Free Space Quantum Network Test Bed

Catherine Lee

Lincoln Laboratory Communications Workshop (LLCW)
Lexington, MA

18–19 May 2022

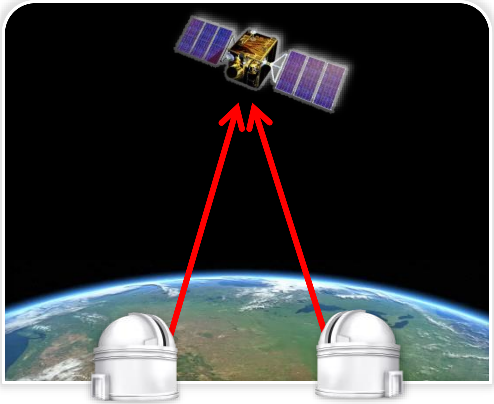
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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.

UNCLASSIFIED

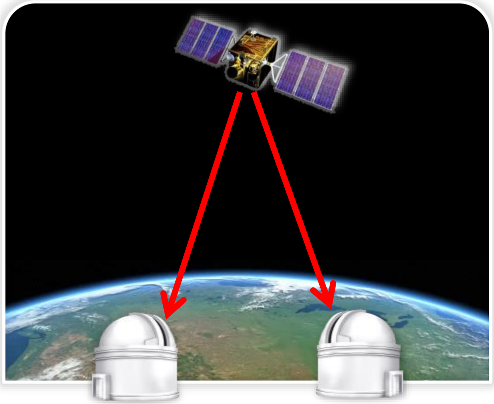
Quantum Network Link Topologies

Dual Uplink



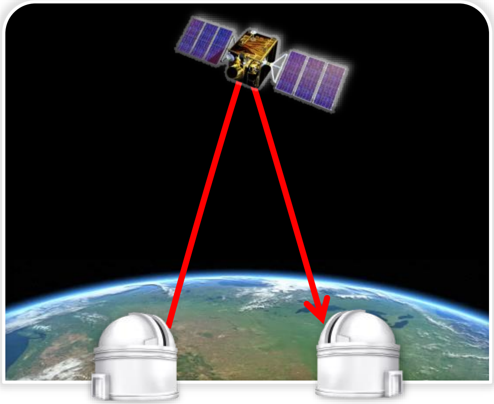
- Entanglement sources at both ground stations send qubits to satellite
- Optical Bell state measurement on satellite entangles remaining qubits at ground stations
- Both uplinked qubits must be synchronized at satellite

Dual Downlink



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

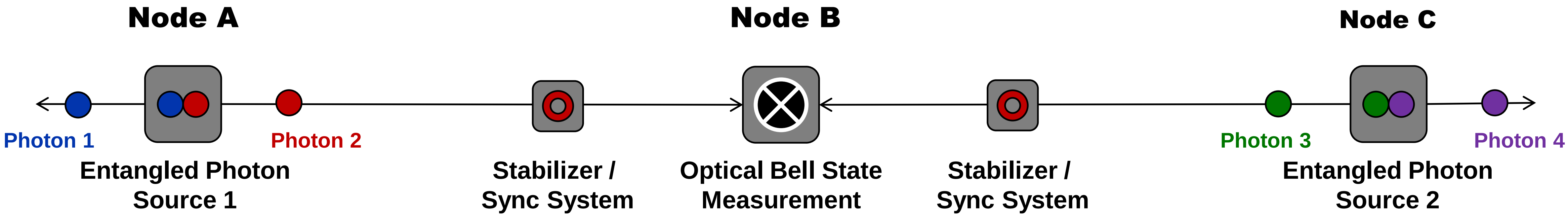
Uplink / Downlink



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

Developing technologies and test beds for multiple relevant quantum network link topologies

Multi-Span Entanglement Distribution



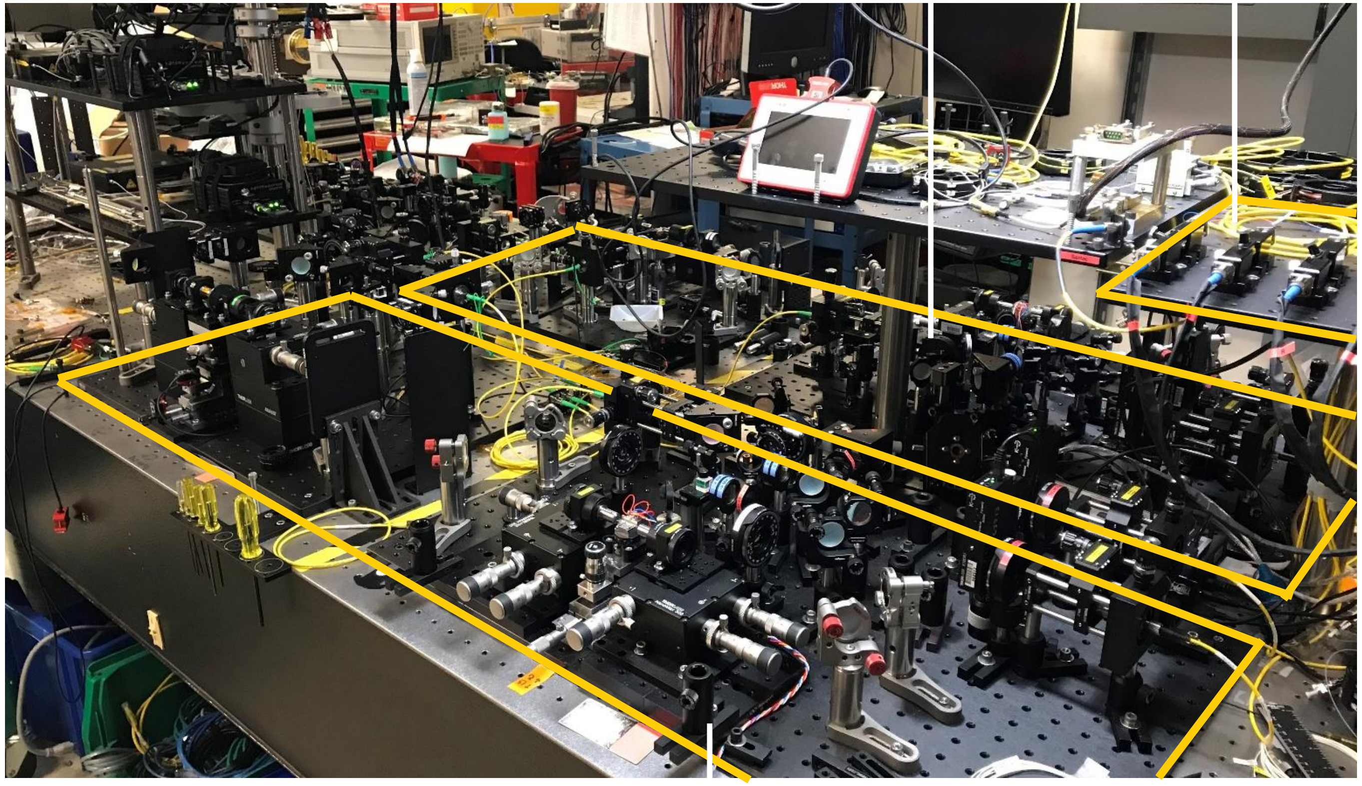
- Entangled Photon Sources produce pairs of entangled photons
- Photons 2 and 3 sent to Optical Bell State Measurement (OBSM)
- OBSM concatenates links, resulting in entanglement between Photons 1 and 4
- Channel stabilizers synchronize photon arrivals at OBSM (ps-class sync required)

Space-Ground Entanglement Distribution Test Bed

Entangled Photon Source Pump Subsystems *(off photo)*

Entangled Photon Source 1

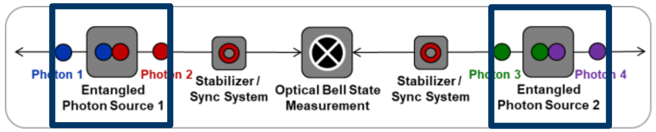
OBSM



Entangled Photon Source 2

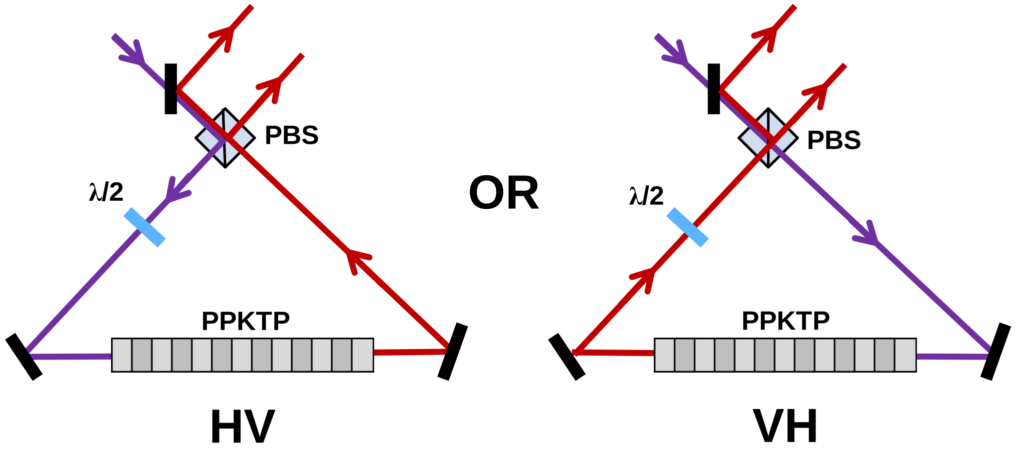
- Two Entangled Photon Sources
- Optical Bell State Measurement (OBSM) with fiber connections to single-photon detectors
- Fiber connections to free-space link across Hanscom AFB
- Rolling integration test approach
  - Table-top testing
  - Free-space link testing

Generating Polarization Entangled States



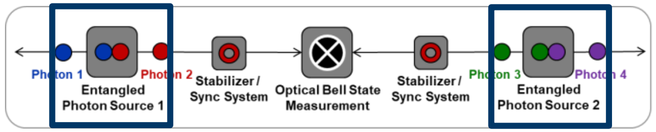
- **Entanglement results from superposition of multiple instances of spontaneous parametric downconversion (SPDC)**
- **Entangled photon source is designed to produce one of the four Bell states**
- **Fidelity is metric of entangled state quality**
  - **Measures "closeness" of two quantum states, $0 \leq F \leq 1$**
  - **Bell states serve as target states for Fidelity computation**

Entanglement Generation via Sagnac Configuration



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

PPTKP: Periodically Poled $KTiPO_4$
PBS: Polarizing Beam Splitter
H: Horizontal Polarization
V: Vertical Polarization

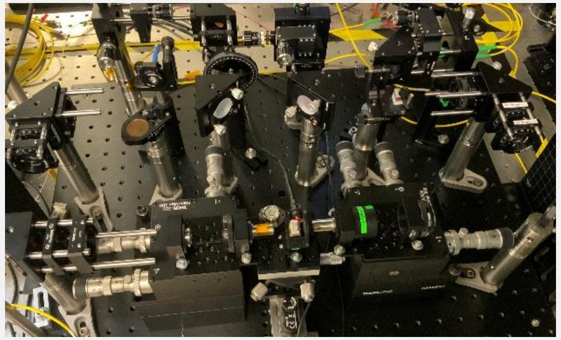


Entangled Photon Sources

Pump Mode-Locked Laser

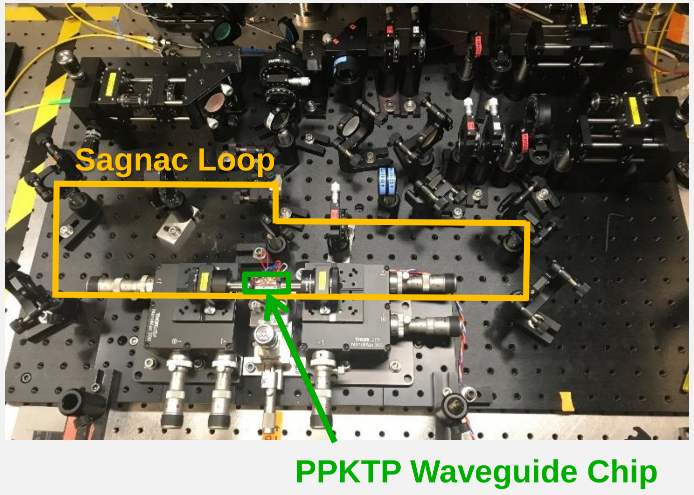
Tunable pulse duration (via filters)
1550 nm center wavelength
1 GHz repetition rate

Pump Wavelength Convertor



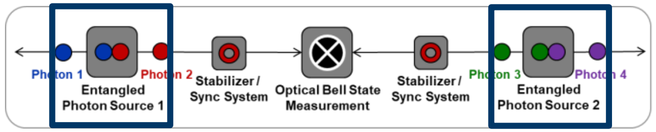
Second harmonic generation (SHG)
1550 → 775 nm

Entanglement Setup (SPDC)

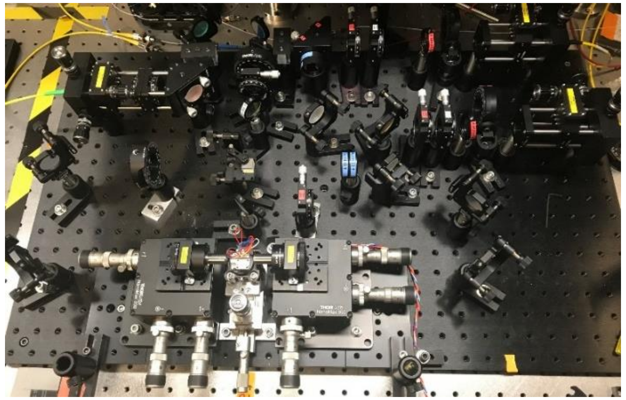


- 1 GHz system clock rate
- 0.05 average pairs / pulse
- 0.963 entangled state fidelity

Entangled State Quality

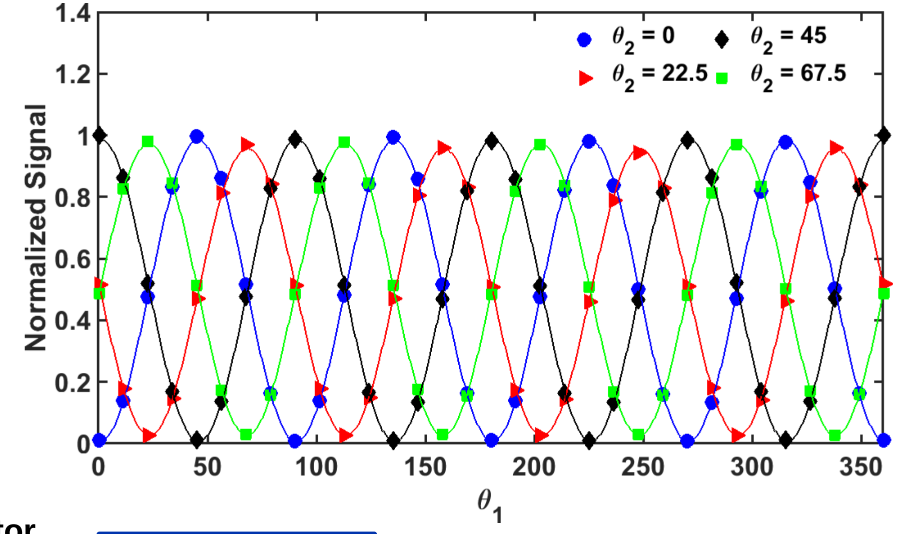


Entanglement Source



Projective Measurements

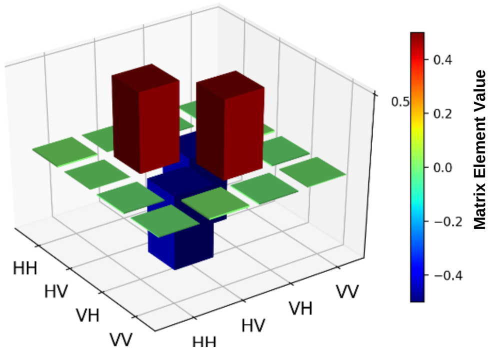
Projective Measurement Results From Single Entanglement Source



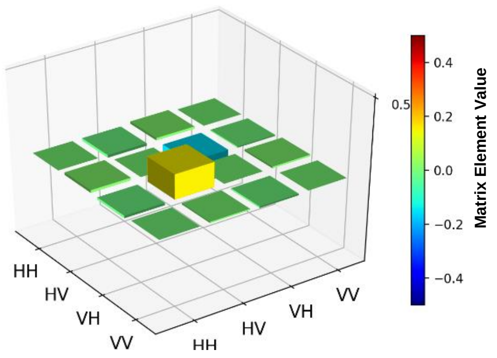
Quantum State Tomography

Estimated State

Real part of Density operator



Imaginary part of Density operator

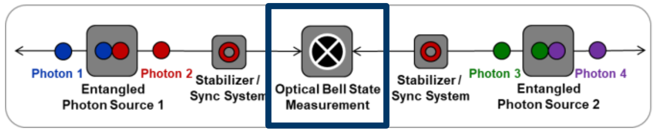


Fidelity Computation

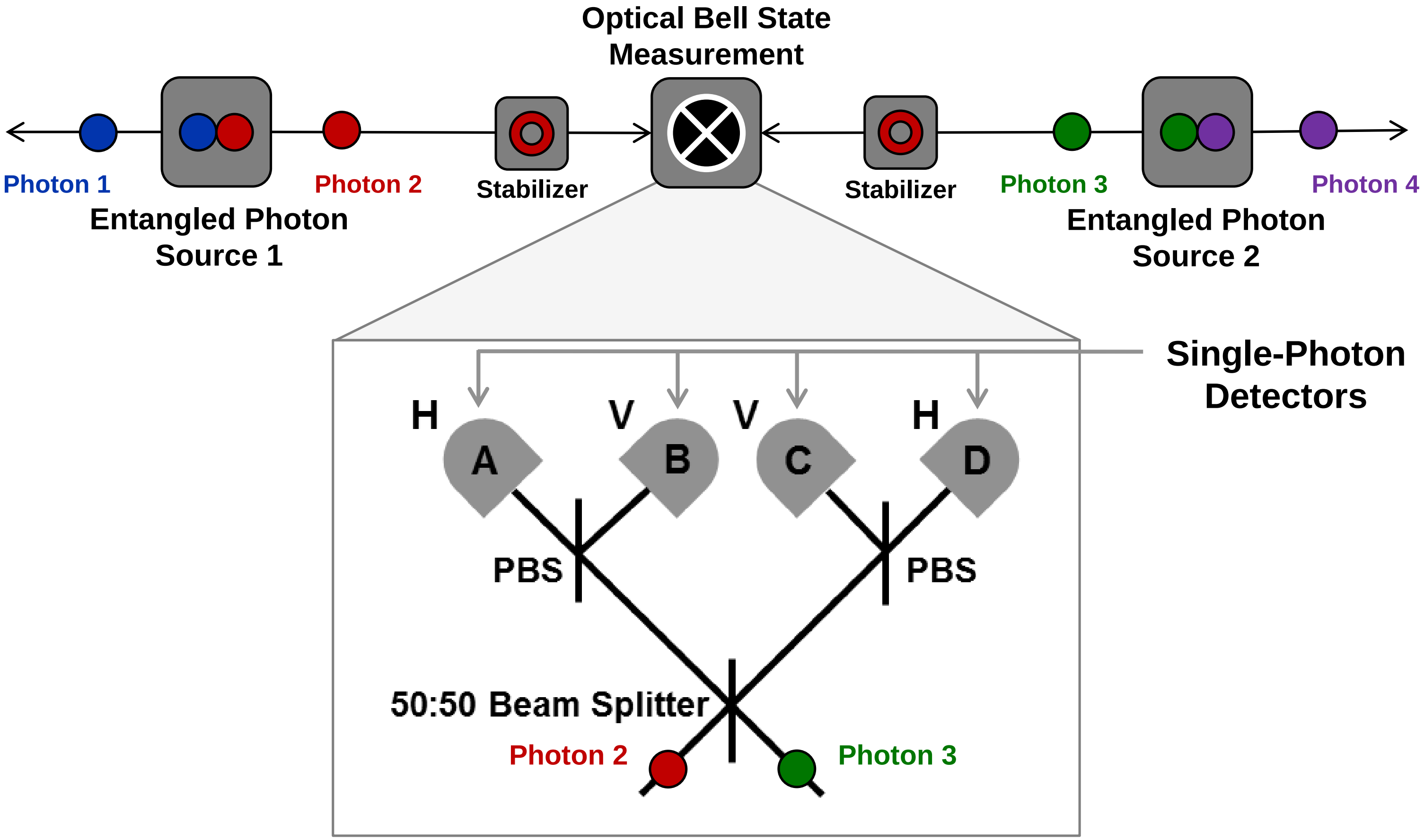
ρ_{target}

96.3% Fidelity to target Bell state → high entangled state quality produced

Optical Bell State Measurement (OBSM)

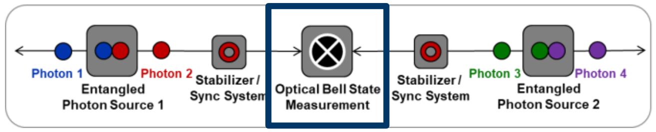


- **OBSM fidelity impacts final output fidelity**
- **OBSM fidelity drives design for other system components**
  - **Single-photon detectors**
  - **Synchronization**

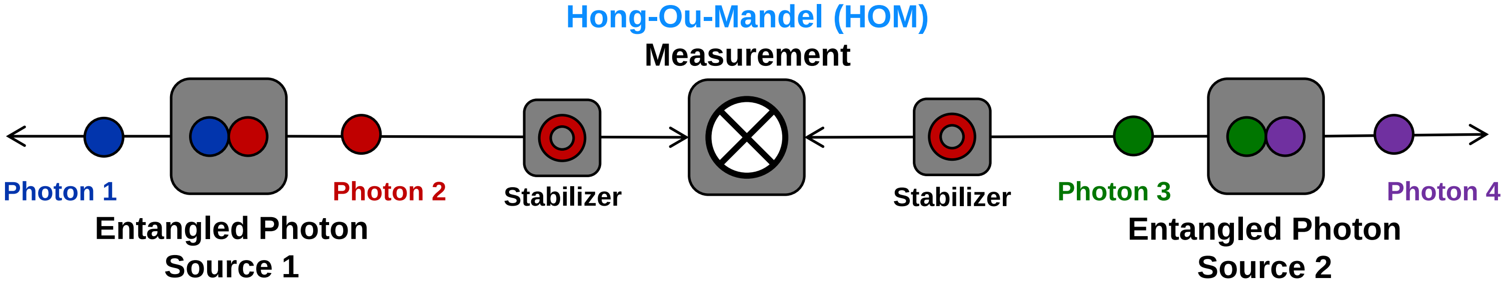


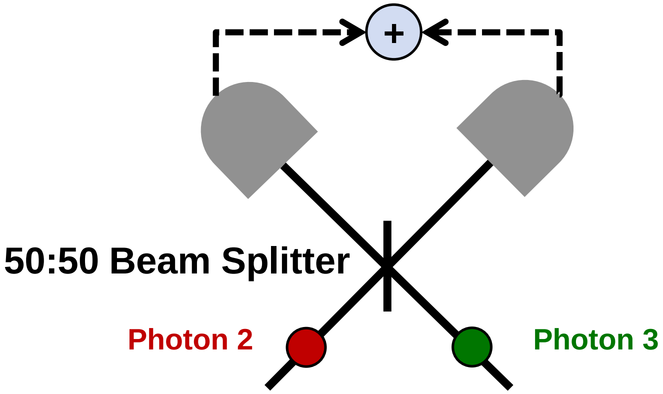
PBS: Polarizing Beam Splitter
H: Horizontal Polarization
V: Vertical Polarization

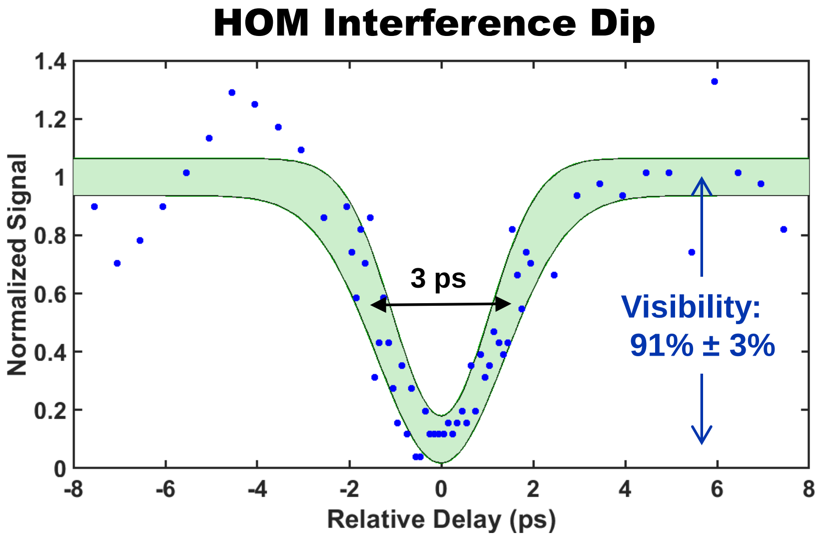
Temporal Overlap at OBSM



- Photons 2 and 3 need to temporally overlap at OBSM
- Overlap precision set by photon temporal duration
- Hong-Ou-Mandel (HOM) interference characterizes photon temporal overlap
  - Places upper bound on OBSM Fidelity
  - Characterizes photon synchronization

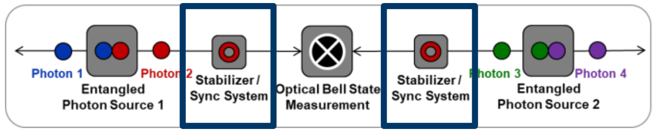




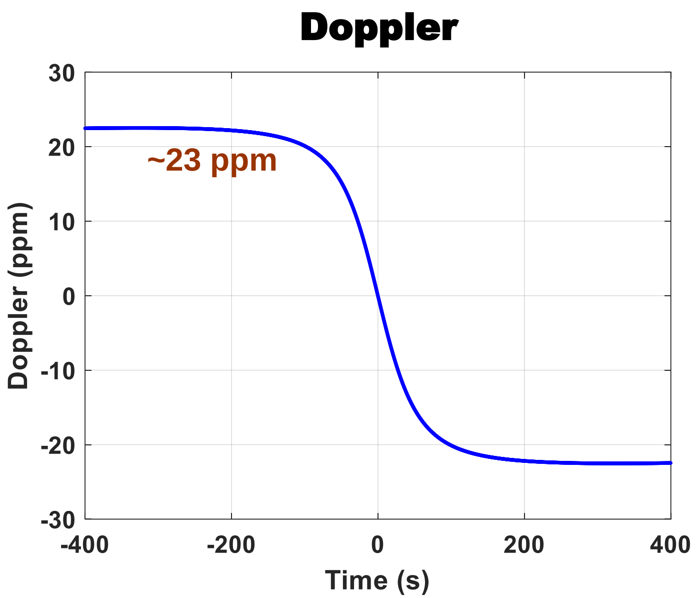


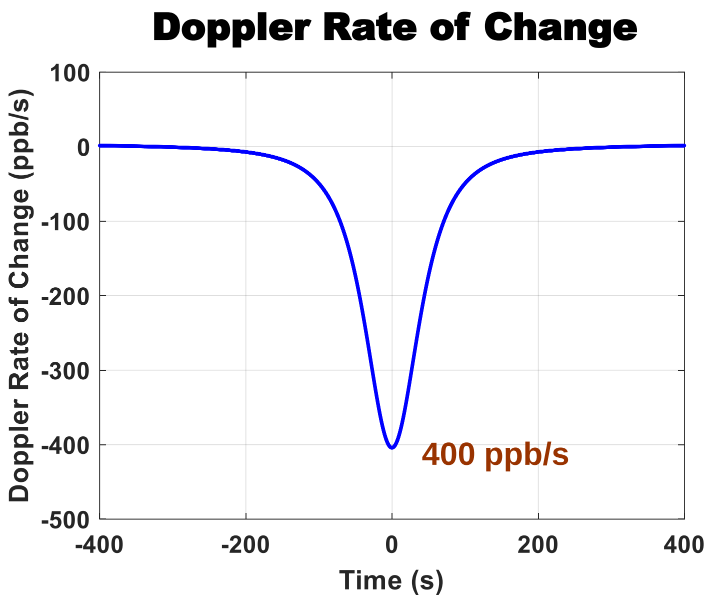
High-Fidelity BSM requires 1-ps-class temporal synchronization

Space-Ground Synchronization System Considerations



- Orbital motion (400 km LEO)
  - 7.7 km/s
- Propagation delay
  - ~1.3 – 9 ms
- Atmospheric dynamics and fading
- Jitter

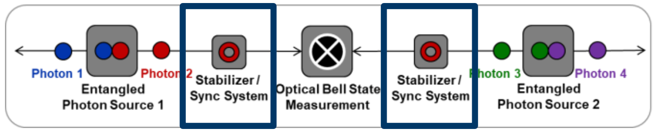


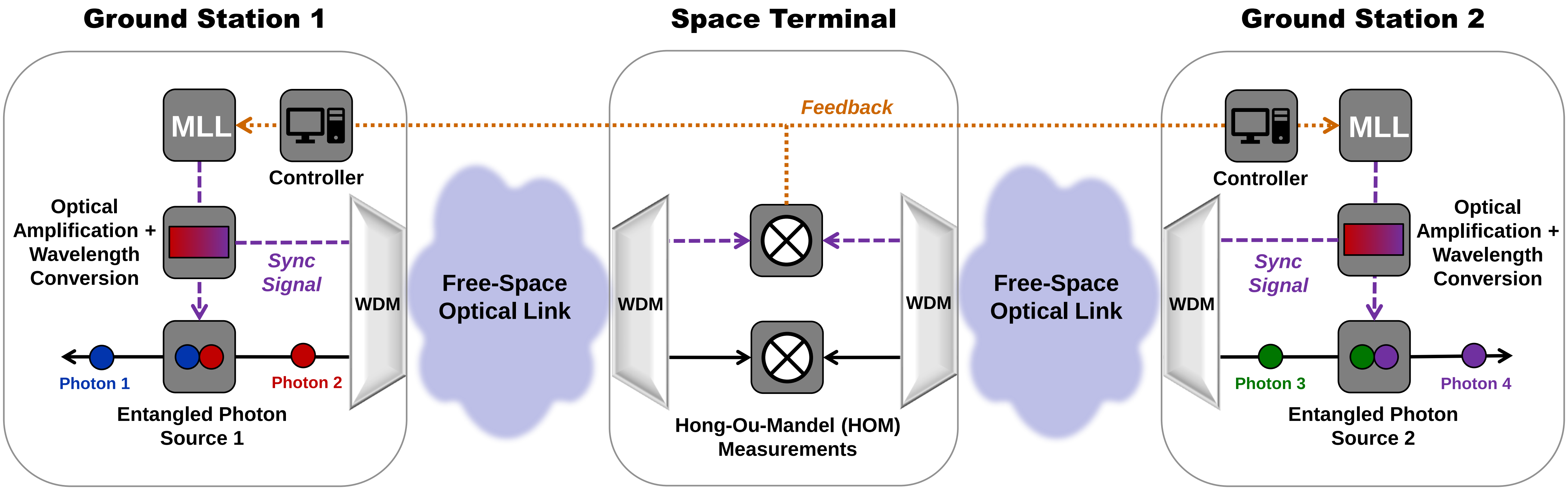


At 1 GHz system clock rate:
23 ppm = 23 kHz

400 ppb/s = 400 Hz/s

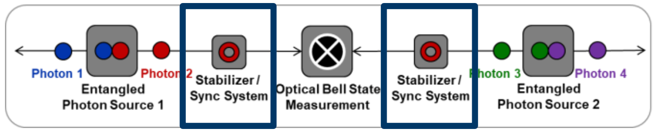
Dual Uplink Synchronization Test Bed Architecture



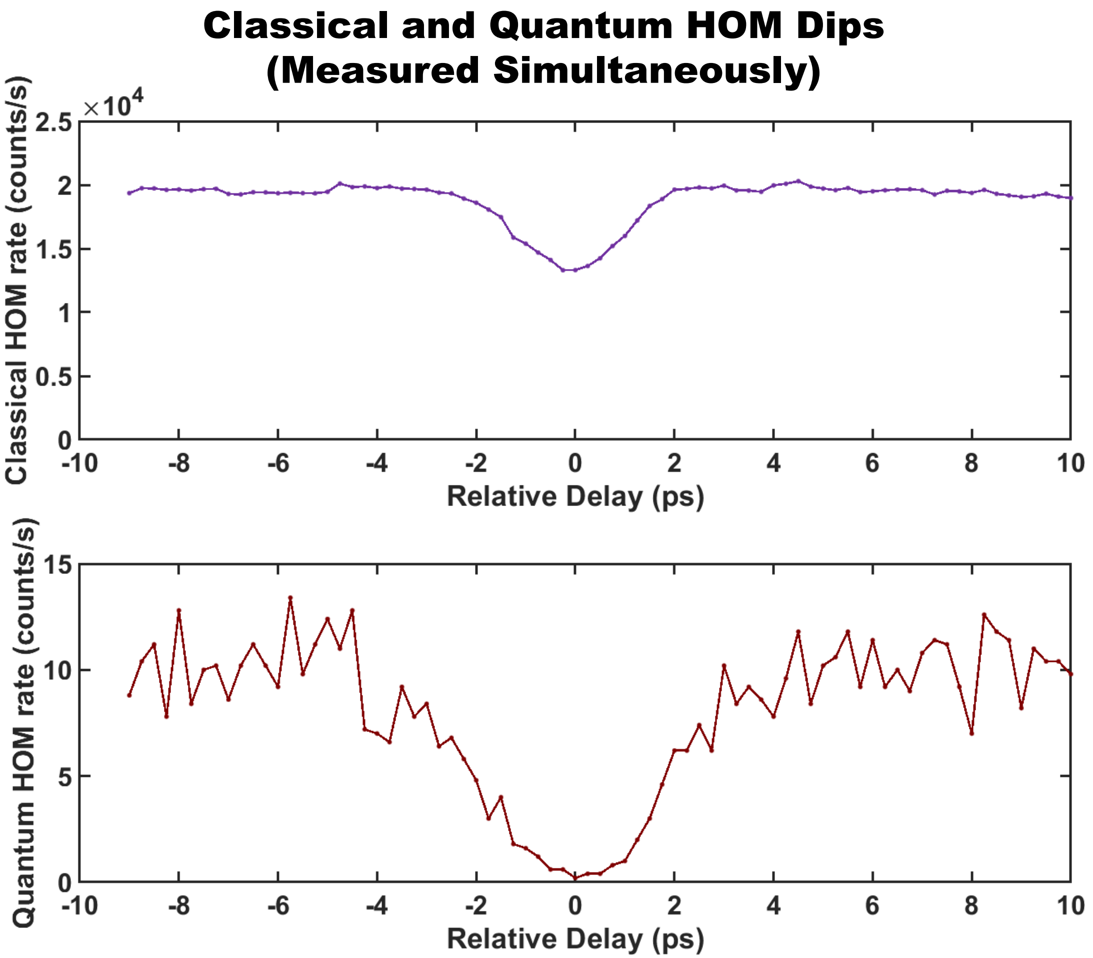


- Provide strong synchronization signal on each uplink for high-SNR HOM measurement at space terminal
- Feedback to ground stations to maintain photon timing alignment

Alignment of Classical and Quantum HOM Dips

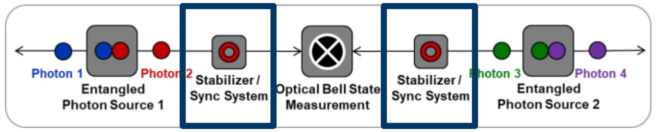


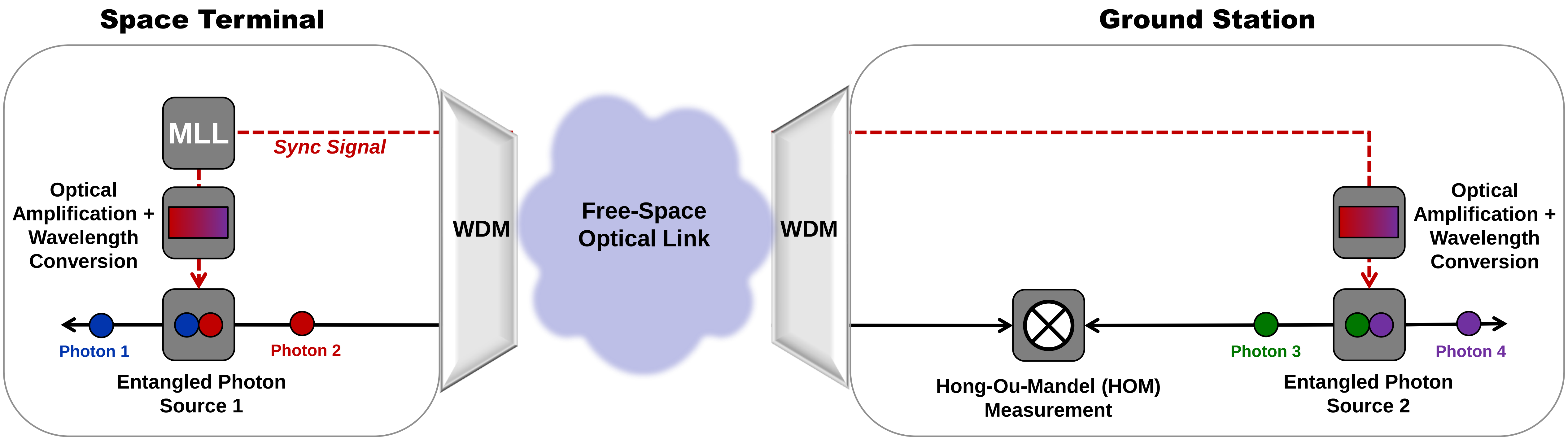
- **Classical HOM dip provides high-SNR timing discriminant for aligning quantum signals**
  - **Variable input photon flux to achieve necessary SNR**
- **Quantum HOM dip demonstrates ps-level synchronization**
  - **98% HOM dip visibility**
- **Future work: High-speed real-time electronic processing path to implement tracking using classical HOM dip**



Test bed has capability for unified classical and quantum HOM synchronization demonstrations in dual-uplink architecture

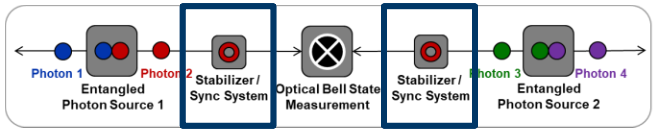
"Pump Forwarding" Downlink Synchronization Architecture



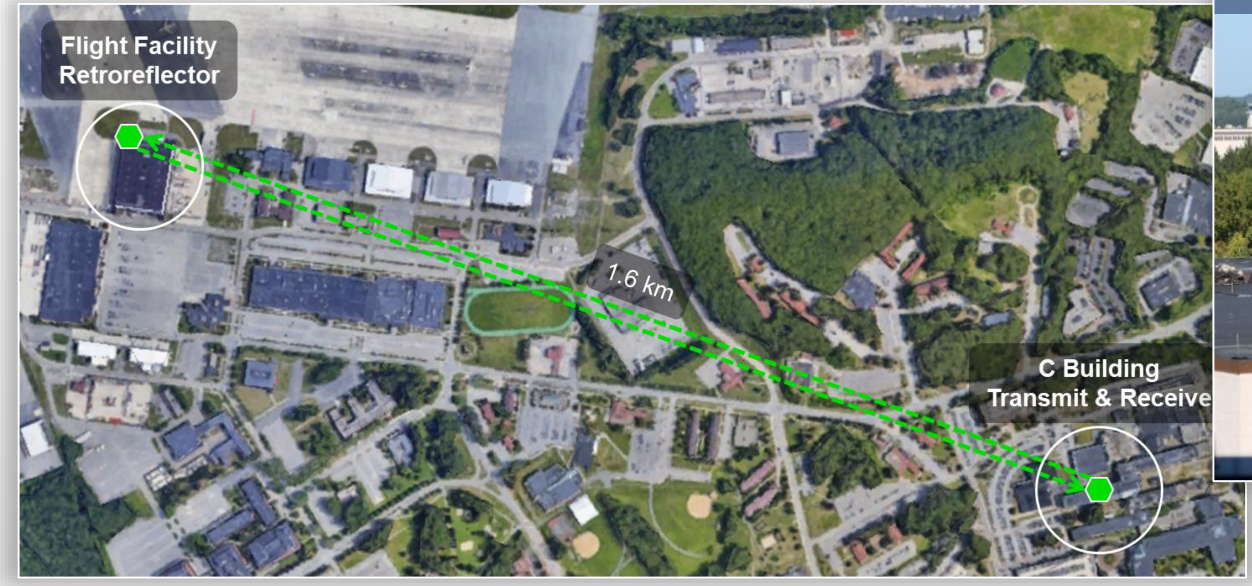


- Master clock mode-locked laser (MLL) provides strong synchronization signal for downlink
- Ground station pump sees identical delay and Doppler shift as entangled photons

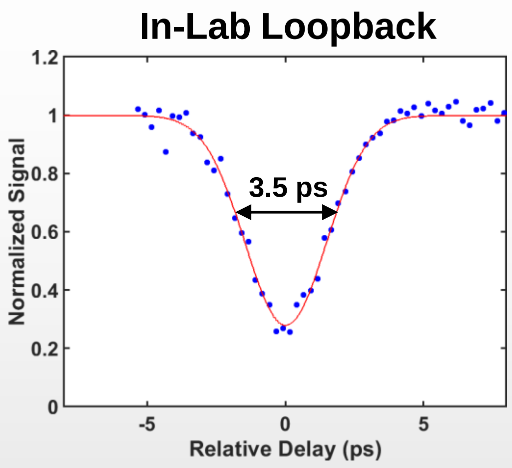
"Pump Forwarding" Downlink Synchronization in Free-Space Test Bed

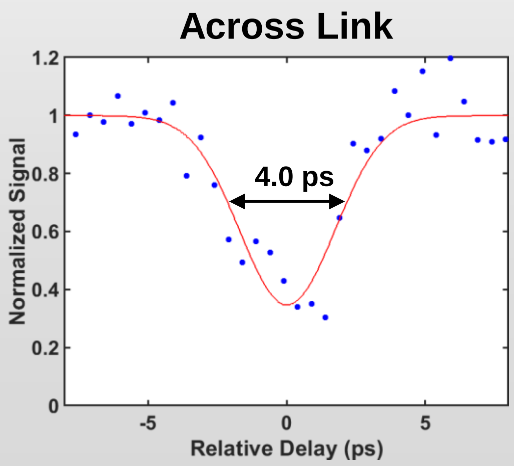


Local 3.2-km Free-Space Optical Link



HOM Dips Over Free-Space Optical Link





HOM dips indicate ps-class synchronization using pump forwarding over dynamic free-space optical link

Summary

- Quantum networks reliably distribute entangled states between multiple physically separate systems
- We are investigating architectures, technologies, and test beds required for entanglement distribution in scalable quantum networks
- We are integrating quantum technologies into test beds to inform future space-ground quantum network demonstrations

Contact Information

LINCOLN LABORATORY
Communications
Workshop 2022

Catherine Lee

Catherine.Lee@ll.mit.edu

Send briefing requests to llcw@ll.mit.edu

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.