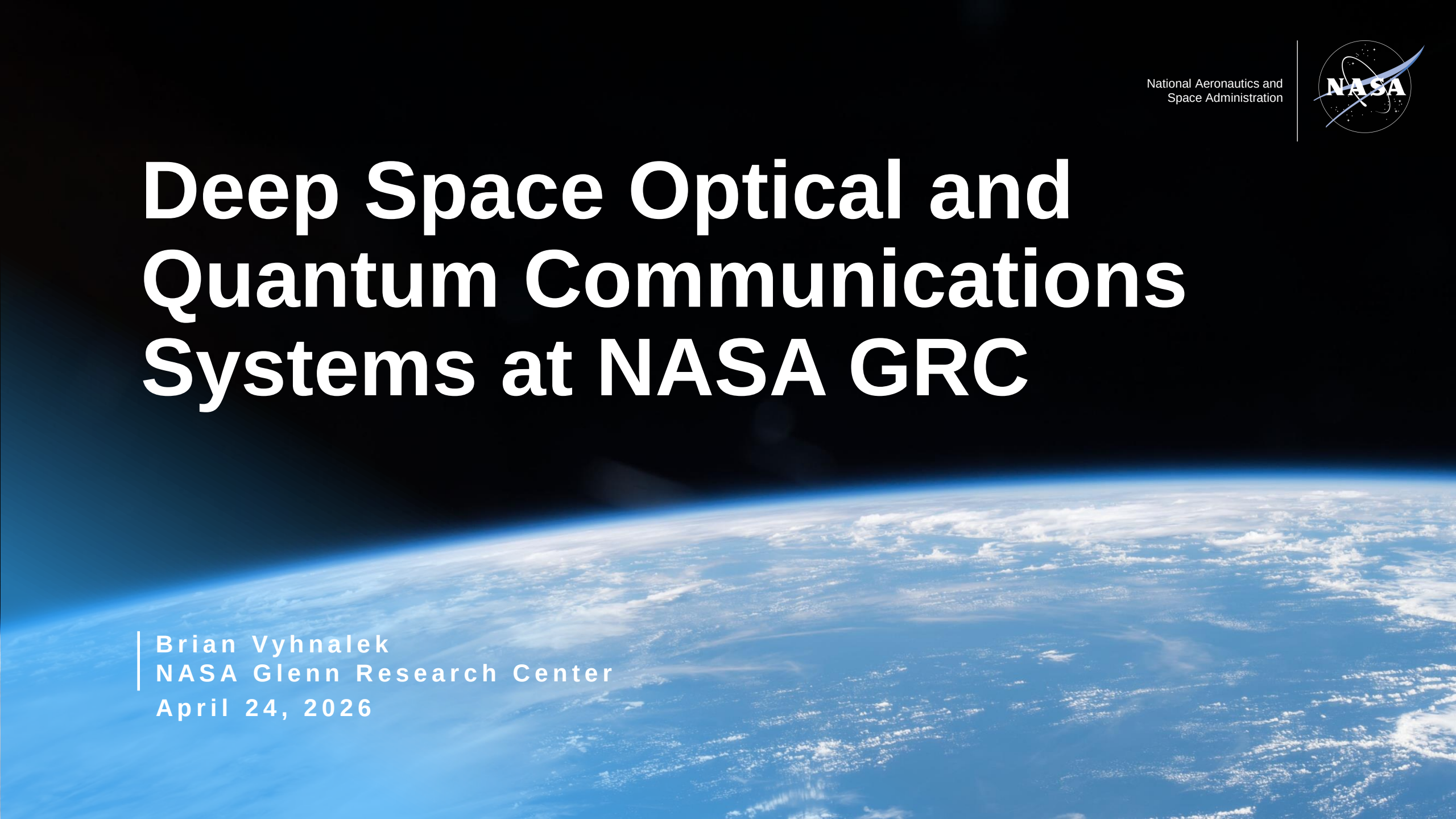
National Aeronautics and Space Administration



Deep Space Optical and Quantum Communications Systems at NASA GRC

Brian Vyhnalek
NASA Glenn Research Center

April 24, 2026

Optical Communications Overview

- NASA communications and navigation systems in the Lunar and deep space environment envisioned for the future will need to accommodate human exploration, science experiments, human and robotic mobility operations, basecamp operations, and other missions in general requiring high data-volume transmissions
- Optical communications can provide orders of magnitude system improvements vs. current RF systems
- Need for operational optical ground stations:
  - Low-cost, 1-meter class (20 – 70 cm) telescopes
  - Efficient multi-spatial mode receivers
  - Low-cost adaptive optics



NASA Laser Communications Relay Demonstration (LCRD)



NASA Orion Artemis II Optical Communications System (O2O)



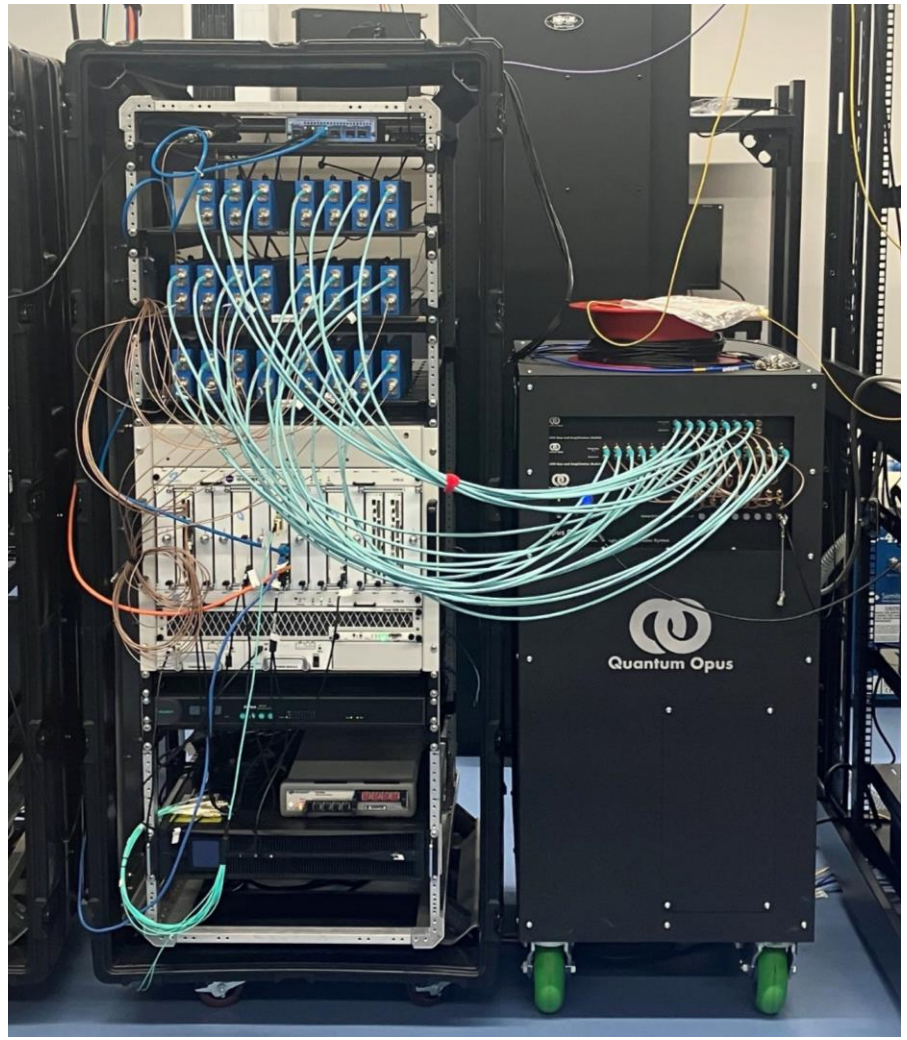
NASA GSFC Low-cost optical terminal (LOCT)



NASA / MITLL optical terminal at White Sands Complex (2013)

Real-Time Optical Receiver Project

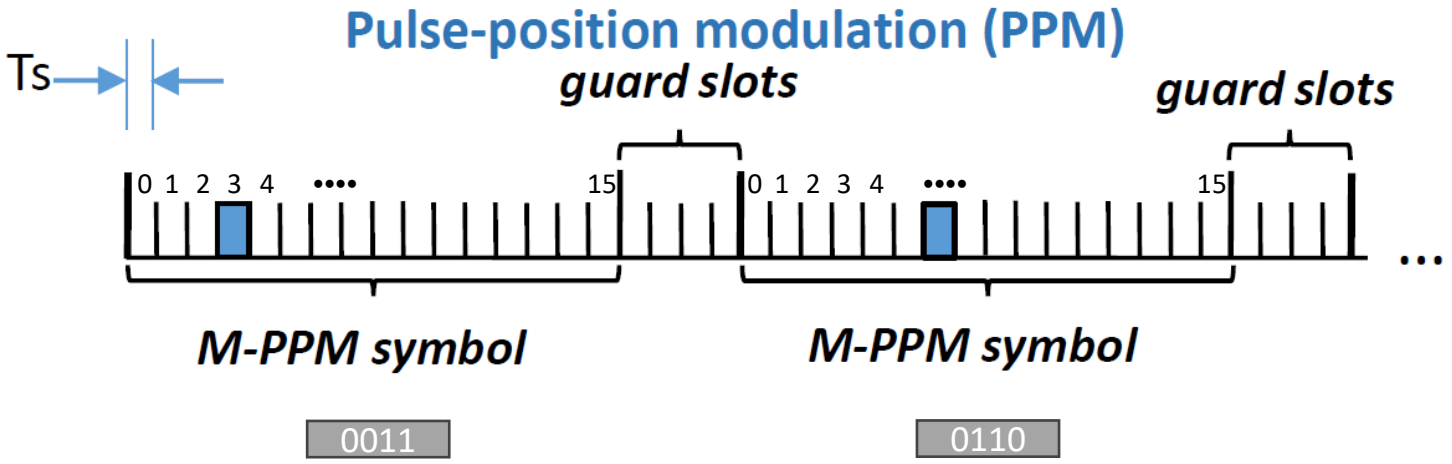
Goal: Research and develop a scalable photon-counting ground transmitter and receiver compatible with the CCSDS HPE standard using commercial off the shelf components to enable proliferation of optical ground stations by NASA, companies, and universities to increase the availability of optical communication service for deep space missions.



High Photon Efficiency (HPE) Signaling

CCSDS High Photon Efficiency standard:

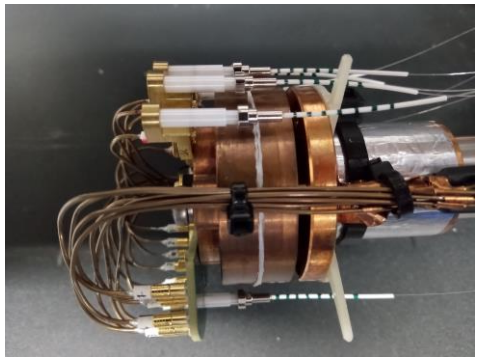
- Pulse-position modulation (PPM) (M = 4, 8, 16, 32, 64, 128, 256; Ts = ½, 1, 2, 4, 8 ns, etc.)
- High peak-to-average power ratio
- Forward error correction, variable code rates (1/3, 1/2, 2/3)
- Interleaving for fade mitigation

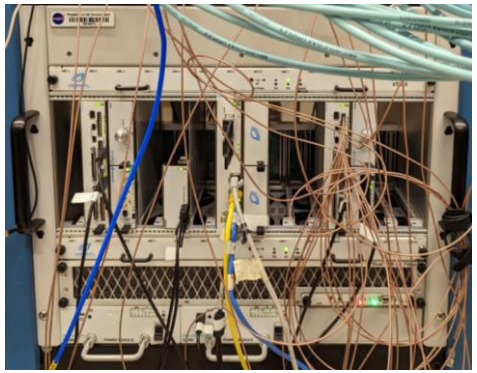


PPM Order (M)	Bits
4	2
8	3
16	4
32	5
64	6

Receiver Subsystems







Fiber Interconnects:

- Photonic lantern (7-ch, 42 – 70 modes) or 6-mode few-mode fiber (FMF)
- Input fiber core size, number of outputs, and output fiber core size scalable to application
- NASA Glenn in-house fabrication

Single Photon Detectors:

- Superconducting nanowire single-photon detectors (SNSPDs)
- Individual FMF-coupled detectors, or single 16-channel array
- Continuous cryogenic < 3 K operation, 60-80% detection efficiency, < 100 ps timing resolution

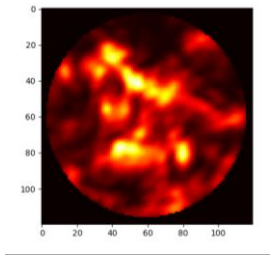
FPGA-based Receiver:

- 1 ADC per detector channel; digital detector channel combining
- Real time processing; COTS development platform
- Compatible with CCSDS downlink optical waveform (high photon efficiency)
- FPGA VHDL/Verilog receiver code will be released

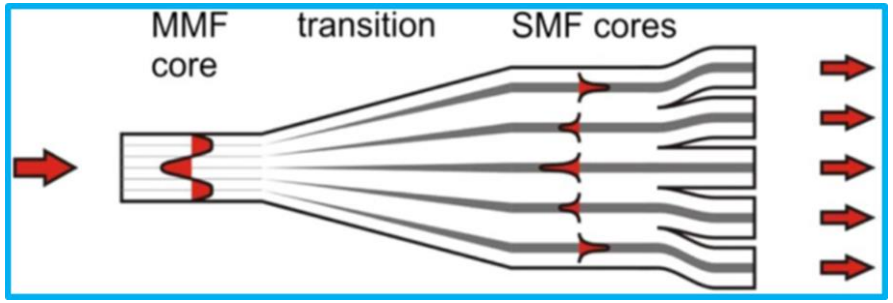
Photonic Lantern

- Optical waveguide transition that produces a **mode system conversion**
- Converts light from a multimode to a single-mode, few-mode, or smaller multimode system and vice versa with low loss
- Originally invented for astronomy, can be applied to optical comm

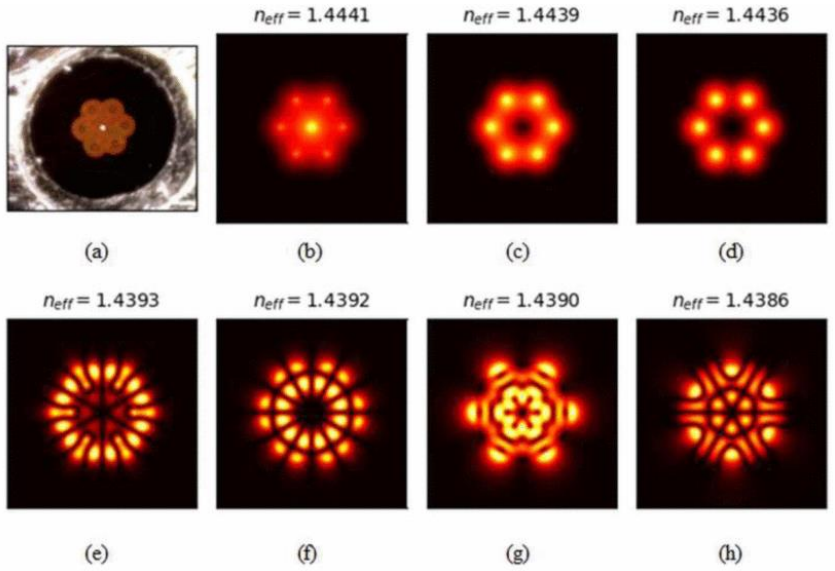
Multi-mode Light from back of Receiver Telescope



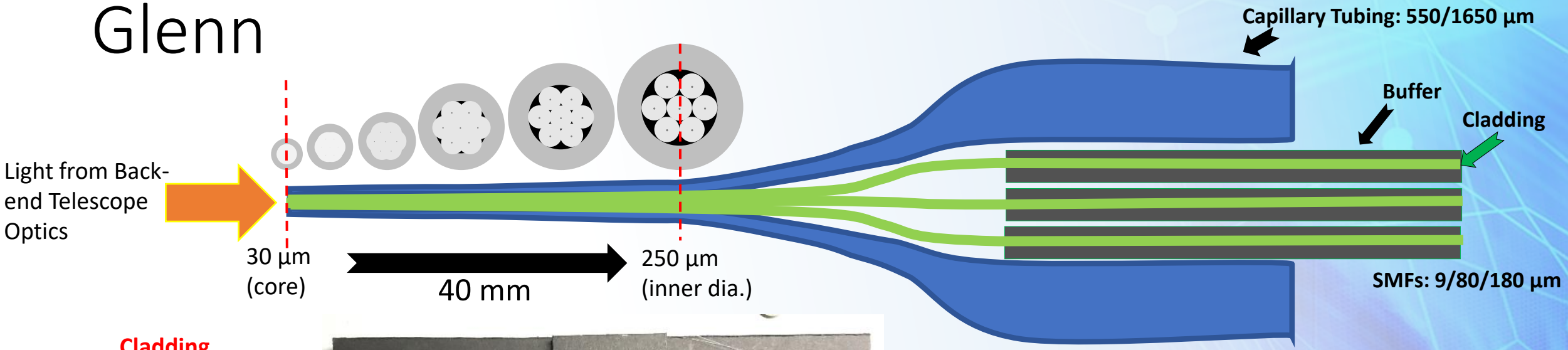
Photonic Lantern

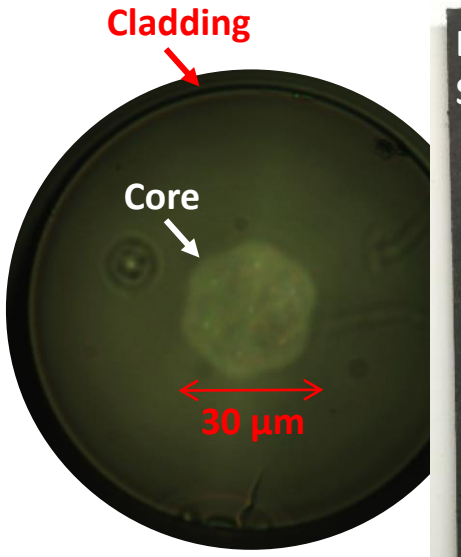


From: S. G. Leon-Saval et al. "Multimode fiber devices with single-mode performance," Opt. Lett. 30, 2545–2547 (2005) 4.

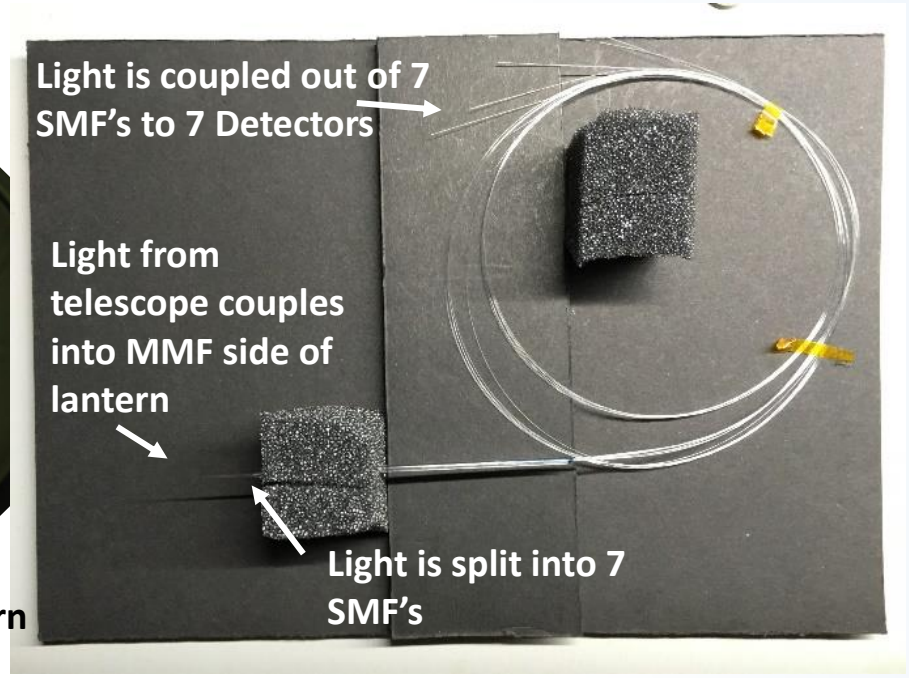


7:1 SMF Photonic Lantern made at NASA Glenn

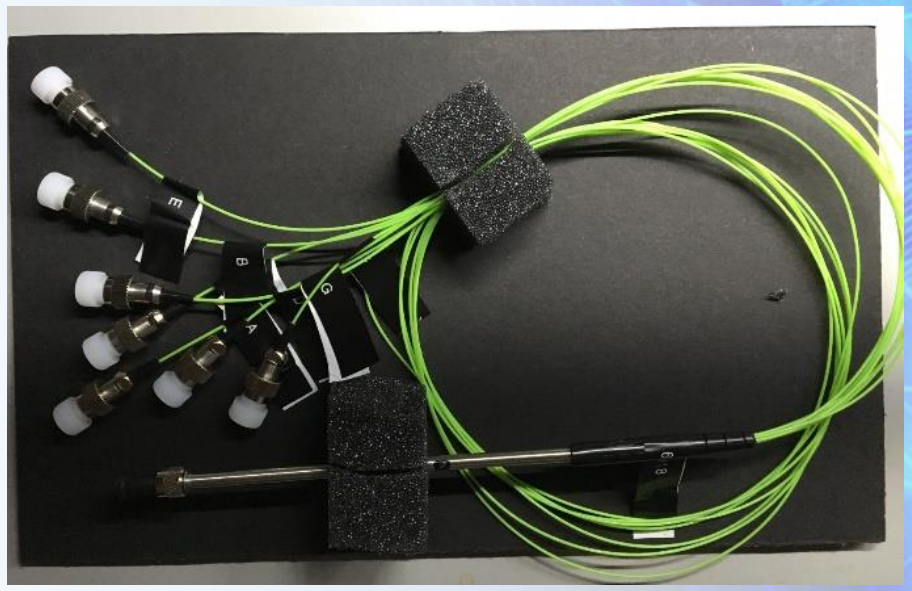




Multimode input of lantern

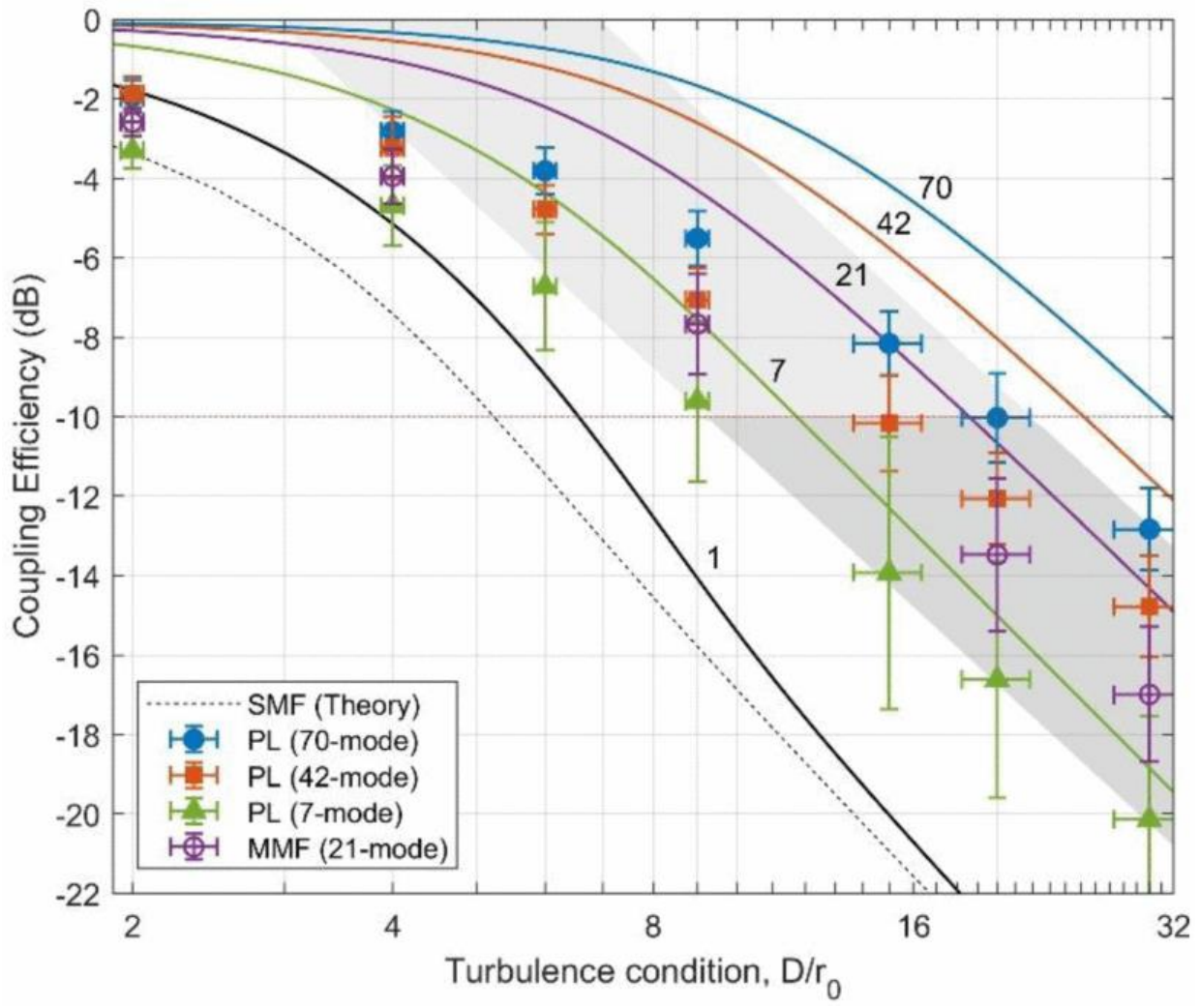


An unpackaged 7:1 SMF photonic lantern.



A packaged 7:1 SMF photonic lantern.

Coupling Efficiency vs. Turbulence



Fiber device	Input/Output Core Size (μm)	Input\Output Numerical Aperture	Number of Supported Modes
Single-Mode Fiber	10.4[a]/10.4[a]	0.12[b]	1
Graded Index 6-mode Fiber	20/20	0.19	6
Graded Index 10-mode Fiber	25/25	0.19	10
Graded Index 21-Fiber	30/30	0.2	15
7-Mode Lantern	30/9	0.08/0.12	7
42-Mode Lantern	56/20	0.13/0.19	42
70-Mode Lantern	55/25	0.16/0.19	70

aMode Field Diameter. bNot given, typical reported, cTheoretical only.

$$\eta = 0.822(1 - e^{-3\Sigma^2})$$

$$\Sigma^2 = \frac{4}{\pi^2} \cdot \frac{M}{(1 + (D/r_0)^{5/3})^{6/5}}$$

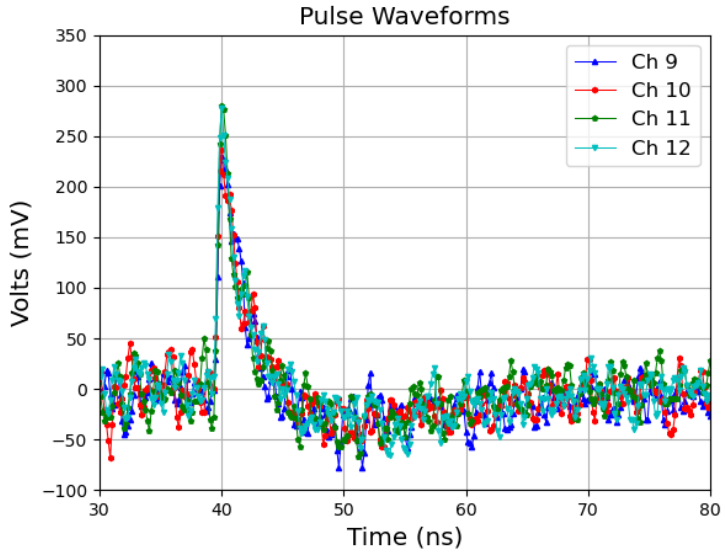
S. A. Tedder, Y. K. Chahine, B. E. Vyhnalek, S. G. Leon-Saval, C. H. Betters and B. Floyd, "Photonic Lanterns With Increased Mode Capacity Per Output Leg for Use in Superconducting Nanowire Single Photon Detector-Based Ground Receivers," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 32, no. 1: Advances in Free Space Laser Communications, pp. 1-12, Jan.-Feb. 2026, Art no. 4300112, doi: 10.1109/JSTQE.2025.3625053

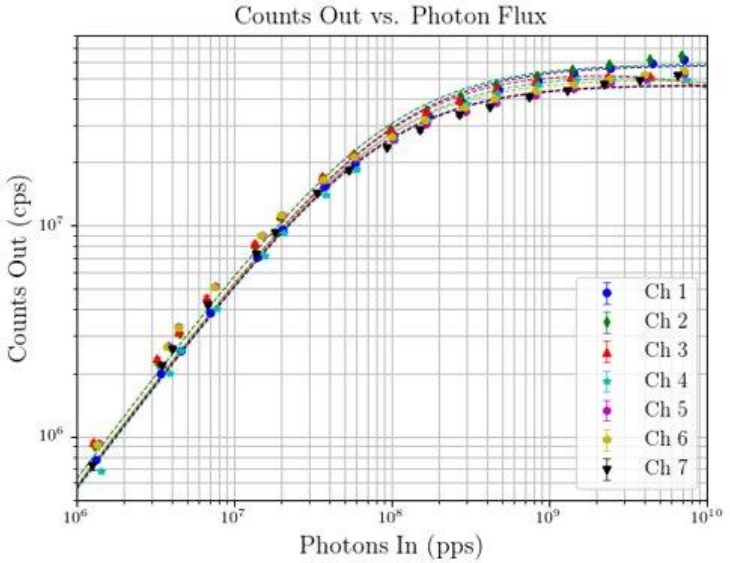
Single Photon Detector System

Superconducting Nanowire Single Photon Detectors (SNSPDs)

Parameter	Value*
Efficiency	≈ 83% max
Dark count rate	3 - 10 kcps**
Polarization loss	1.35 dB
Reset time	5 - 8 ns
Pulse rising edge	600 – 800 ps
Pulse amplitude	240 – 300 mV
Blocking loss	< 1 dB @ 200 Mcps
Count rate (3 dB)	≈ 500 Mcps
Max count rate	≈ 1 Gcps
Jitter (FWHM)	75 – 95 ps
Channel skew	< 150 ps
Crosstalk probability	< 0.002%

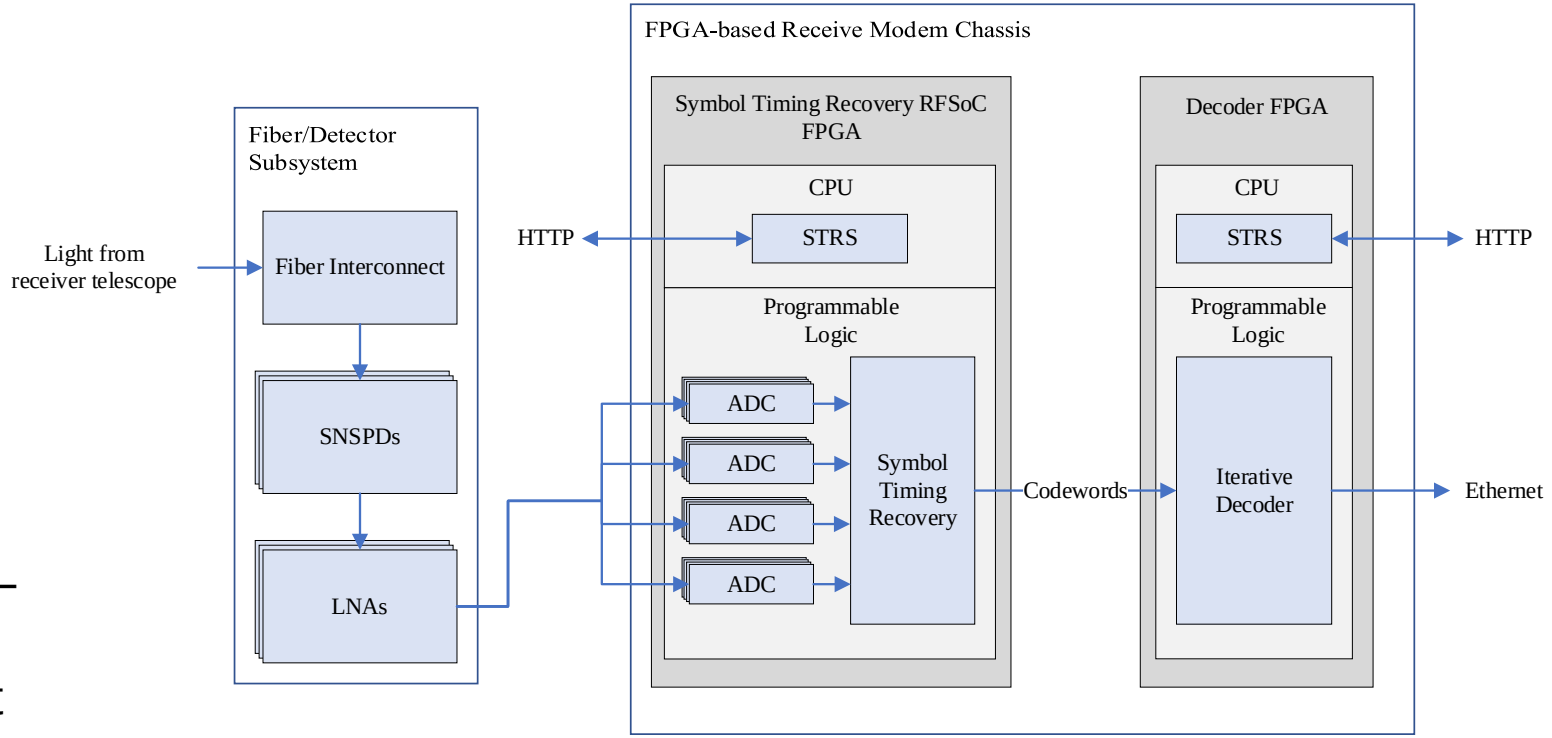






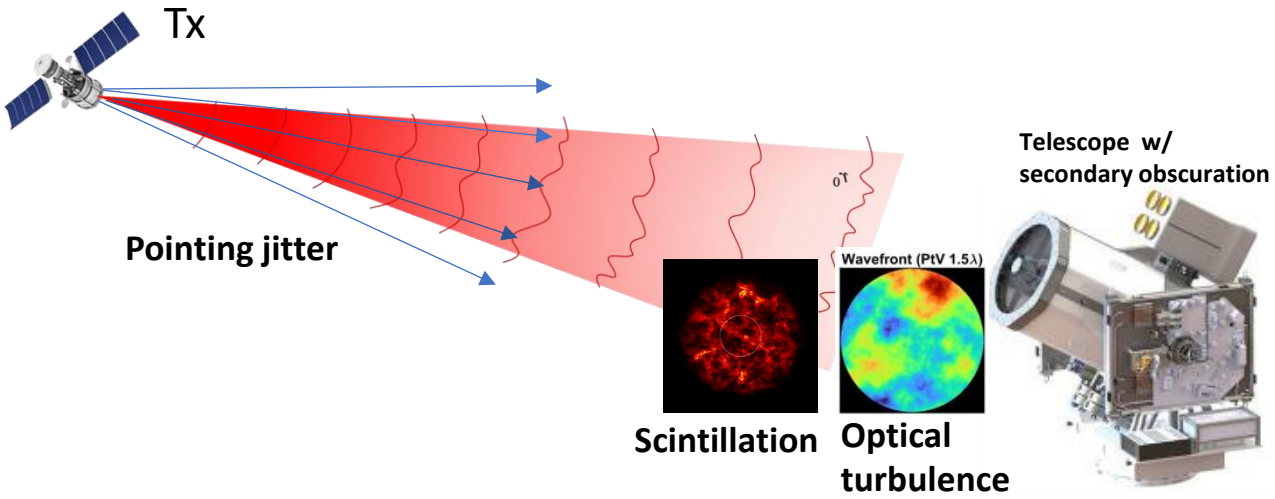
FPGA Processor Electronics

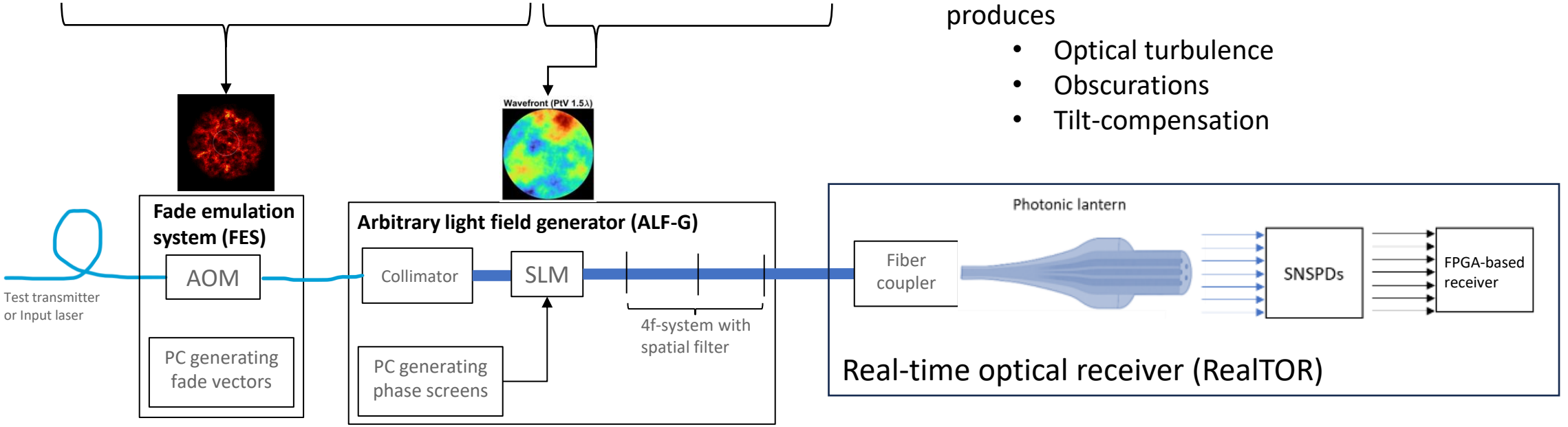
- Two primary FPGAs:
  - Timing recovery FPGA
  - Iterative decoder FPGA
- Connected via a high-speed serial interconnection
- Includes:
  - Detector jitter filtering
  - Parallel processing
  - Resource optimizations
- Maximum data rate of 267 Mbps while remaining below a 10^{-5} CWER – extensible to > 500 Mbps
- Modular design combined with robust performance on a COTS platform
- Backplane can be updated to support synchronization of up to 144 detector channels



William P. Simon, Jennifer N. Downey, Nicholas C. Lantz, Thomas P. Bizon, Michael A. Marsden, Brian E. Vyhnalek, and Daniel J. Zeleznikar "Field-programmable gate array implementation of a single photon-counting receive modem", Proc. SPIE 12877, Free-Space Laser Communications XXXVI, 128771M (12 March 2024); https://doi.org/10.1117/12.3001097

Programmable Atmospheric Channel Emulation Testbed

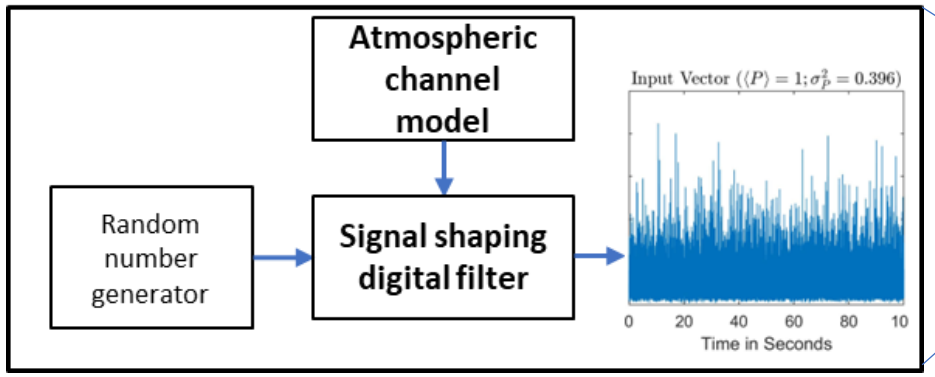


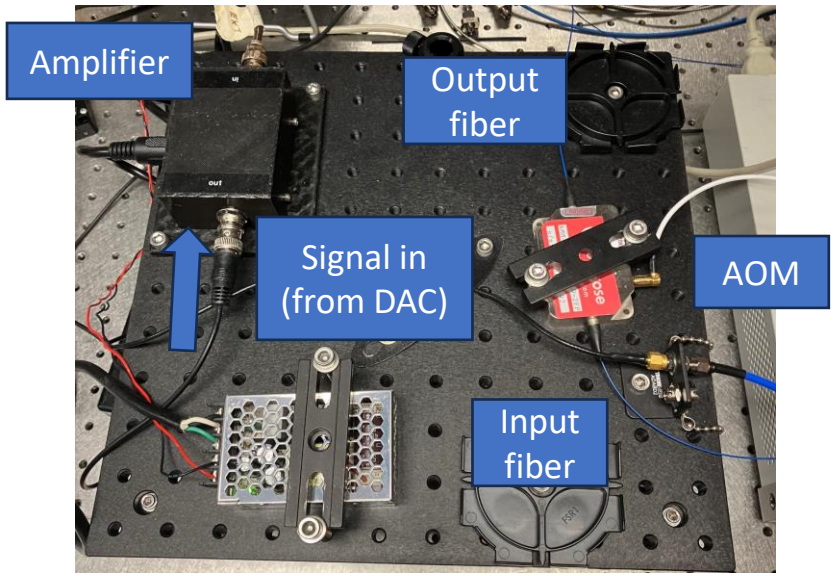


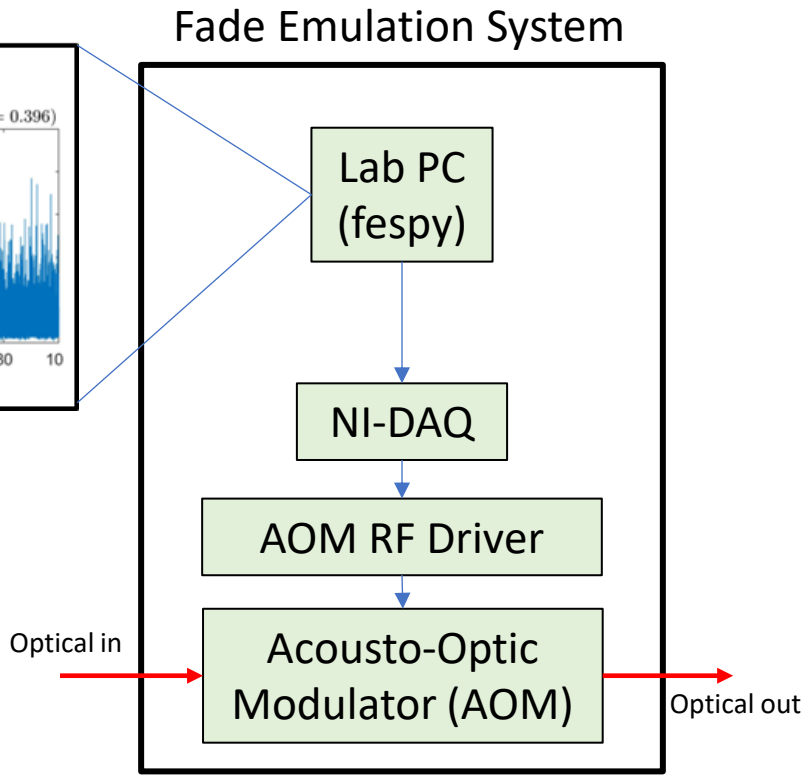
Real-time optical receiver testing performed using a **fully programmable real-time atmospheric emulation system:**

- **Fade Emulation System (FES)**
  Programmable acousto-optic modulator (AOM) produces
  - Pointing-induced fade
  - Scintillation-induced fade
- **Arbitrary Light Field Generator (ALF-G)**
  High-speed spatial light modulator (SLM) holography produces
  - Optical turbulence
  - Obscurations
  - Tilt-compensation

Fade Emulation System (FES)





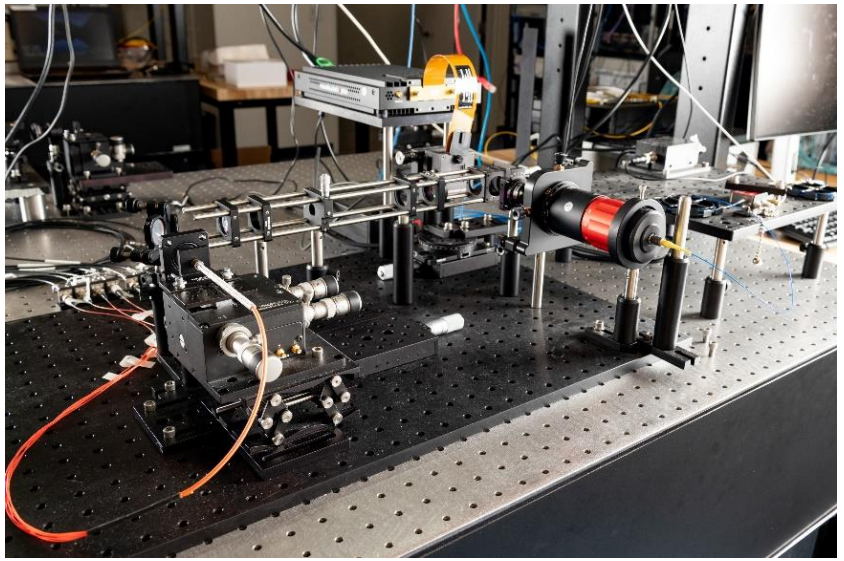


Features:

- Continuous Monte Carlo generation of fading power streams in real-time
- Generates fade streams including both atmospheric **turbulence induced fade** (log-normal; power-scintillation index - PSI) and **pointing-error induced fade** (beta distribution; beam divergence to jitter ratio)
- Arbitrary power spectral density shaping for temporal fade statistics

Arbitrary Light Field Generator (ALF-G)

- Optical turbulence generated by a programmable high-speed liquid crystal spatial light modulator (SLM)
- Holographic technique reproducing both intensity and phase verified to emulate **multi-layer atmospheric turbulence** and aperture obscurations
- Liquid crystal response time of 6 to 9 ms at 1550 nm verified to reproduce **Greenwood frequencies up to 30-90 Hz** with refresh rate of 300+ frames per second
- Driven by custom GPU-accelerated python library capable of Monte Carlo generation of continuous 1024 x 1024 Kolmogorov phase hologram sequences in 2x - 10x playback time for minutes-long playback **of uniquely varying turbulence**
- High resolution WFS measurements verified $\boldsymbol{D/r_0}$ within 3% up to $\boldsymbol{D/r_0 = 10}$ and within 9% up to $\boldsymbol{D/r_0 = 50}$.
- System used extensively for testing of real-time optical receiver system at GRC



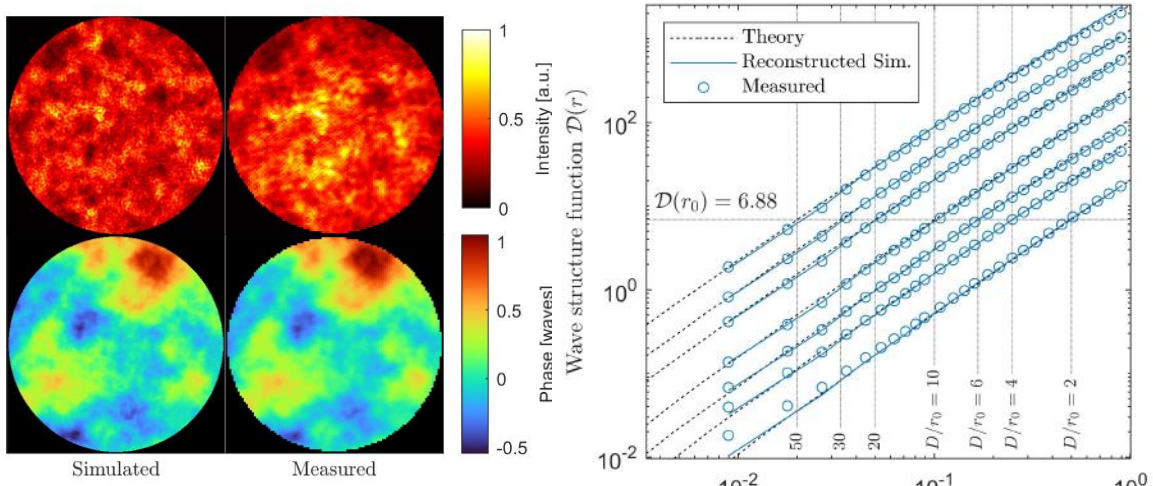
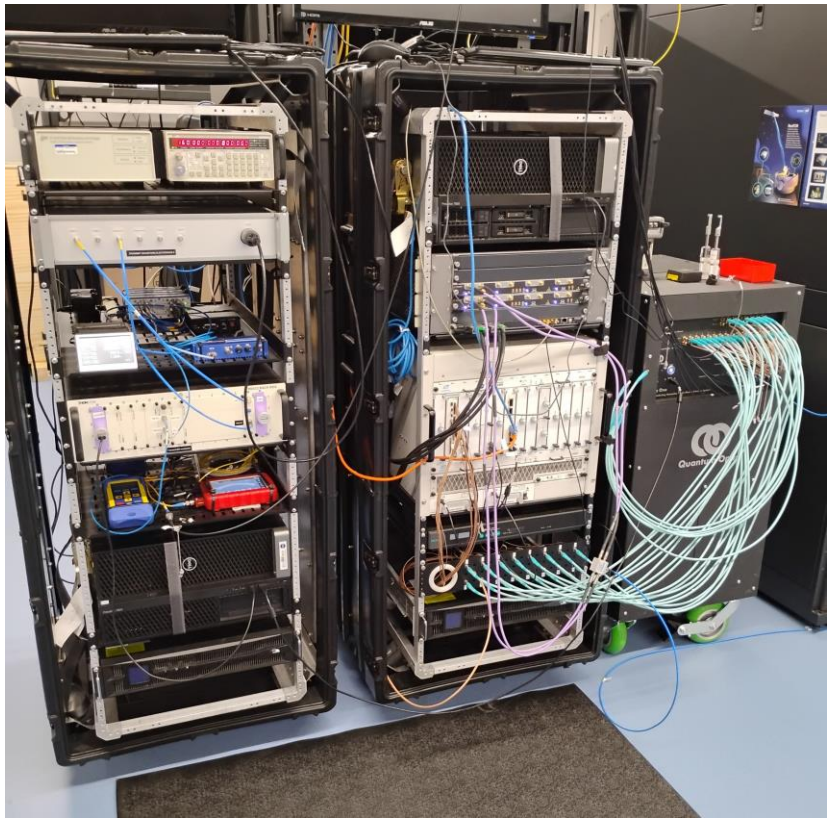


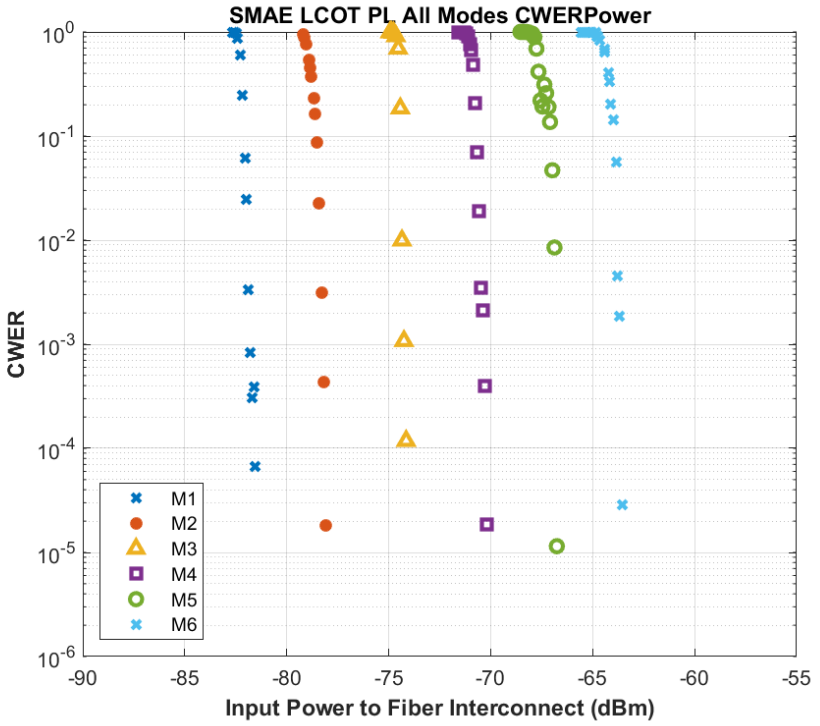
Fig. 6. Example phase and intensity profile with comparison to the simulat
to generate phase holograms with $P_g = 93$ and $D/r_0 = 8$.

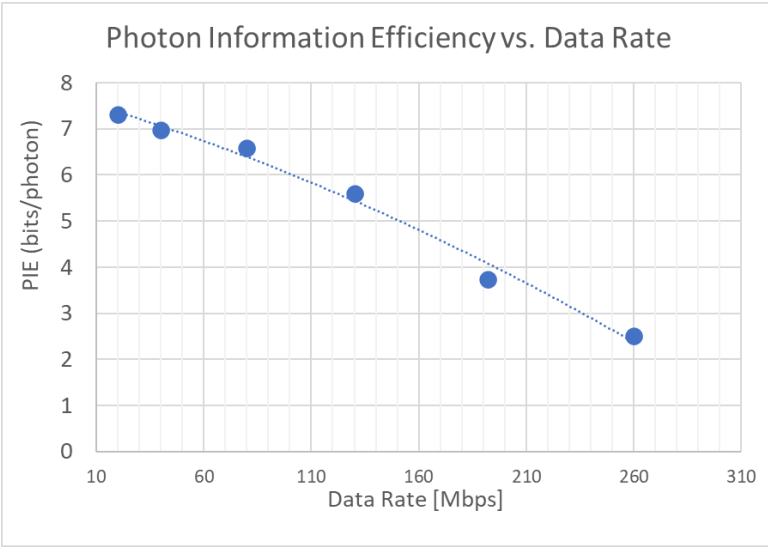
Yousef K. Chahine, Sarah A. Tedder, Bertram Floyd, and Brian E. Vyhnalek, "Verification of the mode fidelity and Fried parameter for optical turbulence generated by a spatial light modulator," Opt. Continuum 1, 2112-2126 (2022)

O2O Downlink Receiver Performance



- Completed end to end system testing including emulated channel conditions, e.g. turbulence, fading, etc.
- Verified performance with O2O space EDU modem





Mode	1	2	3	4	5	6
PPM	32	32	32	16	16	16
T_{slot} (ns)	2	1	0.5	0.5	0.5	0.5
Rate (Mbps)	20	40	80	130	195	260

- **Receiver implementation within 1 dB of code performance**
- **Ultimate sensitivity < 1 photon / bit!!**
- **Dynamic range > 30 dB**
- **Photon counting algorithm on 16-channel RF System-on-a-chip (RFSoC) FPGA can achieve 200 Mcps / ADC channel for total 3.2 Gcps!!!**

Project Impact



Orion Artemis II Optical Communications System (O2O):
Space modem validation and end-to-end system testing.

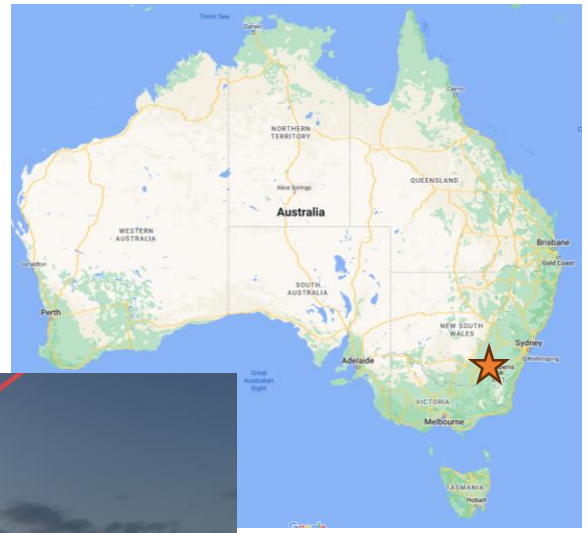


White Sands Optical Ground Station: Uplink Transmitter Electronics



GFSC Low Cost Optical Terminal: Uplink Transmitter Electronics, Downlink Receiver





Australian Ground Station: Technology transfer of Uplink Transmitter and Downlink Receiver

Contributing to 3 O2O ground station transceivers and aided with validation of O2O space modem

Artemis 2 Success!!!



Image credit: ANU

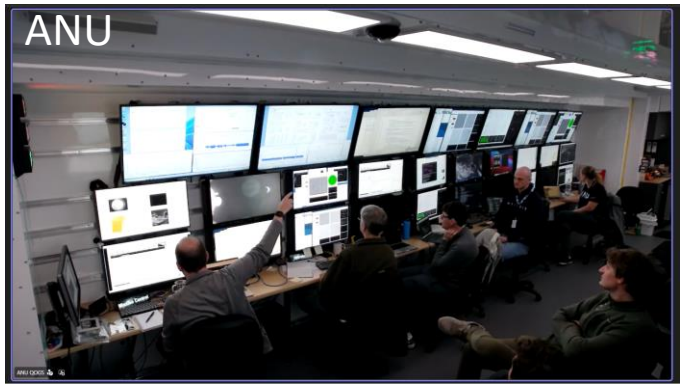




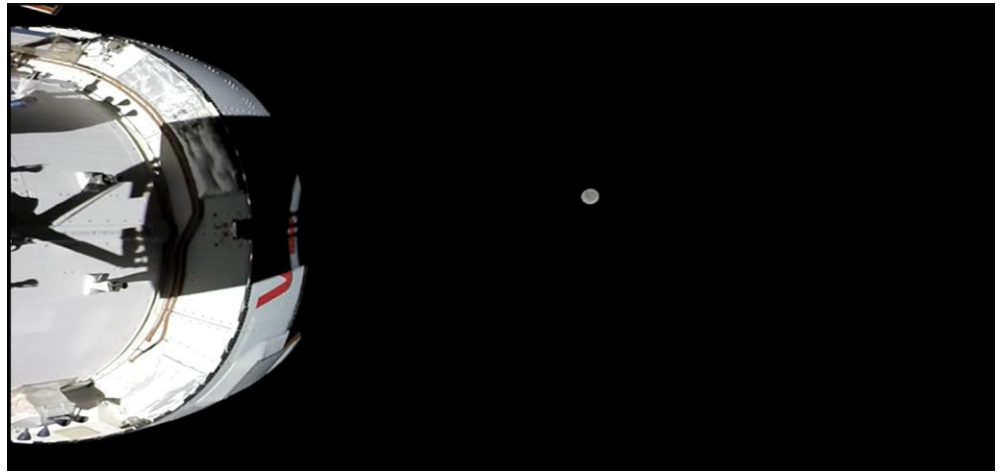


Image credit: ANU



- Receiver deployed in collaboration with NASA GSFC and Australian National University (ANU) at the Mt. Stromlo Quantum Optical Ground Station (QOGS).
- Played a critical role during the Artemis II mission by supporting the downlink of high-definition video footage from Orion to viewers at home.
- The demonstration set records and exceeded the team's expectations in operations and availability

A Few YouTube Screenshots



FD4 – 275,000 km



FD6 – about 400,000 km



FD10 – 125,000 km

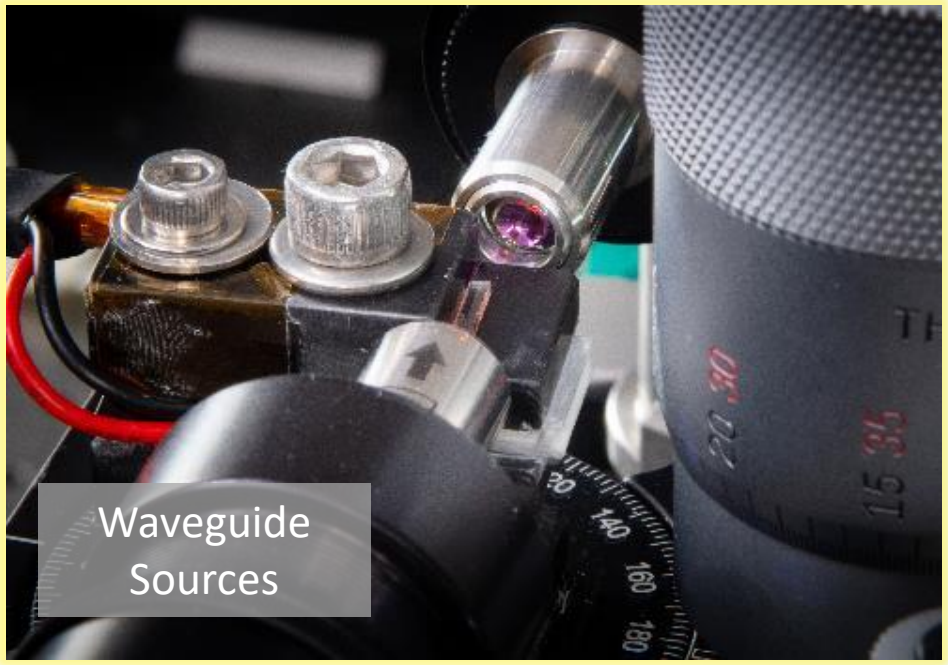


FD10 – 74,000 km

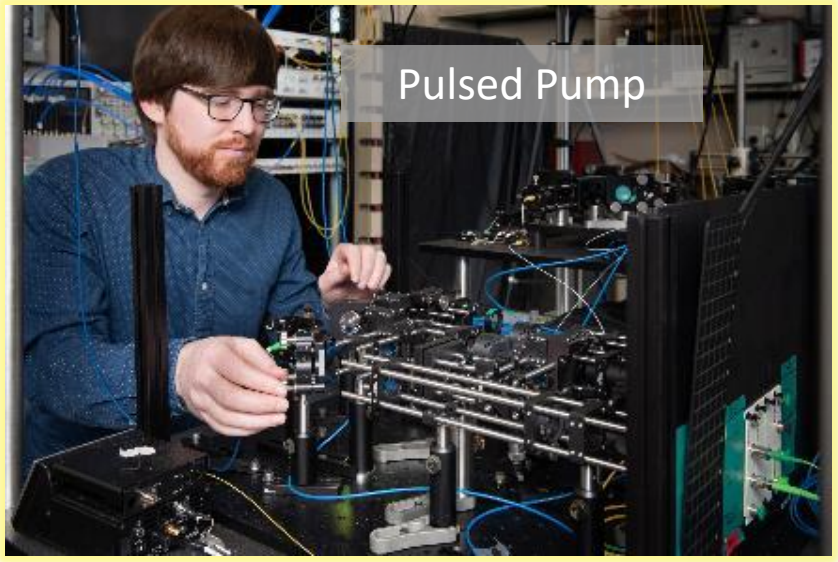
Quantum Communications

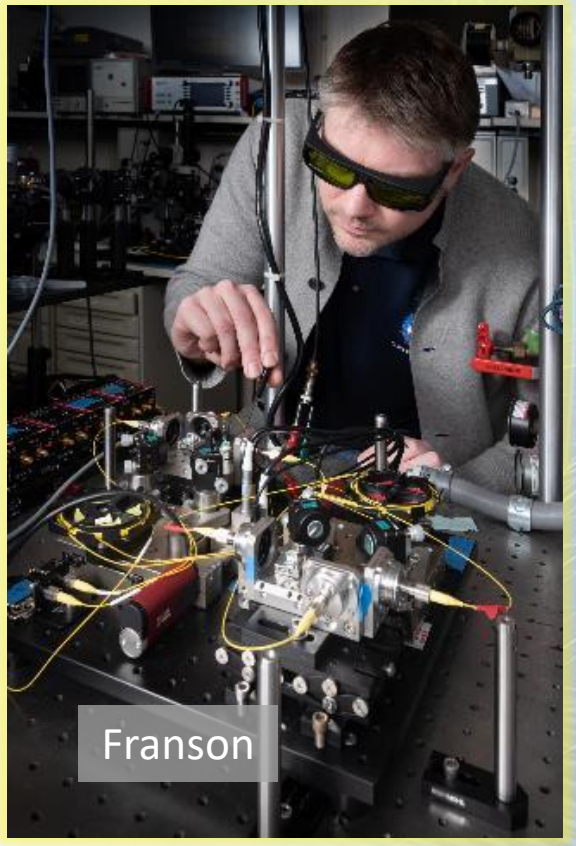


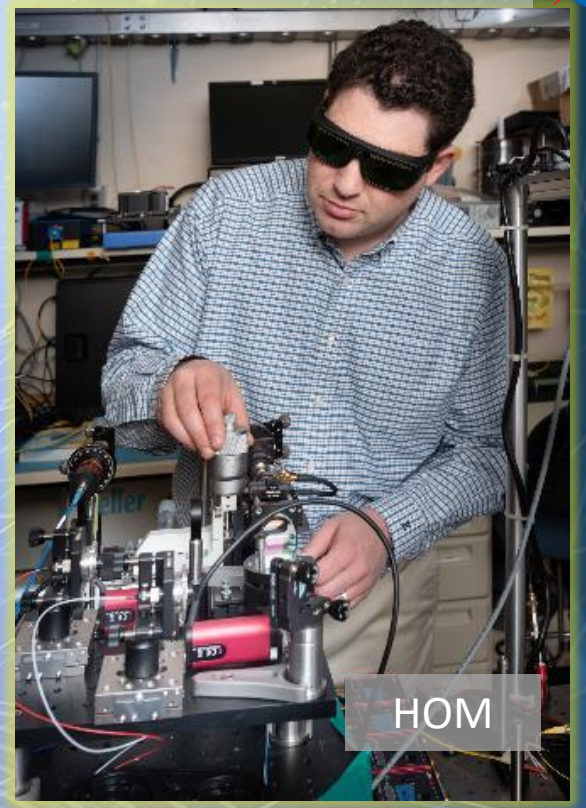
The NASA Quantum Metrology Laboratory (NQML)



Credit to NASA GRC for all pictures



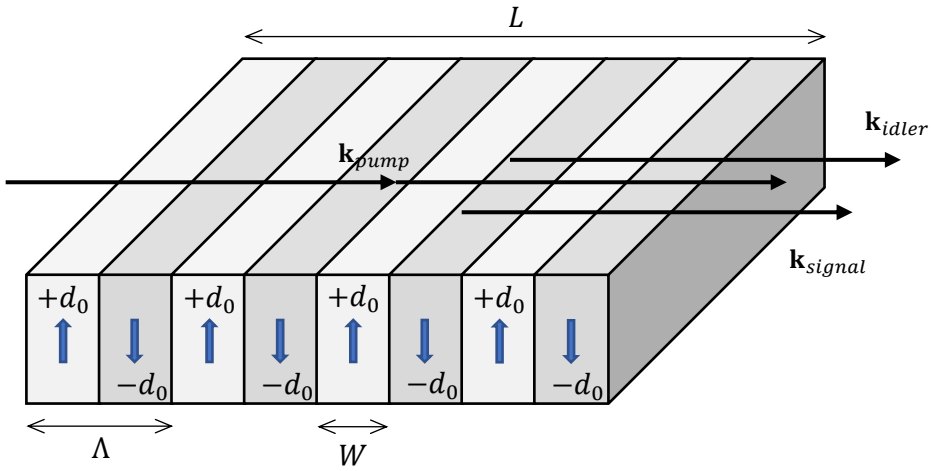




- Non-degenerate and degenerate waveguide sources
- Superconducting Nanowire Single Photon Detectors
- DLCZ Quantum Memory
- Monochromator
- Joint Spectral Intensity
- And more…

Quantum Entanglement Source

Periodically poled ferroelectric crystals



Periodically poled potassium titanyl phosphate (pp-KTP) waveguide



Credit to NASA GRC

Phase matching conditions

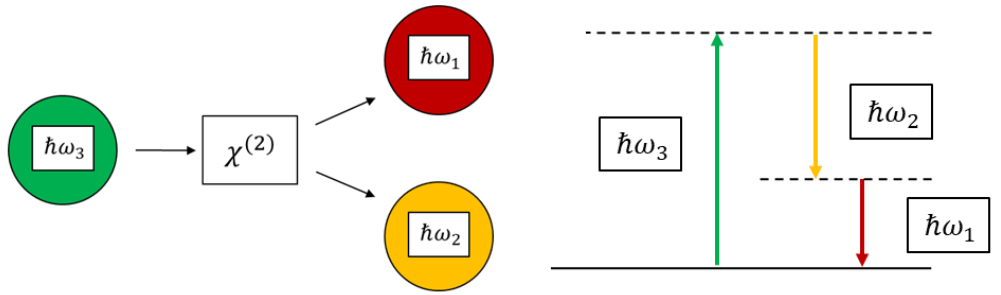
$$\begin{cases} \Delta\mathbf{k}_m = \mathbf{k}_{pump} - \mathbf{k}_{signal} - \mathbf{k}_{idler} - \dfrac{2\pi m}{\Lambda} \\ \psi = \exp\left(-i\dfrac{L}{2}\Delta k_m\right)\left(\dfrac{\sin\frac{1}{2}L\Delta k_m}{\frac{1}{2}L\Delta k_m}\right)^2 \end{cases}$$

QPM order

Crystal length

Poling period

Spontaneous Parametric Down-Conversion (SPDC) Process



PC-12 Flying laboratory interconnected with on the laboratories in the Aerospace Communications Facility

National Aeronautics and Space Administration



Key measures of quantum network performance:

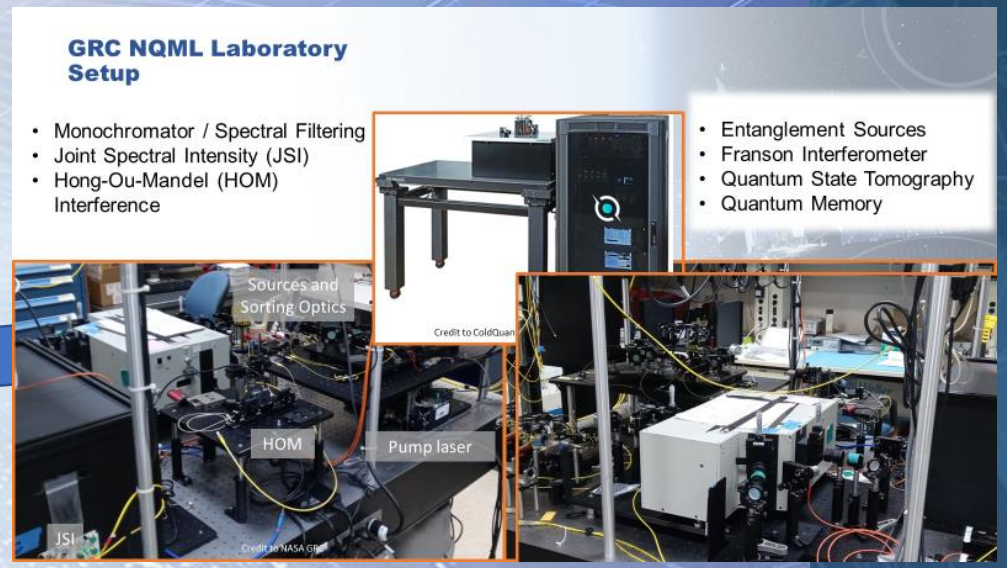
The **rate** R at which quantum states can be transmitted

- A higher rate allows for higher system bandwidth

The **fidelity** F of the quantum state transmission

- A higher fidelity improves measurement SNR

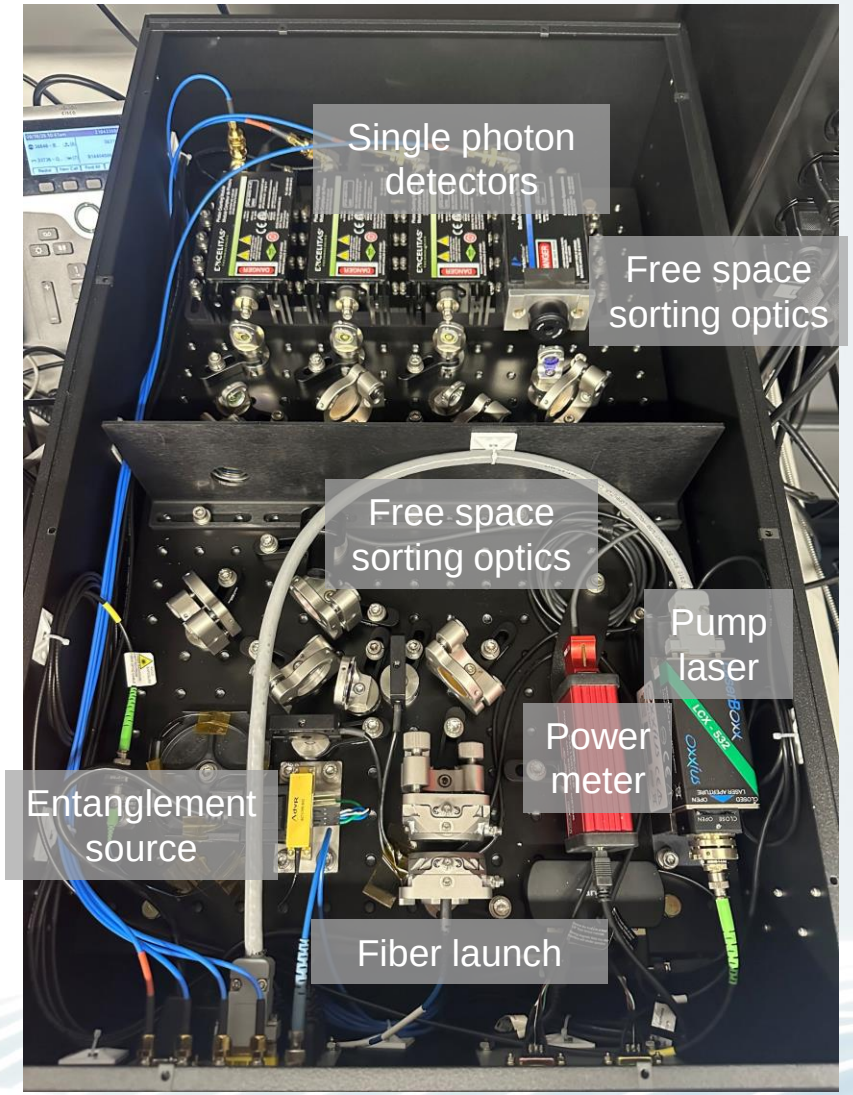




Quantum Flight Transmitter

- Initial design focused around maximizing throughput using already procured, proven components
  - 532 nm pump laser
  - Fiber-coupled in, free-space out entanglement source
  - Free-space silicon single photon detectors for signal photons at 815 nm
  - Fiber-coupled output for idler photon to tie into existing laser communications terminal
  - Stainless steel, vibration tolerant optomechanics

- Flight unit prototype completed
  - Completed emulation of flight hardware with 50 dB link loss in fiber
  - Process for 10 ns timing synchronization complete
  - Aircraft environment temperature measured, and transmitter performance verified over the temperature envelope

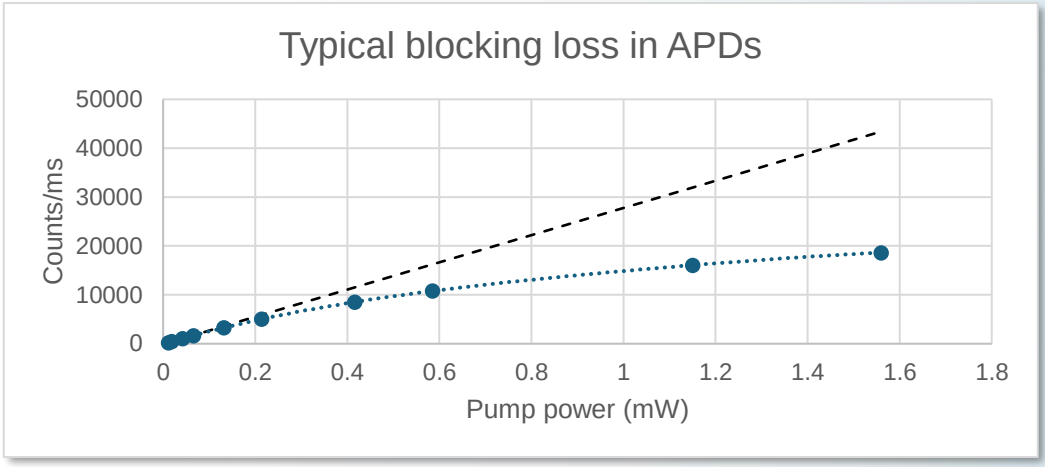


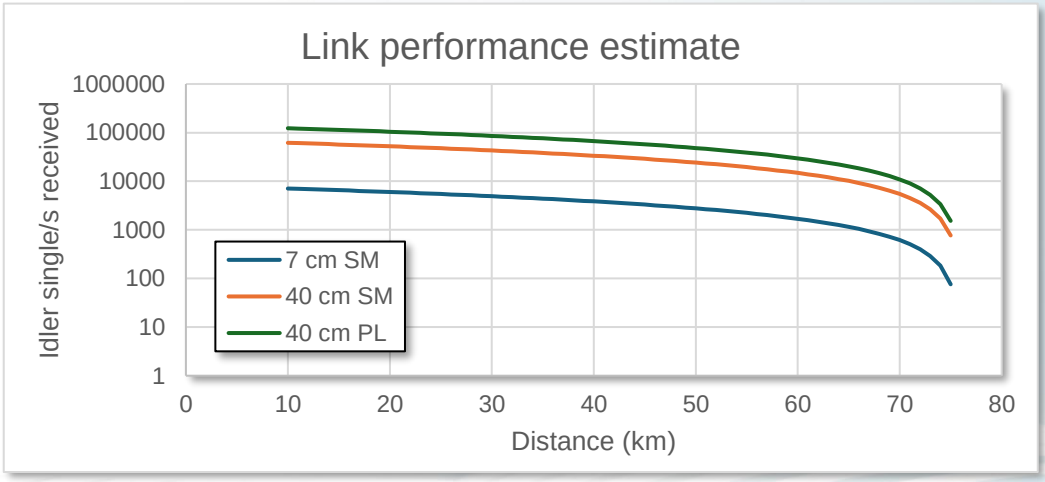
Quantum Flight Transmitter

- Able to calculate absolute detection efficiency through Klyshko method
  - $\eta_{S/I} = \frac{C}{S_{I/S}}$

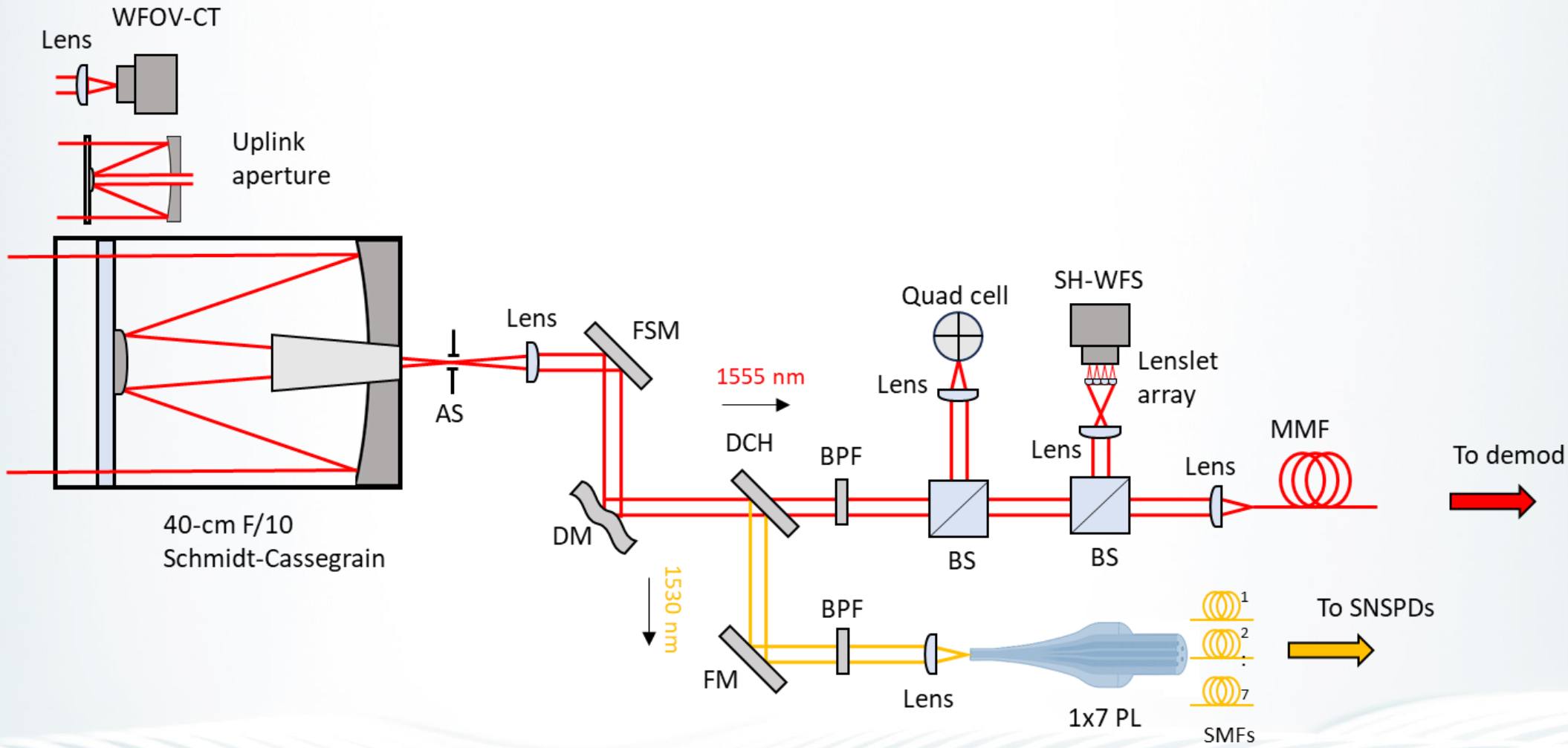
- Quantum flight transmitter performance
  - Actual pair generation rate is 1 gigapairs/second
  - Effective rate at QFT output is 12 megapairs/second
  - Losses due to optics, blocking in the detectors, etc. reduce this significantly
    - e.g., with 4 detectors in the QFT, only 34% of events are recorded
  - Free-space path loss and receiver losses reduce it further
  - Important to maximize rate (while minimizing noise)
  - Used initial system performance characterization to aid in estimating link performance (earlier slide)

Photon	Wavelength (nm)	Detection efficiency	Estimated rate (Mcounts/s)
Signal	815	0.08	86
Idler	1531	0.14	152



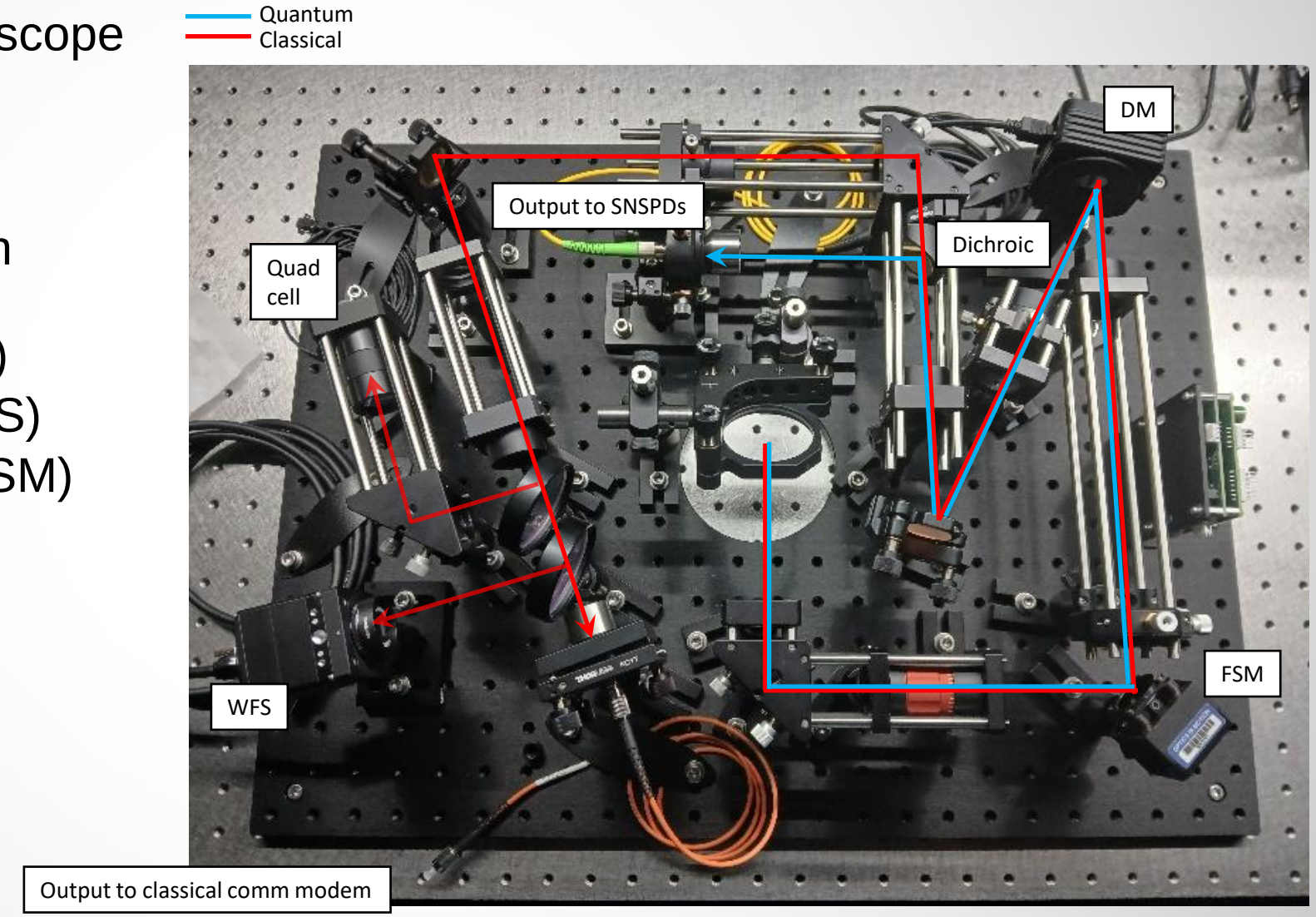


Quantum Ground Receiver (QGR) Schematic



QGR Optical Layout

- Interface from receiver telescope to fiber output
- Classical and Quantum demultiplexer
- Atmospheric correction with adaptive optics
  - Deformable mirror (DM)
  - Wave front sensor (WFS)
  - Fast Steering Mirror (FSM)
- Pointing and tracking
  - Fast Steering Mirror
  - Quad cell
- Mounting to back of 40-cm telescope



QGR Pointing and Tracking (PNT)

- Pointing and tracking testing and demonstration
  - Used a mock-up of the PC-12 aircraft on programmable translation stages
  - Able to match angular velocity and acceleration consistent with previous flights of the optical communications terminal
  - Achieved < 1 arcminute jitter at maximum anticipated relative aircraft transverse velocity



- Tracking software development in optics range
  - ADS-B signal for coarse alignment
  - Wide field camera for finer alignment
  - Quad cell with Fast Steering Mirror for finest alignment



Summary

- We have developed a high-photon efficiency receiver using 70-mode photonic lanterns/few-mode fibers coupled to superconducting nanowire single photon detectors (SNSPDs) and real-time high-rate FPGA processing
- **Receiver demonstrated with the Orion Artemis II (O2O) mission at Lunar distances; 20 – 260 Mbps with < 1 photon/bit sensitivity!!!**
- NASA has unique capabilities to contribute to quantum communications
- Developing a quantum flight transceiver with both a classical optical communications channel and an entangled photon quantum channel
- Quantum ground receiver in development to support long-range classical optical and quantum comm; various subsystems including adaptive optics
- On path to demonstration!


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