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Spatial Mode-Diversity Optical Receivers for Free-Space Optical and Quantum Communications

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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 operational optical ground stations
 - Low-cost, 1-meter class (20 – 70 cm) telescopes
 - Efficient multi-spatial mode receivers
 - Low-cost adaptive optics



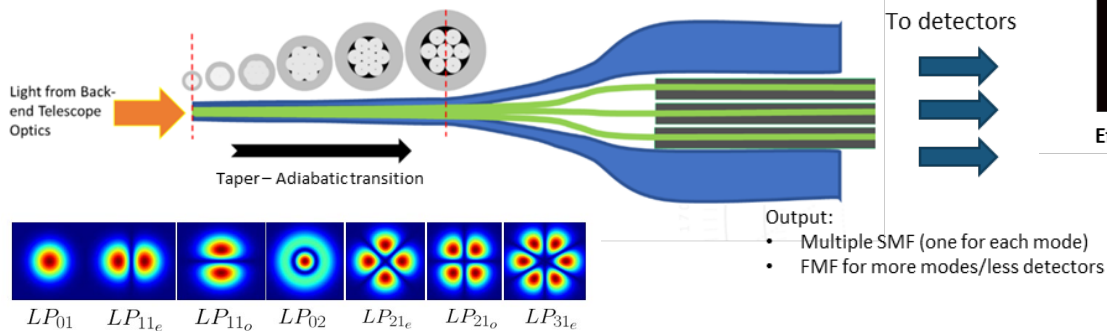
NASA Laser Communications Relay Demonstration (LCRD)



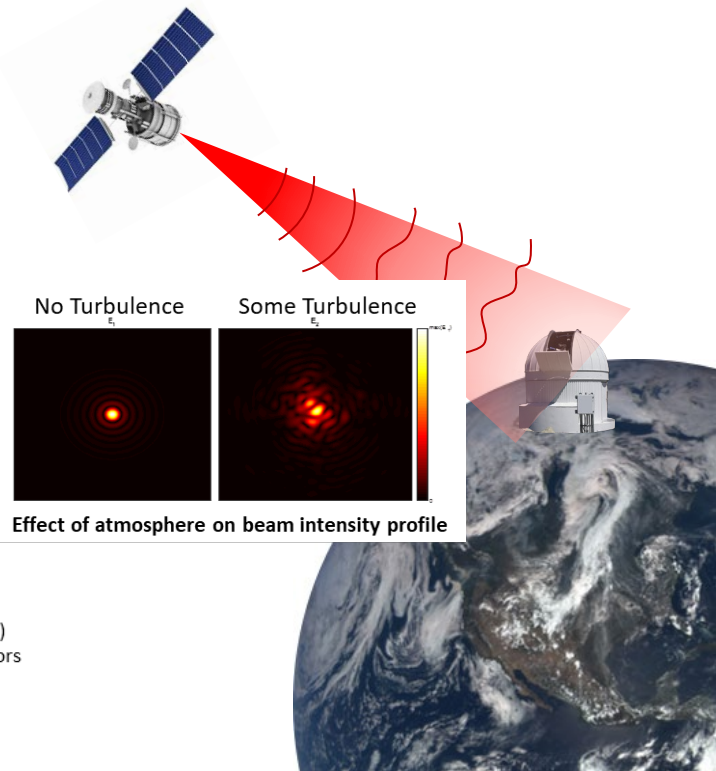
NASA GSFC Low-cost optical terminal (LOCT)

Efficient Multi-Spatial Mode Receivers - Photonic Lanterns

- The laser transmitted from a spacecraft originates as a Gaussian shape (LP_{01})
- Atmosphere distorts the beam profile and scatters energy into higher-order spatial modes
- The number of fiber spatial modes coupled by a photonic lantern matches the sum of the modes supported by the output fibers



A 7:1 SMF photonic lantern can couple these 7 spatial modes



Direct-Detection Photon-Counting Optical Receiver

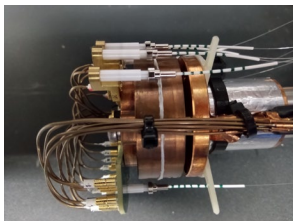
- NASA is using the CCSDS Optical Communications High Photon Efficiency (HPE) waveform on future missions: Optical Artemis-2 Orion (O2O), Psyche
 - PPM: 4, 8, 16, 32, 64, 128, 256
 - Slot widths: 512 ns - 125 ps
 - Maximum data rate: ~2 Gbps
- NASA Glenn is building a photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard
 - PPM: 16, 32
 - Slot widths: 2 ns, 1 ns, 0.5 ns
 - Maximum data rate: 267 Mbps
- Goals:
 - Utilize commercial off the shelf (COTS) components where possible
 - Demonstrate with O2O at the NASA Goddard Low-Cost Optical Terminal (LCOT) ground station

Receiver Subsystems Under Development at NASA GRC



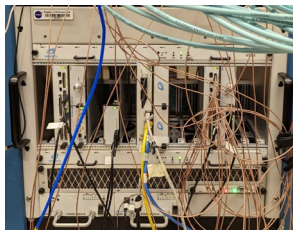
Fiber Interconnects:

- Photonic lantern (one multimode fiber input to 7-FMF outputs) or FMF
- Input fiber core size, number of outputs, and output fiber core size scalable to application
- In house prototyping capability; development partnership with University of Sydney



Single Photon Detectors:

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



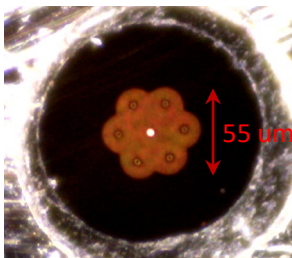
FPGA-based Receiver:

- 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

Fiber-Detector Receiver Subsystem

Photonic Lantern:

- FMFs:
 - 20 μm graded-index core
 - 4LP, 6-mode
- MMF input:
 - 55 μm
 - 42 total modes

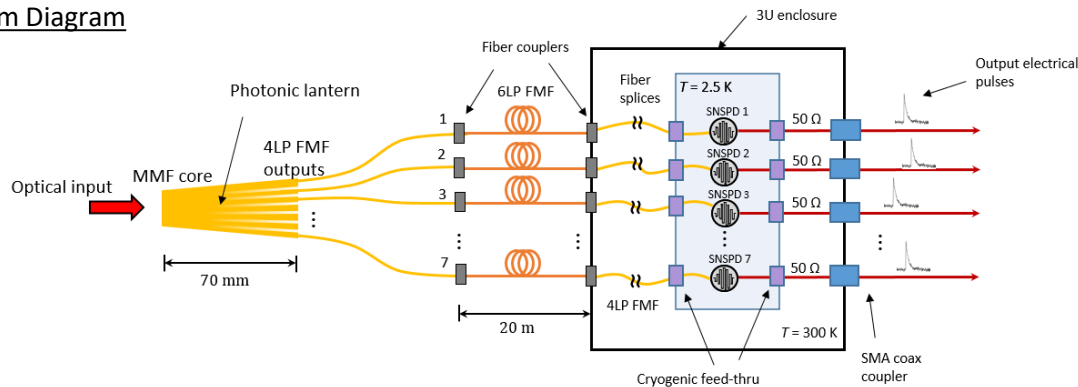


Fully packaged photonic lantern

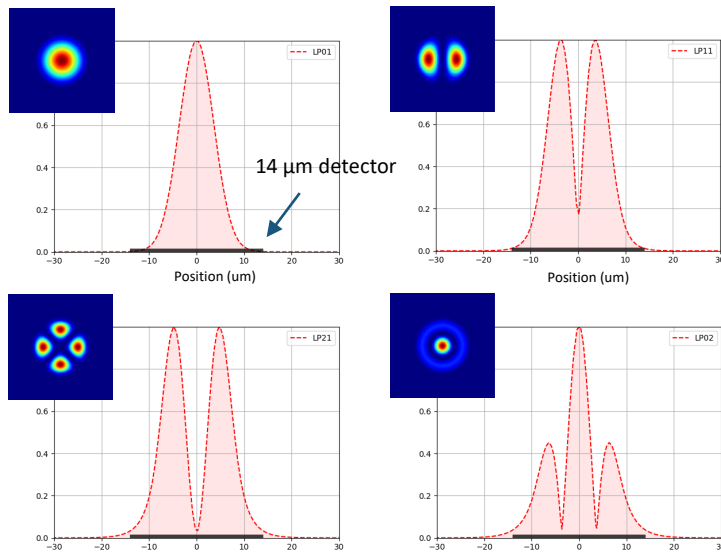


Rack-mounted SNSPD cryogenic system

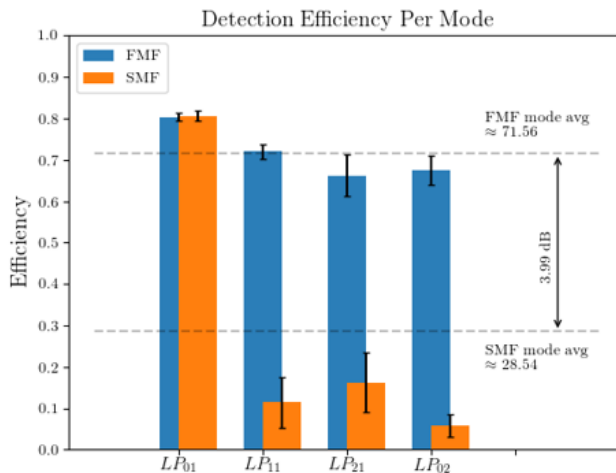
System Diagram



FMF Coupling to Single-Element SNSPDs



Graded-index 20- μm FMF can couple to $\approx 14 \times 14 \mu\text{m}^2$ SNSPDs with minimal fiber/chip coupling loss. Compared with SMF the additional modes represent a gain of ≈ 4 dB



	LP01	LP11	LP21	LP02
MFD (μm)	10.30	14.67	18.43	18.86
A_{eff} (μm^2)	83.12	168.08	235.77	185.13

Detector area $\sim 14 \times 14 \mu\text{m}^2$ ($196 \mu\text{m}^2$)

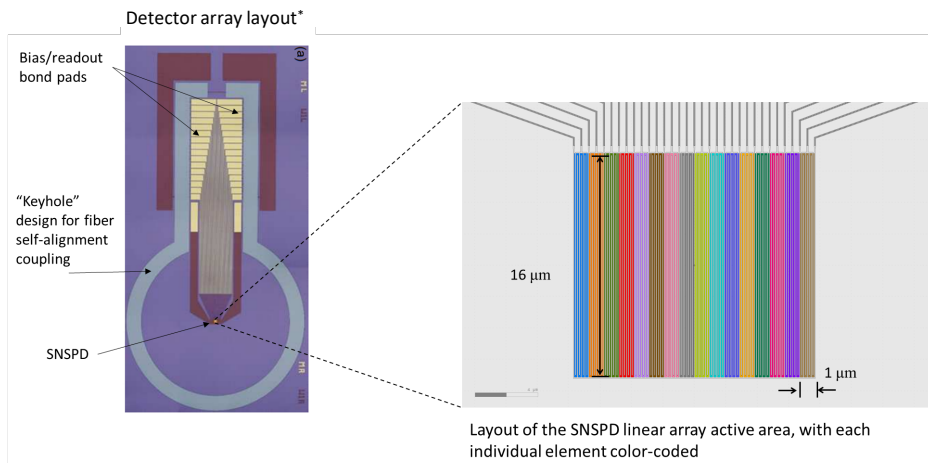
FMF + 16-Channel SNSPD Array

FMF #1 (coupled to SNSPD array):

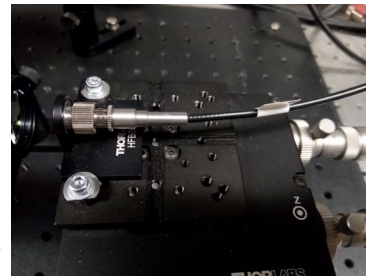
- 20 μm graded-index core
- 4 LP, 6-modes

FMF #2 (20 m system input):

- 25 μm graded-index core
- 6 LP, 10-modes



*Rambo, T. M., Conover, A. R., and Miller, A. J., "16-element superconducting nanowire single-photon detector for gigahertz counting at 1550-nm," (2021). <https://arxiv.org/abs/2103.14086>

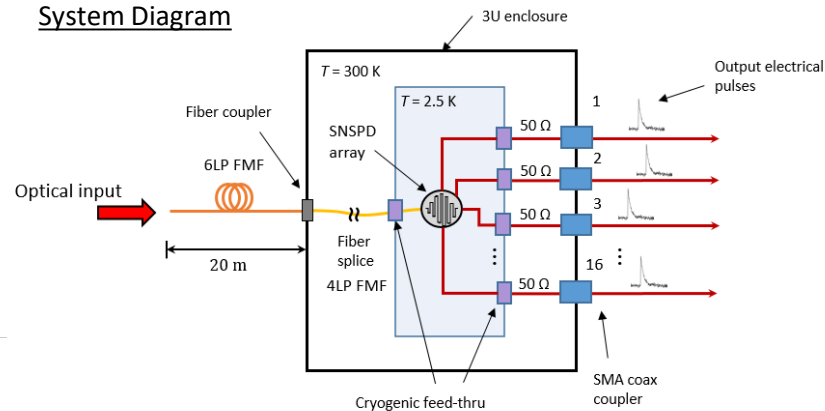


FMF on alignment stage



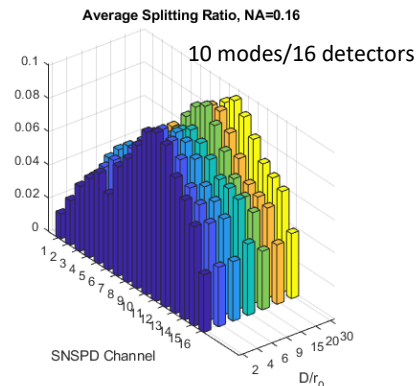
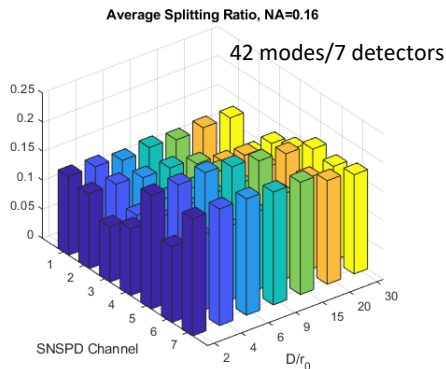
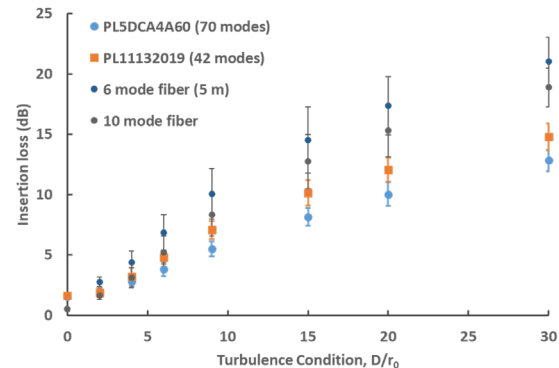
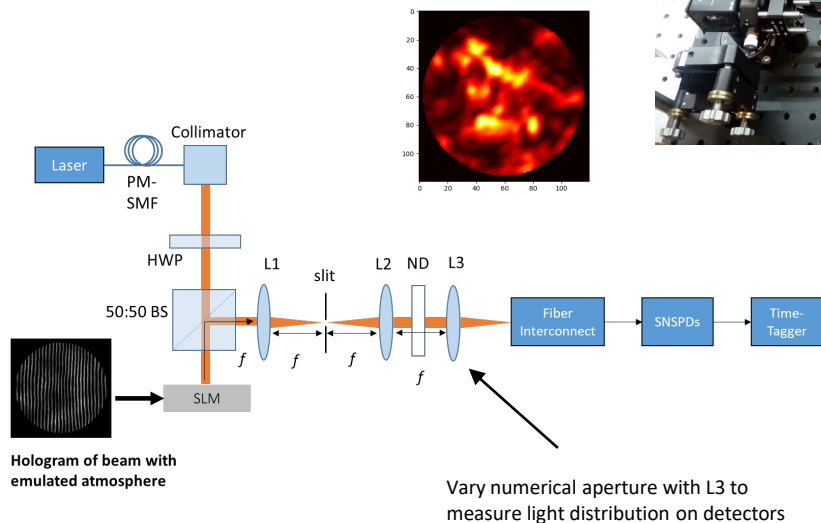
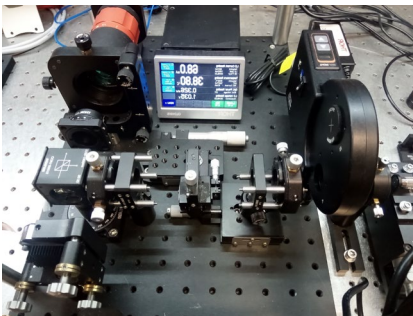
Rack-mounted SNSPD cryogenic system

System Diagram

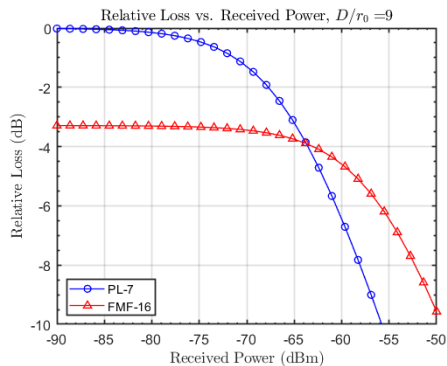
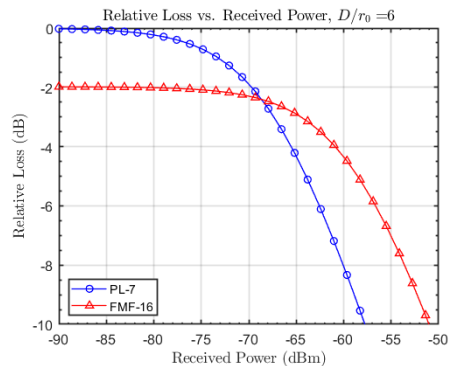
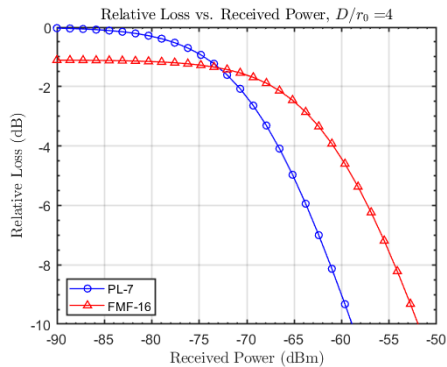
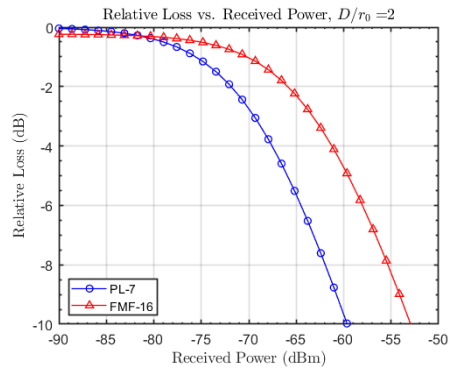


Test Setup With Arbitrary Light Field Generator (ALF-G)

Simulated 2D beam profiles (phase and intensity) are recreated in the lab by modulating the beam via a complex amplitude phase hologram written to the SLM.



Fiber-Detector Subsystem Loss Comparison

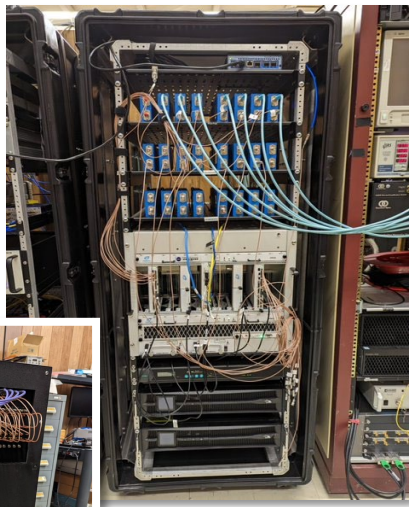
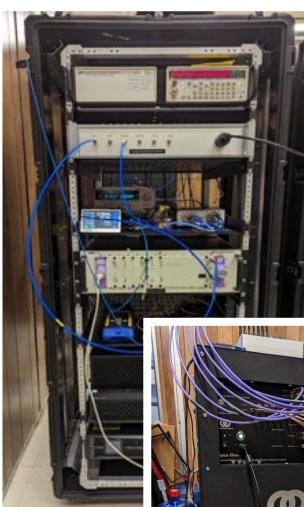


D/r_0	Relative Loss (dB)	P_{RX} (dBm)
2	0.20	-81.31
4	1.08	-72.82
6	1.96	-68.78
9	3.28	-63.53

- Combined coupling loss, blocking loss, and input distribution effects over a range of input power
- FMF/SNSPD array system has more loss at lower received power and higher D/r_0 due to coupling
- Photonic lantern/single SNSPDs system has more loss at higher input powers due to detector count rate limitations/blocking loss
- There is a cross-over input power where relative coupling loss balances detector blocking losses

CWER Results – PPM-16, Code Rate 1/2, 200 Mbps

Test transmitter

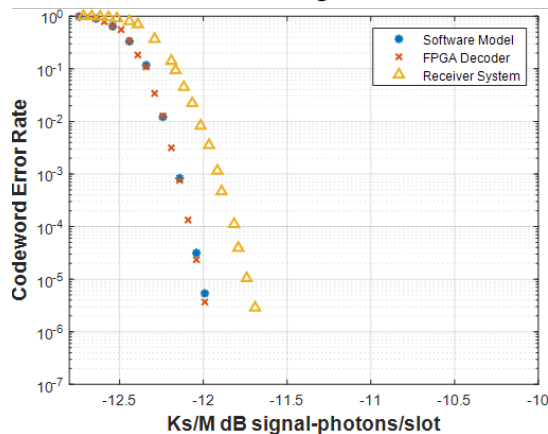


Receiver

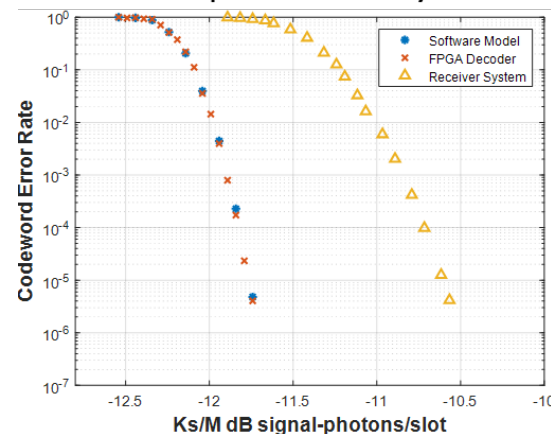


SNSPDs

Photonic Lantern + 7 Single Detectors



FMF + 16-pixel Detector Array

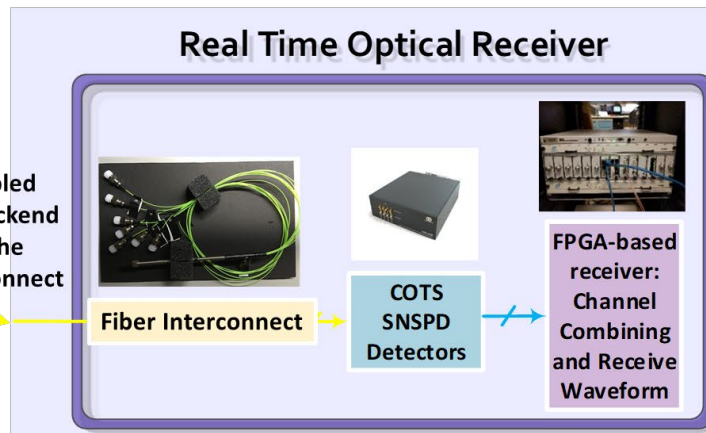


Detector Jitter & FPGA Implementation Loss (dB)		Fiber & Detector Loss (dB)		Measured K_b at 10^{-5} CWER (dB photons/slot)		Required Input Power at 10^{-5} CWER (dBm)	
PL	A	PL	A	PL	A	PL	A
0.3	1.2	9.6	3.5	-24.7	-20.8	-68.7	-73.5

Receiver will be demonstrated at the NASA GSFC Low Cost Optical Terminal*



Light is coupled from the backend optics into the fiber interconnect

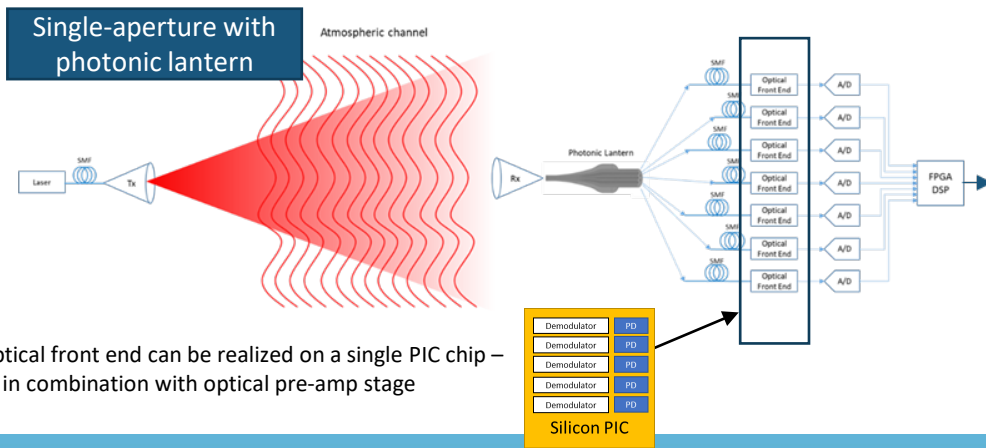
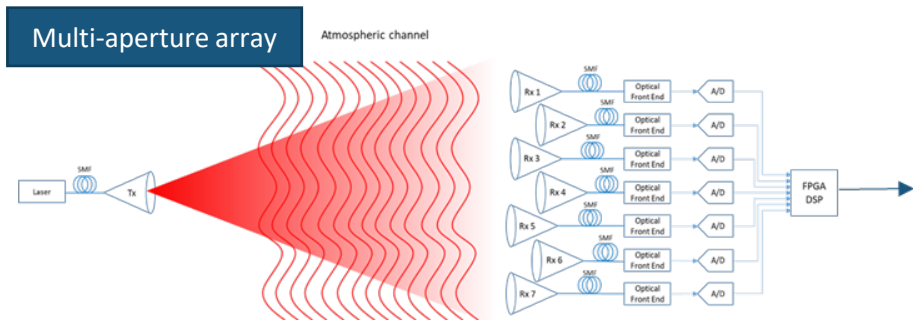


Optical ground station components provided by NASA GSFC LCOT: dome, telescope, back-end optics (includes tracking and pointing)

*Lafon, R., Bai, Y., Caroglanian, A., Dailey, J., Desch, N., Garon, H., Hall, S., Miller, R., Paulson, D., Safavi, H., Sekulic, P., Speer, J., Thompson, P., and Wu, V. "NASA's low-cost optical terminal (LCOT) at Goddard Space Flight Center," SPIE Free-Space Laser Communications XXXV, 12416 (2023).

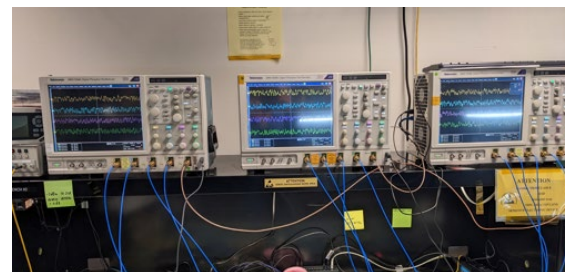
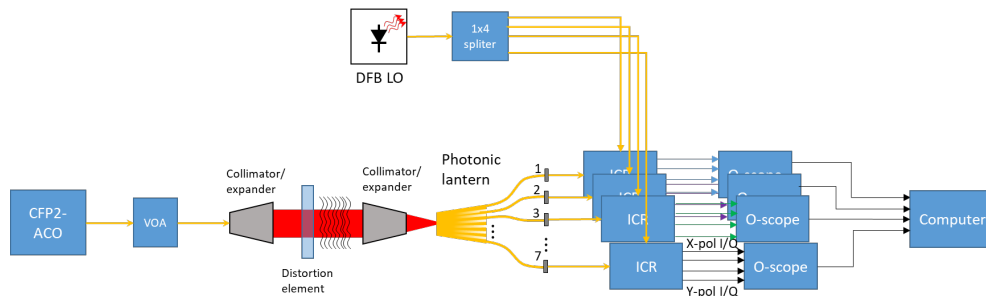
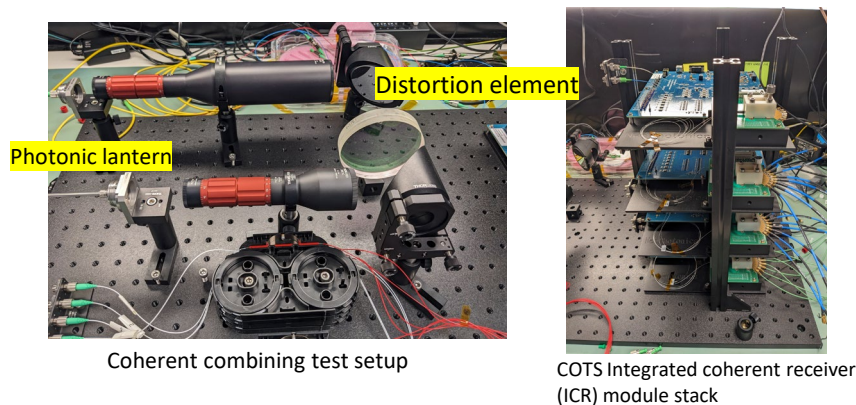
Multi-Gbps Spatial Mode-Diversity Coherent Optical Receivers

- Photonic lantern can provide spatial diversity similar to a multi-aperture array, but with considerable savings in SWaP and cost
- A silicon photonic integrated circuit (PIC), can couple to the photonic lantern and incorporate on-chip demodulators and high bandwidth photodetectors (10s of GHz)
 - Serves as the optical front-end outputting electrical signals for further processing.
 - Accommodate many 10s of channels
 - Wide variety of other functions such as narrowband filtering, and wavelength multiplexing.
 - Can support coherent optical modulations – DPSK, QPSK, dual-polarization, QAM, etc.
- Possible to do active signal combining on-chip to reduce output channels to one SMF for processing – currently under investigation



Photonic Lantern Coherent Combining at NASA GSFC*

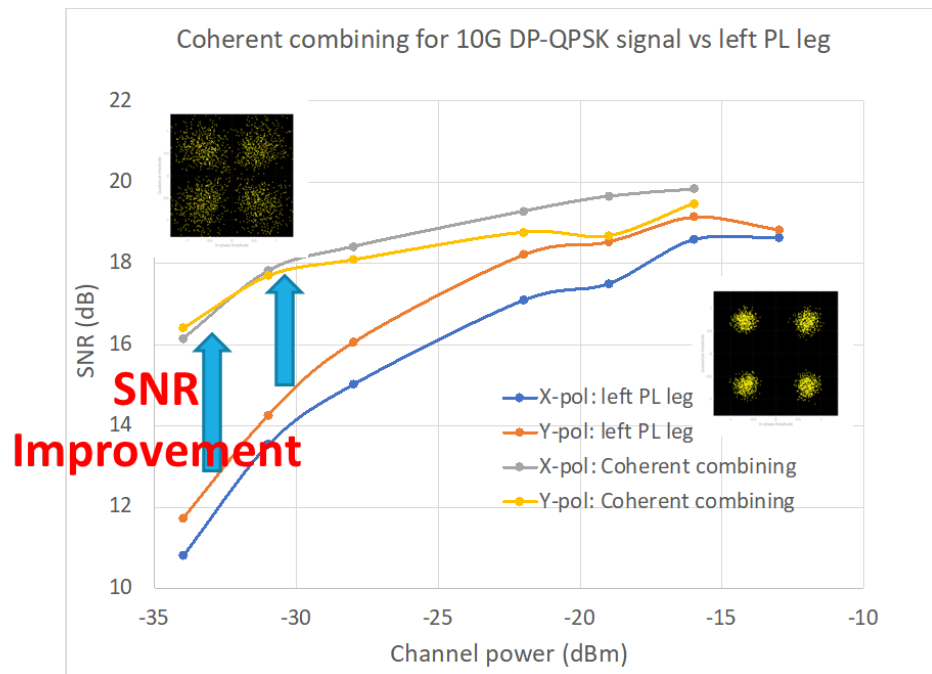
- 10 Gbps DP-QPSK transmit signal from CFP2 module
- Variable optical attenuator and atmospheric distortion emulator
- Four separate integrated coherent receivers (ICR)
- DFB local oscillator shared between integrated receivers
- High sample rate digitizing oscilloscopes collect X/Y-pol I and Q signals for post processing
- Experiments repeated at powers between -3 and -33 dBm



*Yevick, A., Lafon, R., Bayne, R., Garcia, R., Grigoryan, V.S., and J. Veselka,

"Experimental demonstration of coherent receiver with photonic lantern and digital signal processing"

GSFC - Recent Coherent Combining Results*



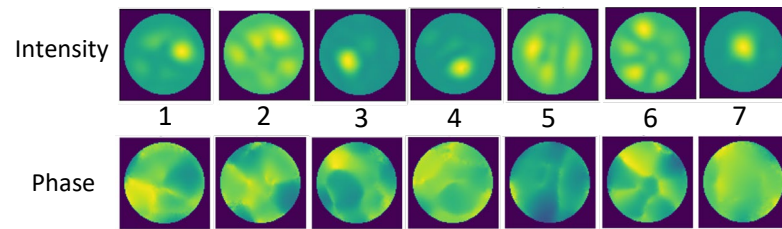
- Digital-domain coherent combining
 - Optical carrier frequency recovery and equalization
 - Optical carrier phase recovery and equalization
 - Signal clock recovery
 - Signal polarization tracking and polarization demultiplexing
 - Time misalignment equalization between PL output legs
 - Optimal digital coherent combining of signals from PL output legs to maximize signal SNR
- SNR improvement due to optimum coherent combining increases as SNR for best individual leg decreases: **SNR improvement reaches $\approx 4\text{dB}$ at $P_{ch} = -34\text{dBm}$**
- Theoretical maximum $\approx 4.77\text{ dB}$
- Power monitoring each signal will maximize SNR improvement

*Yevick, A., Lafon, R., Bayne, R., Garcia, R., Grigoryan, V.S., and J. Veselka,

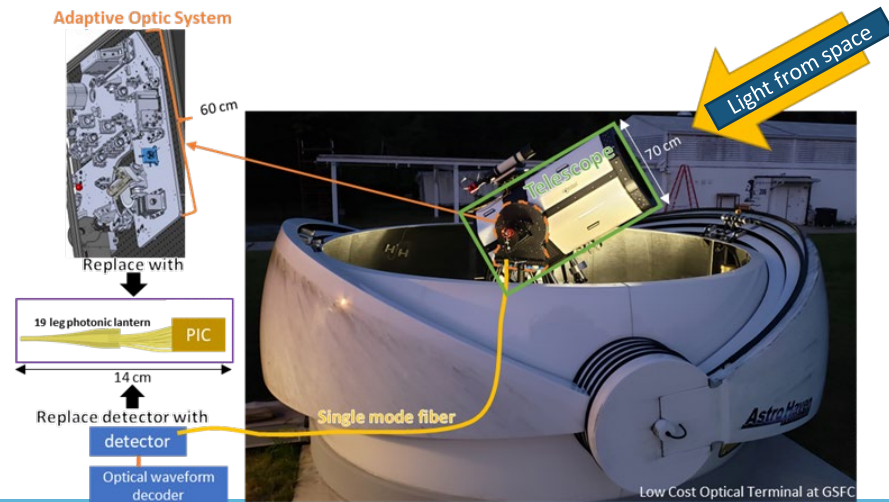
"Experimental demonstration of coherent receiver with photonic lantern and digital signal processing"

Photonic Lantern Wavefront Sensing

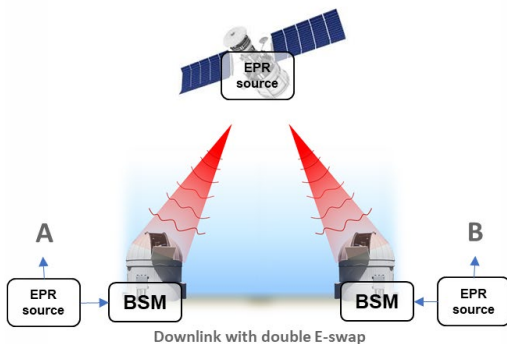
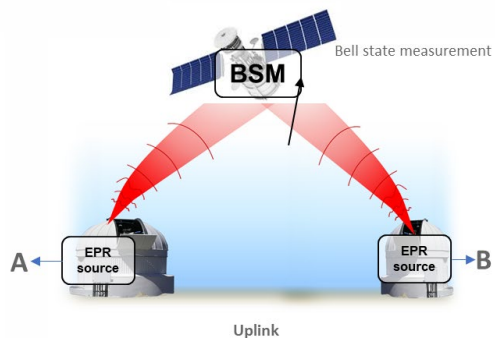
- Photonic lanterns can efficiently couple to single mode fiber (needed for coupling to coherent comm. detectors)
- Intensities and phases of the SM outputs have a direct relationship to both phase and amplitude information of the incident wavefront
- Replace the wavefront sensor (WFS) – expensive part of adaptive optics (AO) systems
- If combined with a photonic integrated circuit, could serve as both light delivery and adaptive optics system through optical coherent combining to greatly reduce size, weight, power, and complexity
- Increase optical ground station scalability



1x7 SMF photonic lantern input/output measured with wavefront sensor



Towards Satellite-Based Quantum Networks

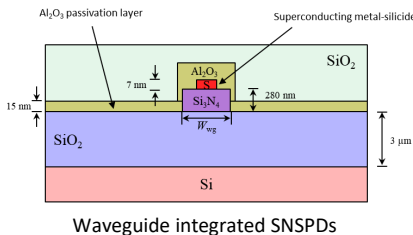


- Quantum entanglement distribution over long distances
 - Quantum key distribution (QKD)
 - Teleportation / entanglement swapping
 - Distributed quantum computing
- NASA GRC has established the NASA Quantum Metrology Laboratory (NQML):
 - Compactified metrology builds: Reduction in system footprints, complexities, and photon losses
 - Environmental emulation: Measurement of space-based environmental impacts on quantum processes.
 - Verification and validation: Entanglement swapping link analysis (among many other link assessment capabilities)
 - Standards for space-based assets: Establishment of definitions consistent with the overall research community
- Analysis and testing of quantum communications protocols
- Currently investigating use of photonic lanterns, multi-plane light conversion (MPLC) for transmit and receive systems

Integrated Quantum Technologies Under Development



Waveguide SPDC source



Sources

- MgO-doped LiNbO₃ spontaneous parametric down-conversion (SPDC) waveguide sources
- Silicon photonic spontaneous four-wave mixing (SFWM) bi-photon sources nominally in the 1530-1570 nm wavelength range; also 775 nm, 794 nm, etc.
- Thin-film lithium niobate (TFLN) SPDC sources (SBIR/STTR)

Analysis

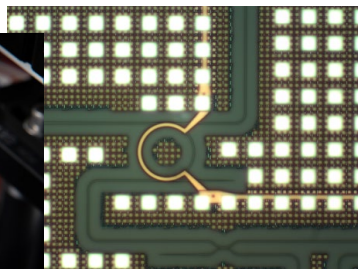
- Bell state analyzer (BSA) with Franson-type interferometry capability for highly-nondegenerate sources, i.e. 1588/794 nm, 1550/775 nm, etc.
- Two-photon interference for BSA and entanglement swapping, or thermal source interference
- Integrated tunable, high-Q resonant filters
- Tunable phase shifters

Detectors

- Waveguide integrated SNSPDs



Integrated photonic chips on probe station



Micro-ring resonator SFWM entanglement source

Summary

- We have developed 1x7 MMF – FMF photonic lantern coupled to superconducting nanowire single photon detectors (SNSPDs) for a spatial-mode diversity photon-counting optical receiver – will demonstrate with the GSFC 70-cm low-cost optical receiver (LCOT)
- With optimal coupling, the receiver concept based on a FMF photonic lantern with 7 single-element SNSPDs has lower total losses - data rate and input power dependent, due to detector blocking
- Currently investigating applications to coherent optical communications – multiple parallel channels digitally combined
- Photonic lanterns can be used for wavefront sensing – can potentially reduce cost and requirements for adaptive optics
- Currently investigating use of photonic lanterns, multi-plane light conversion (MPLC) for quantum communications transmit and receive systems
- Developing photonic circuit packages for integrated receiver systems

Acknowledgements:

- NASA GRC: Sarah Tedder, Jennifer Downey, Bertram Floyd, and Yousef Chahine
- NASA GSFC: Aaron Yevick, Robert Lafon, Vladimir Grigoryan, and John Veselka
- NASA GRC Communications and Intelligent Systems Division
- NASA Space Communications and Navigation (SCaN) Program

