The application of photonic lanterns in free space optical communications

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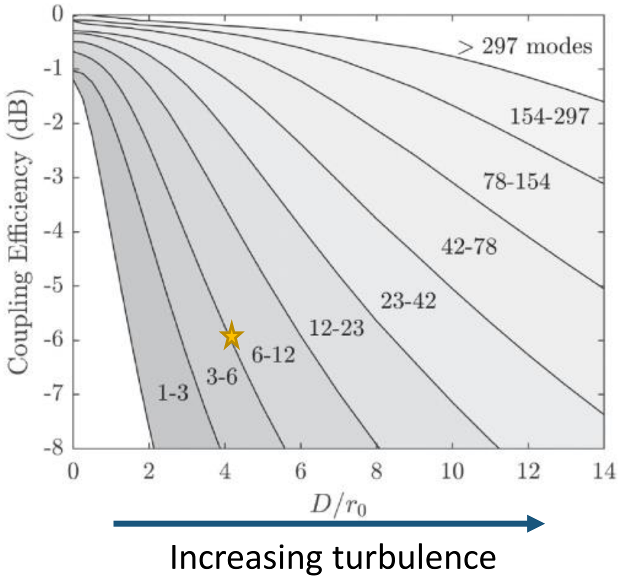
Motivation for Free Space Optical Communications

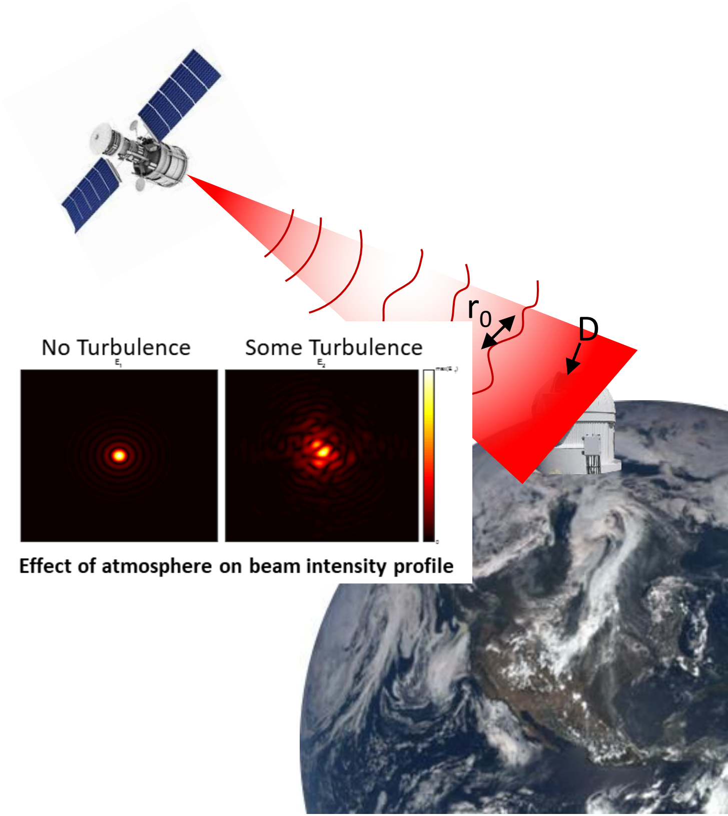
- Future NASA communications and navigation systems in the Lunar and deep space environment will need to accommodate missions requiring high data-volume transmissions
- Optical communications can provide orders of magnitude system improvements vs. current RF systems
- Fiber coupled receivers can offer lower cost, more flexible design options for ground terminals.

NASA Laser Communications Relay Demonstration (LCRD)

Space to ground atmospheric effects impact on fiber coupled receivers

- 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 efficiency of fiber coupling is dependent on the number of the modes supported by the fiber.



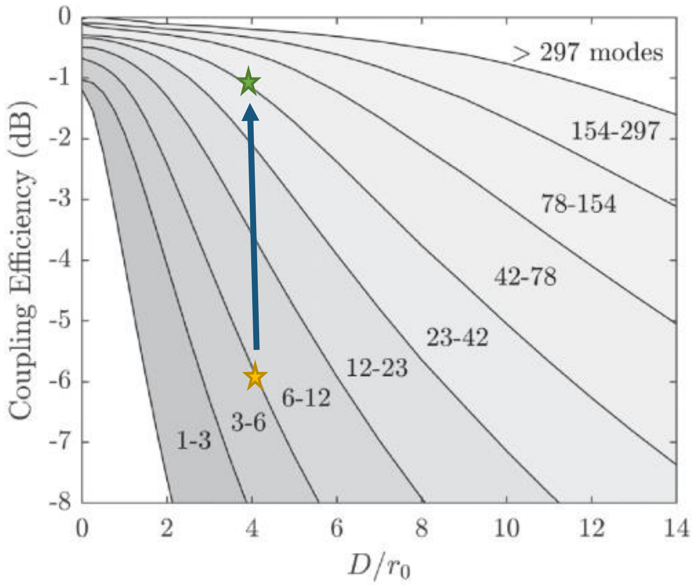


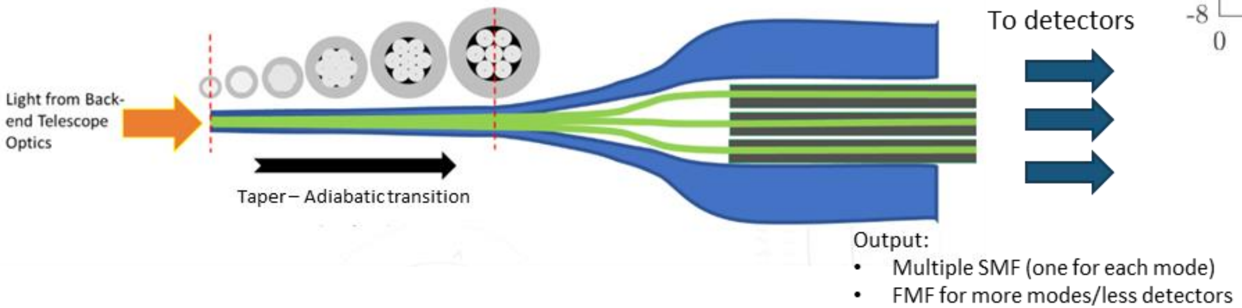
D- diameter of collection aperture

r_0- coherence length

Efficient Multi-Spatial Mode Receivers - Photonic Lanterns

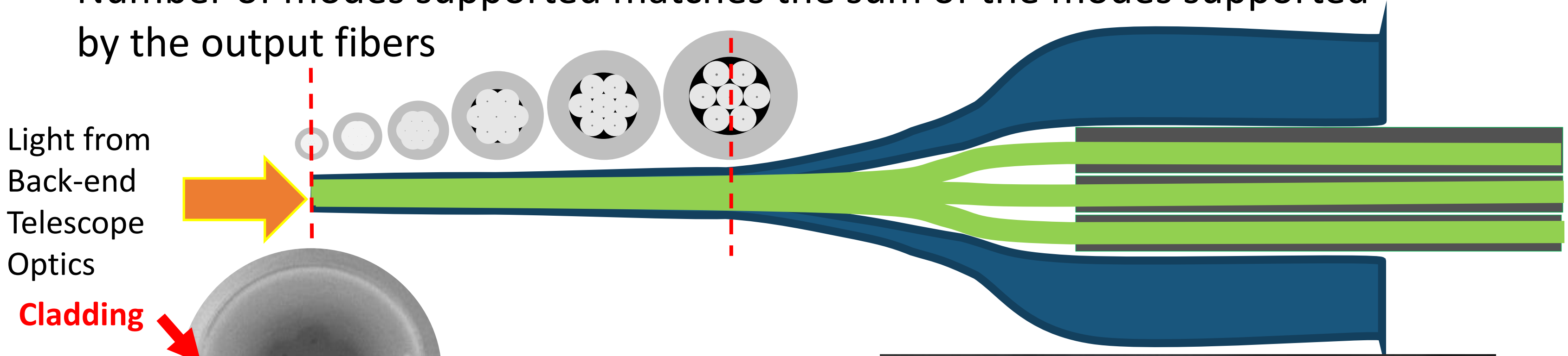
- Increasing number of modes improves coupling
- But increasing number of modes increases fiber core size:
  - Pulse position modulation: poor coupling to small area detectors
  - Coherent modulation requires single mode fiber
- Photonic lantern enables efficient transition of multi spatial modes to multiple smaller core fibers

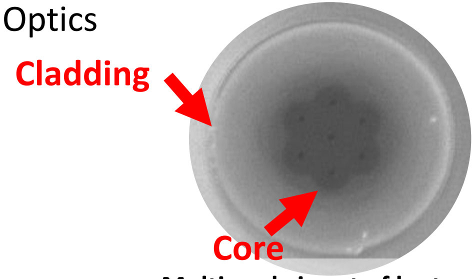




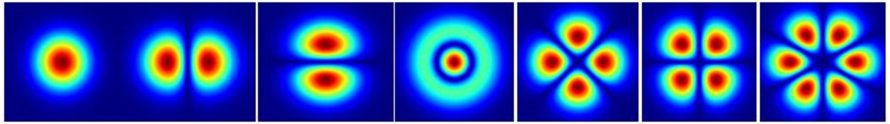
Photonic Lantern

- Number of modes supported matches the sum of the modes supported by the output fibers





Multimode input of lantern



LP_{01} LP_{11_e} LP_{11_o} LP_{02} LP_{21_e} LP_{21_o} LP_{31_e}

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

Fully packaged photonic lantern, next to bare photonic lantern

Pulse Position Modulation Photon-Counting Optical Receiver

- Pulse position modulation uses direct detection of timed pulses
- NASA is using the CCSDS Optical Communications High Photon Efficiency (HPE) waveform: Optical Artemis-2 Orion (O2O) and Psyche
- NASA Glenn is building a photon-counting ground receiver compliant with the CCSDS Optical Communications HPE standard using commercial off the shelf (COTS) components where possible.

Receiver Subsystems Under Development at NASA GRC

Fiber Interconnect

Deliver light from telescope to detectors

Superconducting nanowire single-photon detectors (SNSPDs)

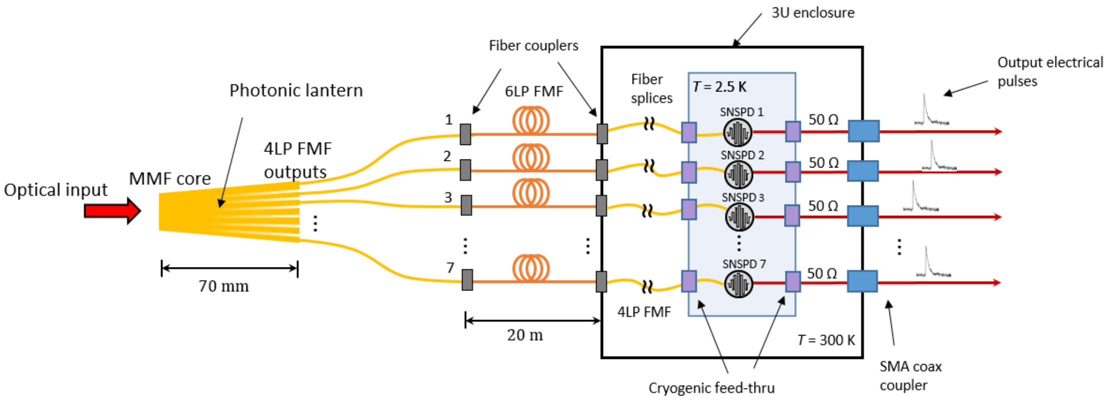
Single Photon Detectors

FPGA-based Receiver

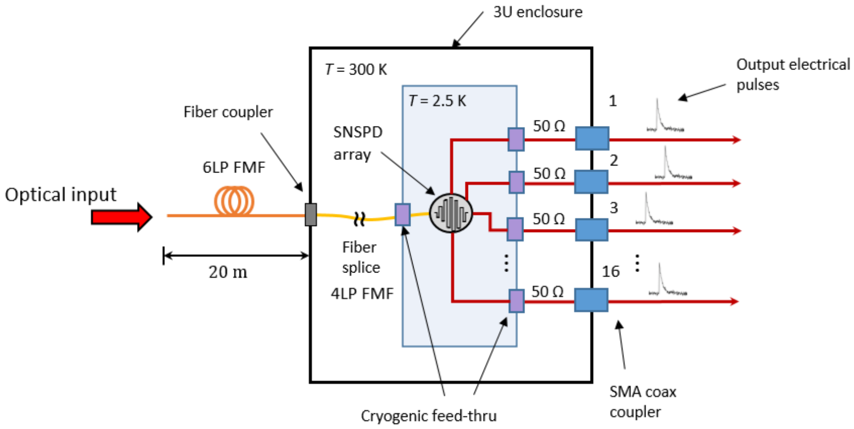
Recovers timing and decodes data

2 Fiber\Detector Architectures under development

FMF Photonic Lantern + 7 single pixel SNSPDs



FMF + 16-Channel SNSPD Array



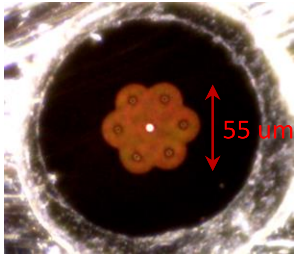
Photonic Lantern/Single Pixel SNSPDs

Photonic Lantern:

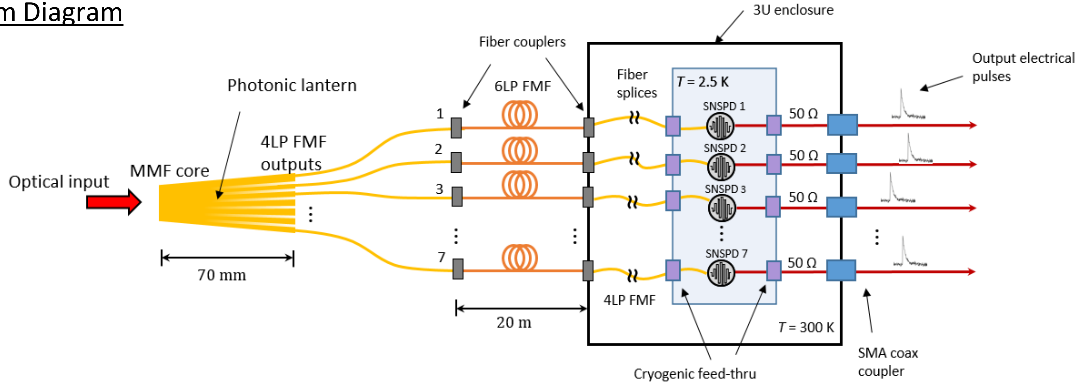
- FMFs:
  - 20 um graded-index core
  - 4LP, 6-mode
- MMF input:
  - 55 um
  - 42 total modes

Fully packaged photonic lantern

Rack-mounted SNSPD cryogenic system



System Diagram

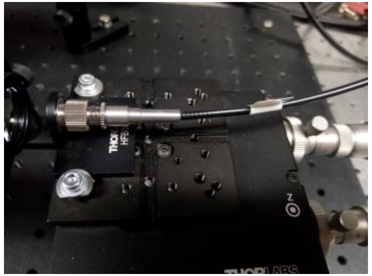


- Detectors can be coupled with FMFs without loss, therefore we created a new type of lantern with FMFs
  - Increase the number of modes supported by each fiber output leg (1 mode→6 modes)
  - Enables higher number of modes coupled with same number of detectors (7 fibers → 42 modes)

FMF + 16-Channel SNSPD Array

FMF #1 (20 m system input):
- 25 um graded-index core
- 6 LP, 10-modes

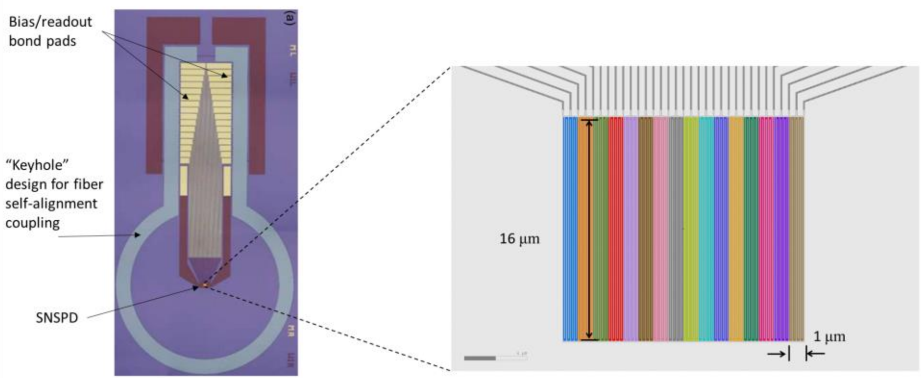
FMF #2 (coupled to SNSPD array):
- 20 um graded-index core
- 4 LP, 6-modes



FMF on alignment stage

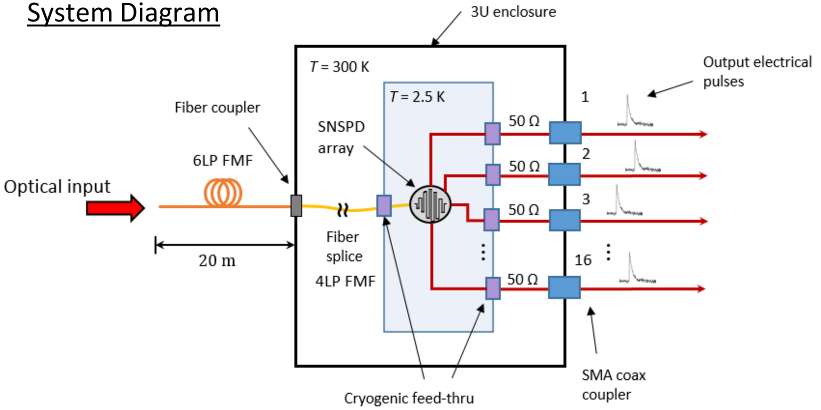
Rack-mounted SNSPD cryogenic system

Detector array layout*



Layout of the SNSPD linear array active area, with each individual element color-coded

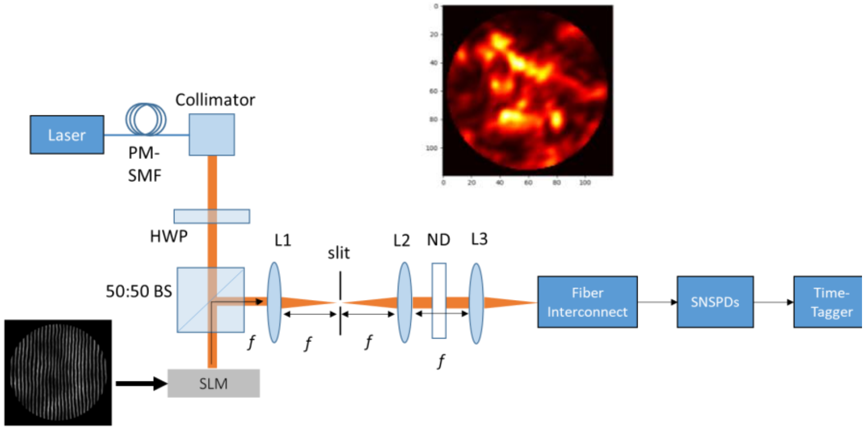
System Diagram



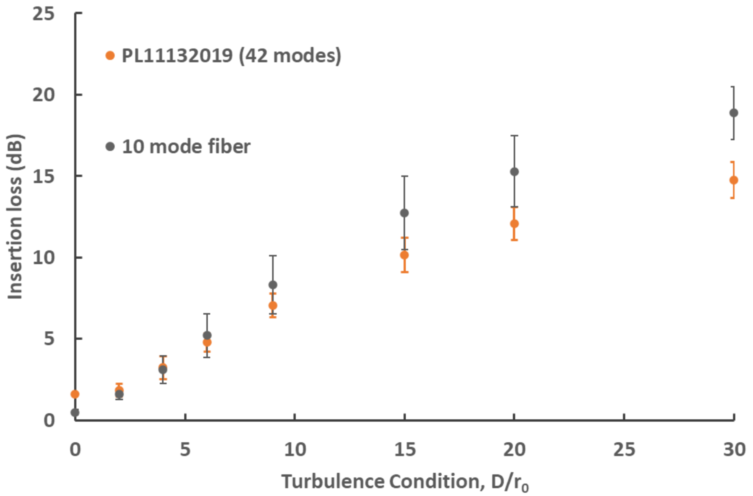
*Rambo, T. M., Conover, A. R., and Miller, A. J., "16-element superconducting nanowire single-photon detector for gigahertz counting at 1550-nm," (2021). https://arxiv.org/abs/2103.14086

Comparing fiber interconnects insertion loss due to atmospheric effects

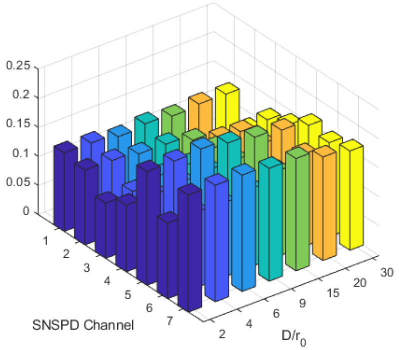
Simulated 2D beam profiles (phase and intensity) are recreated in the lab by modulating the beam via a complex amplitude phase hologram written to the SLM.



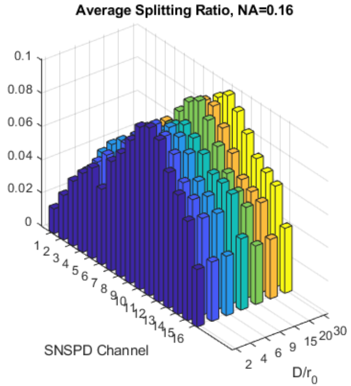
Hologram of beam with emulated atmosphere



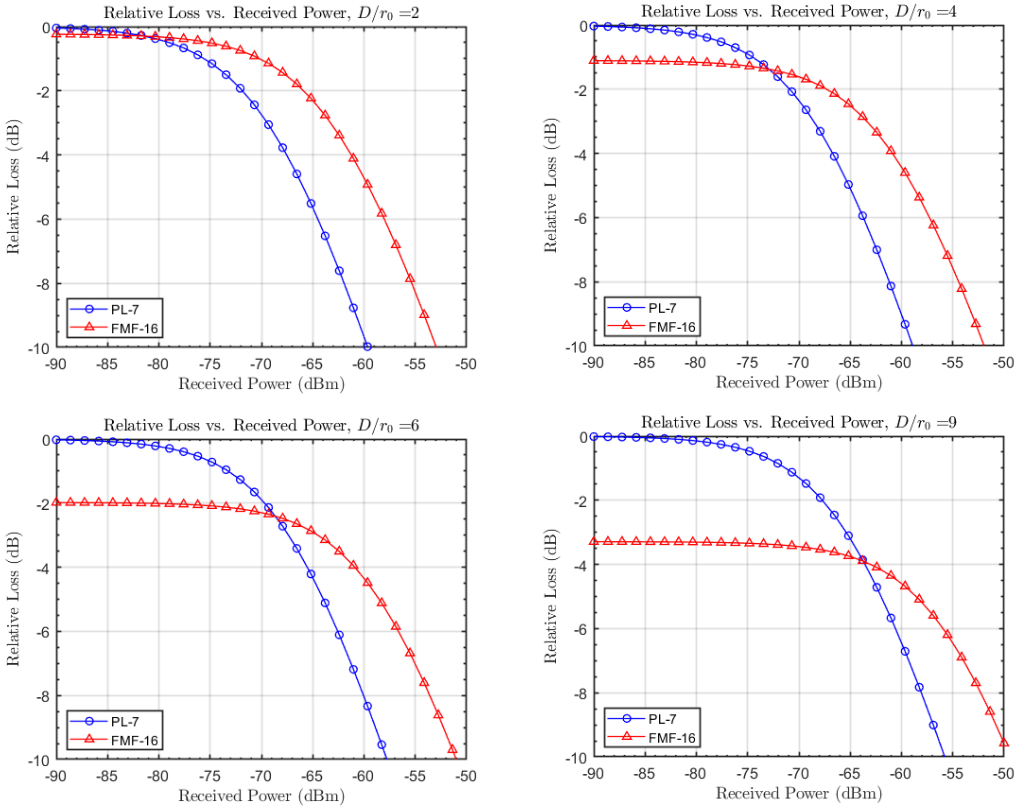
42 modes/7 detectors



10 modes/16 detectors



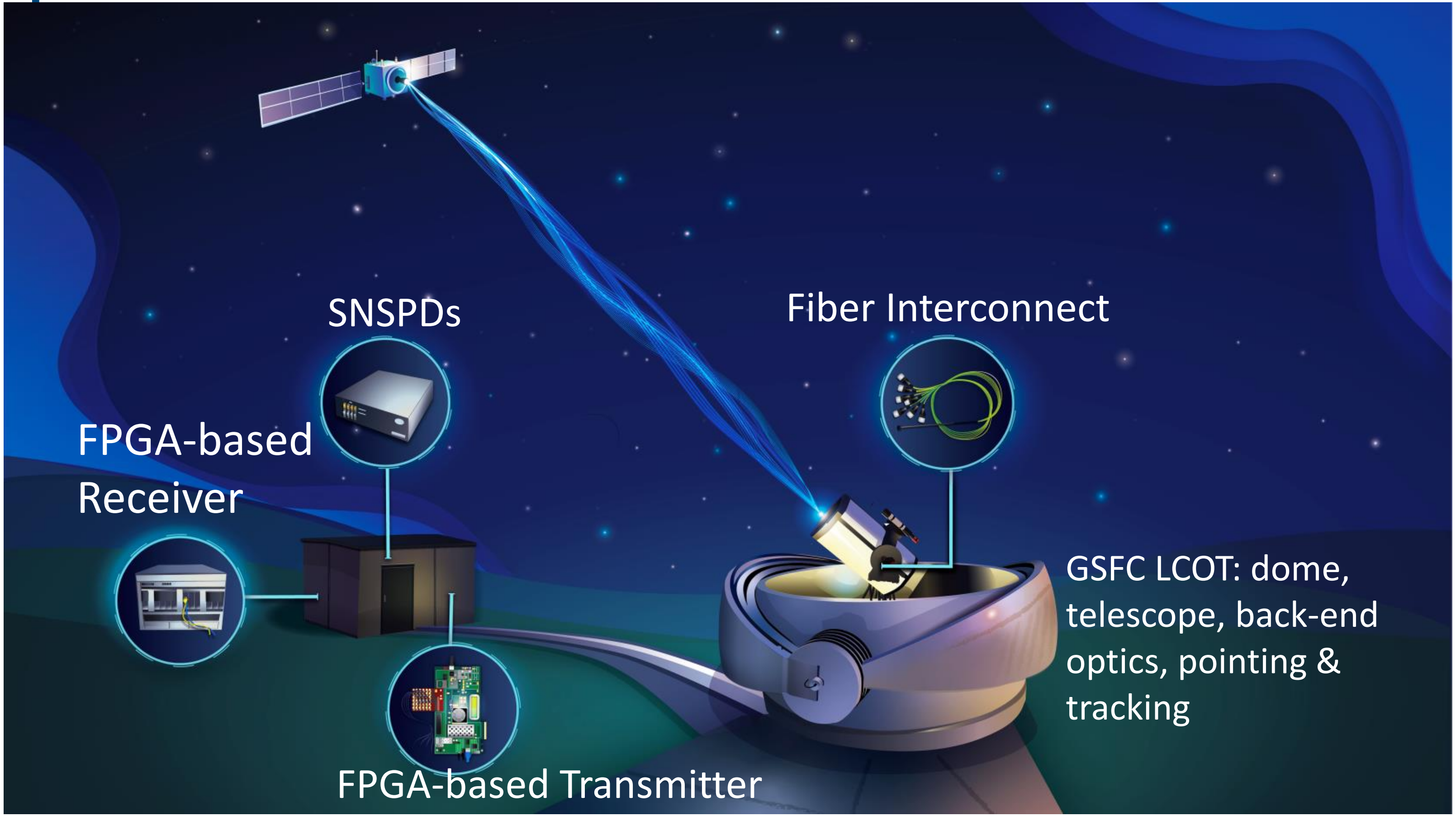
Fiber-Detector Subsystem Loss Comparison



D/r0	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

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

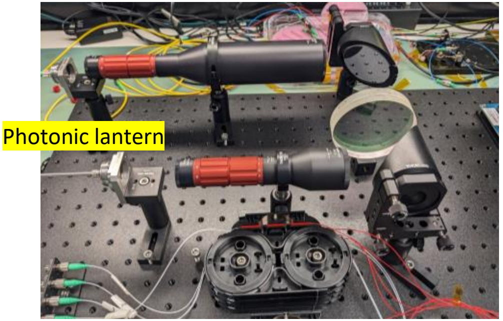


Photonic Lanterns for Coherent Optical Communication

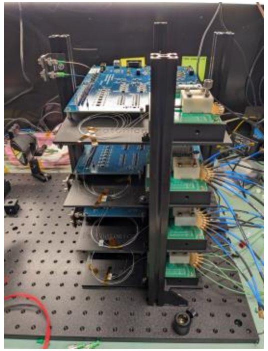
- Adaptive optics is required for efficient single mode fiber coupling
  - Photonic lantern- offer a solution to reduce or eliminate adaptive optic requirements.
  - Could reduce cost, size, weight, power, and complexity
- Light is output in multiple single mode fibers requiring system considerations:
  - Multiple detectors – find the balance between system complexity and increase coupling efficiency
  - Type of signal recombining – optical or digital
  - Time and phase alignment- maintaining coherence information of the signal efficiently.

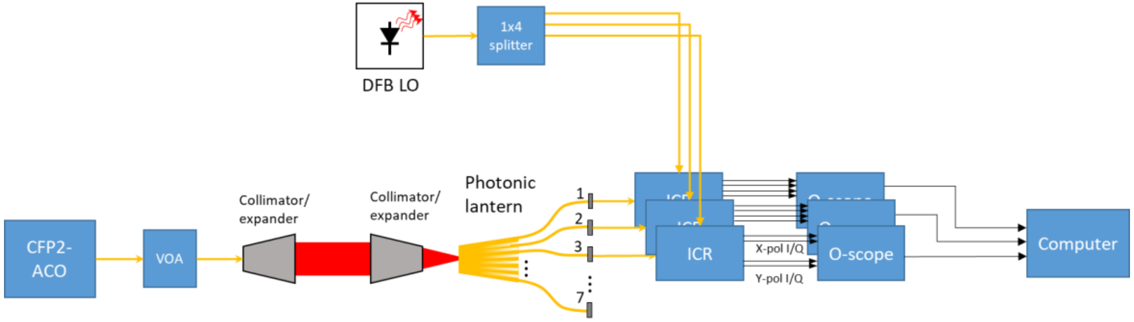
Photonic Lantern Coherent Combining at NASA GSFC*

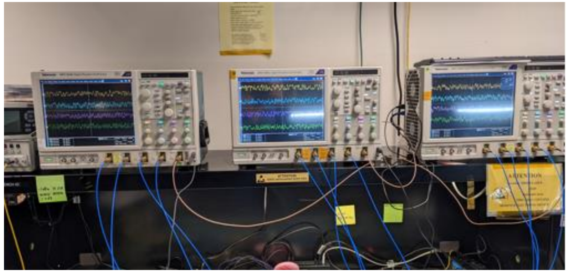
- 10 Gbps DP-QPSK transmit signal from CFP2 module
- Variable optical attenuator
- Three separate integrated coherent receivers (ICR)
- DFB local oscillator shared between integrated receivers
- High sample rate digitizing oscilloscopes collect X/Y-pol I and Q signals for post processing
- Experiments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



Coherent combining test setup

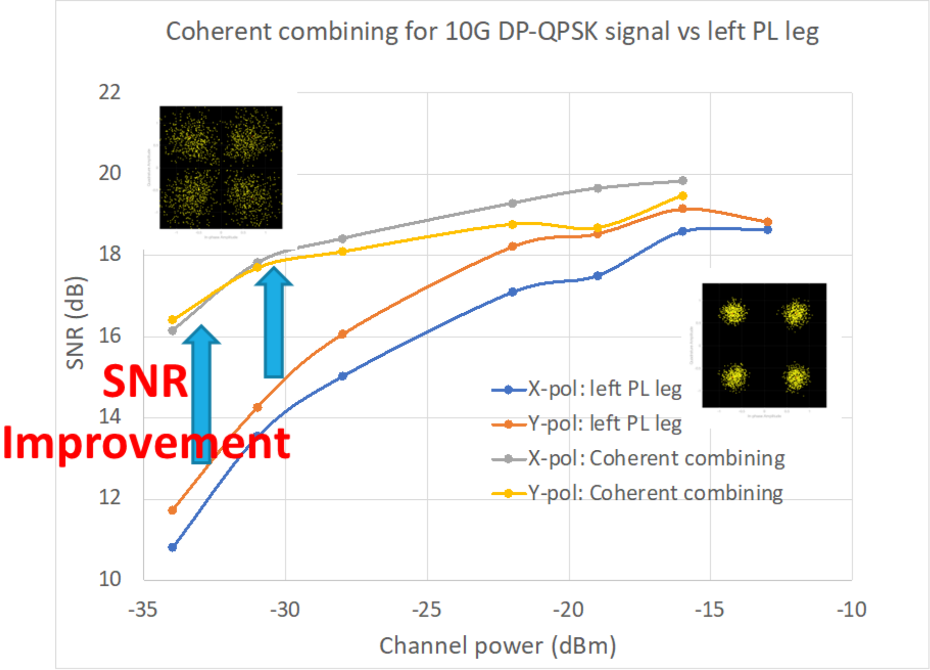

COTS Integrated coherent receiver (ICR) module stack




Multiple sampling oscilloscopes for data collection

*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*

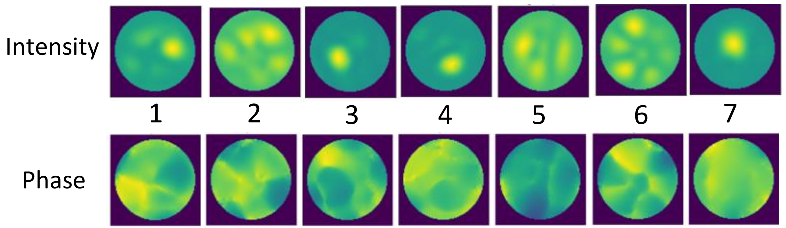


- Digital-domain coherent combining
- SNR improvement due to optimum coherent combining increases as SNR for best individual leg decreases: SNR improvement reaches ≈ 4dB at Pch = -34dBm
- Theoretical maximum ≈ 4.77 dB
- Power monitoring each signal will maximize SNR improvement

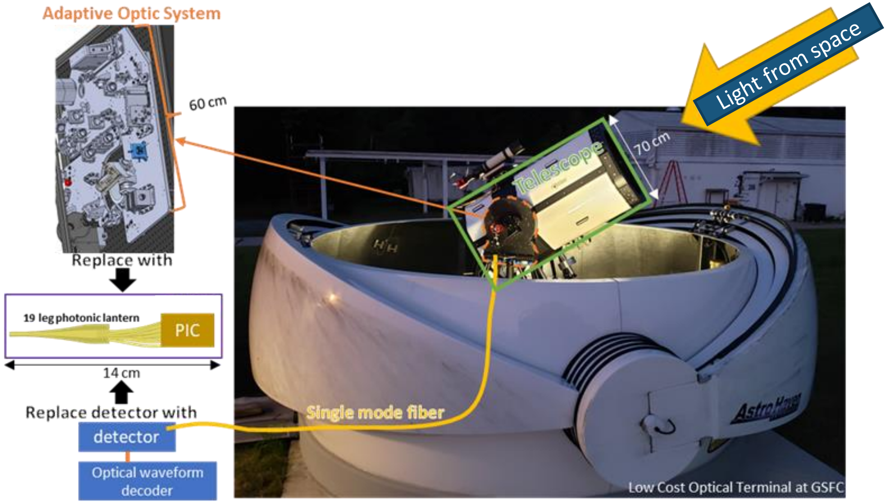
*Yevick, A., Lafon, R., Bayne, R., Garcia, R., Grigoryan, V.S., and J. Veselka, "Experimental demonstration of coherent receiver with photonic lantern and digital signal processing"

Photonic Lantern Wavefront Sensing

- Intensities and phases of the single mode outputs have a direct relationship to both phase and amplitude information of the incident wavefront
- Replace the wavefront sensor – expensive part of adaptive optics 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



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



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).
  - reduces coupling losses at higher turbulence levels.

- Currently investigating applications to coherent optical communications
  - reduces coupling losses in turbulence levels.
  - could reduce cost and complexity.

- Photonic lanterns can be used for wavefront sensing
  - could reduce cost and requirements for adaptive optics.

Acknowledgements:

- NASA GRC: Brian Vyhnalek, 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

Performance of a real-time photon counting optical receiver in the presence of emulated channel fading 31 January 2024 | 11:15 AM - 11:30 AM PST | Room 208 (Level 2 South)