Kwiat
Quantum
Information
Group

Drone-based Quantum Key Distribution

QCrypt 2021

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Drone Applications Overview

Drone Applications:

- Drone Taxis
- Cinematography
  - Many movies use drones
- Situational awareness
  - Disaster awareness
- Defense
  - Predator Drone
- Package delivery
  - Organ donations
  - Covid-19 Vaccine[1]

Drone Taxis

Drone Cinematography

Limited Package Delivery

Defense

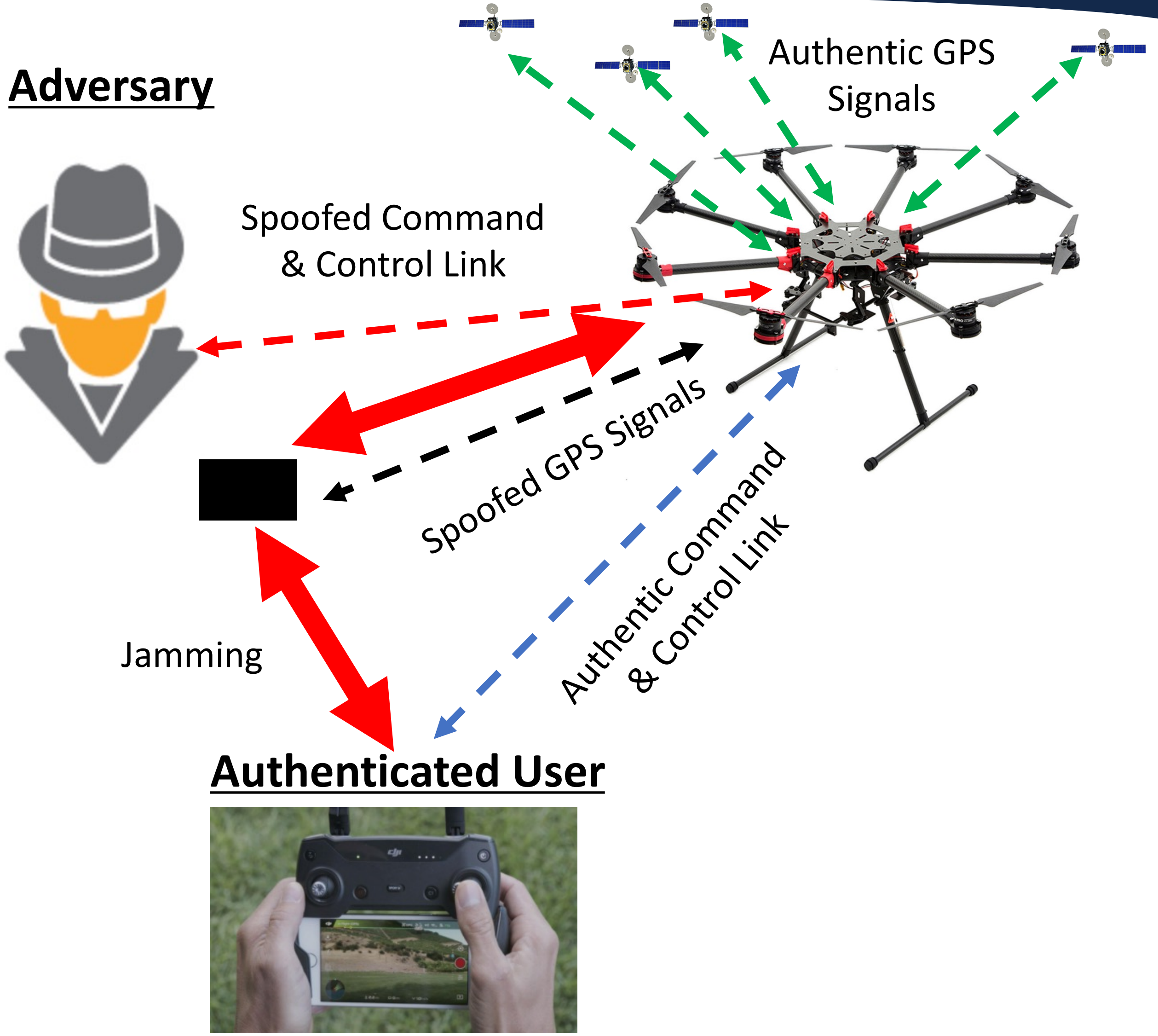
[1] https://www.theverge.com/2021/3/9/22320965/drone-delivery-vaccine-ghana-zipline-cold-chain-storage

Drone Attack Vectors

Drone Attack Vectors:

- Signal Spoofing:
  - Command and control signals
  - Sensor inputs
- Denial of Service:
  - Command and control signals
  - Sensor inputs

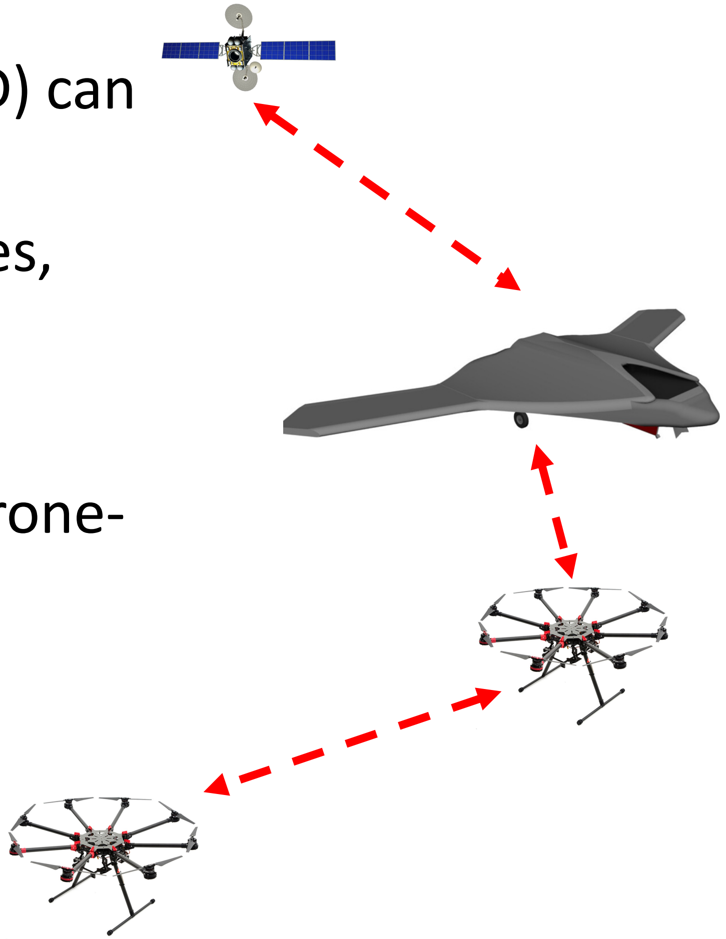
Captured RQ-170 Drone



Quantum Security

Quantum approaches such as Quantum Key Distribution (QKD) can offer improved security for future done constellations

- Many applications require free-space links, e.g., ships, planes, satellites
- Turbulence and fog mitigation
- Entanglement distribution has been established between drone-ground[1], and drone-drone-ground relay[2]
- Gap:
  - **Short-range mobile QKD Communication Systems**
  - **Drone-to-Drone Full-System QKD**



[1]Liu, Hua-Ying, et al. "Drone-based all-weather entanglement distribution." *arXiv preprint arXiv:1905.09527* (2019).
[2]Liu, Hua-Ying, et al. "Optical-relayed entanglement distribution using drones as mobile nodes." *Physical Review Letters* 126.2 (2021): 020503.

Drone-based QKD

Critical Subsystems

- Drone Platform
- Compact QKD Source (Dual Technology Development)
- TX Optics (Quantum State Preparation)
- Pointing, Acquisition, and Tracking (PAT) Subsystem
- RX Optics (Quantum State Projection)
- Single-Photon Detectors
- Time-Tagger
- Time Synchronization (Dual Approach)

DJI S1000+ Drone

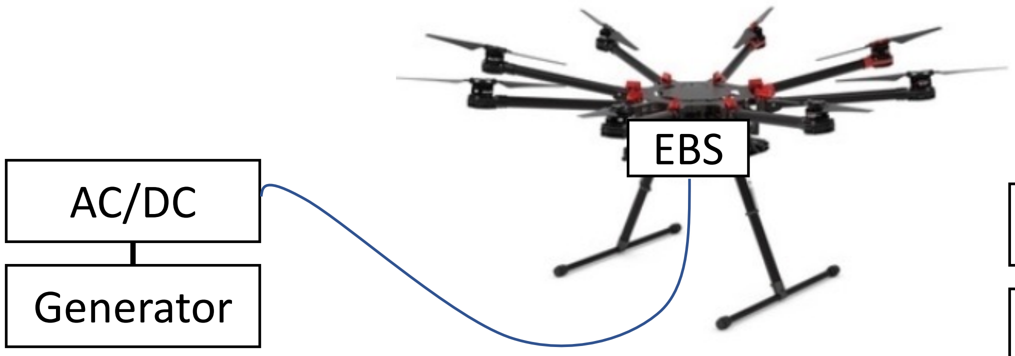
Drone Platform

DJI S1000+ Specifications

- Manufacturer: DJI [China]
- Diameter: 1.045 m
- Max Power: 4 kW
- Payload Capacity: 6.6 kg
- Flight Controller: A2/WooKong [both Chinese]
- Hover Time: ~~15 min~~ ∞ (power tether)
- Redundant Subsystems: None

Alta 8 Pro Specifications

- Manufacturer: Freefly Systems [U.S. Based]
- Diameter: 1.325 m
- Max Power: 7.6 kW
- Payload Capacity: 11.9 kg
- Flight Controller: Freefly Custom Build
- Hover Time: ~~~15 min~~ ∞ (power tether)
- Redundant Subsystems: Dual Batteries, Dual Flight Controller Wire Harnesses



QKD Source (Resonant Cavity LEDs)

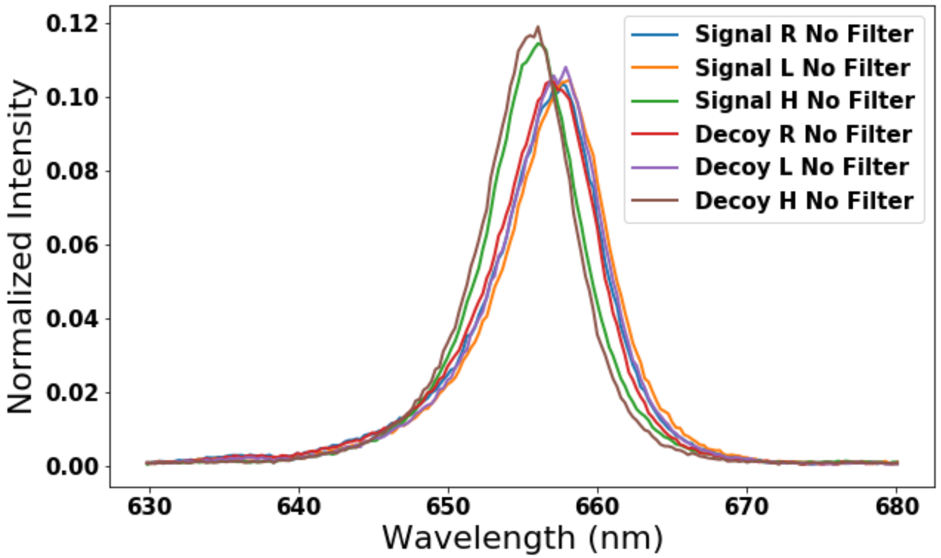
Use one emitter per quantum state

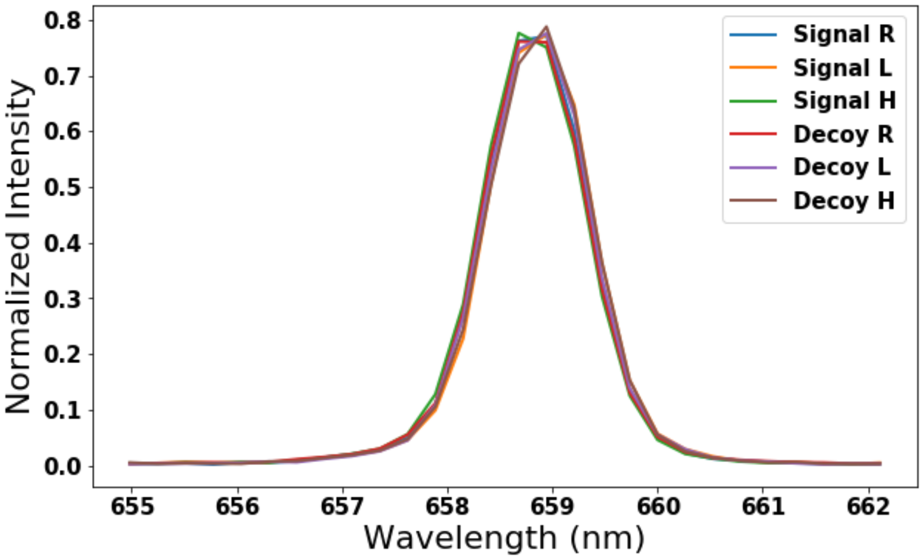
Need low power and weight for drone operation

- Broad-band light resonant-cavity LED[1],
- The spectra from the three LEDs is broad (~12 nm) and they are partially distinguishable (78% overlap), as shown in Figure 2.
- By passing the optical pulses through a 1 nm narrow-band filter (Andover 656FS02-12.5), the overlap is drastically improved to 94.6%.

QCypt 2021 Poster Session

209. **Preparing Indistinguishable States for a Prepare-and-Measure BB84 Polarization-Based Decoy State QKD Protocol Using Three FPGA-Driven LEDs**
Daniel Sanchez-Rosales (Ohio State University); Roderick D. Cochran (Ohio State University); Daniel J. Gauthier (Ohio State University)



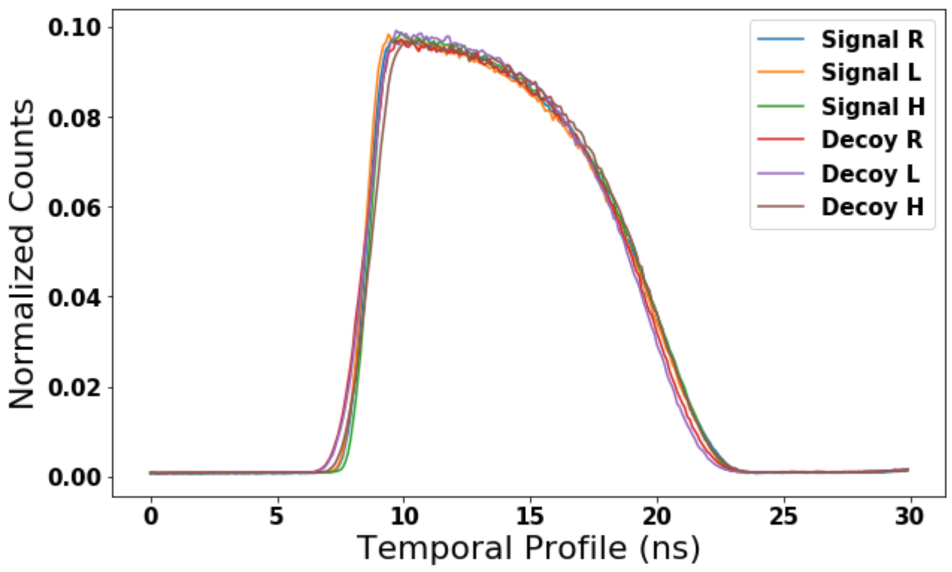


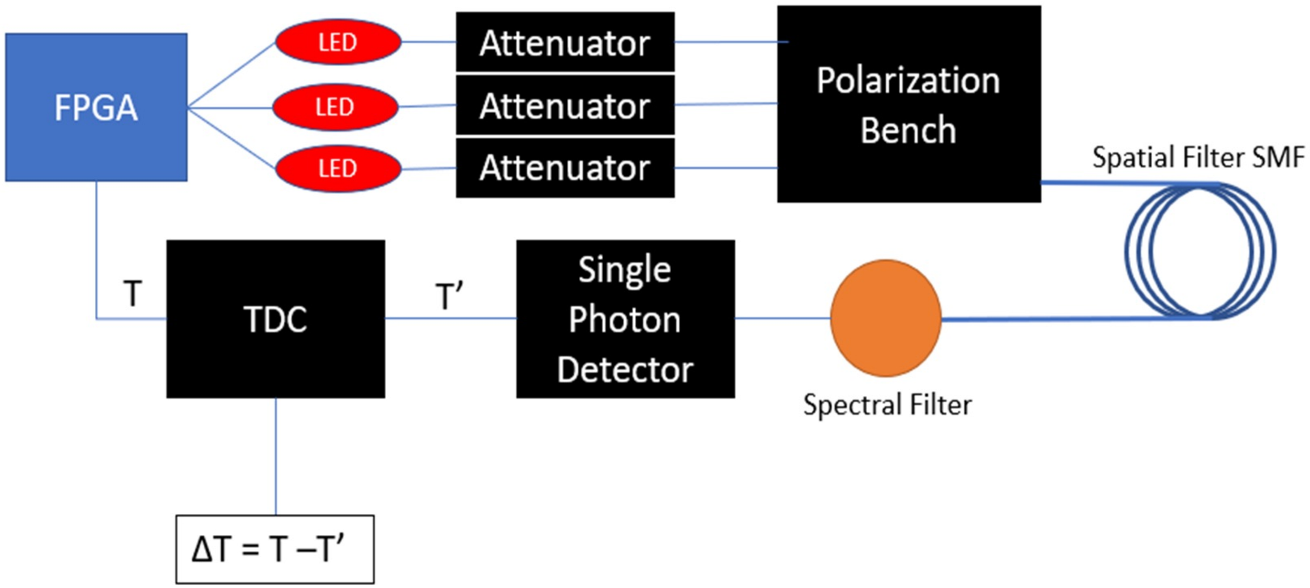
Roithner LaserTechnik RC650-TO46FW

[1]Chun et al. 'Handheld free space quantum key distribution…,' Opt. Express 25, 6784 (2017).

Temporal Overlap

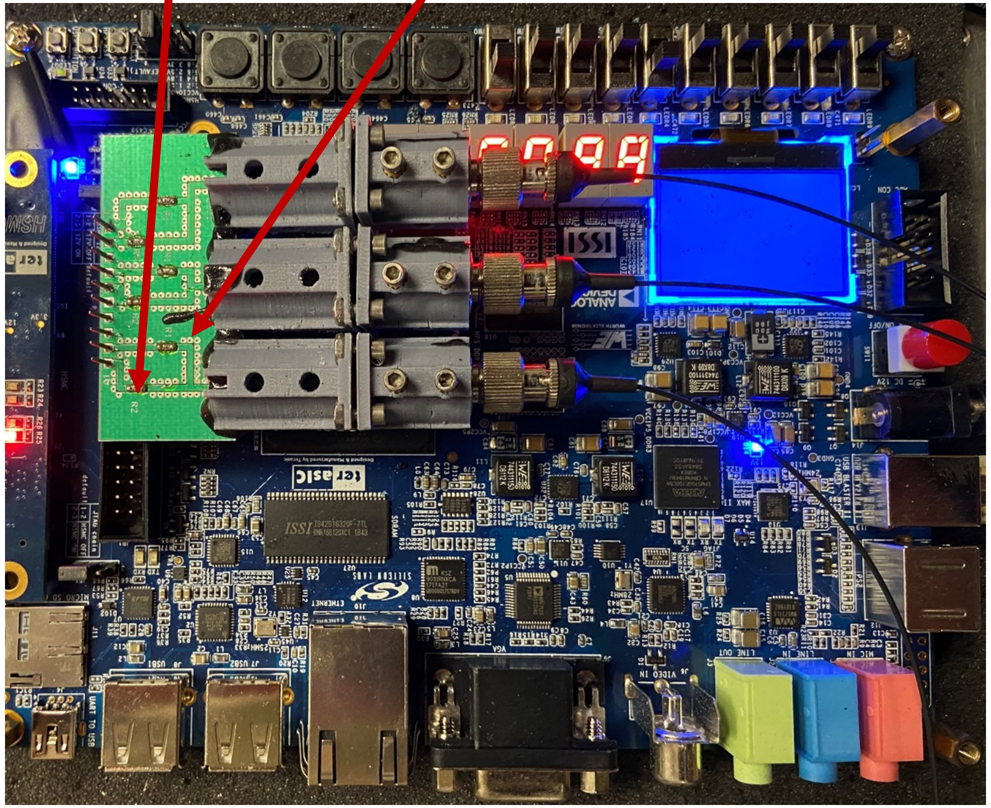
- We use dynamic shifting of the FPGA phase-locked-loops to control the phase and the width of the electrical pulses that drive the LEDs.
- This allows us to control the optical pulses produced by the LEDs with a resolution of 250 ps.
- We drive a single LED with a 10-ns wide electrical signal at a repetition rate of 12.5 MHz.
- The resulting adjusted temporal waveforms are 97.1% overlapped



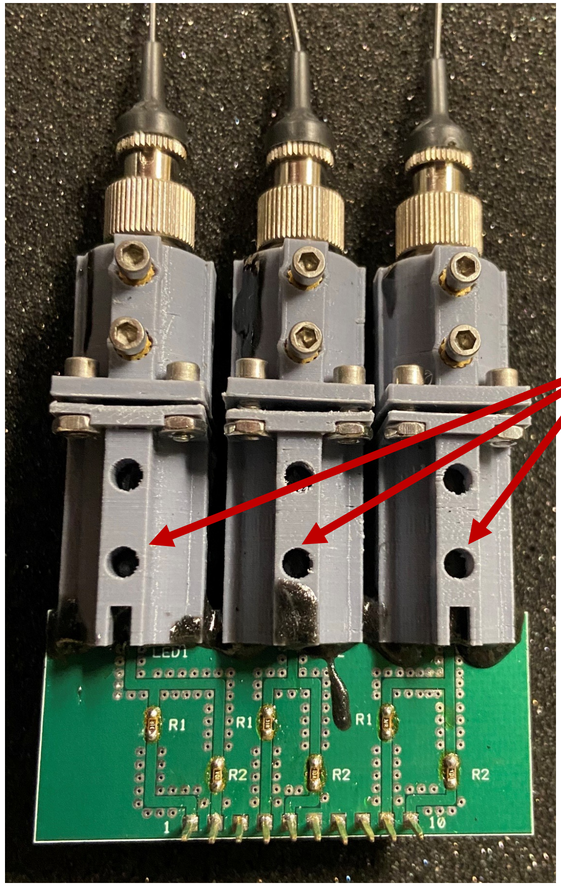


QKD Source (Resonant Cavity LEDs)

- Direct-drive LEDs with FPGA (Altera DE0-SoC)
- Two FPGA channels drive a single LED for signal and a decoy state



- 3D-printed custom coupler to mate with single-mode fiber
- Adjustment screws maximize SMF coupling



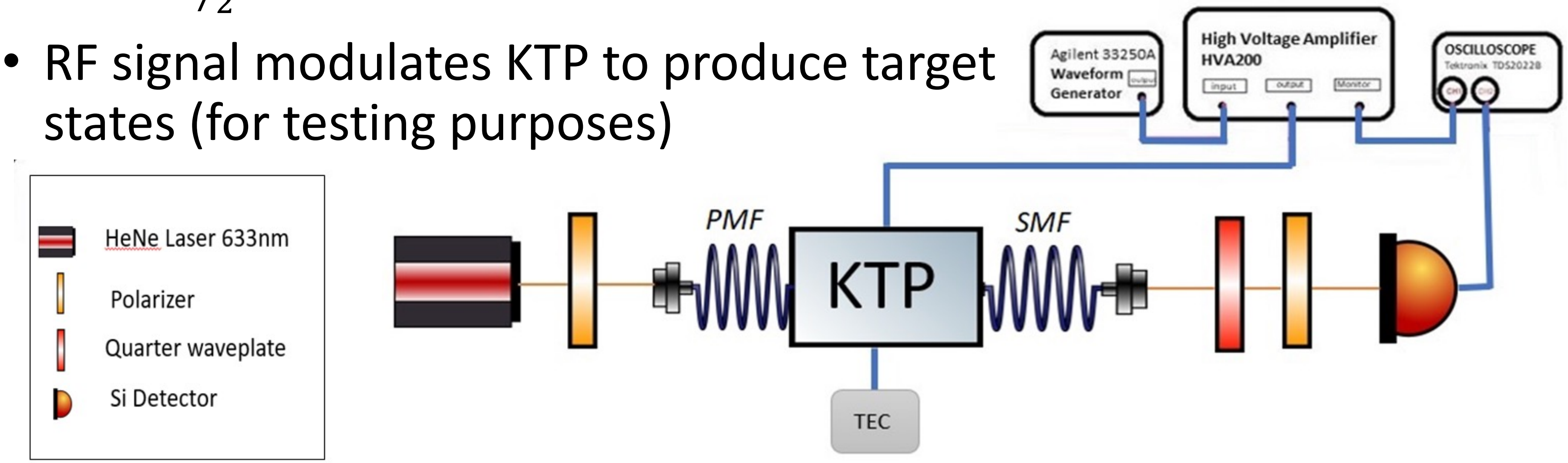
Roithner LaserTechnik RC650-TO46FW

QKD Source (Polarization Modulator)

Secondary QKD Source

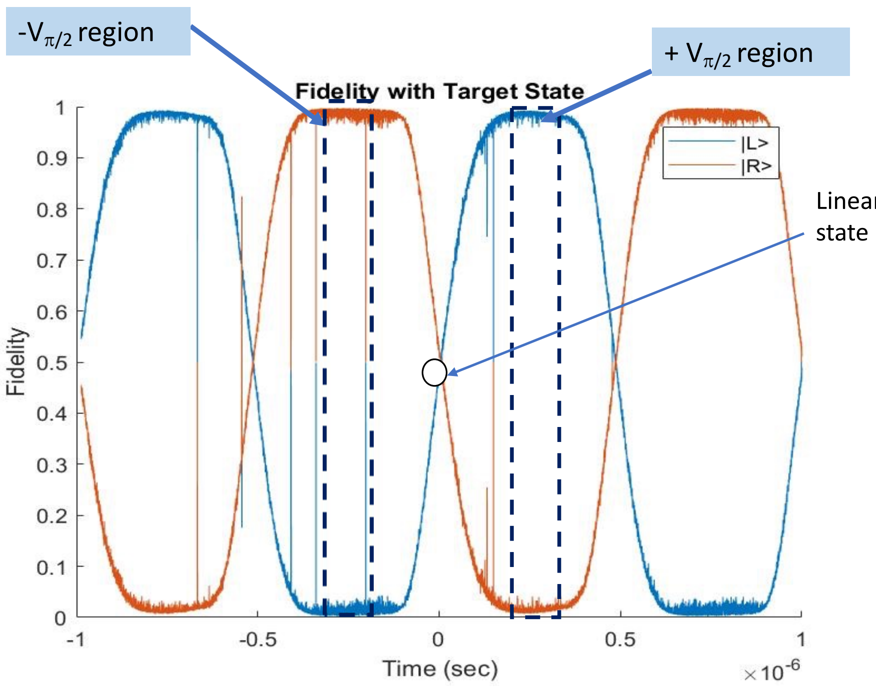
- Custom Polarization Modulator (AdvR)
- Input Polarization Maintaining Fiber (PMF) is keyed at 45° w.r.t. KTP fast axis
- Frequency response 6 GHz
- Low $V\pi/_2$
- RF signal modulates KTP to produce target states (for testing purposes)

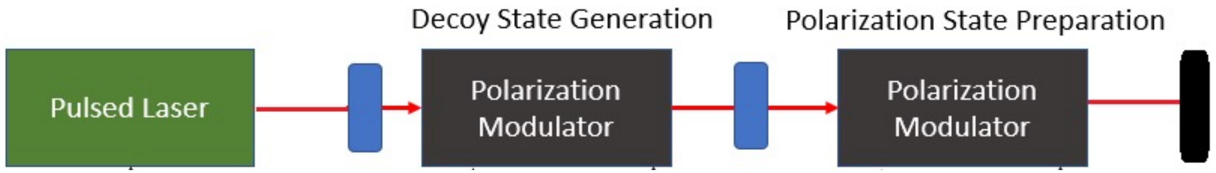
Voltage	Phase	State
0	0	$\|D\rangle$
$+V\pi/_2$	$e^{+i\pi/2}$	$\|R\rangle$
$-V\pi/_2$	$e^{-i\pi/2}$	$\|L\rangle$

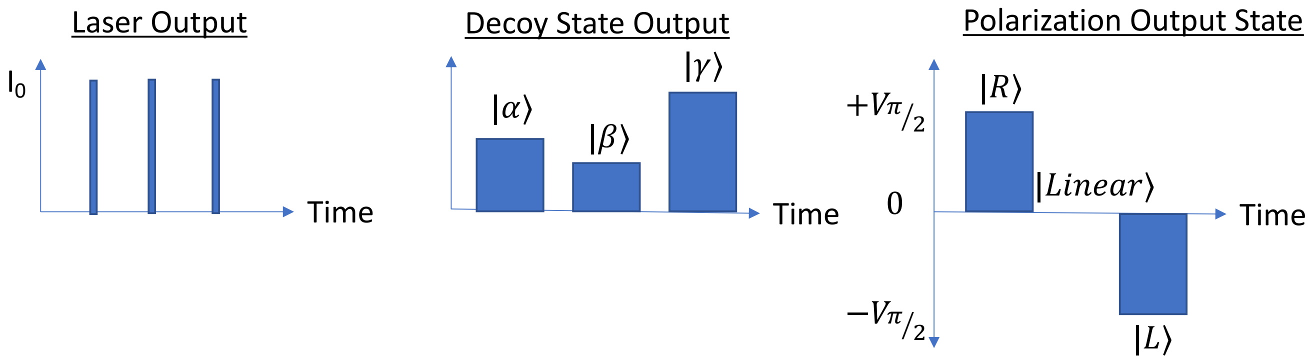


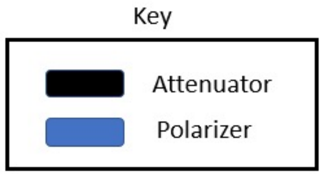
Fidelity and Quantum Bit Error Rate

RF Voltage	Phase	Target State	QBER
$+V\pi/_2$	$e^{+i\pi/2}$	$\|R\rangle$	0.01035
$-V\pi/_2$	$e^{-i\pi/2}$	$\|L\rangle$	0.0109
0	0	$\|Linear\rangle$	0.0123





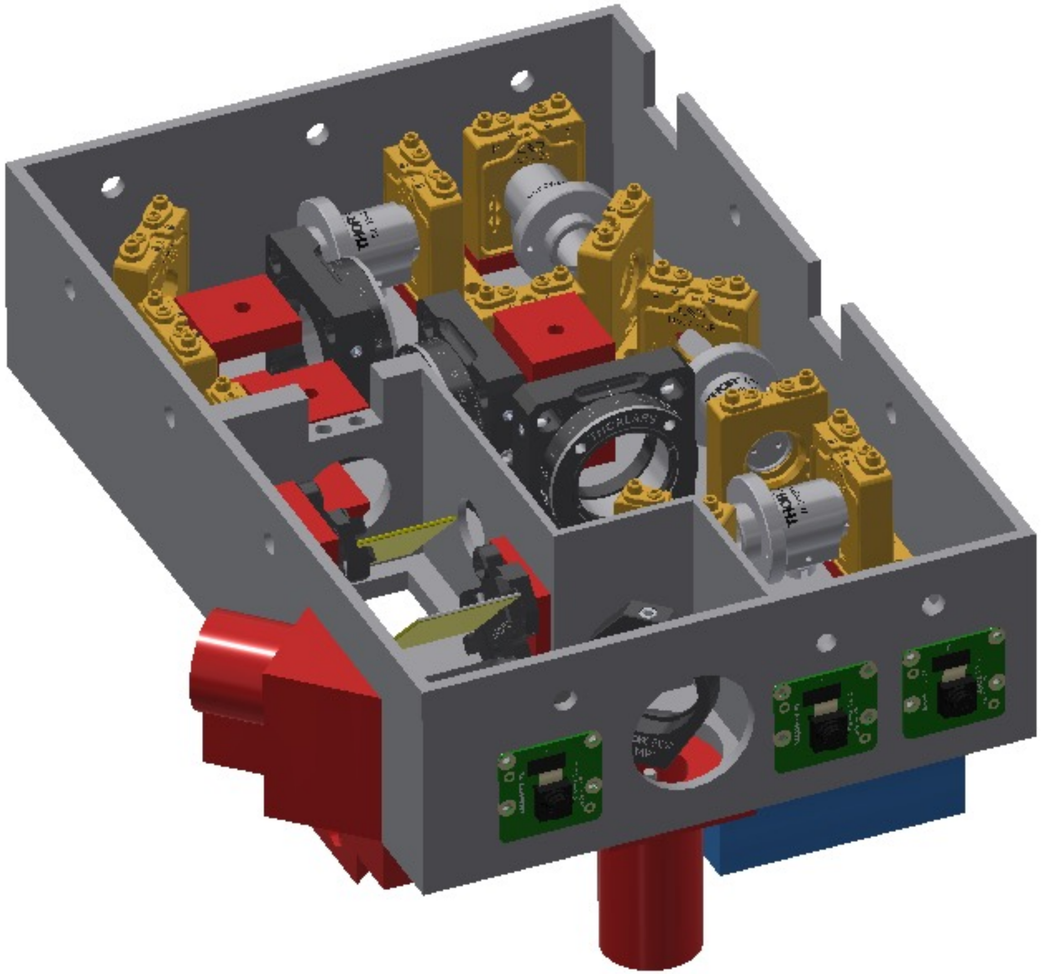




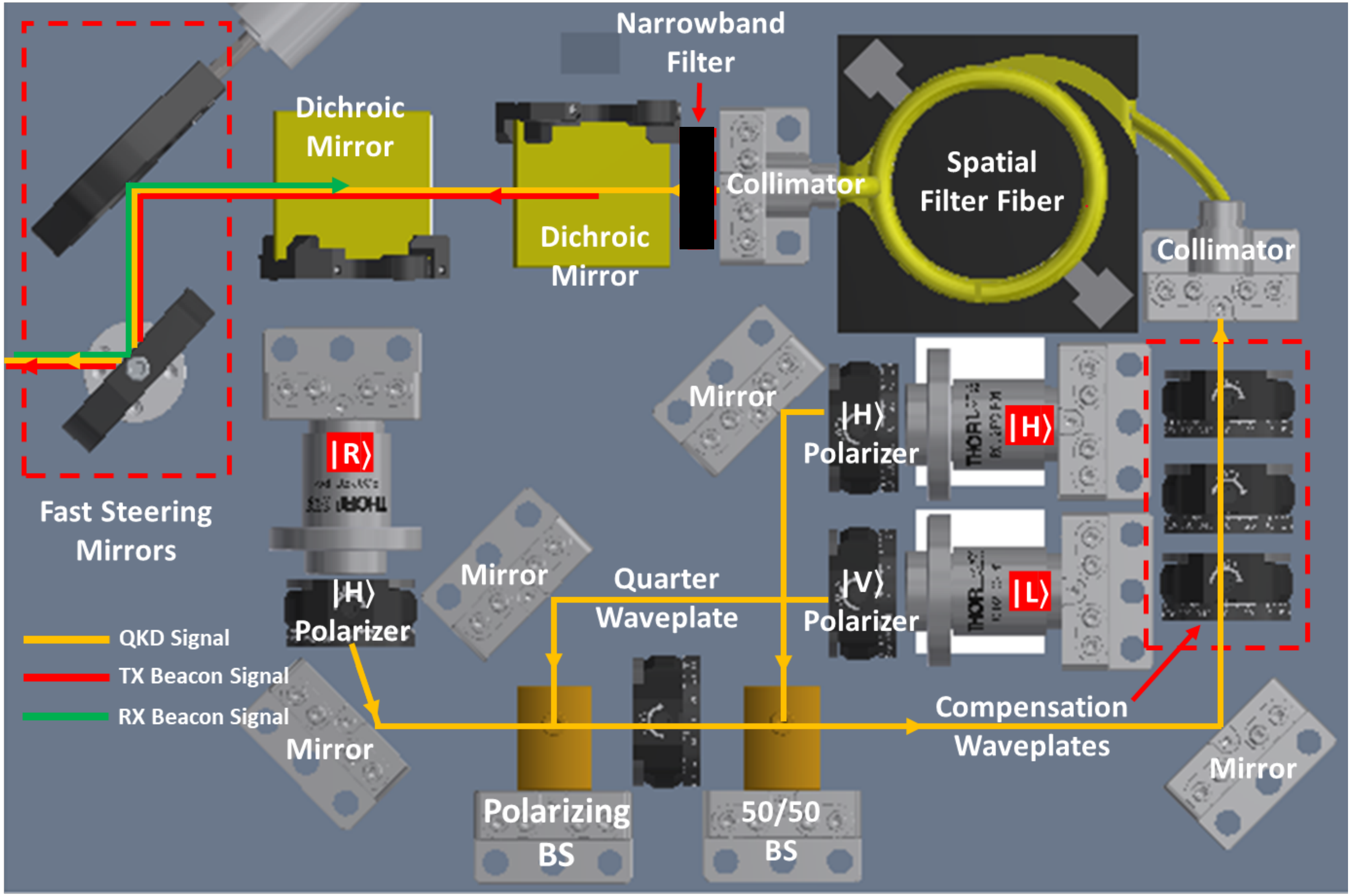
TX/RX Optics

TX/RX Optics

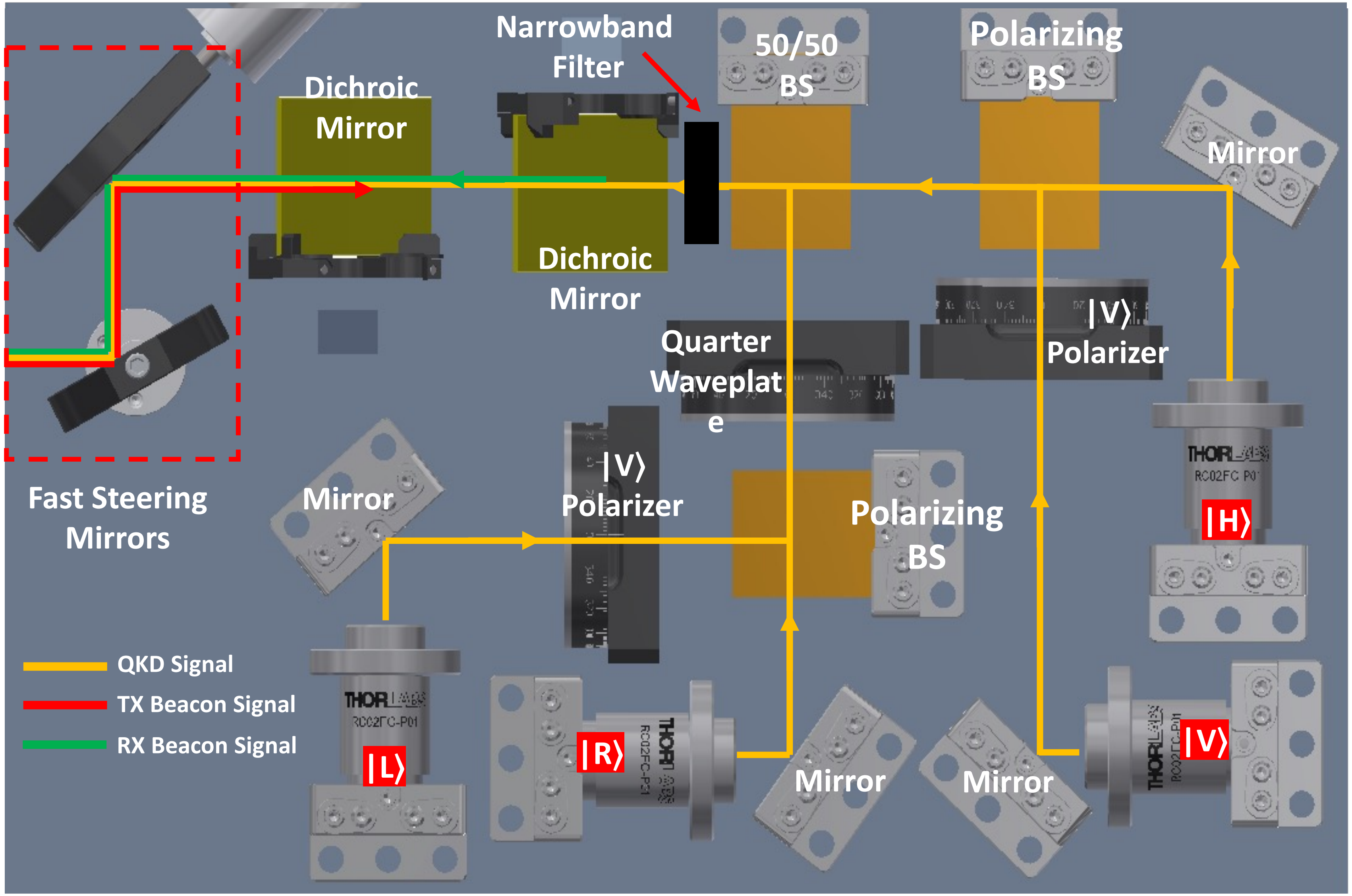
- Custom 3D-printed Design
- TX: Quantum State Preparation
- RX: Quantum Projection Measurements
- Critical Components:
    - Polarizing Beam Splitter (PBS)
    - Beam Splitter
    - Polarizers
    - Waveplates
    - Collimators
    - IR Beacon
    - IR Camera
    - Fast Steering Mirrors (FSM)



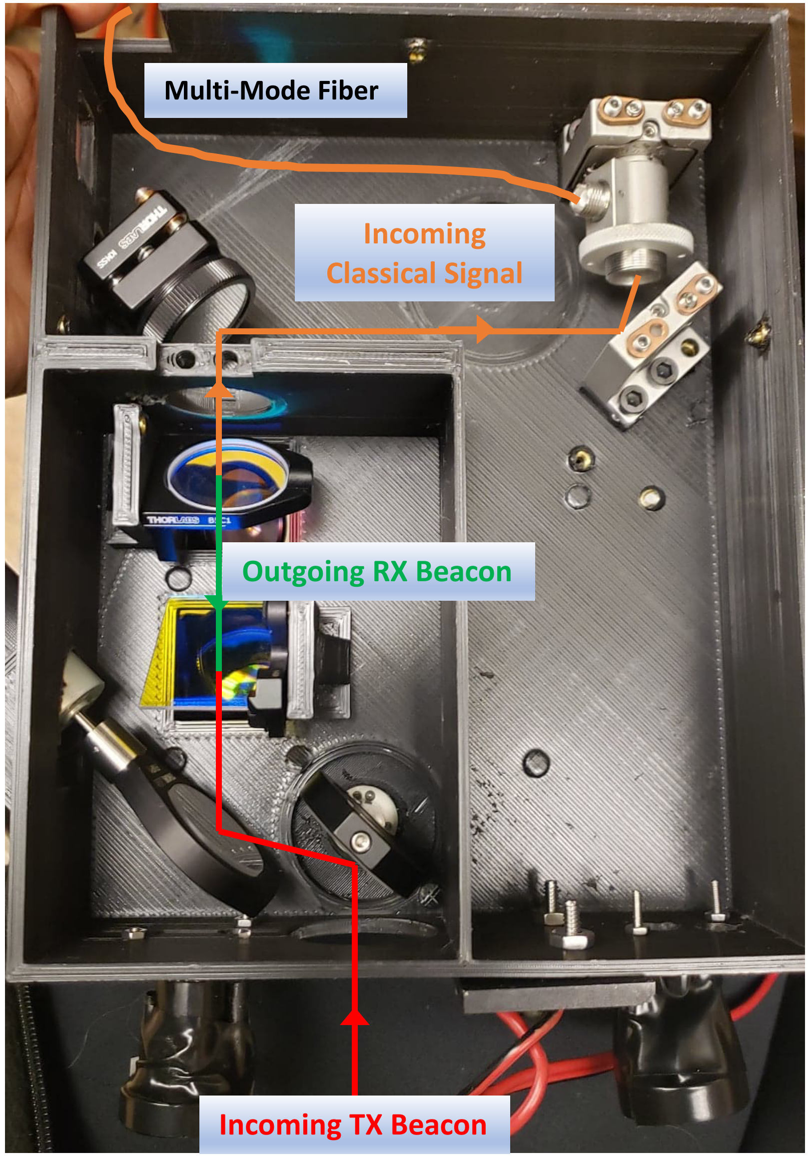
TX Optics Bench

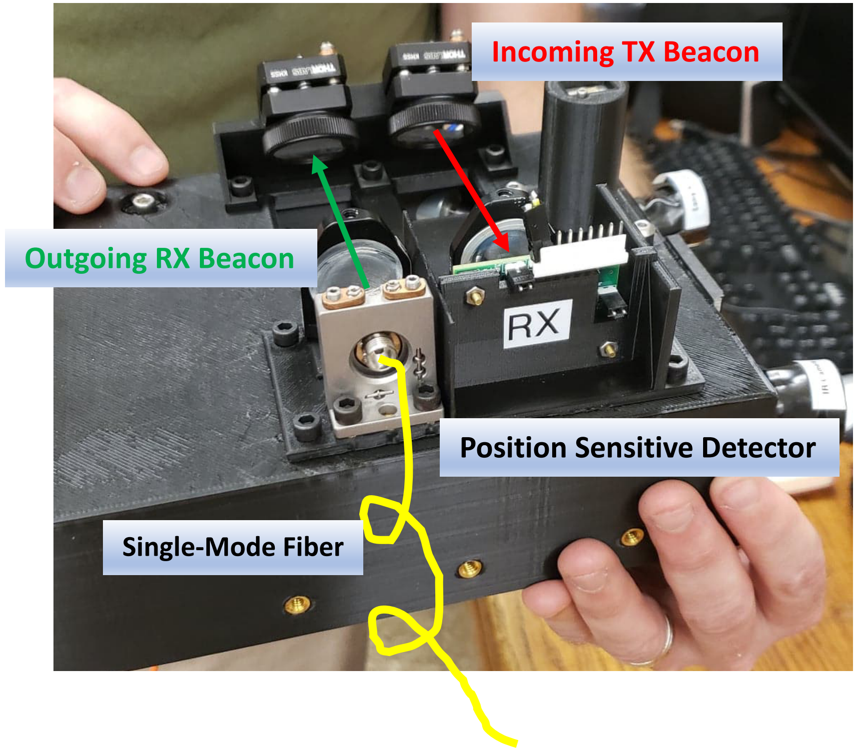


RX Optics Bench



RX Payload For PAT Testing



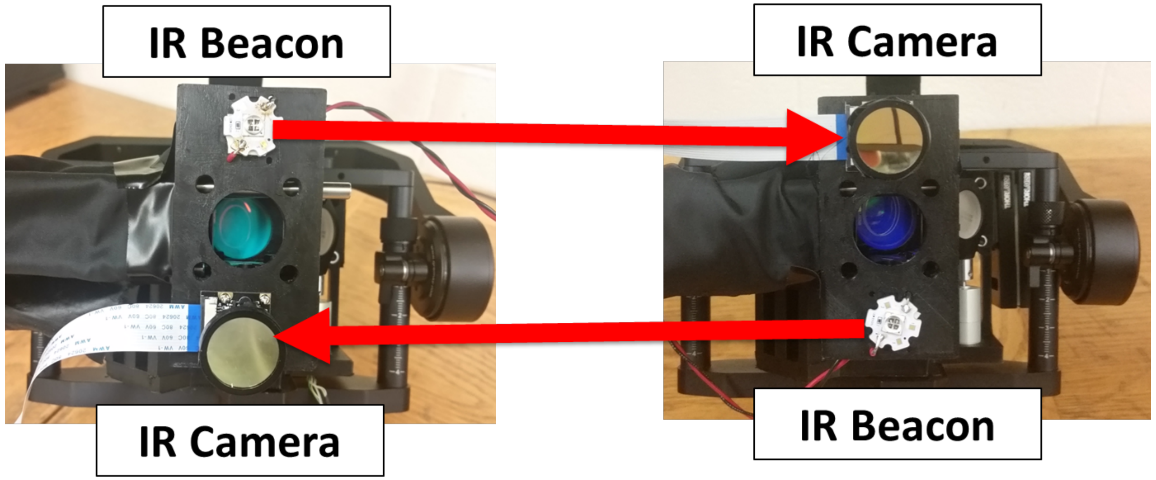


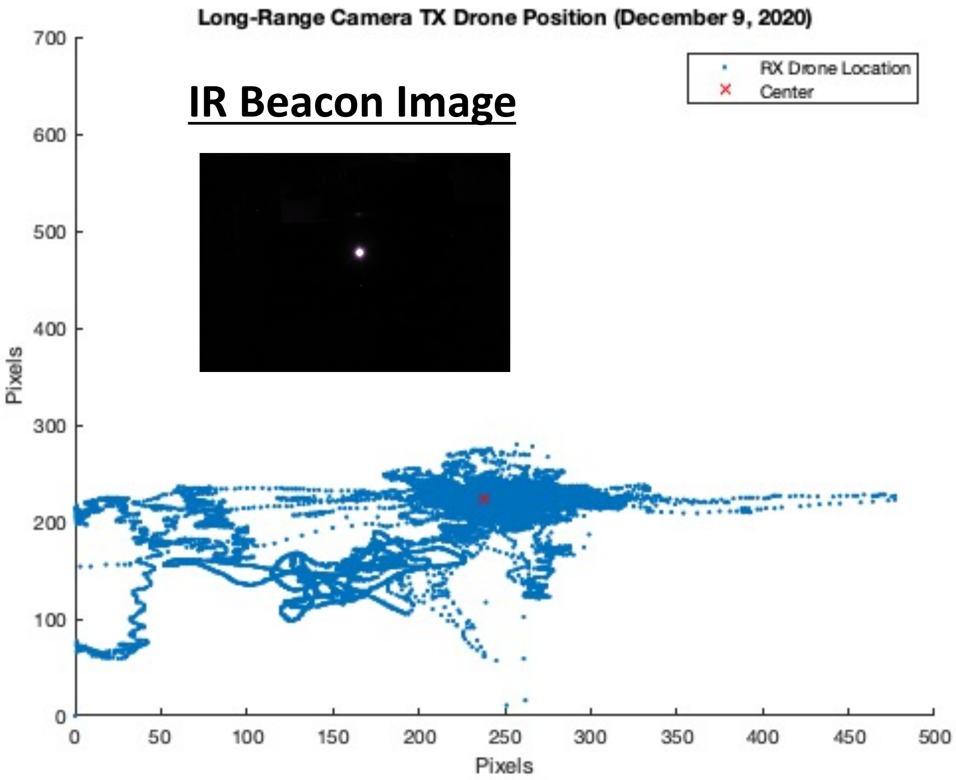
PAT Subsystem (Course Adjustment)

Outer-Control Loop Calibration

- Course pointing corrections
- IR Beacon/IR Camera
- Image processing to identify location in camera's reference frame
- Steers gimbal to drive IR image location to setpoint
- Older design iteration

TX Drone | **RX Drone**

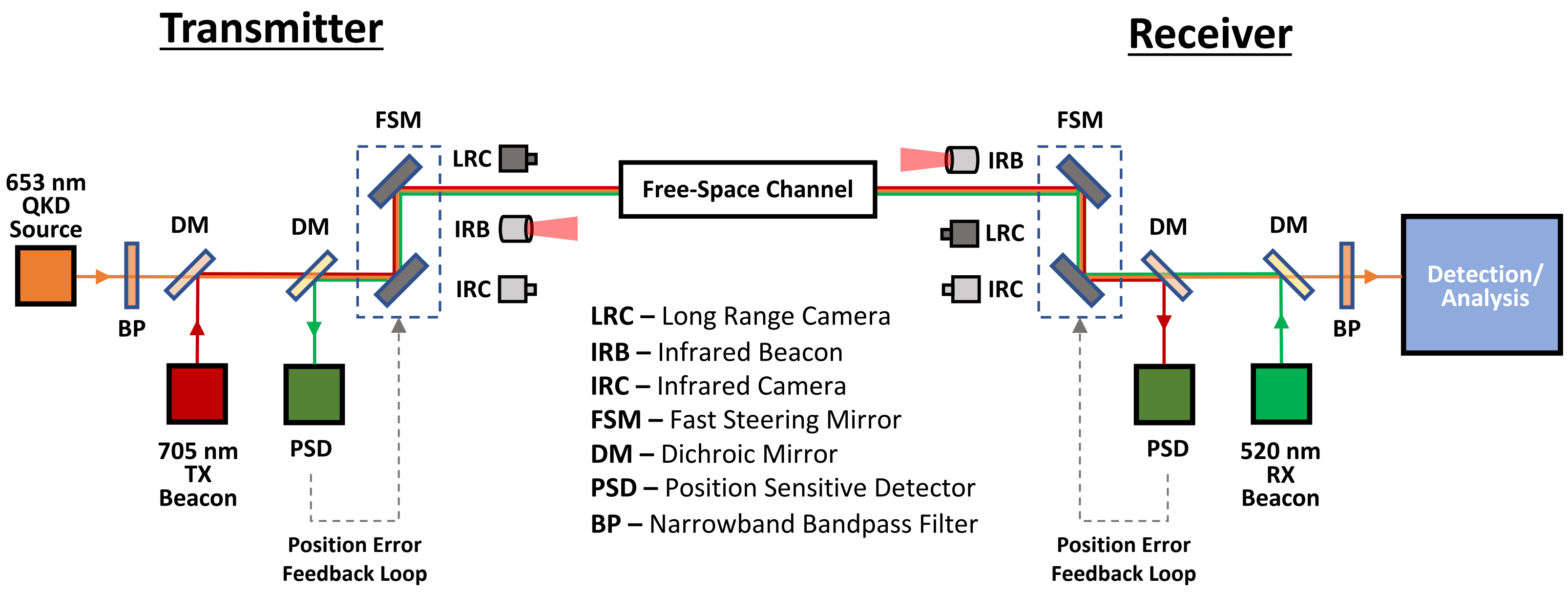




PAT Subsystem (Fine Adjustment)

PAT Subsystem (Fine Adjustment)

- Co-propagating beams
  - TX: 705-nm Beacon
  - RX: 520-nm Beacon
- Position Sensitive Diode (PSD)
  - Senses beacon beam location
  - Two Fast Steering Mirrors (FSM) receive error signal and adjust beacon beam location
- Long-Range IR camera is used for initial acquisition and re-acquisition

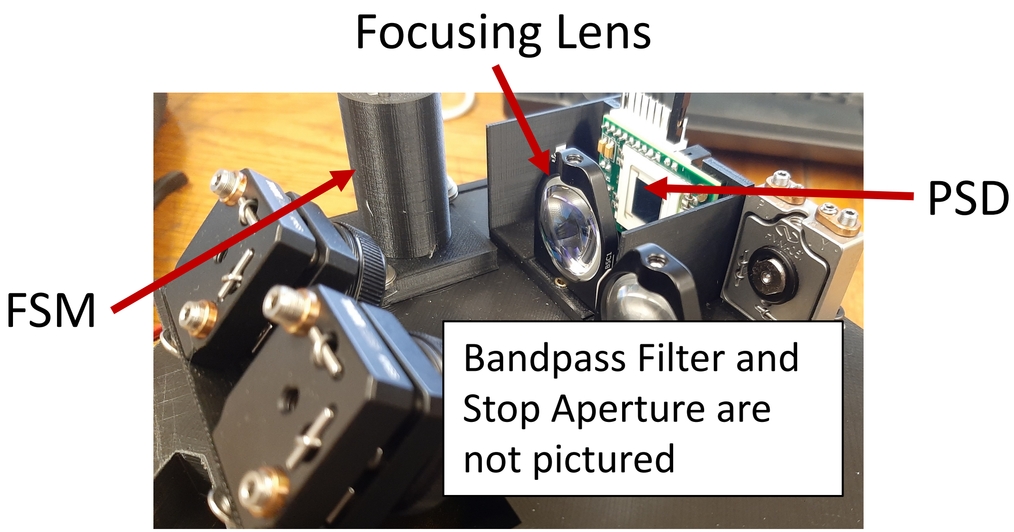


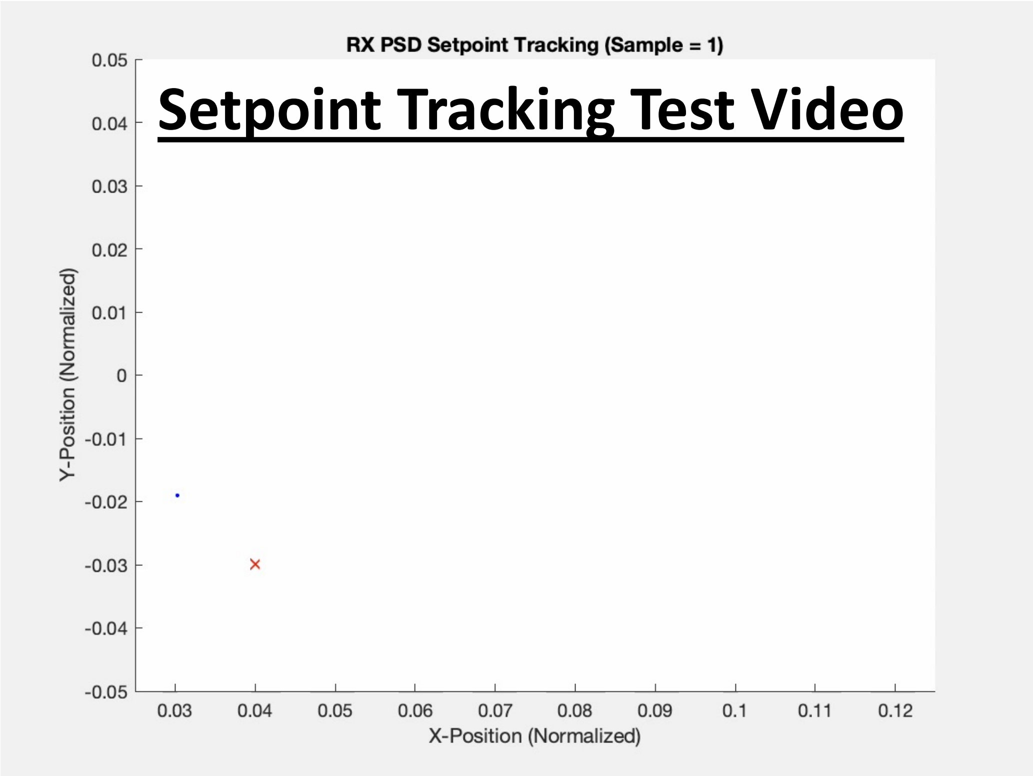
Inner-Loop Calibration

Inner-Control Loop Calibration

- Angular Resolver (AR) sensor is constructed using a focusing lens and a Position Sensitive Diode (PSD)
- Senses incoming Angle of Arrival (AoA) of beacon
- Closed-Loop control adjusts FSMs to set Angle of Departure (AoD) equal to AoA

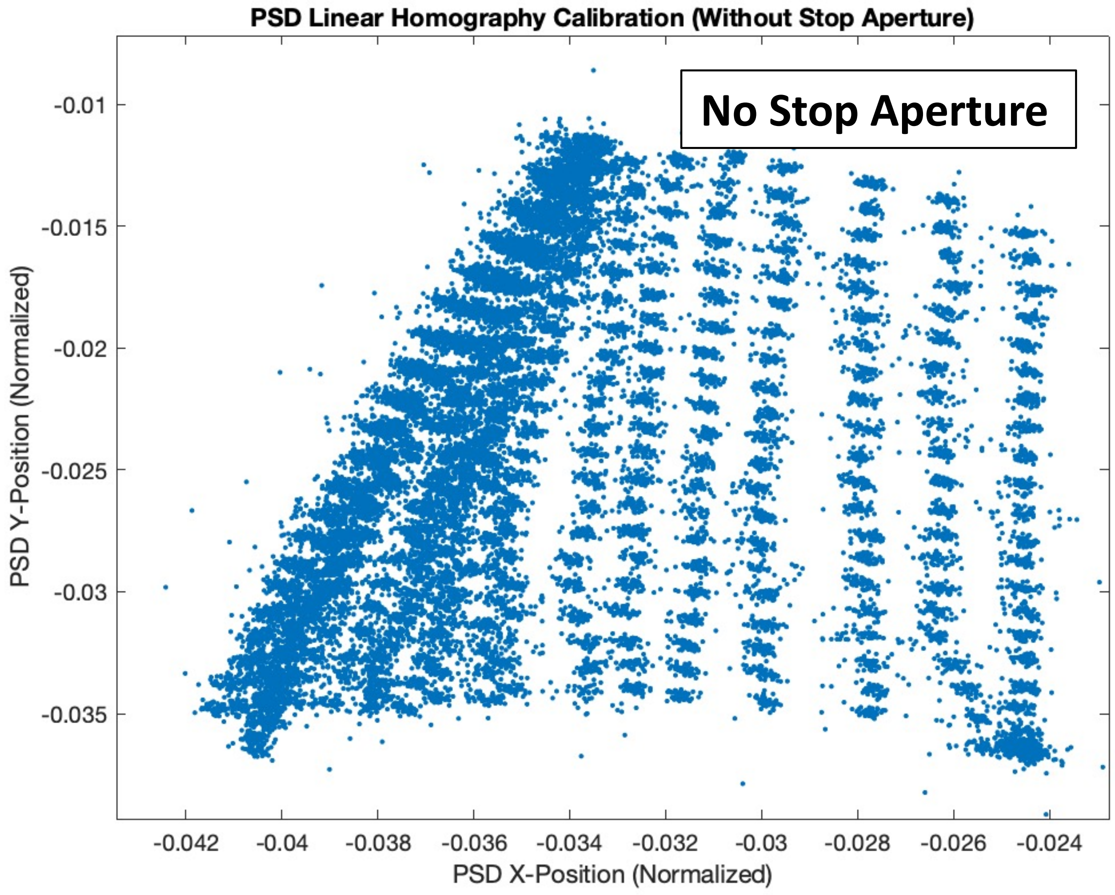
Angular Resolver Sensor

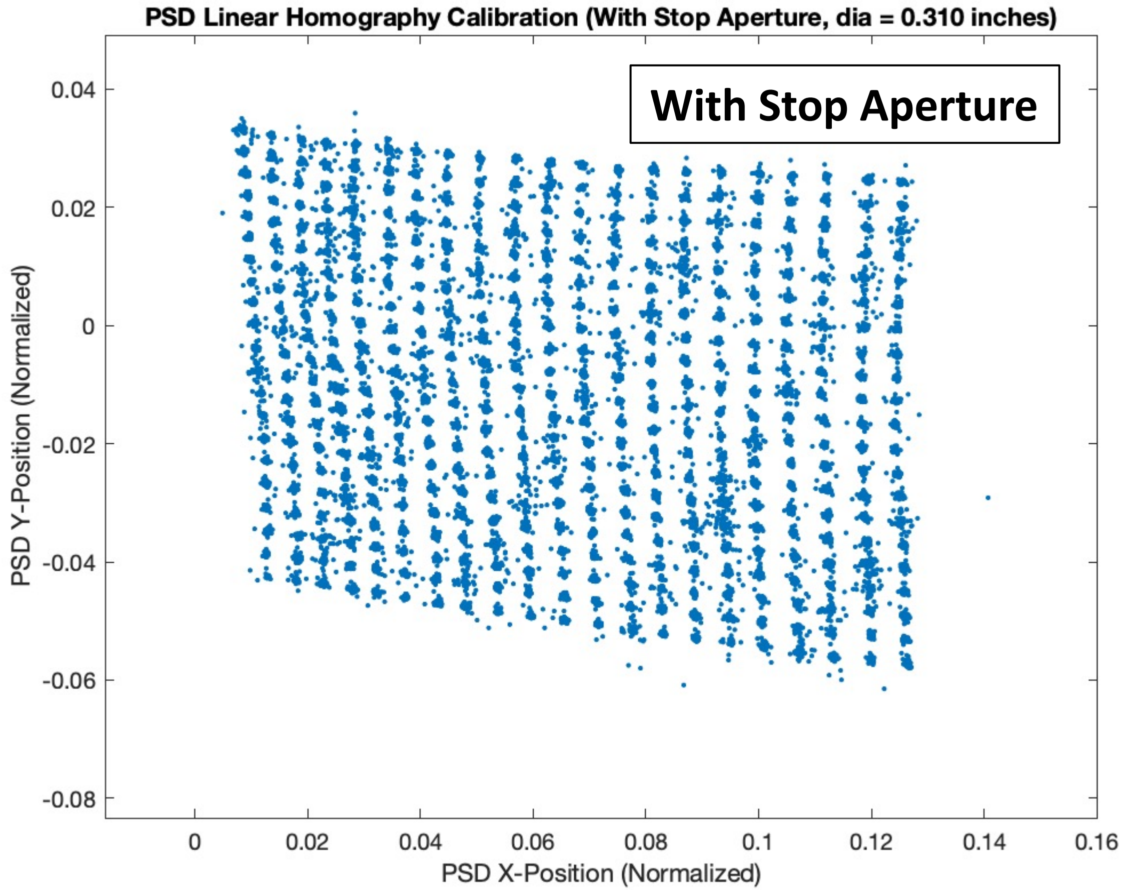




Inner-Loop Calibration

<u>Linear Homography Calibration</u> – Added a stop aperture to reduce image distortion on PSD.

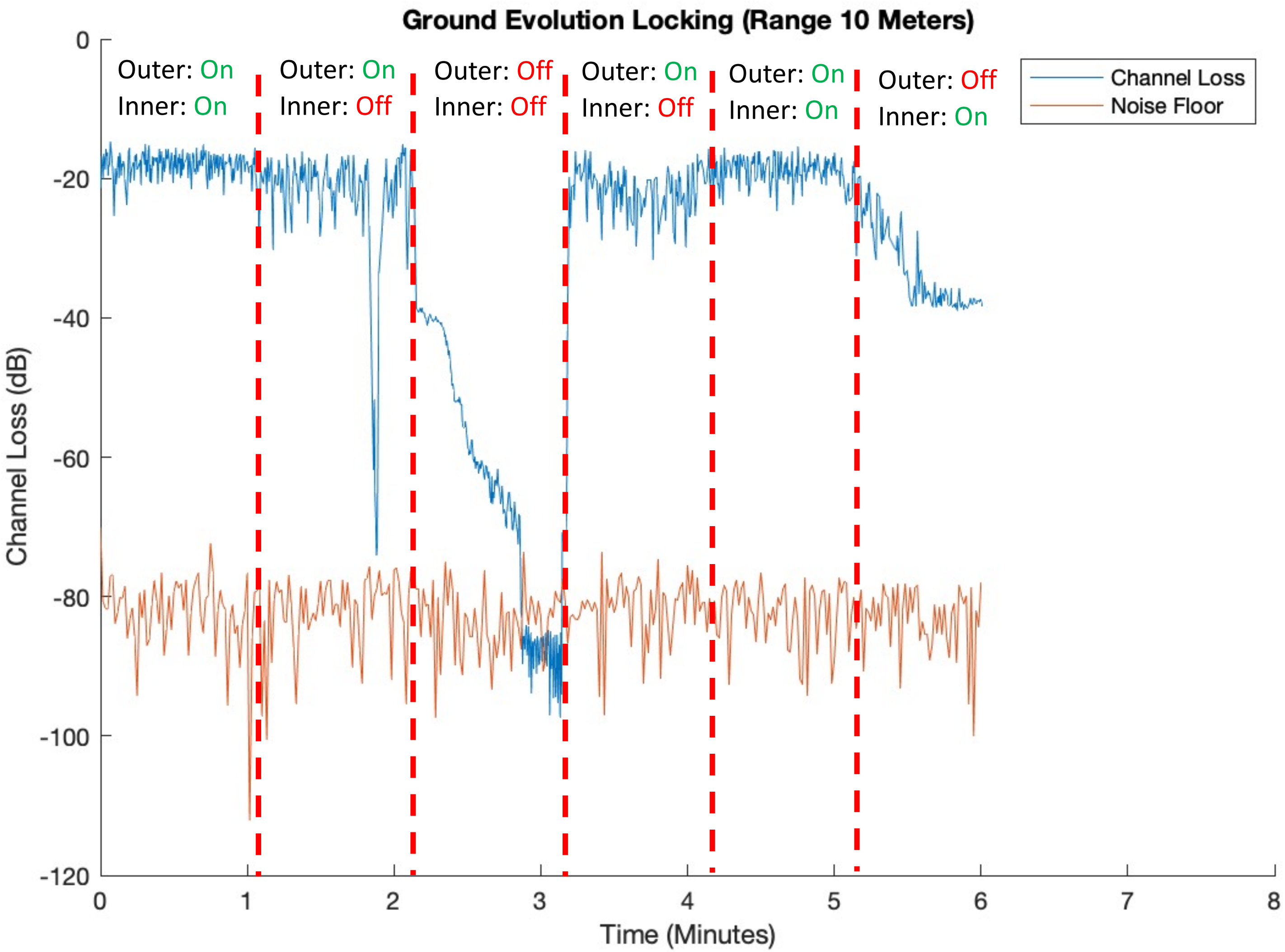




PAT System Performance: Ground Locking

Outdoor Ground-to-Ground Locking:

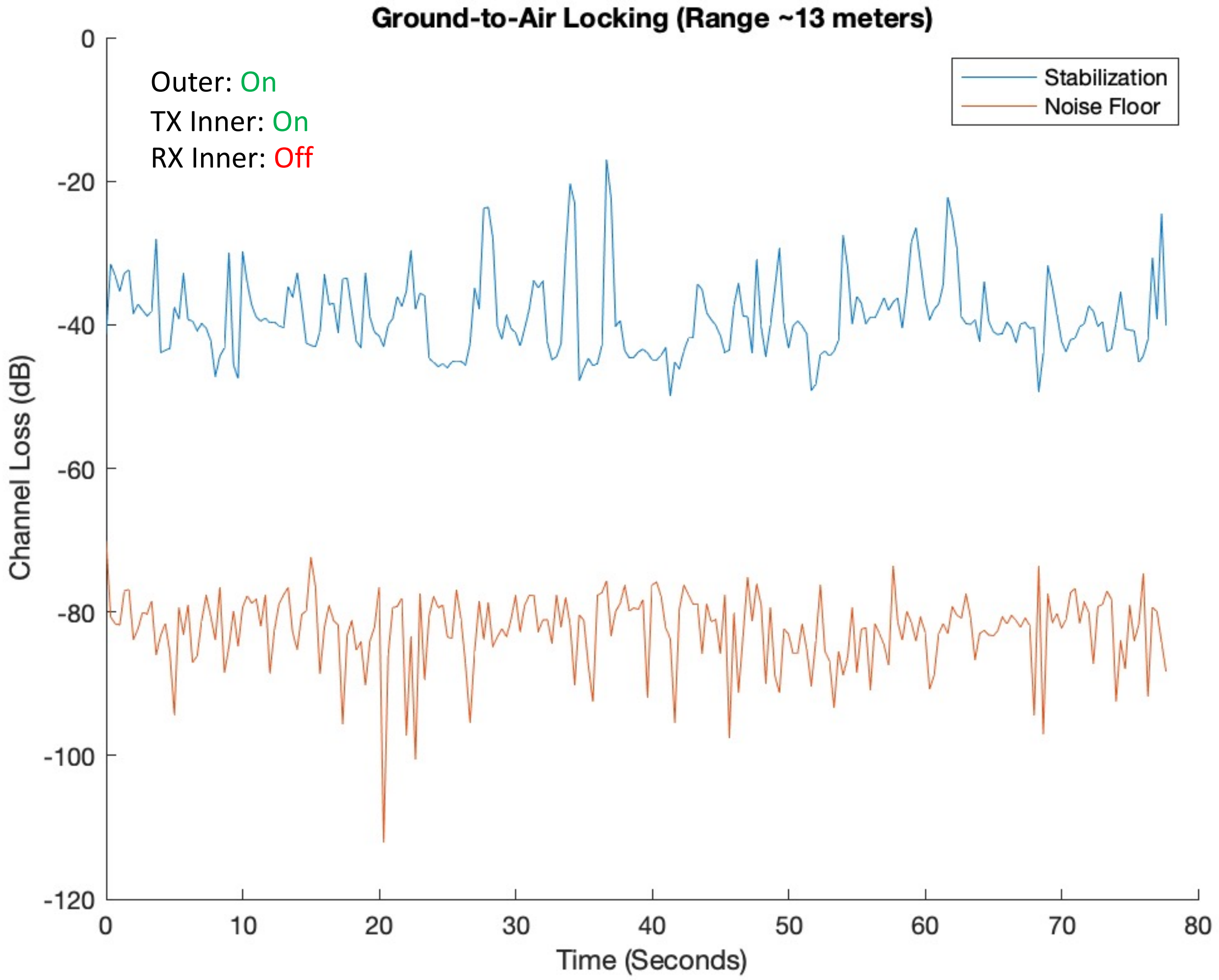
- Both drones are on the ground and 10 meters apart
- Measured Coupling Efficiency
- Outer and Inner Control Loops are sequentially turned on
- Channel loss is minimum when both control loops are operational



Ground-to-Air Locking

Outdoor Ground-to-Air Locking:

- TX Drone on ground, RX Drone in air
- Measured Channel Loss (dB)
- Outer and Inner Loops are both on
- **High wind environment (22 km/hr)**

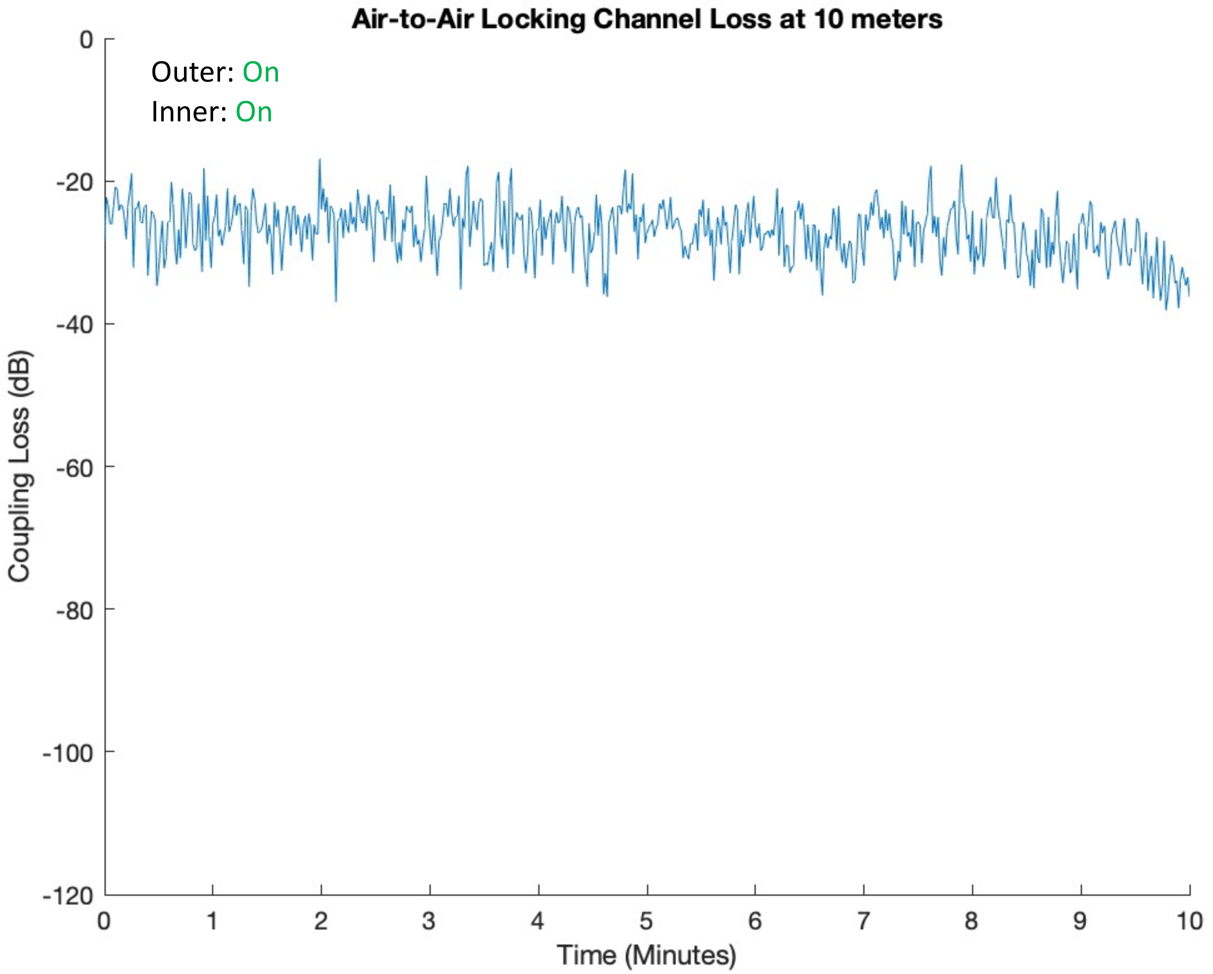


Air-to-Air Locking

PAT System Performance: Air-to-Air Locking

Outdoor Air-to-Air Locking:

- Both drones are airborne and 10 meters apart
- Measured an average **27.1 dB Channel Loss** through free-space channel (10 min duration)
- Low wind environment
- Limiting factor is the latency of feedback data link between drones (older design iteration)



Single-Photon Detectors

Single-Photon Detector

- 4 Channel
- Perkin Elmer (Part Number: SPCM-AQ4C)
- ~60% efficiency @ QKD wavelength
- 1.5 M C/s before saturation
- Custom cable assembly allows interface card to wrap under the detector module → reduce largest dimension

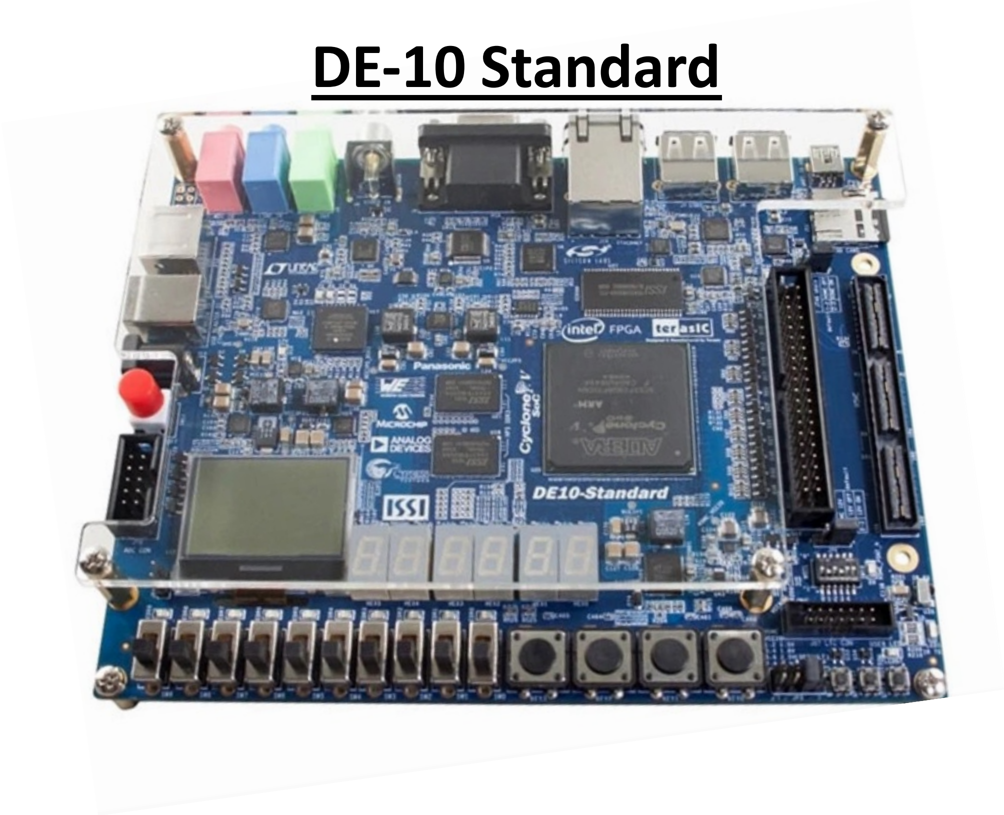
SPCM-AQ4C

FPGA Time Tagger

FPGA Time Tagger

- FPGA Model Number (Intel DE-10 Standard)
    - Cyclone VSX
    - High-Speed I/O
- Single-Photon Detector outputs clicks recorded using a reference clock of 100 MHz
- Records channel information and time tags to an on-board SD card

DE-10 Standard

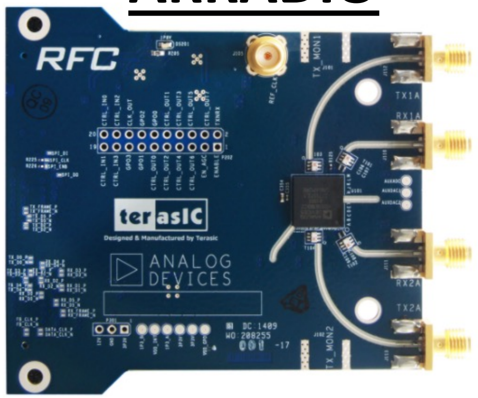


Time Synchronization

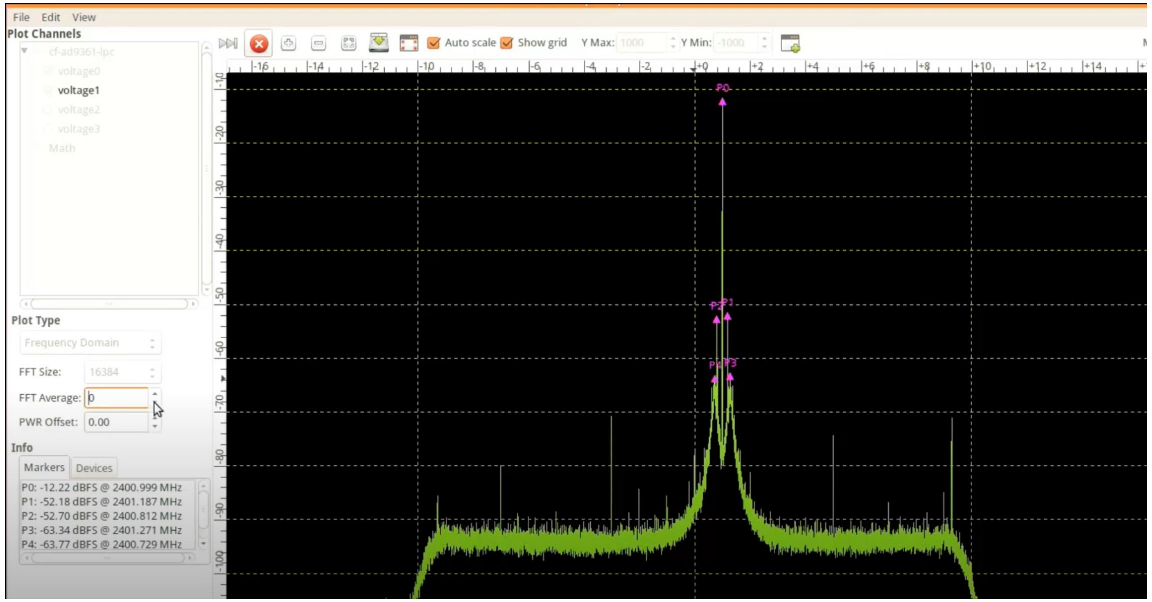
Software Defined Radio (SDR)

- Frequency Range 70 MHz – 6 GHz
- Instantaneous Bandwidth: 56 MHz
- QKD and Timing signal delayed by the same amount
- **Idea**: QKD and RF signals travel at the same speed → compensates for relative motion between drones

ARRADIO



I-Q Timing Spectrum



Software-based Time Synchronization

Time-Synchronization Algorithm

- Probabilistic synchronization approach
- Performed during post-processing:
  1. Alice and Bob exchange basis information
  2. Bob computes likelihood that a given data in time tags was sent from Alice (using a-priori probabilities, e.g., mean photon number, detector dark counts, and expected polarization)
  3. Likelihoods are compared using a Bayesian aggregation approach
  4. Number of events at each interval computed via Fast Fourier Transform (FFT)

QCrypt 2021 Poster Session:

192. **Qubit-based clock synchronization for QKD systems using a Bayesian approach**
Roderick D. Cochran (The Ohio State University); Daniel J. Gauthier (Ohio State University)
[abstract]

Alice

Bob

Detection Event History

Quantum Drone Team

PI

Paul G. Kwiat

UIUC

Co-PI

Daniel J. Gauthier

OSU

OSU

Roddy Cochran, Daniel Sanchez-Rosales, and Akash Gutha (not pictured)

UIUC

Brian Wilens, AJ Schroeder, Ian Call, Hudson Jones Samantha Isaac, Andrew Conrad, Tati Rezaei (Timur Javid not pictured)

Questions?

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