Kwiat
Quantum
Information
Group

Quantum Key Distribution Links between Mobile Platforms

QCRYPT 2023

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Outline

- Motivation
- System Overview
- Results
- Next Steps

Motivation

Mobile Quantum Network

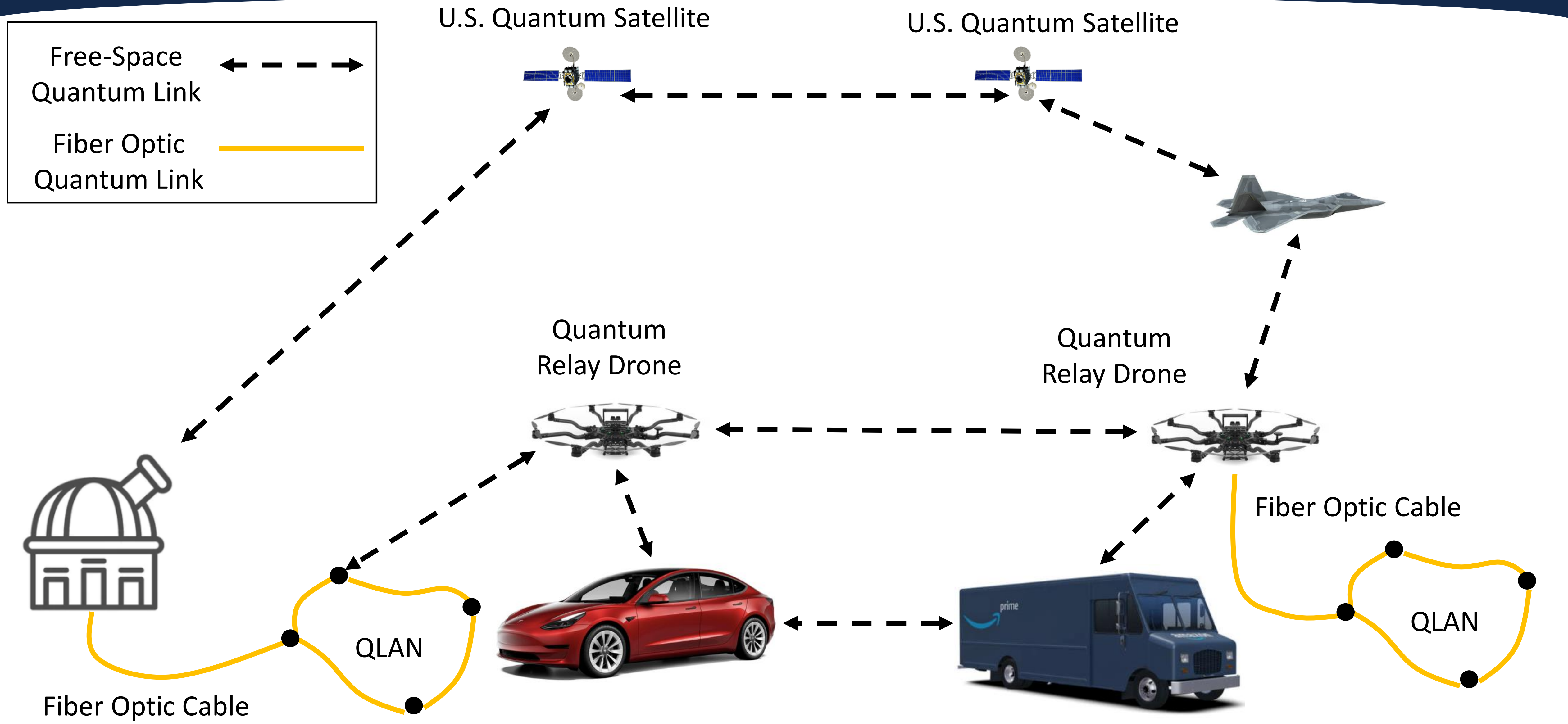
<u>Future Quantum Internet</u>

- <u>Core Pillars</u>: Secure communication, distributed sensor networks, distributed quantum computing
- Many QKD efforts are focused on fixed fibers, or very long free-space links
- Mobile Quantum Links can extend the benefits of the future quantum internet for humans on the go:
  - Drones, cars, planes, satellites, buildings, etc.
- Prior mobile QKD links:
  - satellite-to-ground [1]
  - ground-to-airplane [2]
  - airplane-to-ground [3]
  - drone-to-ground [4]
  - stationary ground-to-moving-vehicle [5]

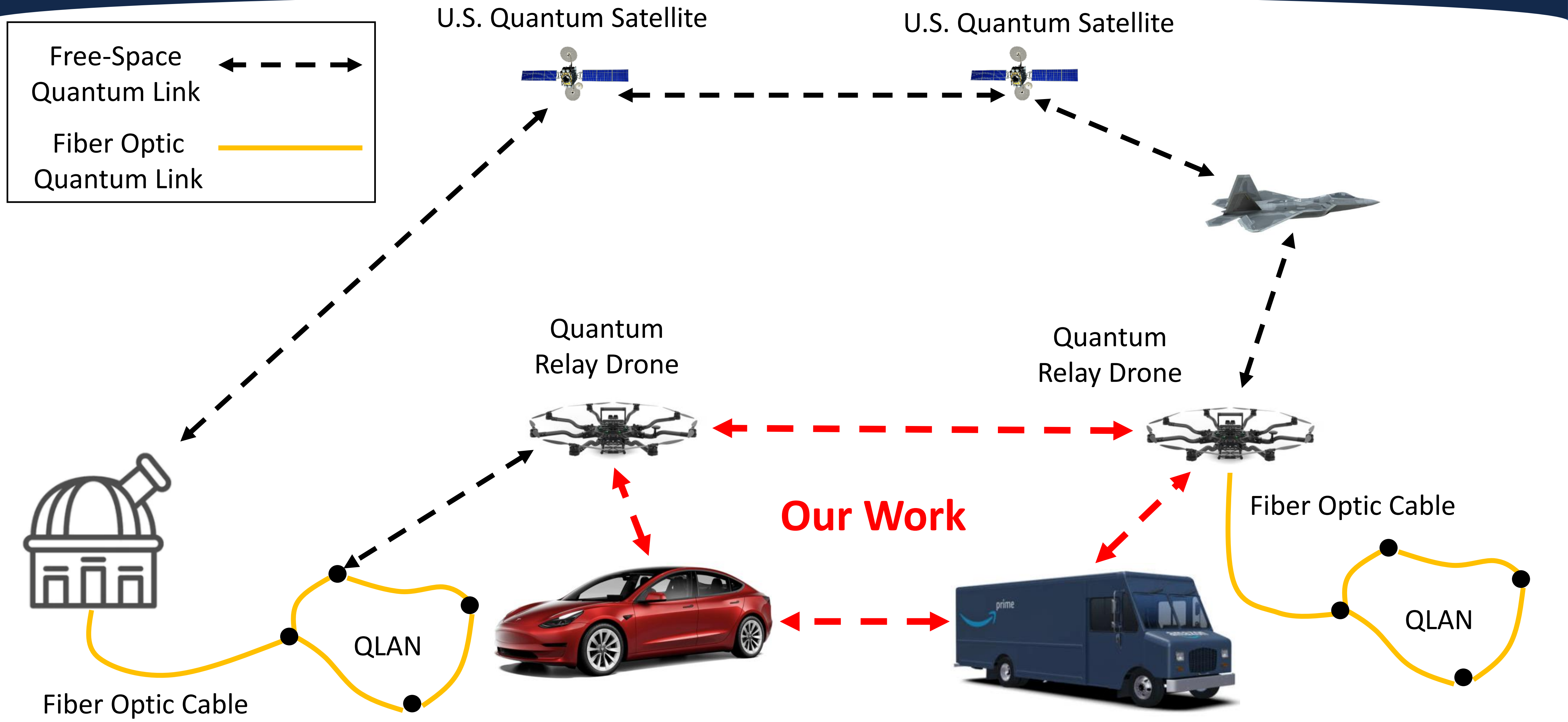
This image was generated with the assistance of AI

[1] Liao, et al. "Satellite-relayed intercontinental quantum network." *PRL* 120.3 (2018): 030501.
[2] Pugh, et al. "Airborne demonstration of a quantum key distribution receiver payload." *Quantum Science and Technology* 2.2 (2017): 024009.
[3] Nauerth, et al. "Air to ground quantum key distribution." *Quantum Communications and Quantum Imaging X*. Vol. 8518. SPIE, 2012.
[4] Tian, et al. "Drone-based quantum key distribution." *arXiv preprint arXiv:2302.14012* (2023).
[5] Bourgoin, et al. "Free-space quantum key distribution to a moving receiver." *Opt. Exp.* 23.26 (2015): 33437.

Free-Space Quantum Network



Free-Space Quantum Network



System Overview

System Design

System Overview:

- Quantum Transmitter (Alice)
    - Quantum Key Distribution (QKD) source:
        - Resonant cavity LED
        - Decoy state
        - Polarization encoded
    - Custom optics benches
- Quantum Receiver (Bob)
    - Single-Photon Detectors (SPCM-AQ4C)
    - FPGA-based Time-Tagger
    - Qubit-based Time Synchronization (Post-processing)
- Pointing, Acquisition, and Tracking (PAT) system
- Mobile Platforms:
    - Drone
    - Car

Image Courtesy Timur Javid

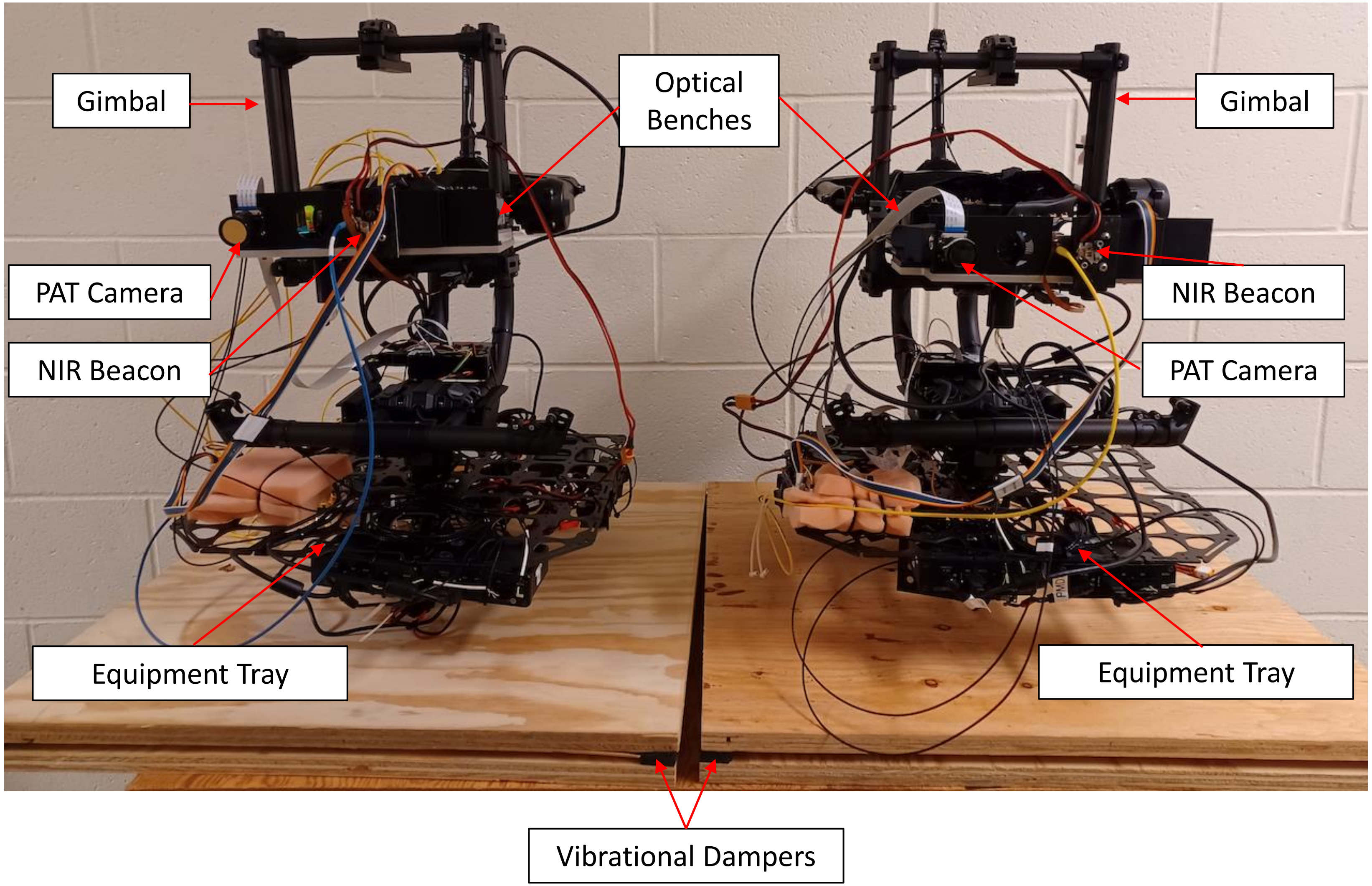
Modular Design

Modular Design:

- Our QKD system shares no resources with host mobile platform
  - Power
  - Control
  - Communication
- Single quick-release connection with drone

  → Place QKD transmitter (receiver) on other platforms (*e.g.*, vehicle) with no required hardware changes

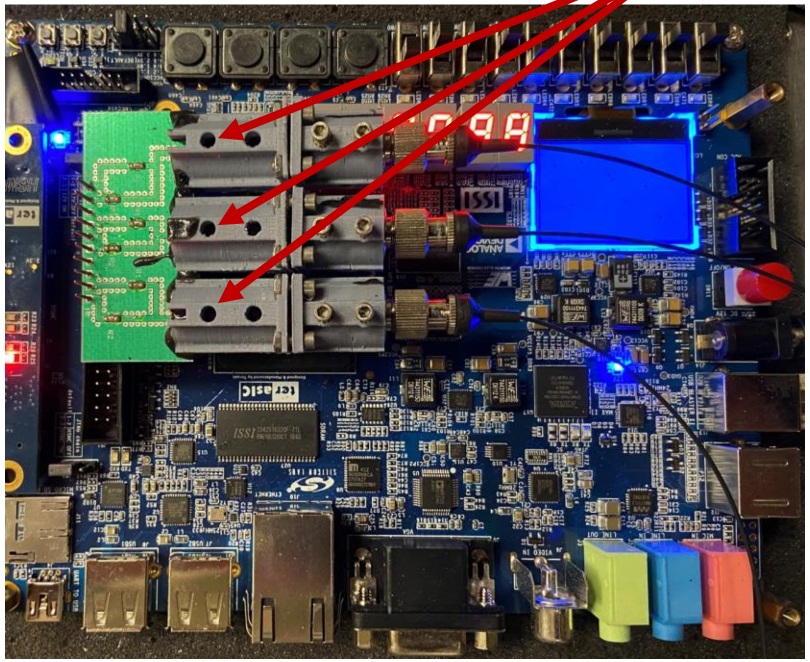
QKD Transmitter (Alice) **QKD Receiver (Bob)**



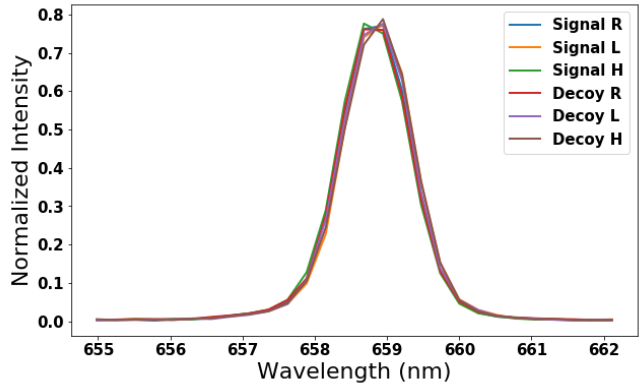
QKD Source (Resonant Cavity LEDs)

- **Decoy State Quantum Key Distribution (QKD)**
- Resonant Cavity LED Source
- Encode in Polarization Degree of Freedom (DoF)
- Signal + 2 Decoy Intensities
- FPGA-based Hardware True RNG
- 3-State protocol:
  - Signal Basis - $|R\rangle / |L\rangle$
  - Error Checking - $|H\rangle$

Roithner LaserTechnik RC650-TO46FW



- **Spectral Overlap:** 94.6% for all states, using 1-nm narrow-band filter (Andover 656FS02-12.5)



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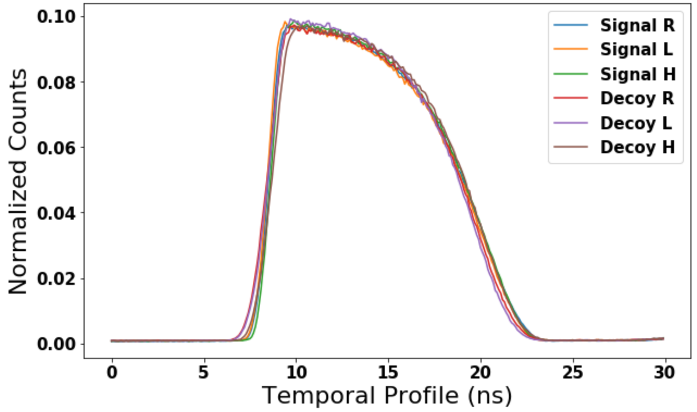
Roddy, Daniel

- **Temporal Overlap:** 97.1% for all states, after calibrating FPGA phase-locked loops



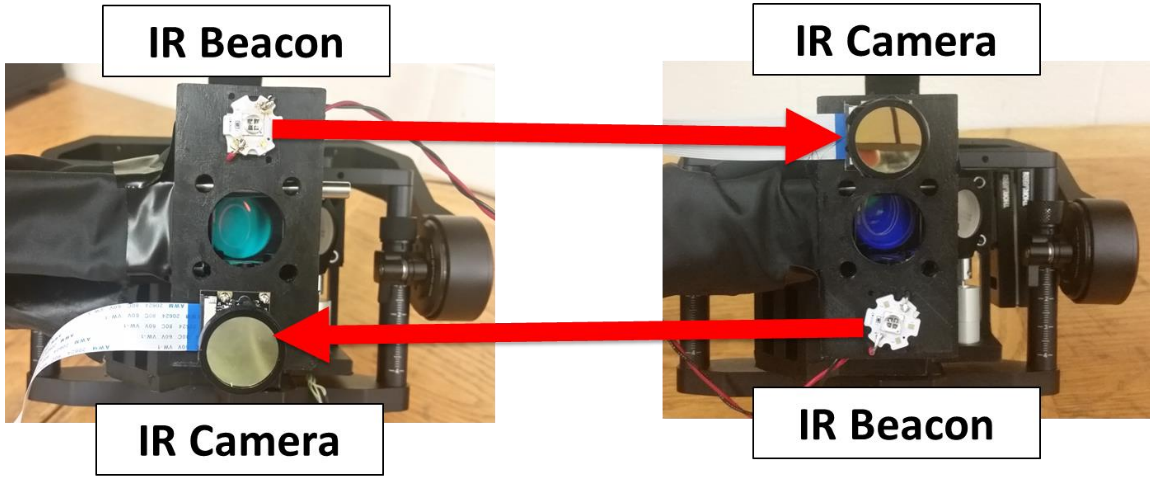
- **Spatial Overlap:** achieved using single-mode fiber (SMF)

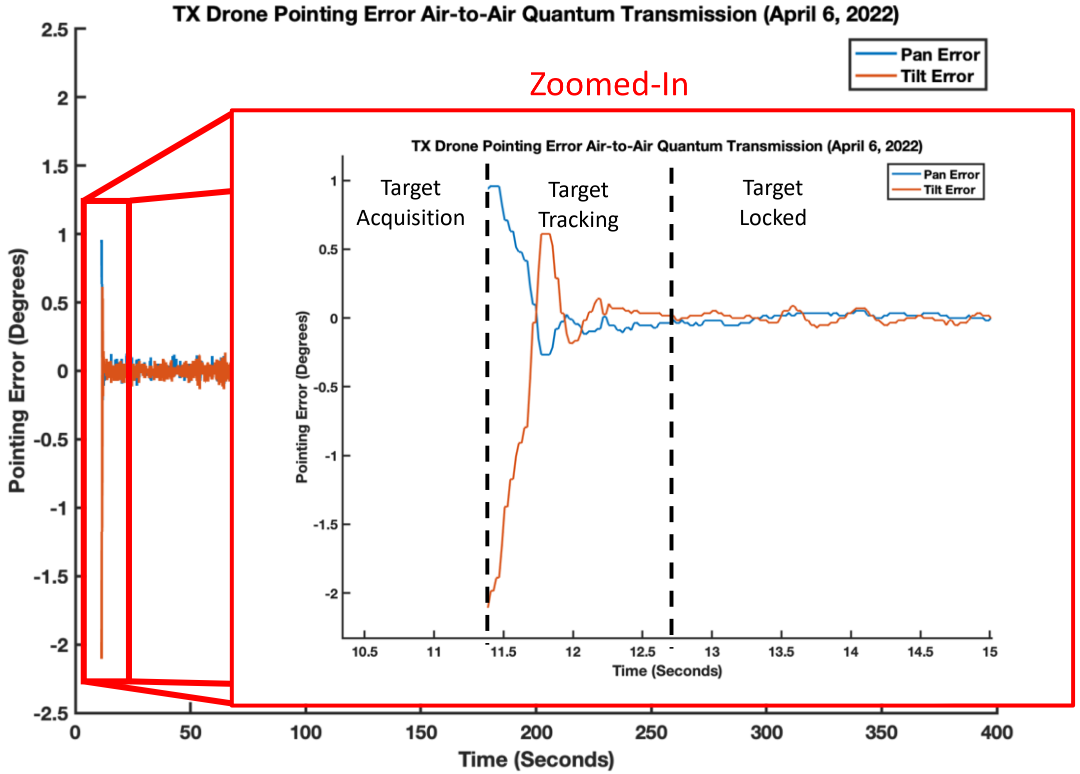
PAT Subsystem (Course Adjustment)

Outer-Control Loop Calibration

- Initial Pointing, acquisition, and course pointing
- IR Beacon/IR Camera
- Image processing to identify location in camera's reference frame
- Feedback Control

TX Drone **RX Drone**





Gimbal (Movi Pro)

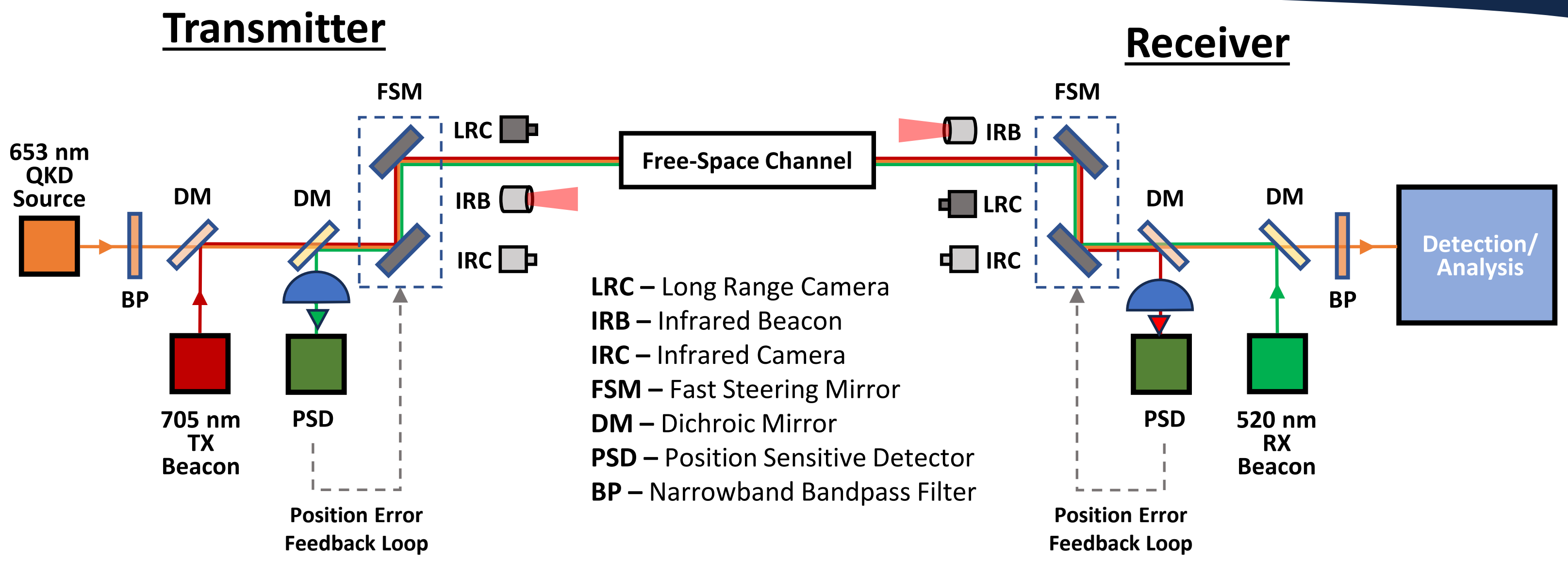
- Tracking Performance:
  - Pan RMS Error = 0.0230°
  - Tilt RMS Error = 0.0263°

Gimbal Jitter Specification = 0.02°

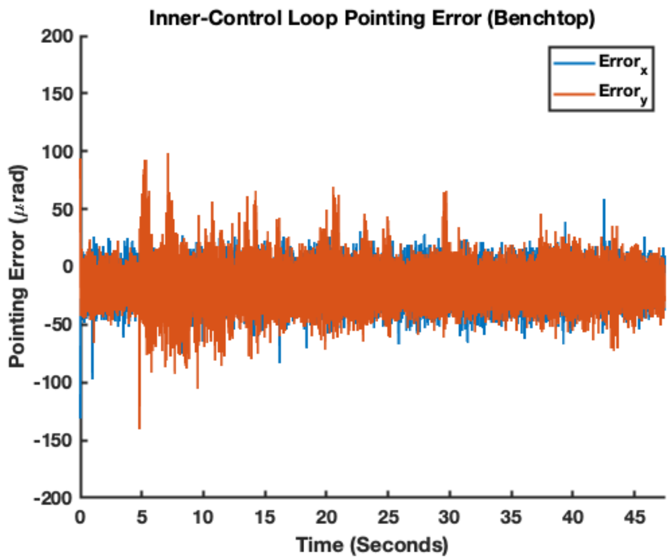
PAT Subsystem (Fine Adjustment)

PAT Subsystem (Fine Adjustment)

- Co-propagating laser beacons
  - Transmitter: 705-nm beacon
  - Receiver: 520-nm beacon
- Fast Steering Mirrors + Position Sensitive Diode (PSD)
- Senses incoming beacon beam Angle of Arrival (AoA)
- Raspberry Pi single-board computer
- Local (no PAT communication between drones)



Fast Steering Mirrors (Model LR-17)



Pointing Error_x = 21.1 μrad
Pointing Error_y = 22.9 μrad

Results

Air-to-Air Classical Locking

Drone Platform

- Alta 8 Pro Drone
- 20 lbs payload capacity
- Two 10,000 mA-hr Lithium Polymer Batteries

System Characterization

- Classical Air-to-Air Locking into multimode fiber
- Average 2.25 dB Channel Loss (60% transmission)
- 10-meter distance

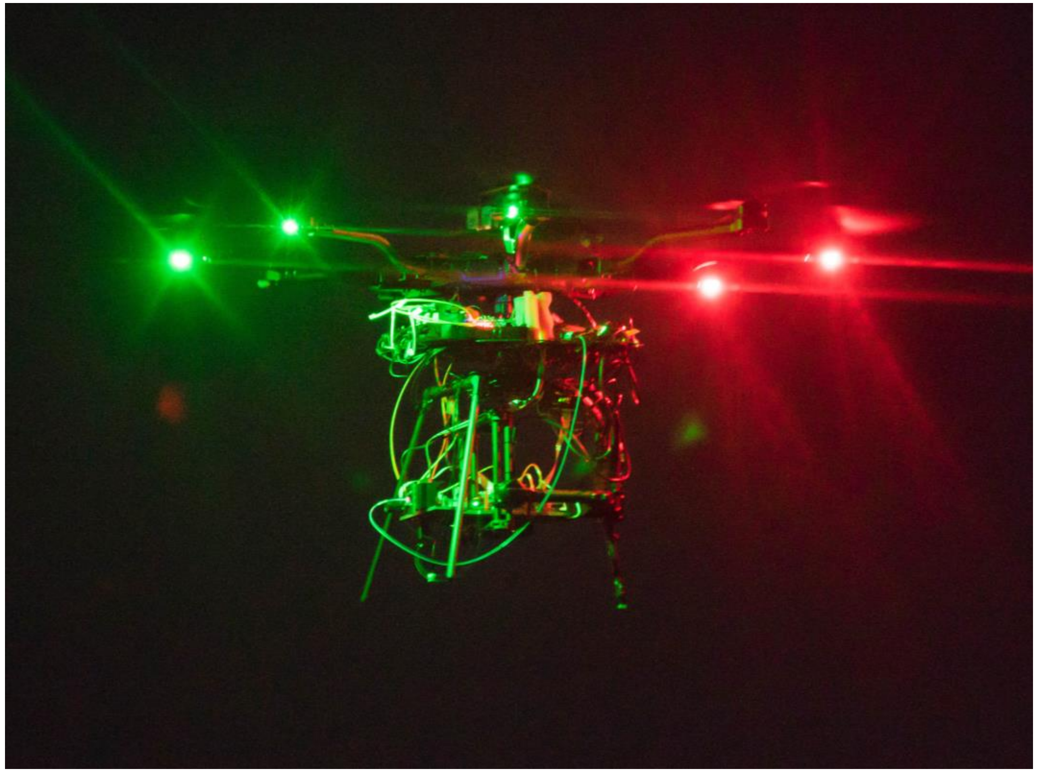
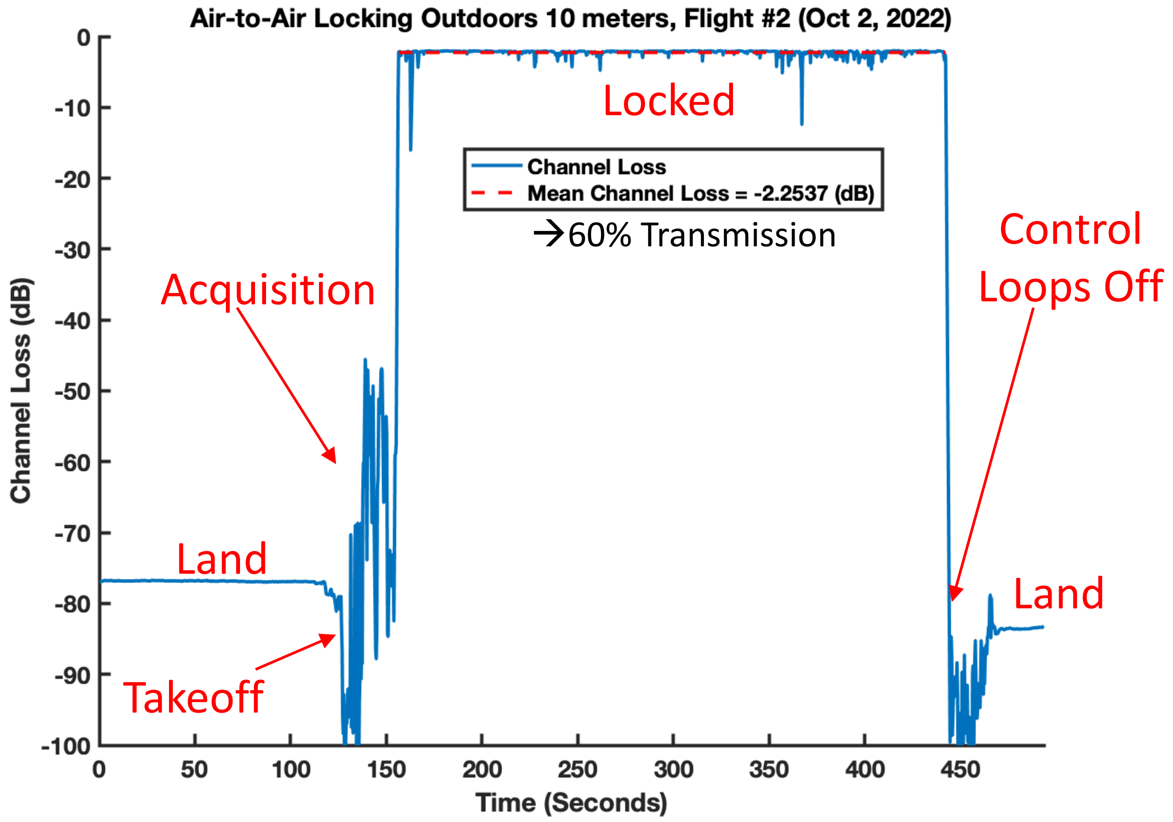


Image Courtesy Timur Javid



Drone Air-to-Air QKD Video

Drone Air-to-Air QKD Flights (Nov 2nd, 2022)

Air-to-Air QKD Setup

- Both drones hovering
- 10-meter distance between drones
- Altitude ~5 meters above ground

Quantum Transmission

- Average QBER =2.9% (R/L Basis), 3.0% (H/V Basis)
- 1st demonstration of drone-to-drone QKD
- Collaborating with Lütkenhaus group to develop tailor-made finite key analysis

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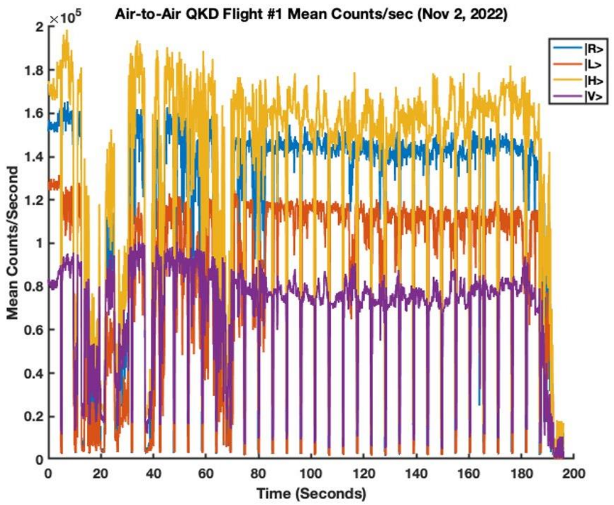
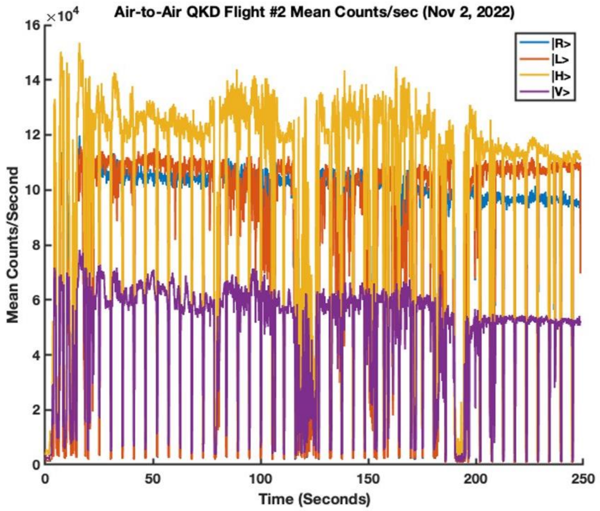
Scott, Lars

Image Courtesy Timur Javid





	Flight #1	Flight #2	Flight #3
QBER (R/L)	2.0%	1.8%	5.0%
QBER (H/V)	3.6%	3.1%	2.4%
Mean Photon Number μ	0.78	0.78	0.73

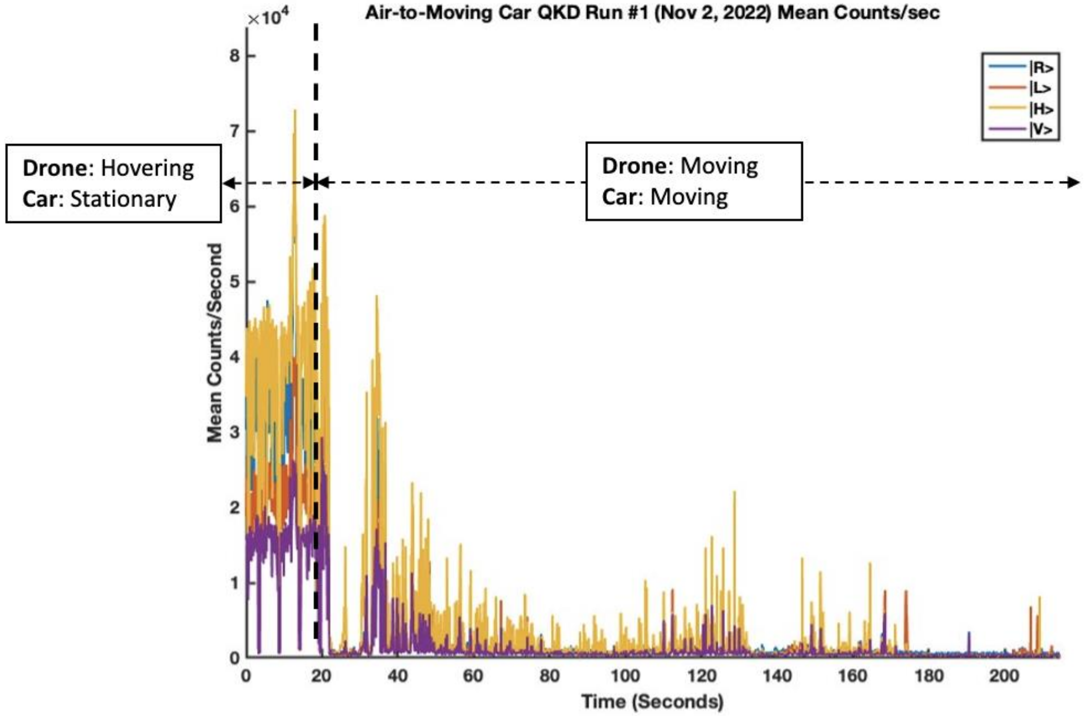
Drone-to-Vehicle Results

Air-to-Car Setup
- Drone flying parallel to moving car
- Speeds up to 10 mph
- Transmitter on drone, receiver on car

Classical Transmission
- Average coupling efficiency 38% into multimode fiber

QKD Transmission
- Average QBER = 6.4% (R/L Basis), 3.0% (H/V Basis)

Image Courtesy Timur Javid

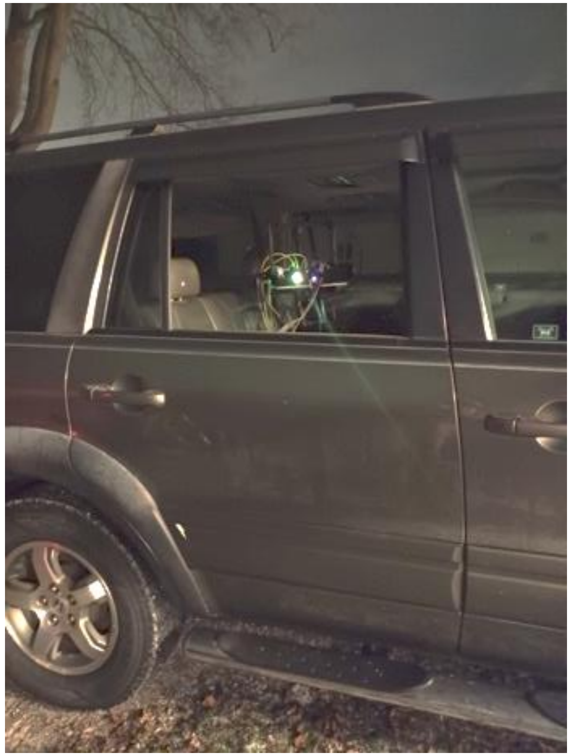


Vehicle-based Quantum Networking

Car-to-Car Setup

- Transmitter and receiver in separate cars
- Payloads are placed in car's back seat
- Speeds up to 10 mph

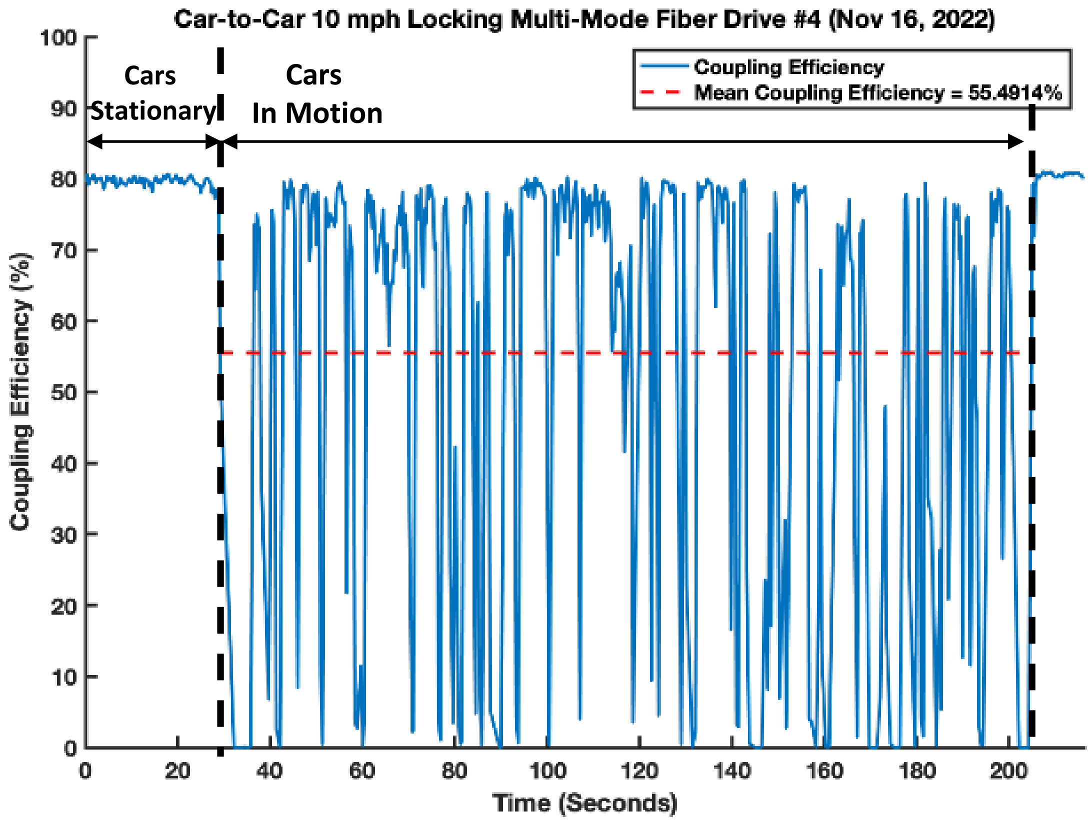
Transmitter



Receiver

Classical Transmission

- Average classical coupling efficiency 55% into multimode fiber



70 mph Vehicle-to-Vehicle Quantum Transmission

Car-to-Car Quantum Setup

- 70 mph
- Interstate Highway (I-57)
- Outer-Control Loop only (Near-IR Beacon)
- No alignment lasers
- Attenuated laser quantum source
- Coupled into multi-mode and single-mode fiber
- Achieved 70 mph 28.6 dB SNR into multimode fiber and 17.4 dB SNR into single-mode fiber
- **We believe this is the first demonstration of a car-to-car quantum link on public highway**

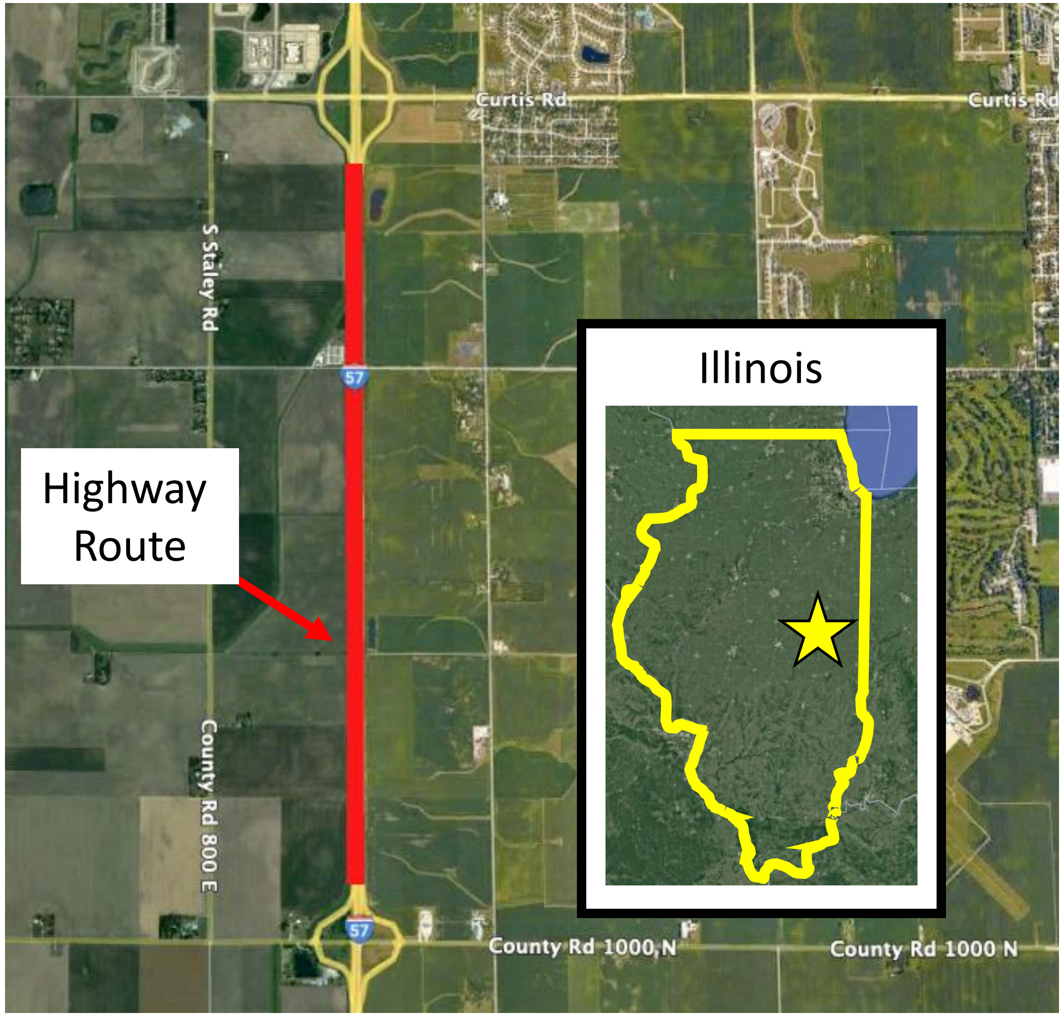


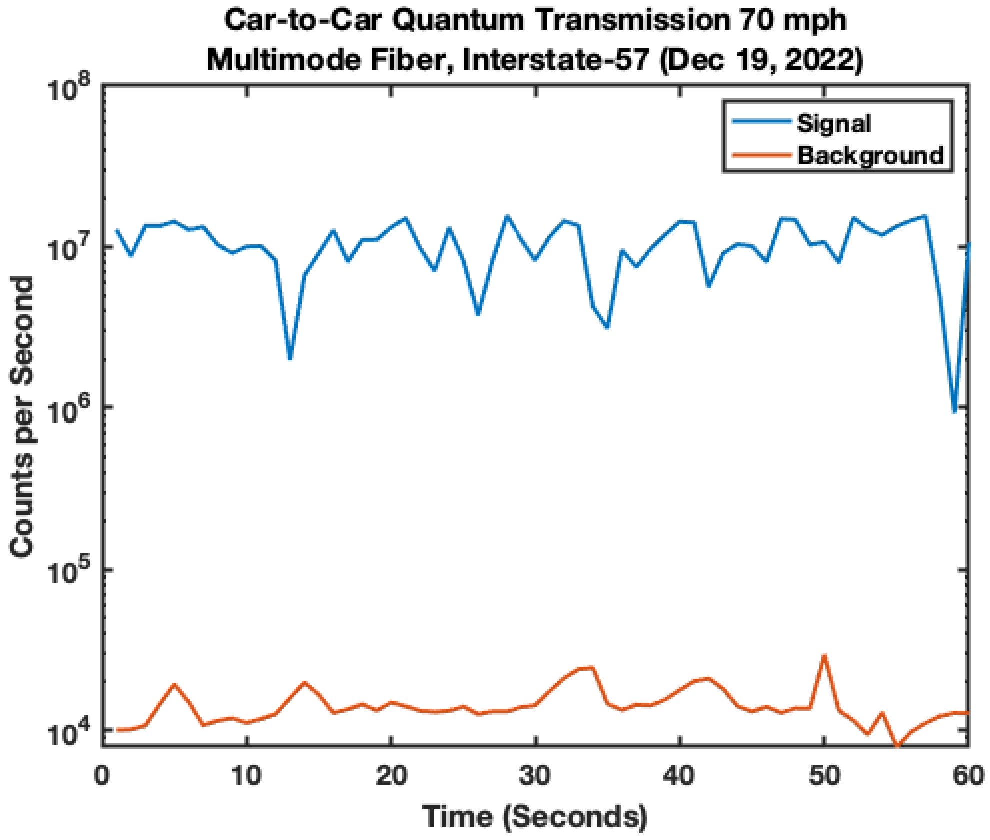
Image Courtesy Google Earth

70 mph Vehicle-to-Vehicle Quantum Transmission

70 mph Car-to-Car into Multimode Fiber

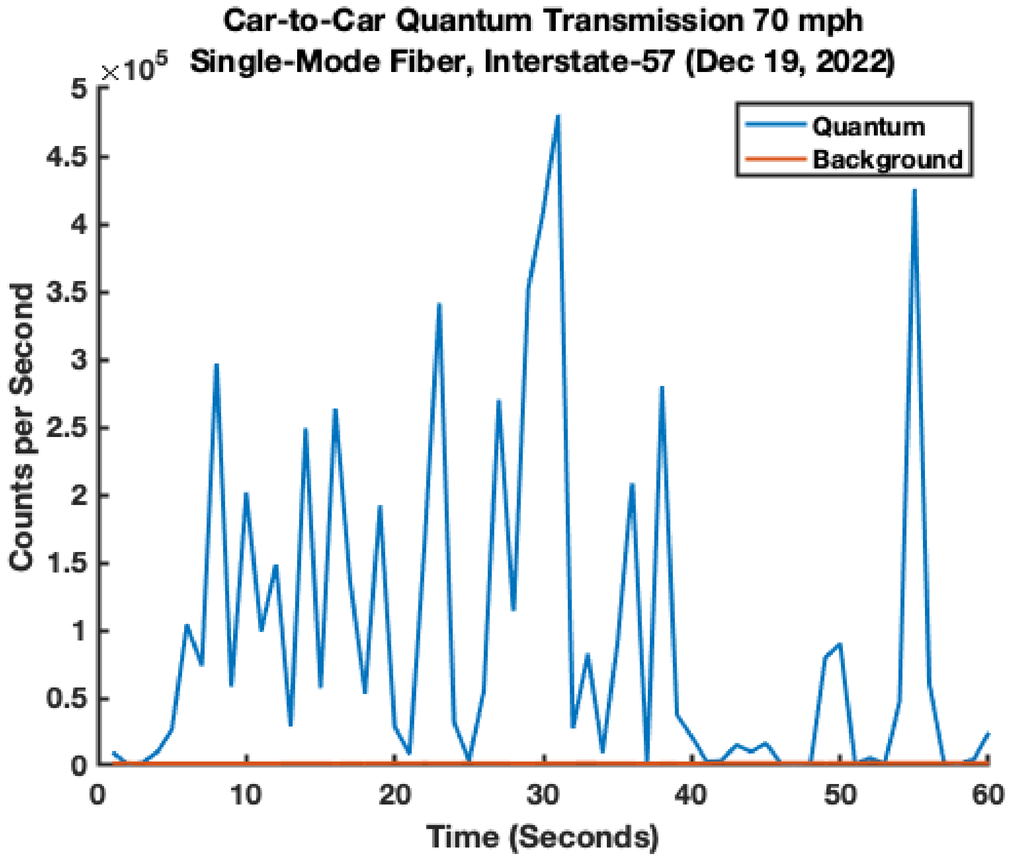
Multimode Fiber

- Mean Signal = 10,465,380 counts/sec
- Mean Background = 14,440 counts/sec
- Mean Signal-to-Noise (SNR) = 28.6 dB



Single-Mode Fiber (SMF)

- SMF needed for quantum teleportation, entanglement swapping, etc.
- Mean Signal = 97,080 counts/sec
- Mean Background = 1,730 counts/sec
- Mean Signal-to-Noise (SNR) = 17.4 dB



Summary

Summary

Summary

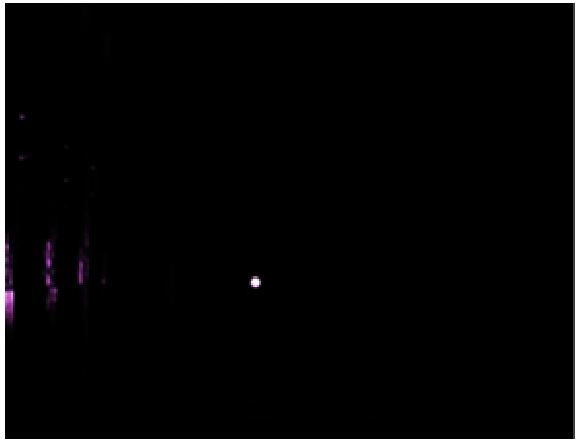
- Drone-to-Drone QKD link
  - Average QBER: 2.9% (R/L Basis), 3.0% (H/V Basis)
  - 60% mean classical coupling efficiency
  - 1^{st} known demonstration
- Drone-to-Car QKD link
  - Average QBER = 6.4% (R/L Basis), 3.0% (H/V Basis)
  - 38% mean classical coupling efficiency
  - 1^{st} known demonstration
- Car-to-Car Quantum link
  - 70 mph on highway
  - 28.6 dB SNR into multimode fiber
  - 17.4 dB SNR into single-mode fiber
  - 1^{st} known demonstration

Next Steps

System Upgrades

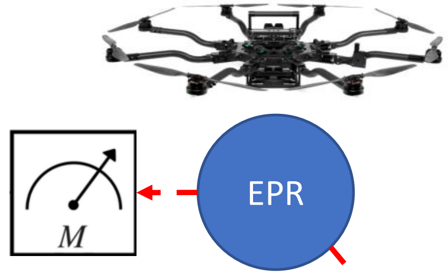
- Increase operating distances
  - 275 meters on ground
- Night → Daytime Operation:
  - SMF coupling
  - More spectral filtering
  - Pulsed beacons

NIR Beacon as seen by PAT Gimbal Camera (275-m Distance)

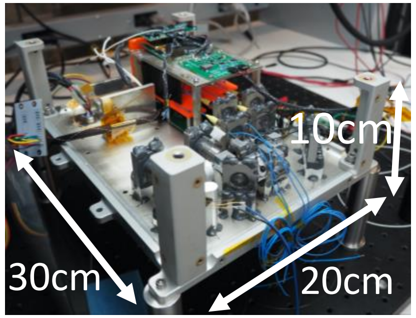


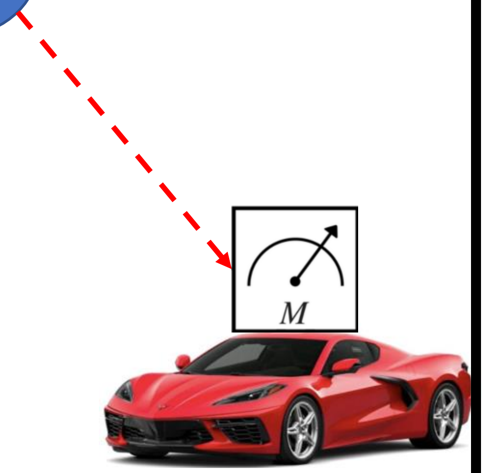
Entanglement Distribution

- Distribute EPR Pair between two mobile platforms
- Requires free-space quantum link
- Building block for distributed quantum sensors



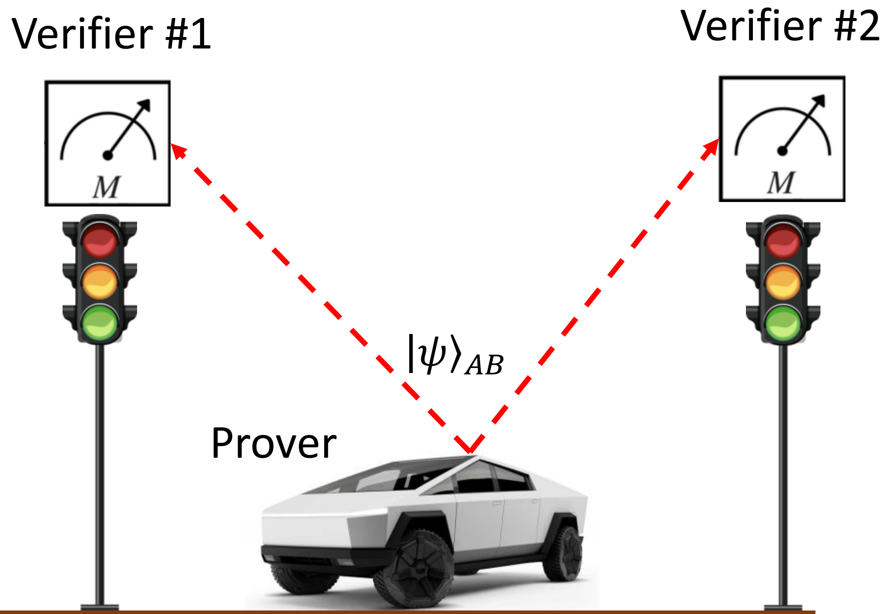
SEAQUE Entanglement Source [1]





Quantum Position Verification (QPV)

- Authenticate the position of a mobile platform using Quantum Resources
- Verifiers collaborate to accept or reject the proposed position of a prover (P)
- Modulated Entanglement state: $|\psi\rangle_{AB}$



[1] Ortiz, Kelsey. "SEAQUE (Satellite Entanglement and Annealing Quantum Experiment)." *Bulletin of the American Physical Society* (2023).

Research Team

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Image Courtesy Alan Mitchell

Office of Naval Research ONR Science & Technology

NAWC Aircraft Division NAVAL AIR WARFARE CENTER

NDSEG NATIONAL DEFENSE SCIENCE AND ENGINEERING GRADUATE FELLOWSHIP PROGRAM

The Grainger College of Engineering
Illinois Center for Transportation

SOCHE Strategic Ohio Council for Higher Education

Questions?

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Photo: Timur Javid

Quantum State Tomography

Quantum State Tomography Results

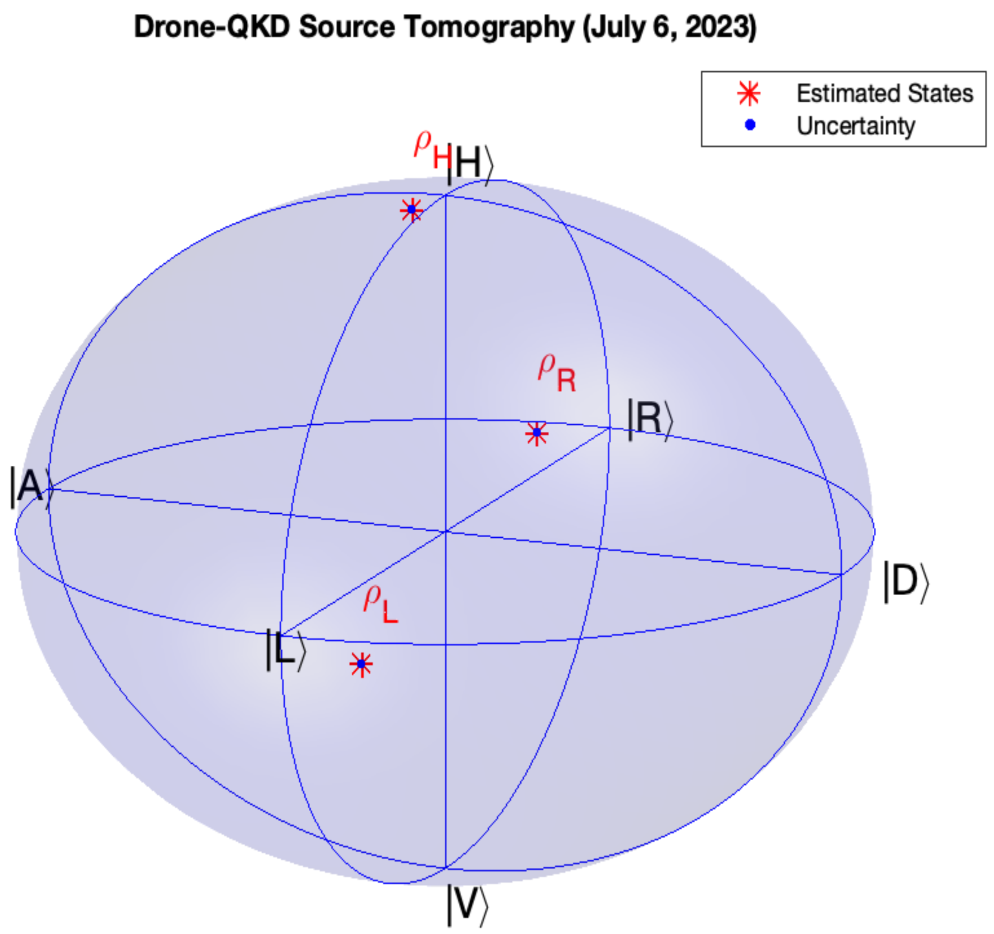
$$\rho_H = \begin{pmatrix} 0.9958 + 0.0000i & -0.0155 + 0.0625i \\ -0.0155 - 0.0625i & 0.0042 - 0.0000i \end{pmatrix}$$

$$\rho_R = \begin{pmatrix} 0.4831 + 0.0000i & -0.0868 - 0.4909i \\ -0.0868 + 0.4909i & 0.5169 + 0.0000i \end{pmatrix}$$

$$\rho_L = \begin{pmatrix} 0.4646 + 0.0000i & 0.0958 + 0.4845i \\ 0.0958 - 0.4845i & 0.5354 + 0.0000i \end{pmatrix}$$

State	Purity	Purity Uncertainty	Fidelity	Fidelity Uncertainty	RMS Error
$\|H\rangle$	1	+/- 1.69e-07	0.99	+/- 6.00e-6	5.59e-4
$\|R\rangle$	0.99	+/- 2.34e-04	0.99	+/- 1.19e-4	1.68e-06
$\|L\rangle$	0.99	+/- 3.54e-05	0.98	+/- 1.35e-5	1.27e-08

$$\text{QBER Estimate} = \frac{1}{2} \cdot (\text{trace}(\rho_L \cdot |R\rangle\langle R|) + \text{trace}(\rho_R \cdot |L\rangle\langle L|) = 1.2\%$$



Quantum Transmitter Bench