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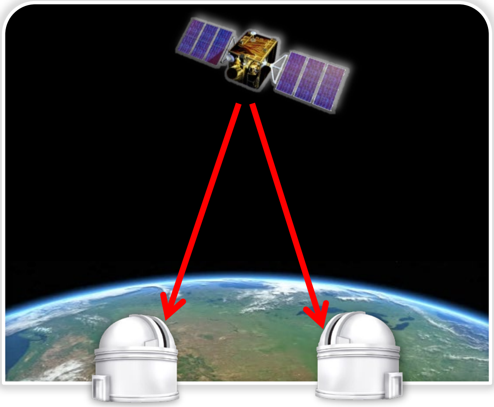
Outline

- Introduction
- Entanglement distribution & synchronization
- Synchronization control architecture & analysis
- Testbed implementation
- Laboratory results
- Next steps, Summary, and Acknowledgements

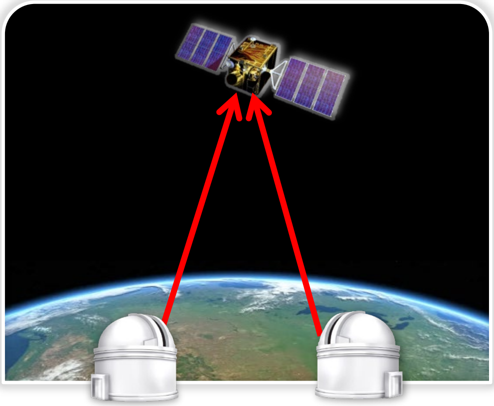
Link Topologies

Dual Downlink



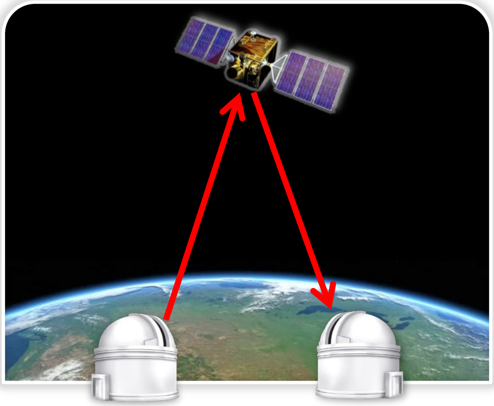
- Entanglement source on satellite
- Photonic qubits (signal and idler) downlinked to different ground stations
- Pump forwarding space-ground synchronization for each downlink

Dual Uplink



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

Uplink / Downlink



- Entanglement source at one ground station
- Signal sent to satellite, idler retained at ground station
- Satellite is a passive relay to second ground station
- No space-ground synchronization required

MIT-LL is conducting risk-reduction to enable dual-uplink architecture: Adaptive optics for efficient uplinks and uplink synchronisation

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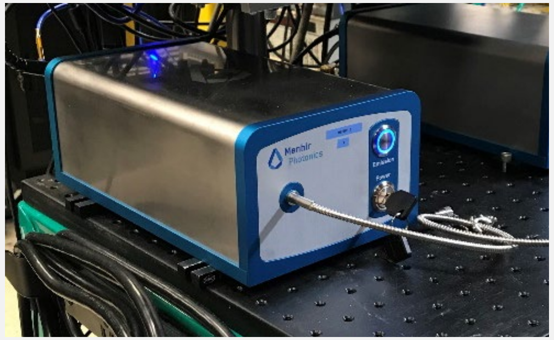
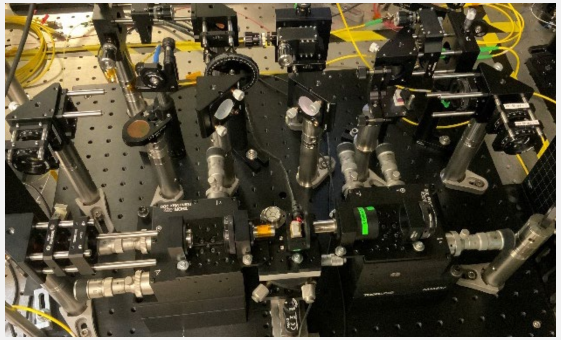
Entangled Photon Sources

Pump Mode-Locked Laser



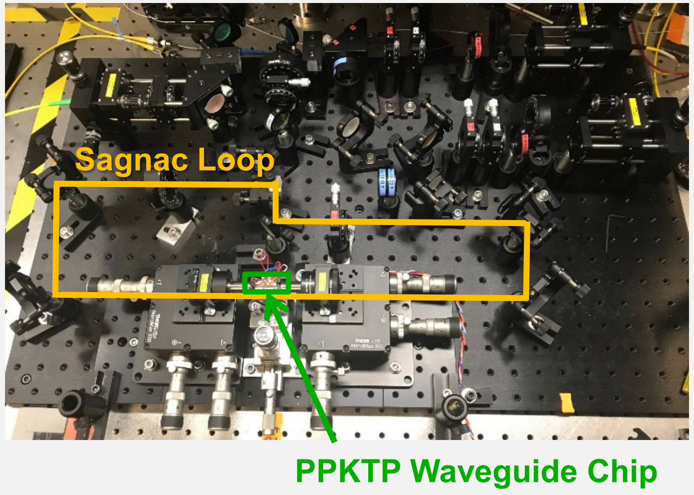
1550 nm center wavelength
1 GHz repetition rate

Pump Wavelength Converter



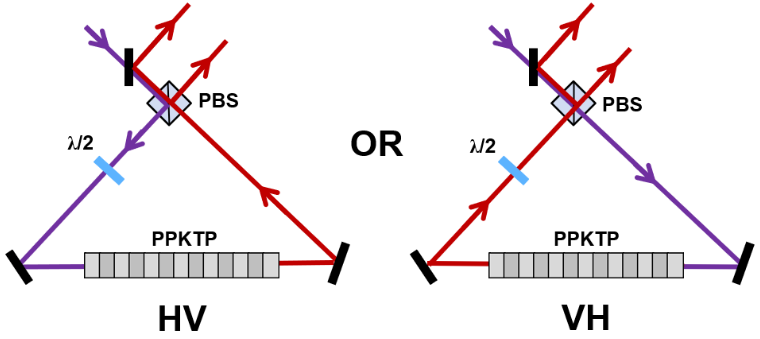
Second harmonic generation (SHG)
1550 → 775 nm

Entanglement Setup (SPDC)



- Entanglement sources generate pairs at high rate with high fidelity using tunable mode-locked laser sources well suited to needs of TDM architecture
- Short pulse duration presents challenging synchronization requirements

- 1 GHz system clock rate
- ~1 ps pulse duration
- 0.05 average pairs / pulse
- 0.963 entangled state fidelity
  - Measure of “closeness” of two quantum states



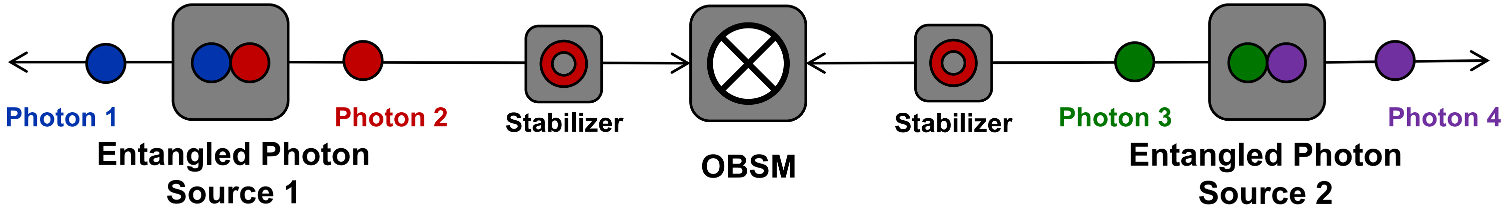
$$|\Psi^-\rangle \propto |HV\rangle - |VH\rangle$$

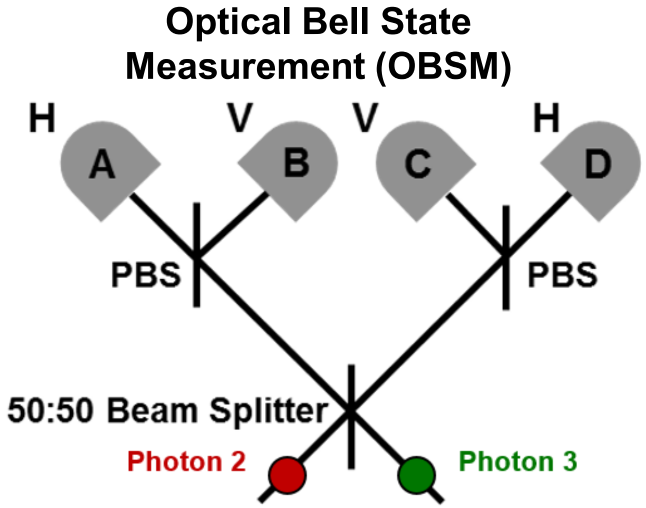
SPDC: Spontaneous Parametric Down Conversion
PPTKP: Periodically Poled $KTiPO_4$

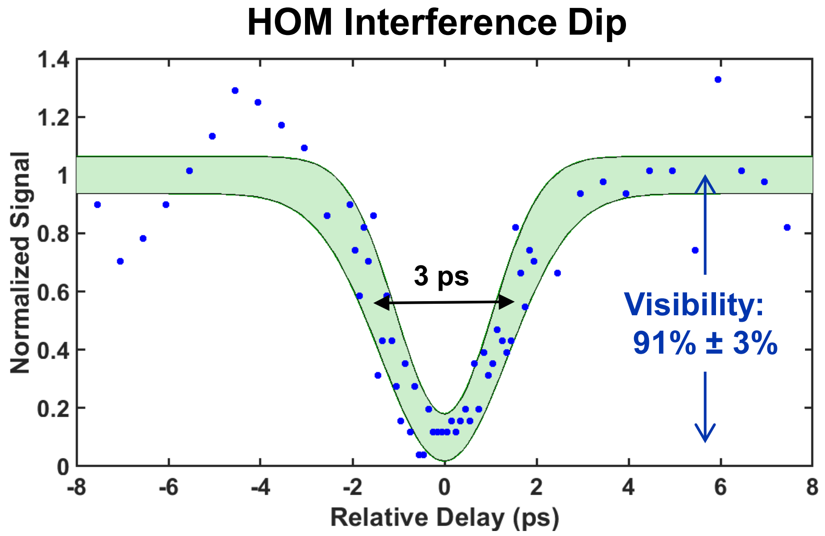
H: Horizontal Polarization
V: Vertical Polarization
PBS: Polarizing Beam Splitter

Entanglement Swap and Temporal Overlap at OBSM

- **OBSM swaps entanglement to remote photons 1 and 4**
- **Photons 2 and 3 need to temporally overlap at OBSM**
  - **Overlap precision set by photon temporal duration**
- **Hong-Ou-Mandel (HOM) interference 'dip' exhibits photon temporal overlap**
  - **Places upper bound on entanglement swap fidelity**
  - **Characterizes photon synchronization**







High-fidelity, high-rate entanglement swap with SPDC sources demands 1-ps-class synchronization

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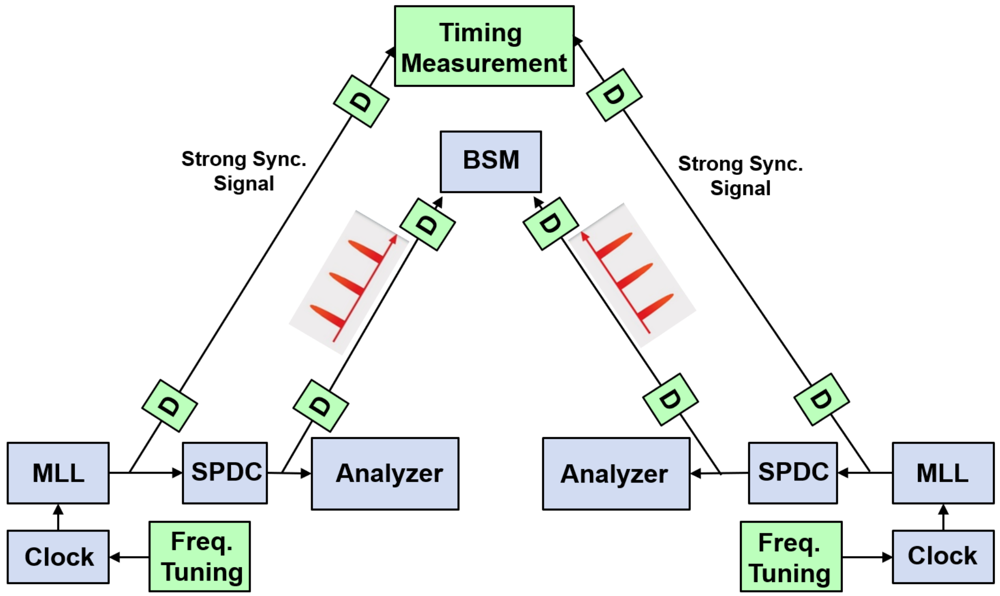
Synchronization Architecture and Analysis



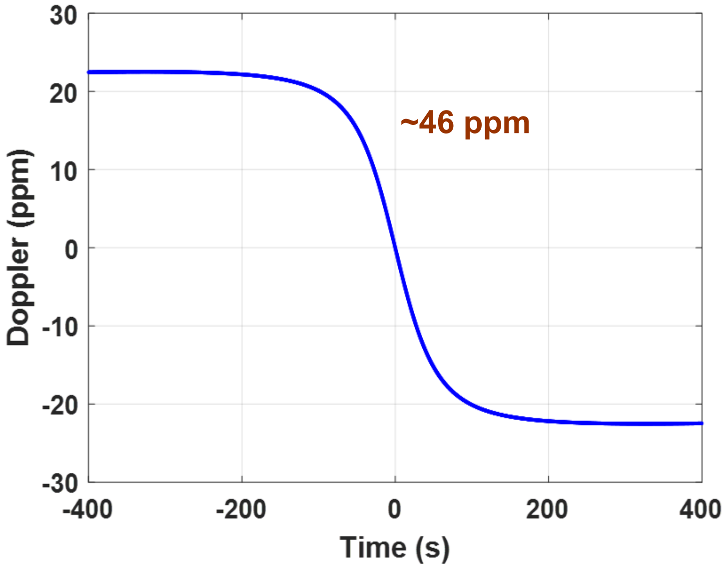
- **Proposed synchronization control technique:**
  - Relative timing measurement at space terminal via HOM dip (precise and doesn't add hardware)
  - Provide additional 'classical' timing signal
  - Feed HOM coincidence count information to mode-locked-laser (MLL) frequency tuning control loop on ground
- **Analysis considerations**
  - Orbital motion (Doppler, Doppler rate-of-change, round-trip time)
  - Signal-to-noise ratio and tracking loop bandwidth
  - Doppler pre-compensation
  - Atmospheric effects
  - Source and spacecraft jitter

High-level analysis examined performance drivers to determine viability of proposed technique

SPIE Quantum West, paper 12446, March 2023
Optica Quantum 2.0, paper QW3A.5, June 2023

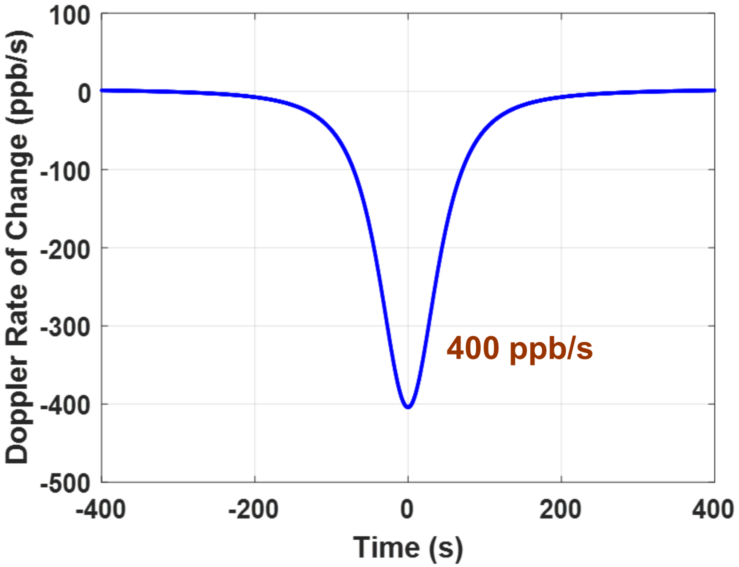
Orbital Motion

Doppler



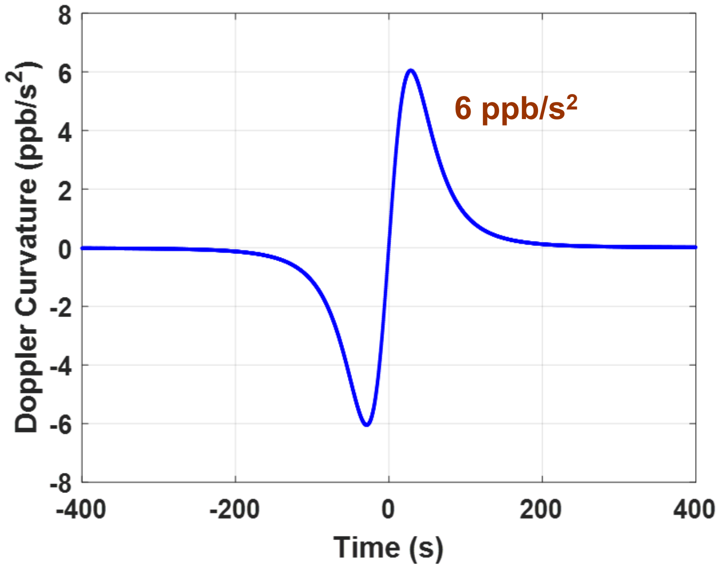
- *Doppler sets control loop throw requirement*

Doppler Rate of Change



- *Doppler rate of change sets loop bandwidth requirement*

Doppler Curvature



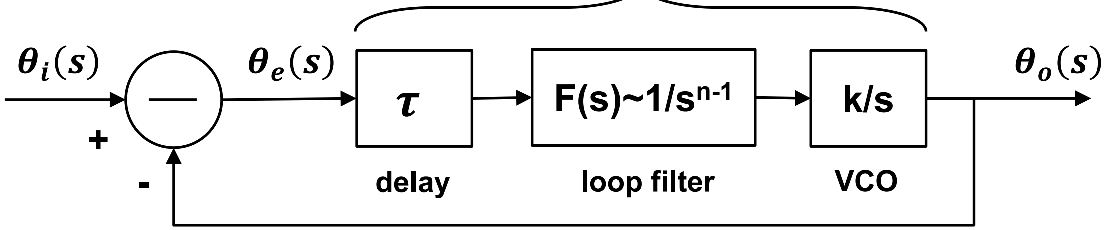
- *Curvature sets control loop residual error*

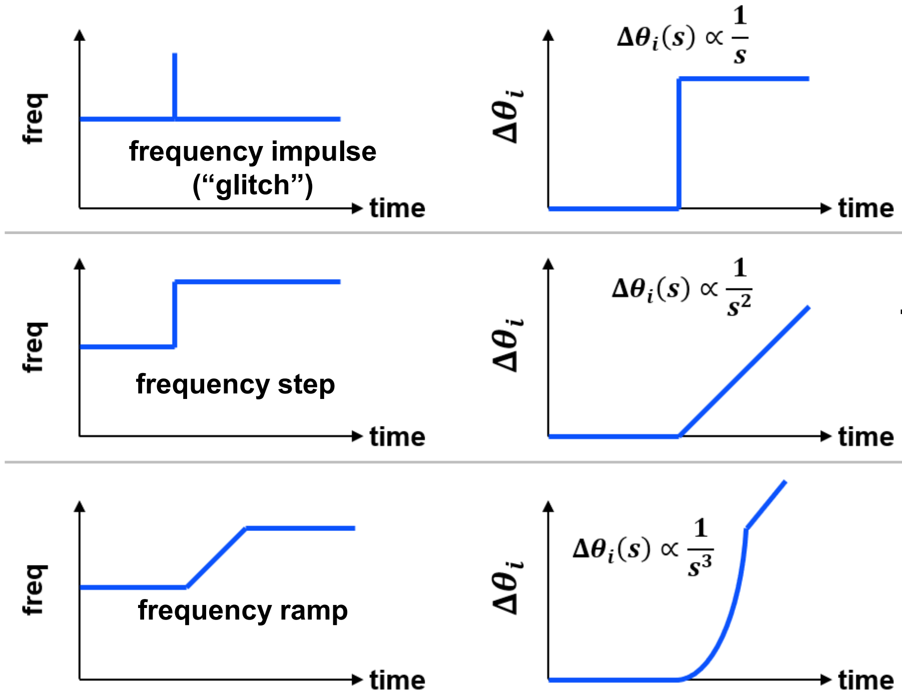
400 km Low Earth Orbit 7.7 km/s Orbital Speed ~1.3-9 ms Propagation Delay

Link architecture & satellite motion puts fundamental constraints on synchronization methods

Phase-Locked Loop (PLL) Overview

$$G(s) = \frac{\theta_o(s)}{\theta_e(s)} = \frac{e^{-\tau s} k F(s)}{s}$$





Type-1 loop nulls out a phase step

Type-2 loop nulls out a frequency step

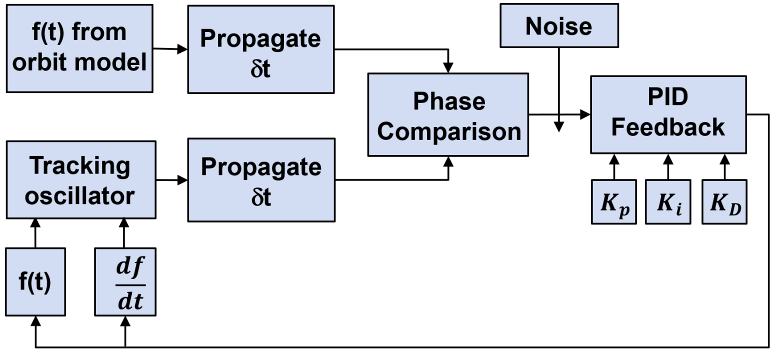
Type-3 loop nulls out a frequency ramp

- **PLL uses feedback to control a voltage controlled oscillator (VCO) frequency to null the residual error**
- **Design trades and challenges:**
  - Loop bandwidth: must be slower than inverse round trip time
  - Long time delays can create loop instabilities
  - Signal to noise ratio

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

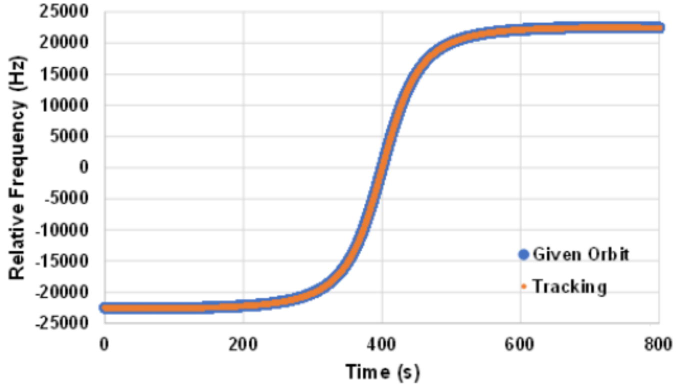
F. Gardner, Phaselock Techniques, Wiley, 2005
S. Golestan, et al., IEEE Trans. Power Elec., vol. 28, Nov. 2013

Control Loop Modeling Results

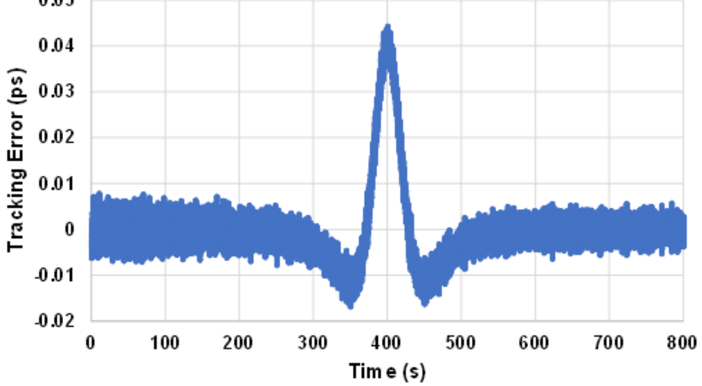


- **Implemented a simple discrete-time control loop model**
  - **Included propagation time delay that can introduce instability**
  - **Modelled orbital motion**
- **Modelled photon-counting HOM-based synchronization tracking discriminant**

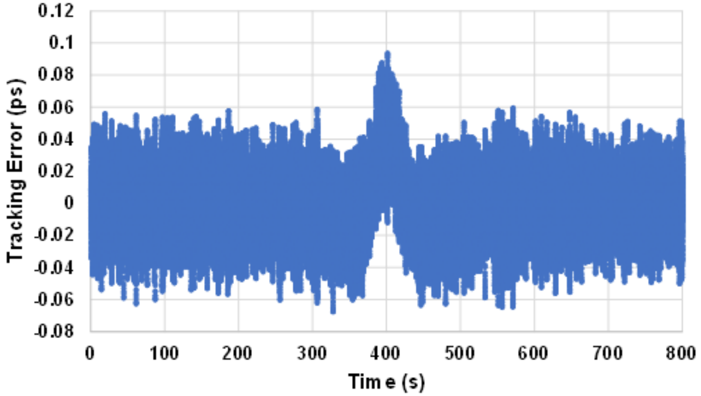
Orbital Frequency Profile



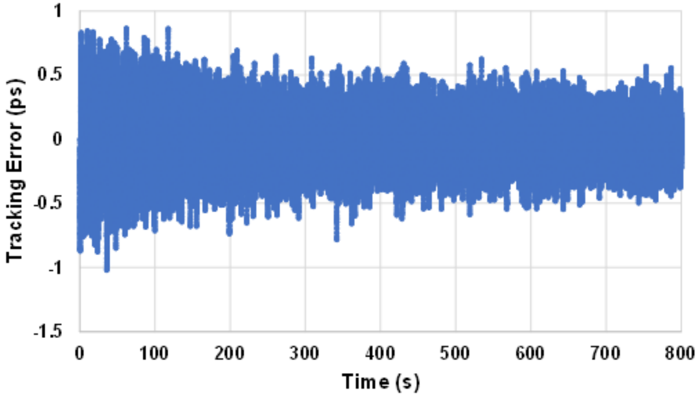
10^9 coincidences/s



10^7 coincidences/s



10^5 coincidences/s



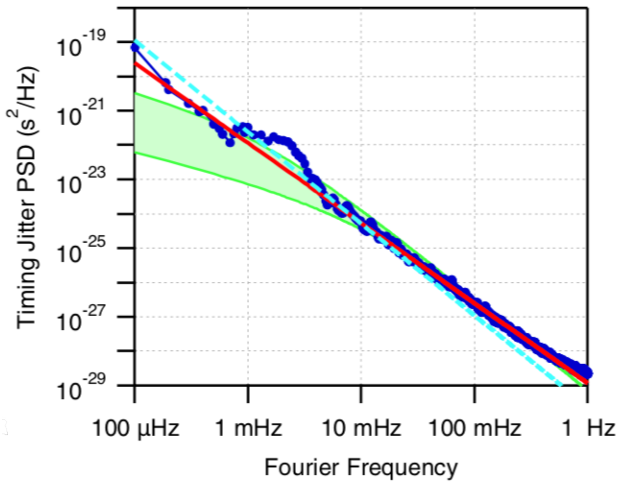
Worst-case bounds indicate that needed supplemental synchronization signal is compatible with HOM timing measurement concept and realistic detector count rates

Atmospheric Timing

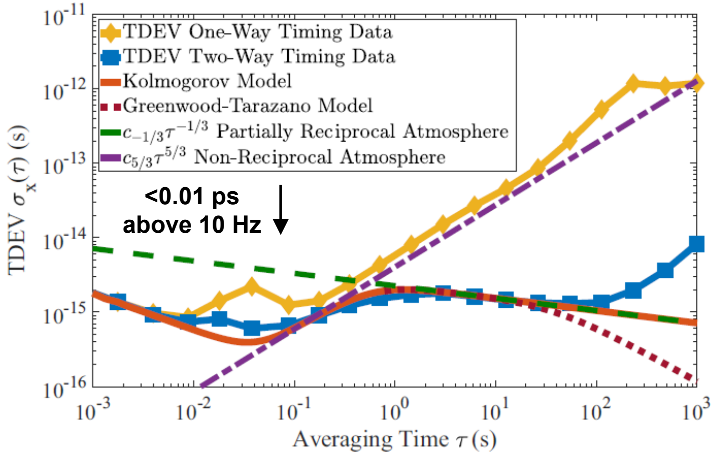
- Each uplink samples a different and changing section of the atmosphere
- Expect <100 fs jitter for <1 s time scales
  - Track slower atmospheric effects (<~1 Hz) as part of Doppler tracking loop
- Changes in total atmospheric path length
  - Air index of refraction n~1.000275 at 775 nm
  - For ~20 km thick atmosphere at zenith, delay is ~18 ns (~5.4 m)
  - At 20°, ~3x delay
  - Need to track out ~10 m path length change over duration of session

Atmospheric effects do not appear to impose additional control requirements beyond those already needed for other effects

Example Atmospheric Timing Jitter PSD



Example Atmospheric Timing Jitter Prediction



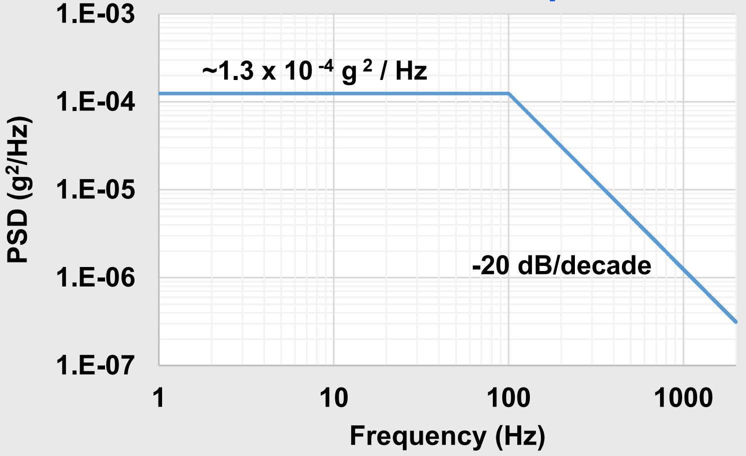
PSD: Power Spectral Density

Sinclair, PRA 89 023805 (2014)
Taylor, PRA 101 033843 (2020)

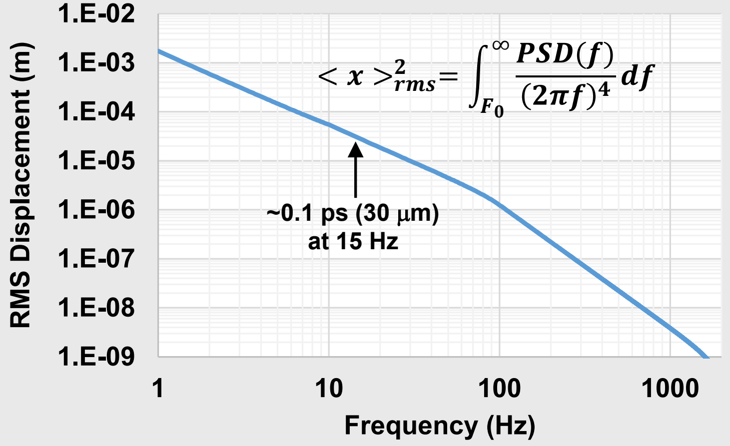
Jitter

- Mode-locked laser timing jitter
  - Stable (<0.1 ps jitter) on fast time scales (>100 Hz)
  - Slow drifts (<100 Hz) can be tracked by frequency tuning PLL
- Spacecraft jitter
  - Differential linear acceleration between two terminals
  - Estimate from single terminal PSD
  - Would require analysis for specific configurations
- If necessary, could mitigate fast jitter via local path-length control
  - Need actuator with ~100 Hz bandwidths (e.g, mechanical delay line, piezo-electric stretcher)
  - Zero mean effects reduce throw requirement

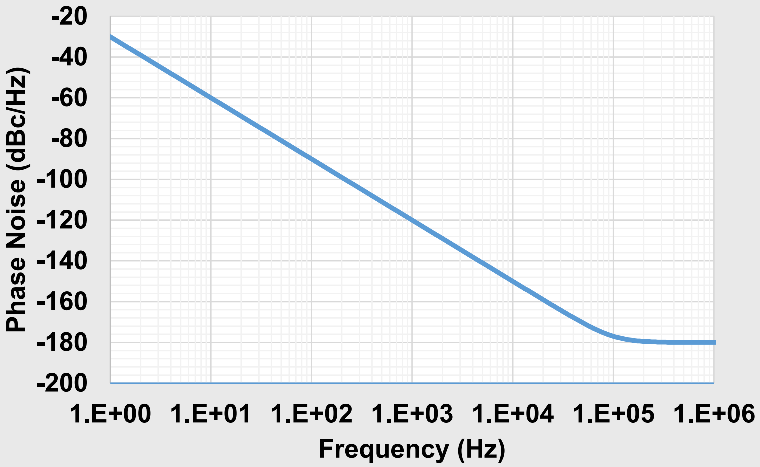
Example Space Terminal Linear Acceleration Input*



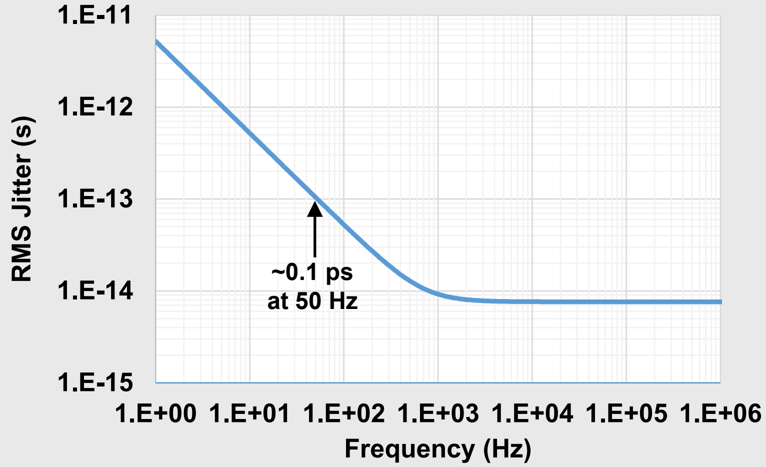
RMS Displacement



Example MLL Open Loop Phase Noise



Open Loop RMS Temporal Jitter



*B. Dilworth, "LLCD Experimental Line-of-Sight Jitter Testing", Sensors and Instr., Vol. 5, The Proceedings of the Society for Experimental Mechanics, 2015.

RMS: Root Mean Square

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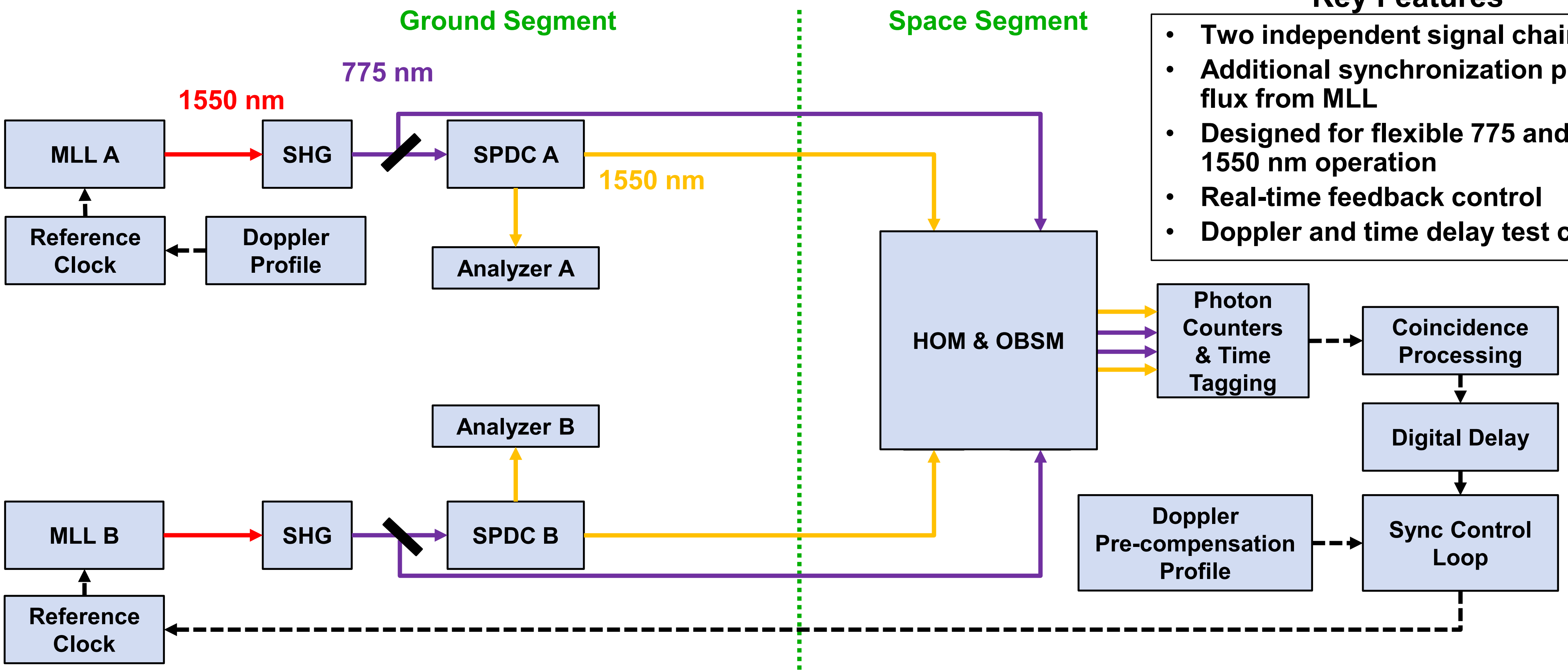
Uplink Synchronization Laboratory Demonstration

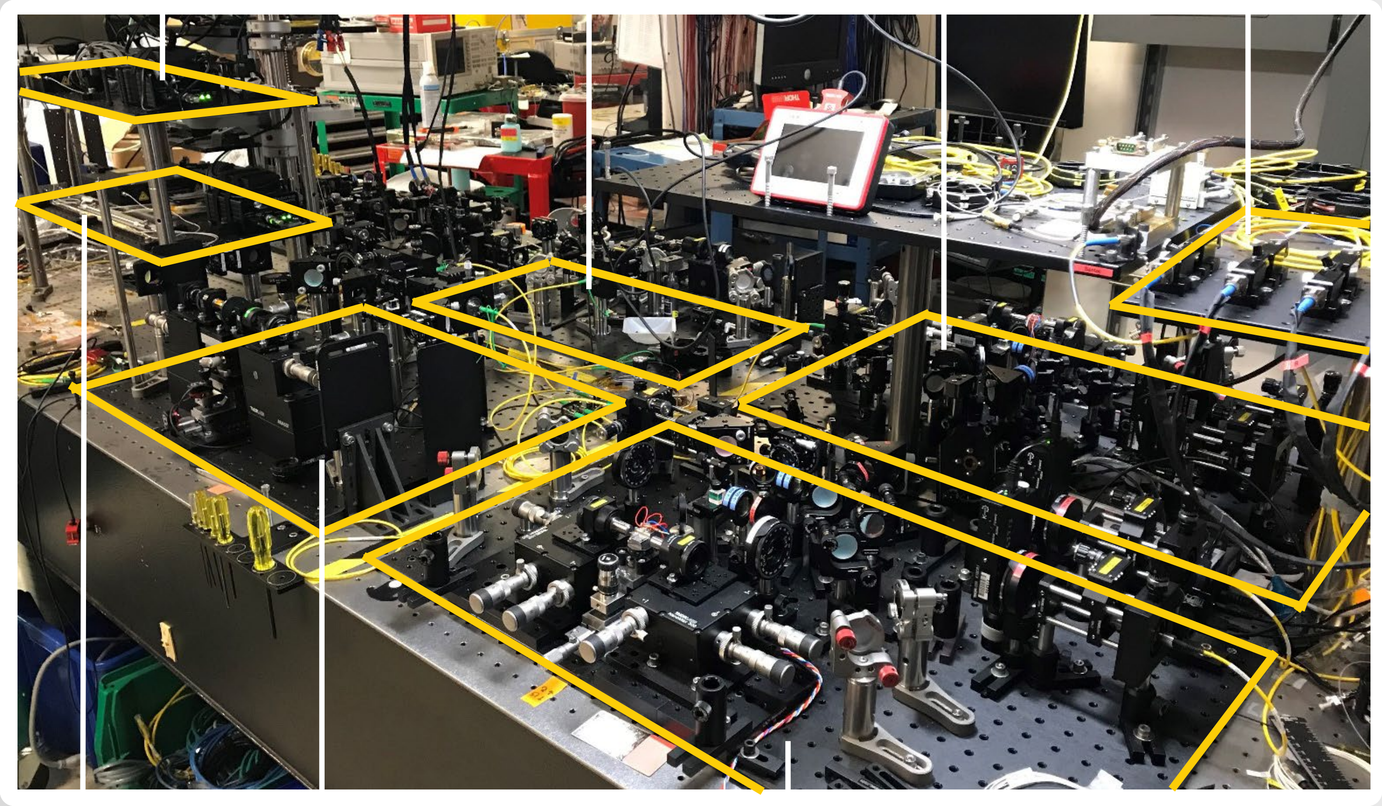


Key Features

- Two independent signal chains
- Additional synchronization photon flux from MLL
- Designed for flexible 775 and/or 1550 nm operation
- Real-time feedback control
- Doppler and time delay test capability

Synchronization Testbed designed to validate required hardware synchronization control mechanisms

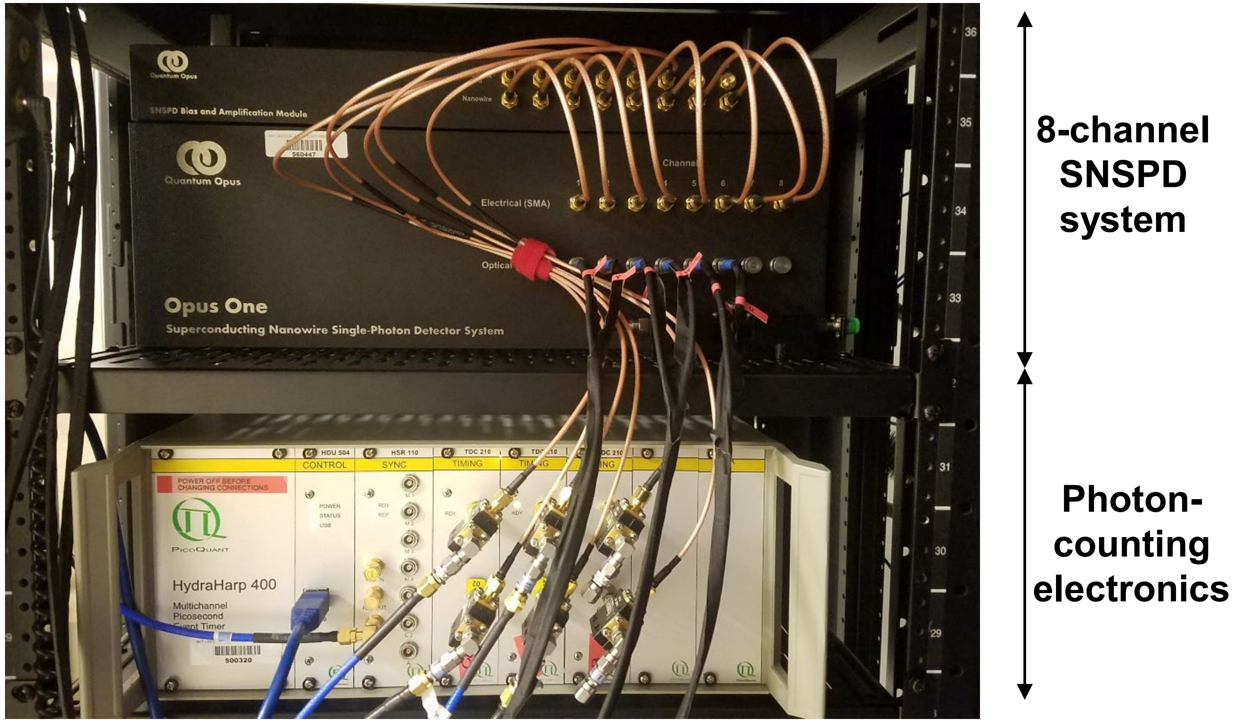
Synchronization Testbed



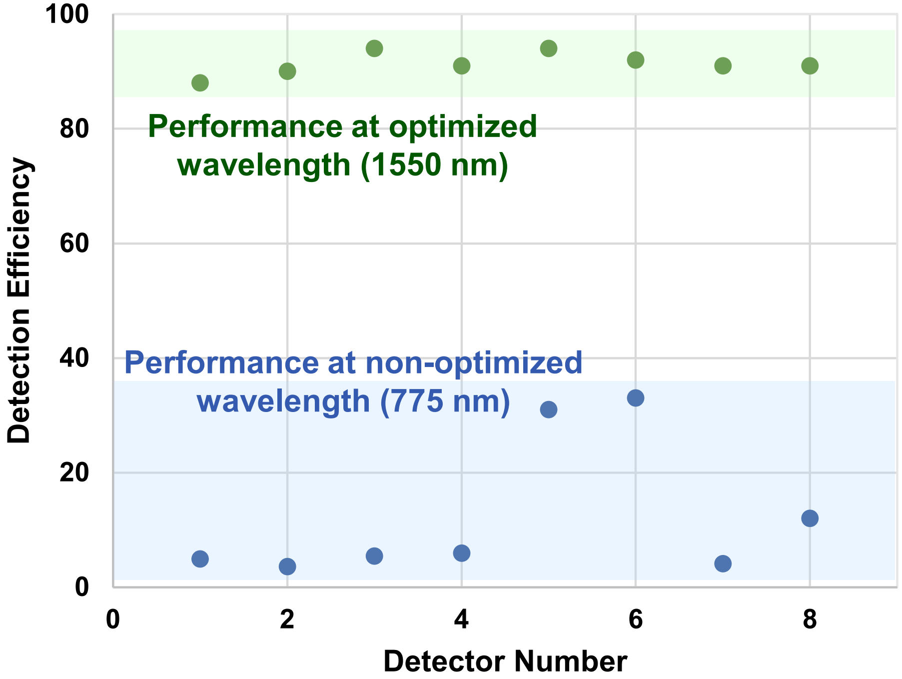
- **Two independent entanglement generation chains**
  - **Mode-locked laser with controlled repetition rate**
  - **Power amplification**
  - **Second harmonic generation**
  - **Entanglement source**
- **Single photon detector readout of:**
  - **Classical sync signal (1550 and/or 775 nm)**
  - **Quantum signal**
- **Synchronization:**
  - **HOM phase detection**
  - **Real-time coincidence processing & synchronization feedback**
  - **Doppler emulation**

Superconducting Nanowire Single Photon Detectors (SNSPDs)

Rack-Mounted 8-channel SNSPD System with Photon-Counting Electronics



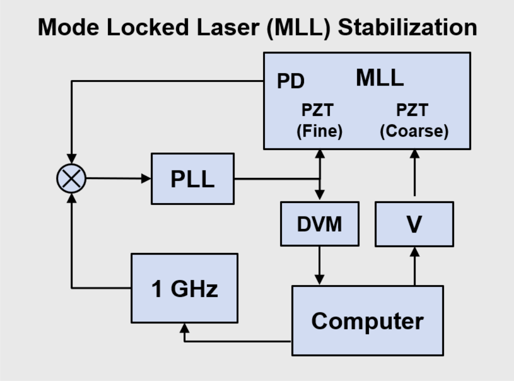
Detection Efficiency



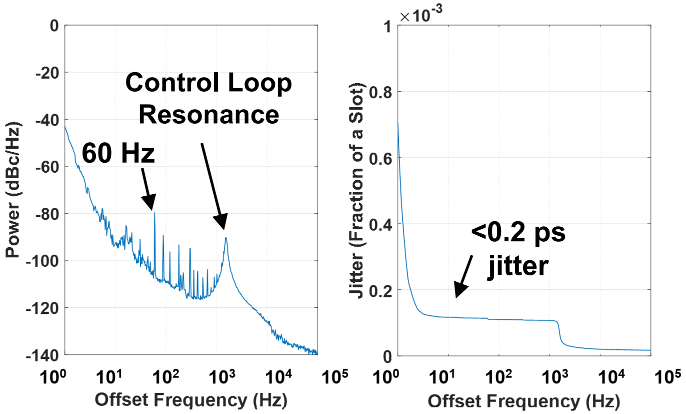
Testbed SNSPDs used at 775 nm provide adequate sensitivity despite having been optimized for operation at 1550 nm

Source Stabilization

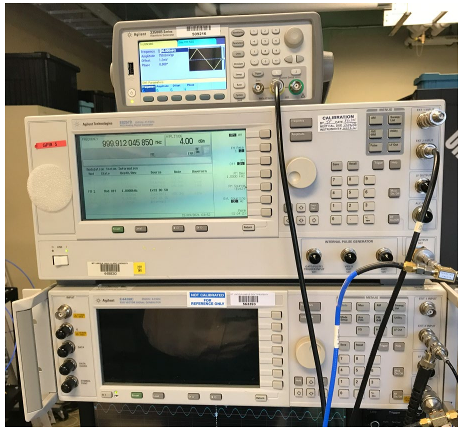
MLL and Stabilization Hardware



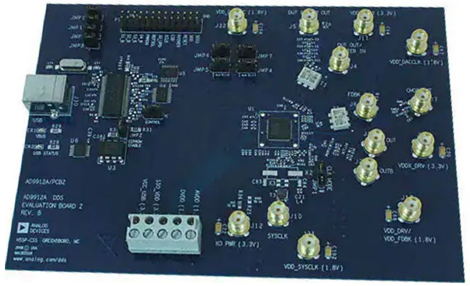
Stabilized Phase Noise & Jitter

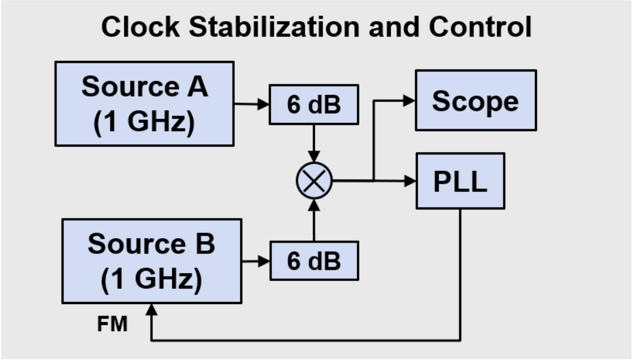


Stable Reference Clock

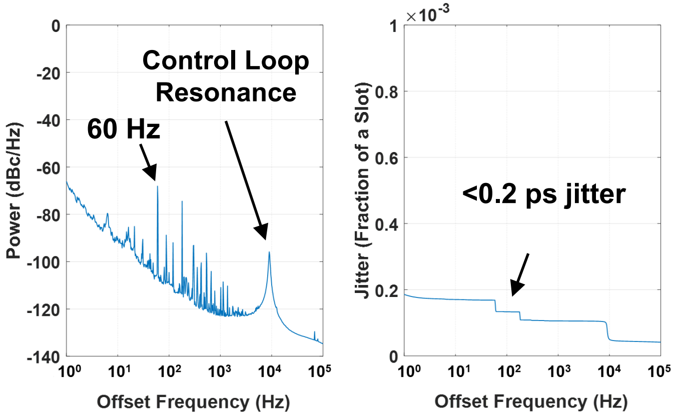


48-bit Tunable Direct Digital Clock Synthesis





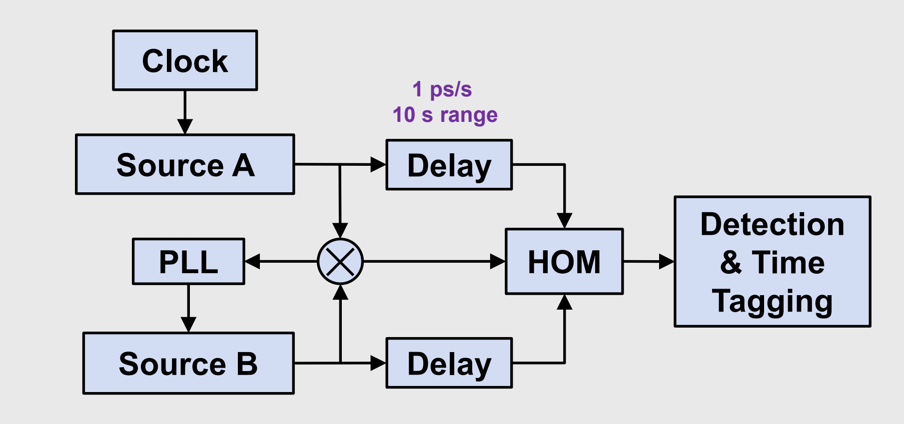
Source B Phase Noise & Jitter While Locked to Source A



Results show that clock and laser sources meet stability and tunability requirements for <1 ps synchronization

HOM Measurement via Time-Tagger and Real-time FPGA Coincidence Processing

Measurement Configuration

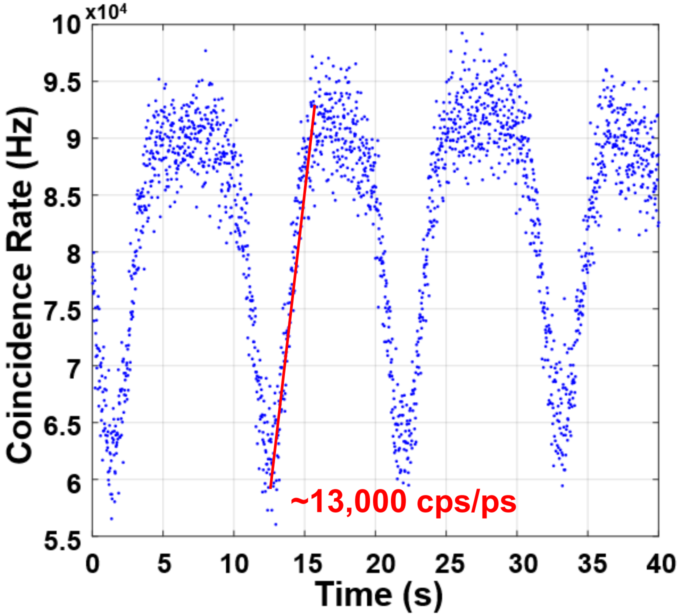


- **Measurements**
  - HOM shape and count rates
  - Confirmation of source temporal stability
  - Estimation of control loop SNR

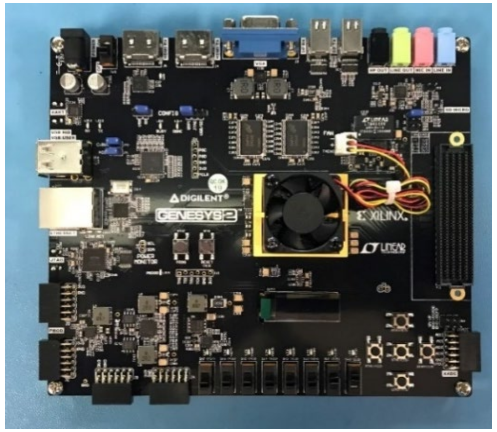
Results show precision time delay measurement capability provided by HOM interference

High-Speed Time Tagger

HOM Coincidence Scan



Real-time FPGA Control



- ~13,000 cps/ps HOM slope
- For 100 Hz (10 ms) integration time at operating point (75,000 cps), expect 750 counts and ~27 count uncertainty
  - For 130 counts/(10 ms-ps) slope, this means 27/130~0.2 ps expected timing uncertainty

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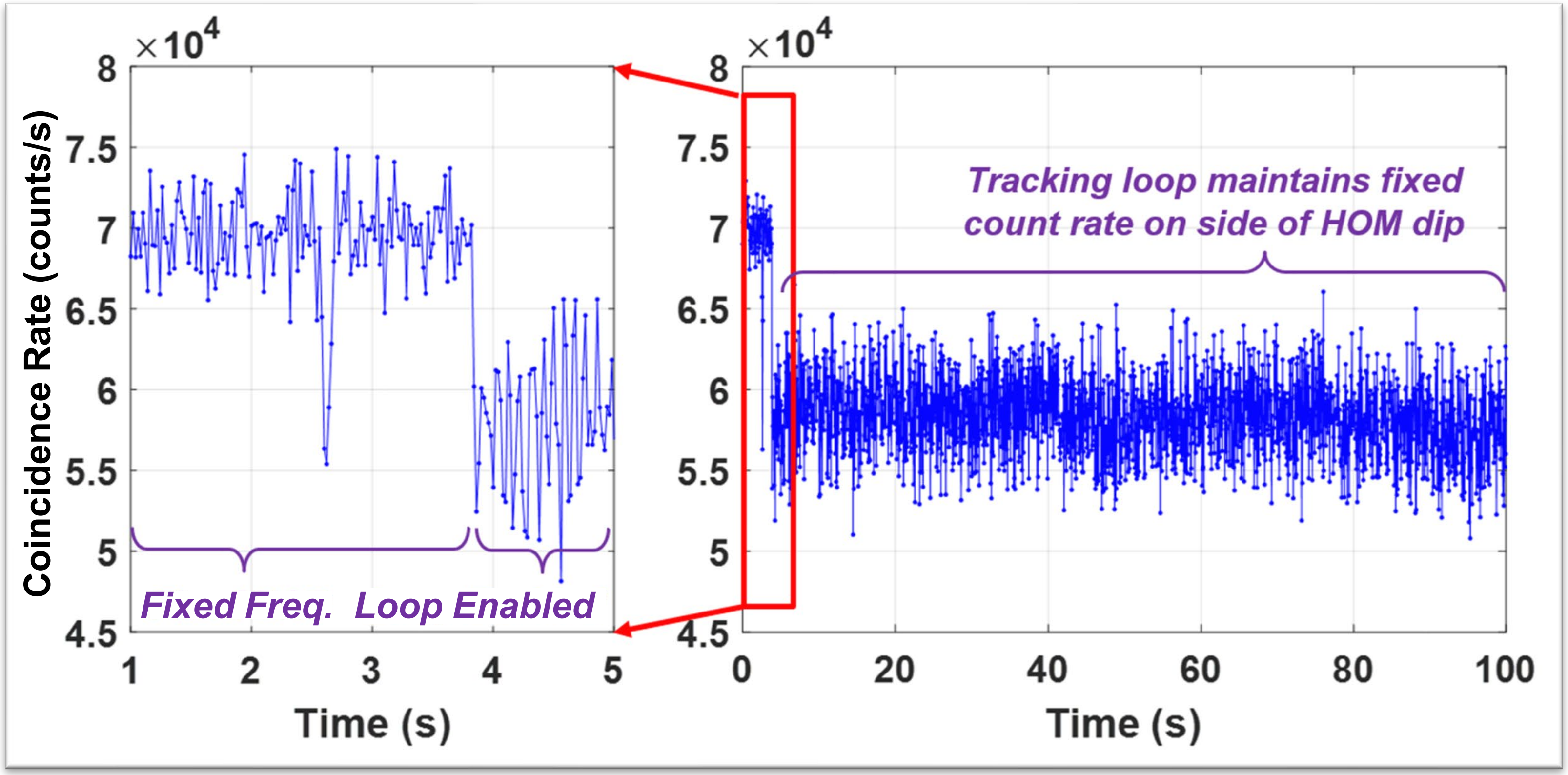
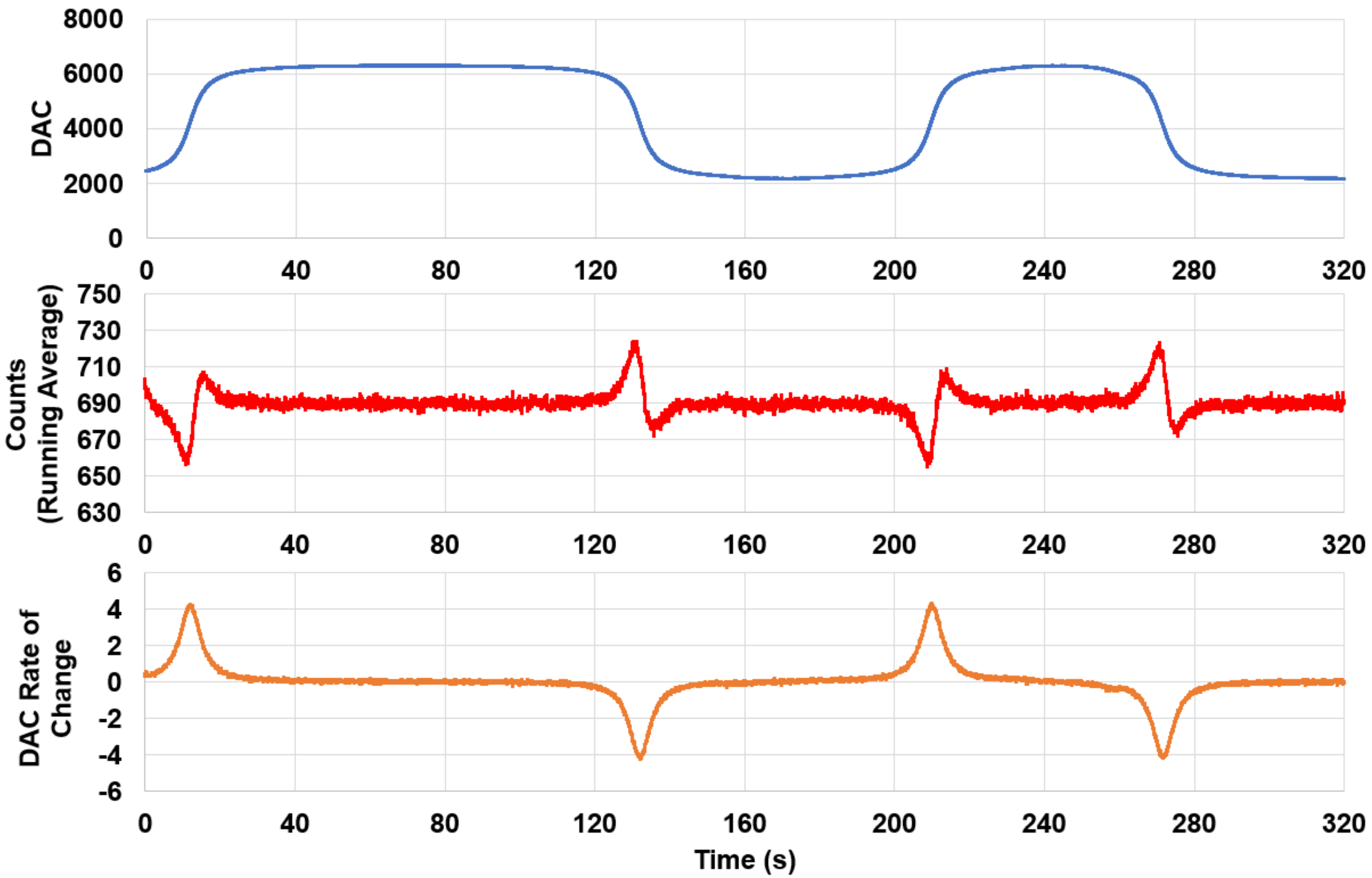
Demonstrating Synchronization



- Simple control algorithm used coincidence-count linear feedback to control MLL pulse repetition rate to phase align with 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

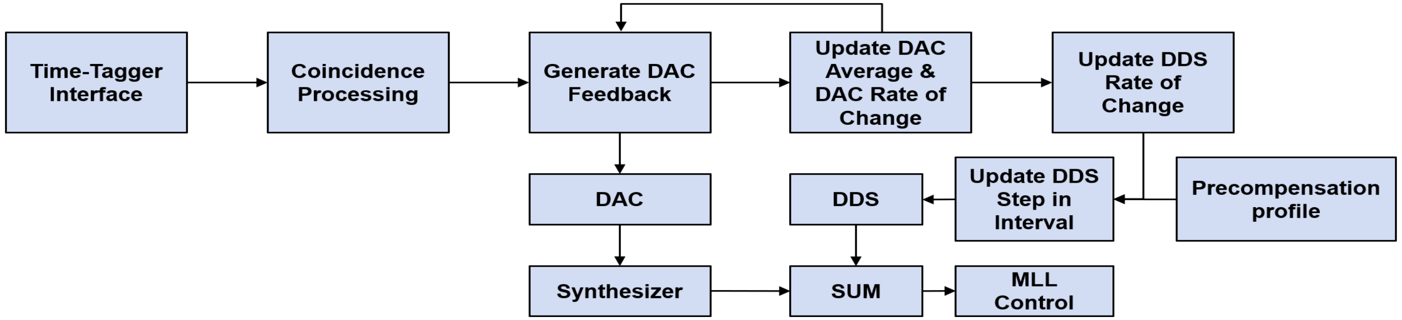


- Type-3 control loop tracks the frequency and frequency rate of change to maintain synchronization with a primary source whose frequency is ramping
- Control approach compatible with the space-to-ground delay
- Testing over modest ranges
  - ~16 ppb frequency range
  - ~1.5 ppb/s peak rate of change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

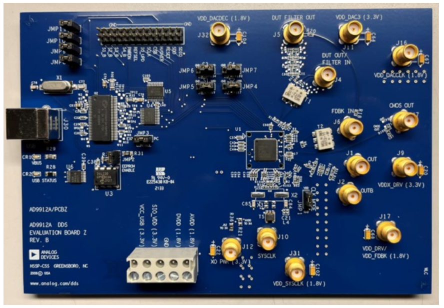
Demonstrated type-3 loop operation appropriate for space-to-ground synchronization; next step was to extend Doppler range and rate capability

Testbed Configuration: DAC Relaxation for Extended Range Operation

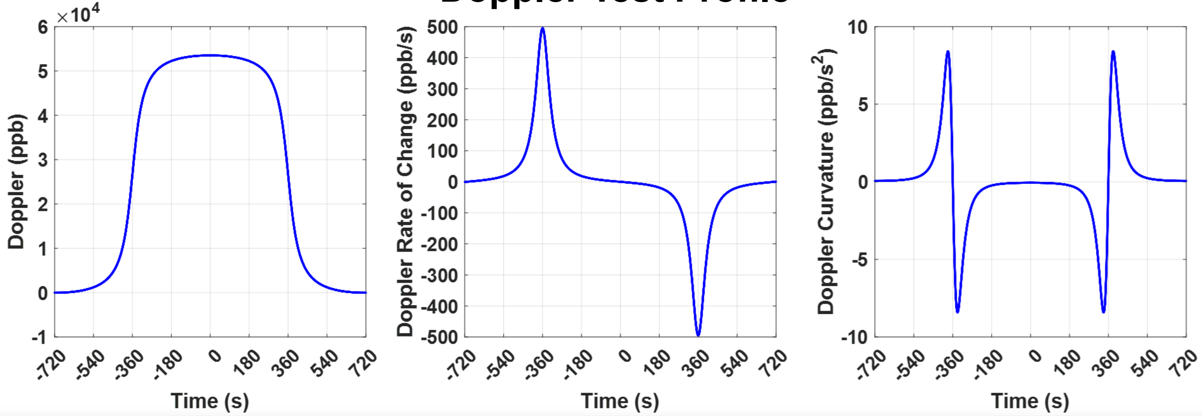
Inner/Outer Relaxation Control Architecture



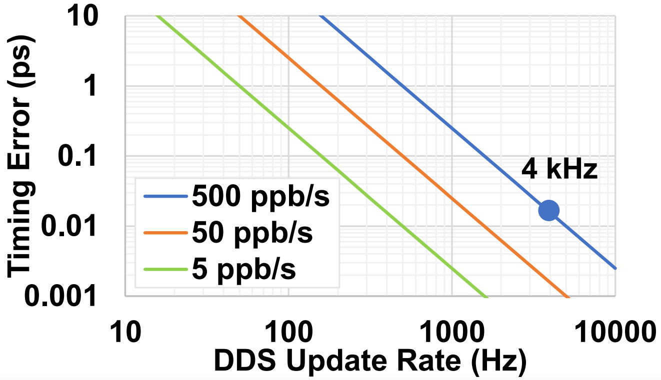
AD9912 Direct Digital Synthesis (DDS) 48-bit control, used at 4 kHz update rate



Doppler Test Profile



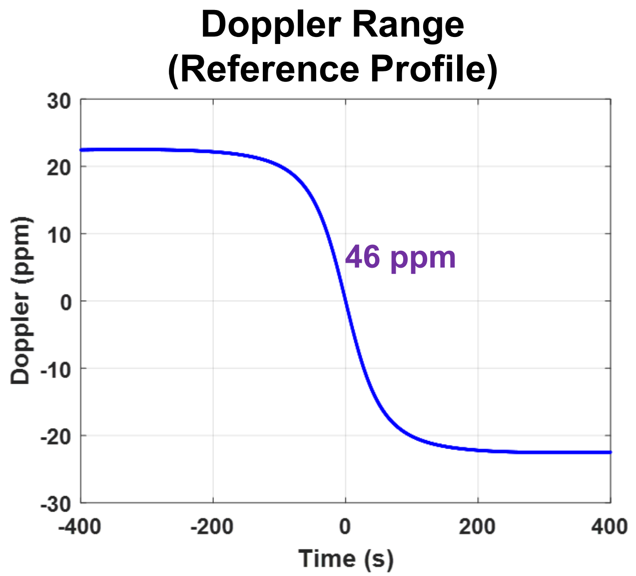
DDS Timing Error vs. Update Interval

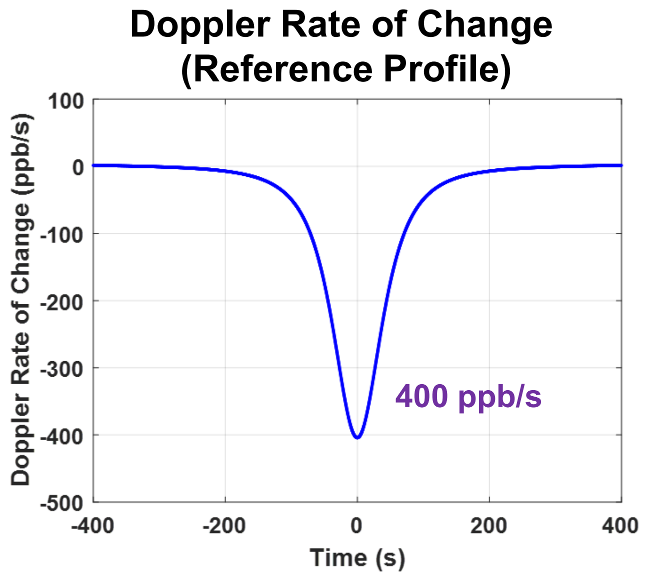


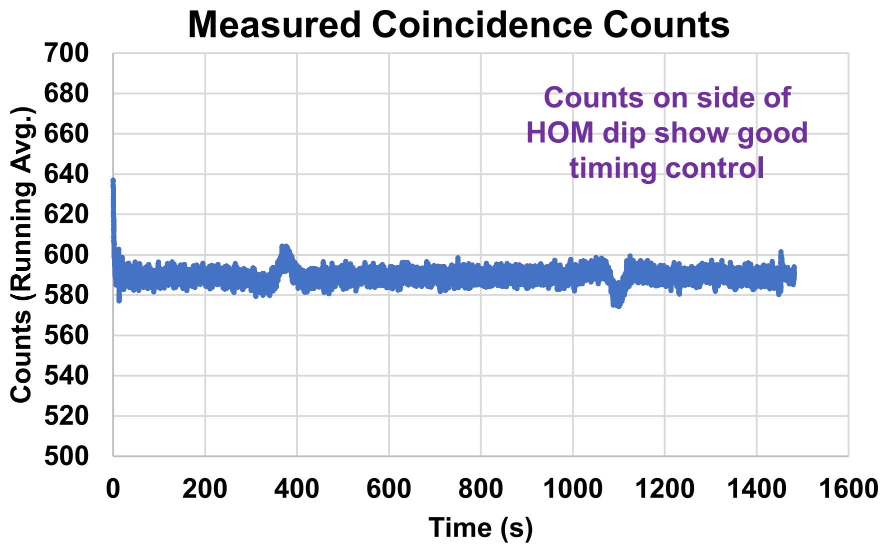
Testbed upgraded to relax DAC by observing DAC rate of change and counter-tuning DDS source

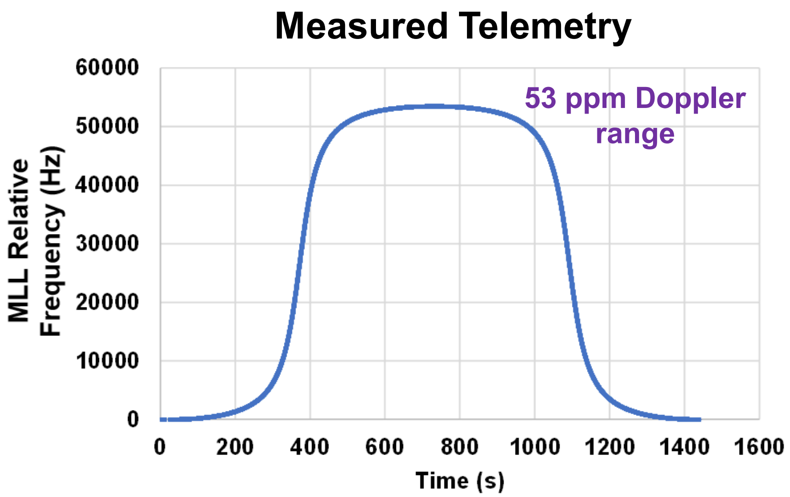
Optica Quantum 2.0, paper QW3A.5, June 2023

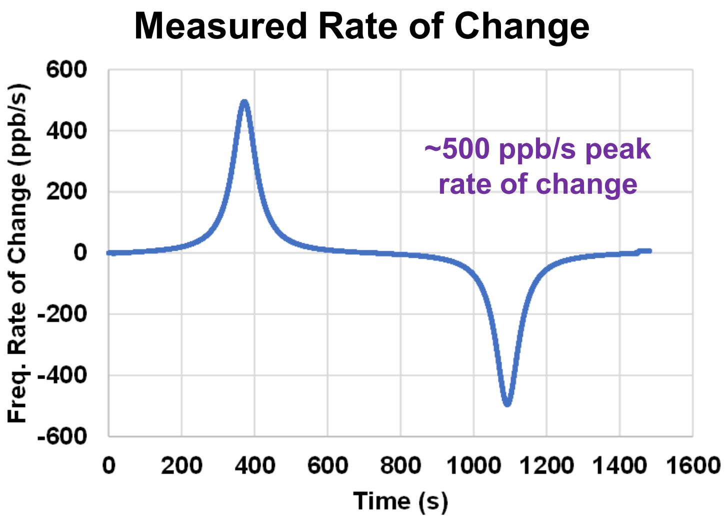
Synchronization control over full Doppler range & rate











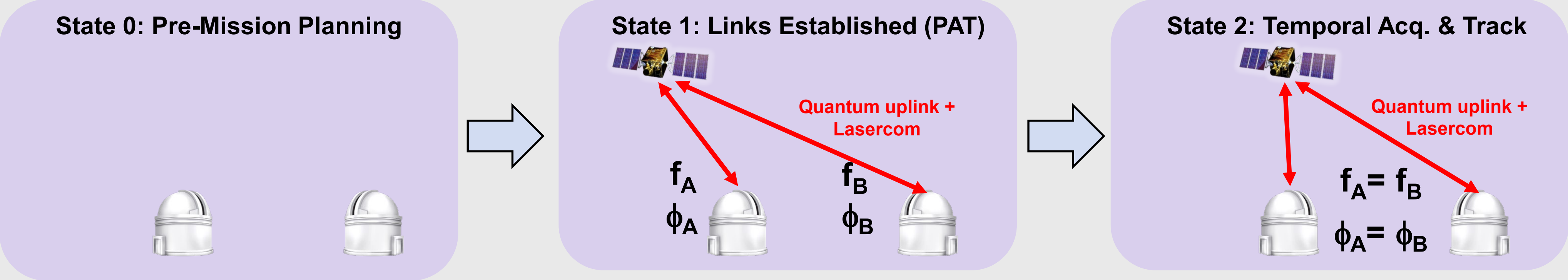
Synchronization testbed has demonstrated precision tracking capability over full realistic Doppler ranges and rates

SPIE Quantum West, paper 12911-11, January 2024

Outline

- Introduction
- Entanglement distribution & synchronization
- Synchronization control architecture & analysis
- Testbed implementation
- Laboratory Results
- ⇨ Next steps, Summary, and Acknowledgements

Temporal Acquisition



State 0: Pre-Mission Planning

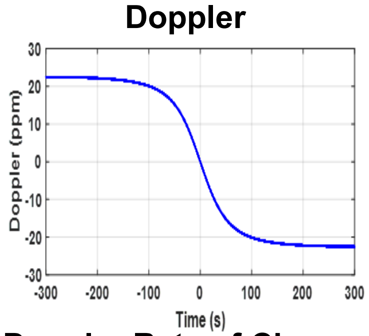
- Update ephemeris
- Create Doppler pre-compensation profiles

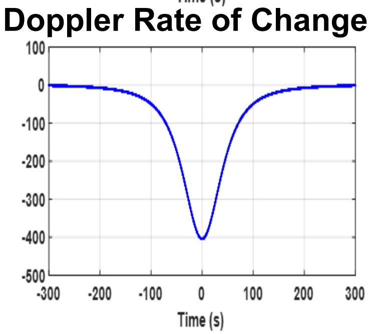
State 1: Links Established (PAT)

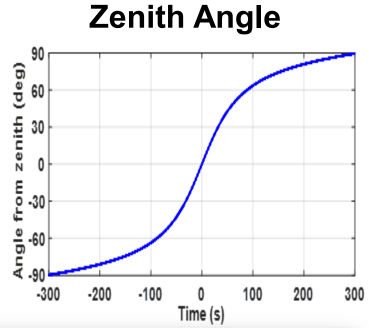
- Establish lasercom link
- Transmit quantum/sync waveforms (power in fiber to quantum receiver)

State 2: Temporal Acq. & Track

- Sources aligned in freq. and phase
- Begin quantum operations
- Operations continue until loss of link at low elevation







- **Considerations**
  - Source frequency repetition rate accuracy
  - Spacecraft ephemeris and Doppler prediction accuracy
  - Information available from PAT system (e.g. pointing knowledge)
  - …
- **Designing a tiered acquisition technique that will be robust against uncertainties**

Key challenge is bringing the two sources into relative phase and frequency alignment in a timely manner compatible with short duration LEO sessions

Summary

- **Realizing high-rate long-distance free-space entanglement distribution is critical to future quantum networking and distributed quantum sensing**
  - **Strong interest in flight demonstrations**
  - **Dual-uplink architecture can reduce cost and enable an evolving test capability with a satellite resource**
  - **SPDC-based entanglement sources drive systems to operate with short duration optical signals**
- **MITLL has developed a viable synchronization concept and is reducing the concept to practice in a testbed**
- **Techniques will impact synchronization methods that will be needed for emerging quantum-memory-based sources and systems**

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