Real-Time Optical Receiver Project

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***NASA Glenn Research Center**

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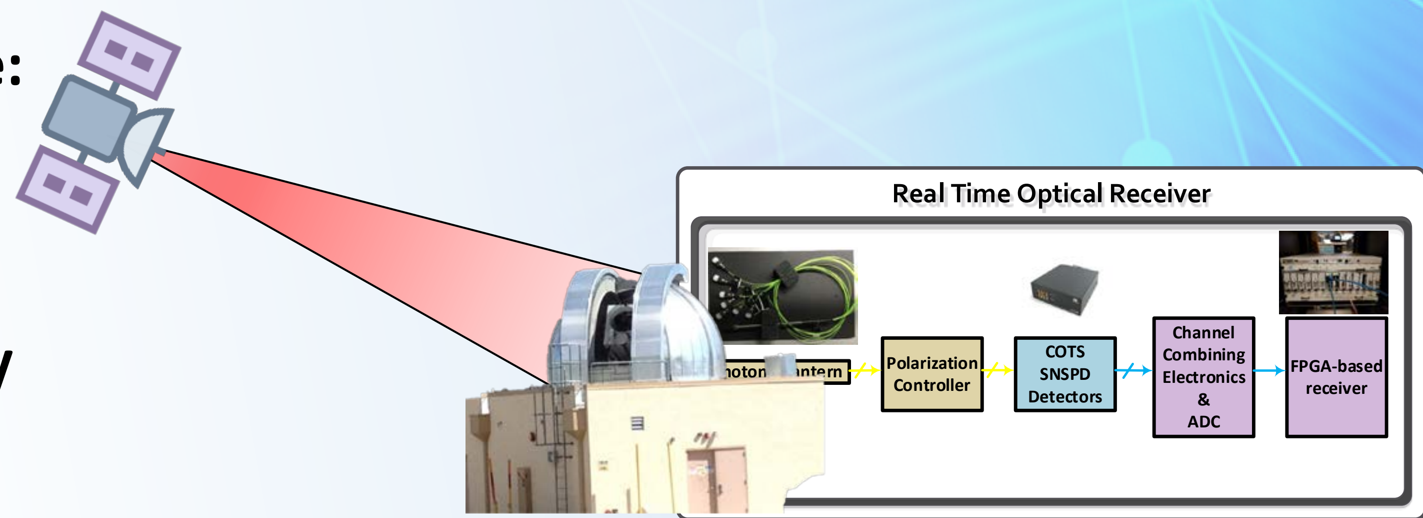
Project Introduction

Motivation

Photon-counting Optical ground stations are:

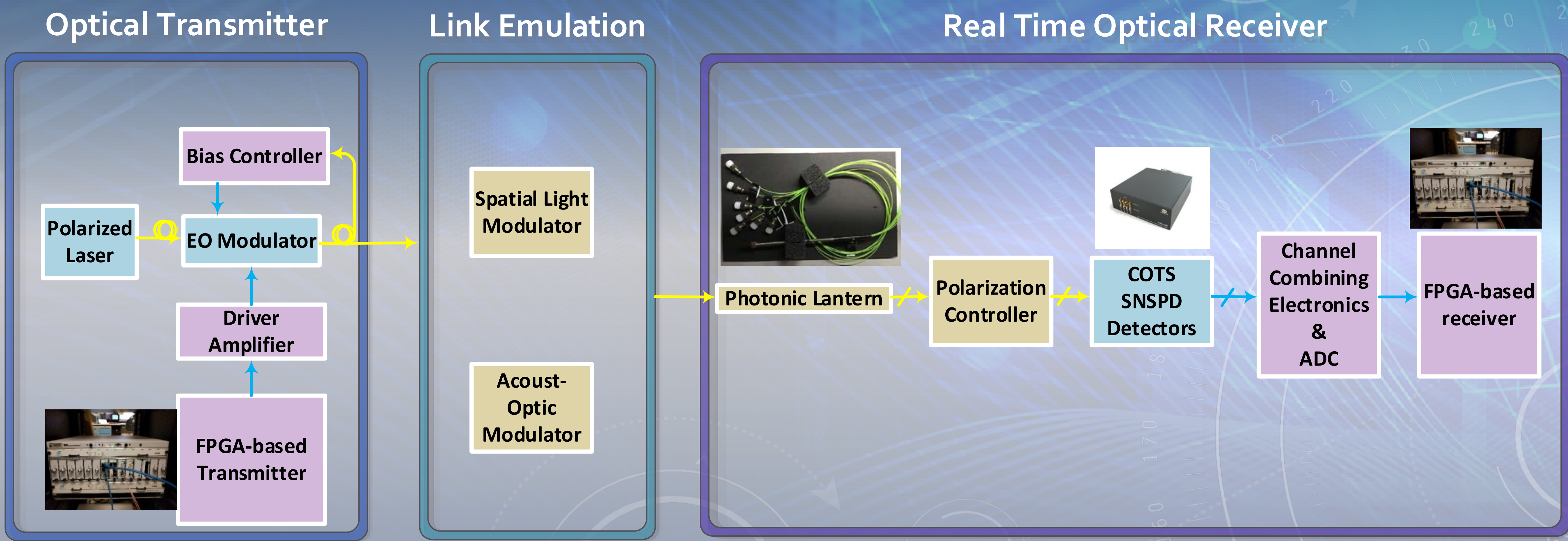
- **Custom made → Expensive**
- **Not standardized**
- **Limited in number → reduces availability**



Goals

1. **Infuse Consultative Committee for Space Data Systems High Photon Efficiency standard into missions, such as Artemis.**
2. **Provide a real time ground receiver solution (fiber device, detector, real time FPGA-based receiver) that is:**
   - **Scalable: data rate, atmosphere conditions, telescope aperture, etc.**
   - **Uses COTS components when available and work with companies to move custom parts to COTS.**
   - **Lower recurring costs (>$1M → $400k)**

Test Bed Block Diagram



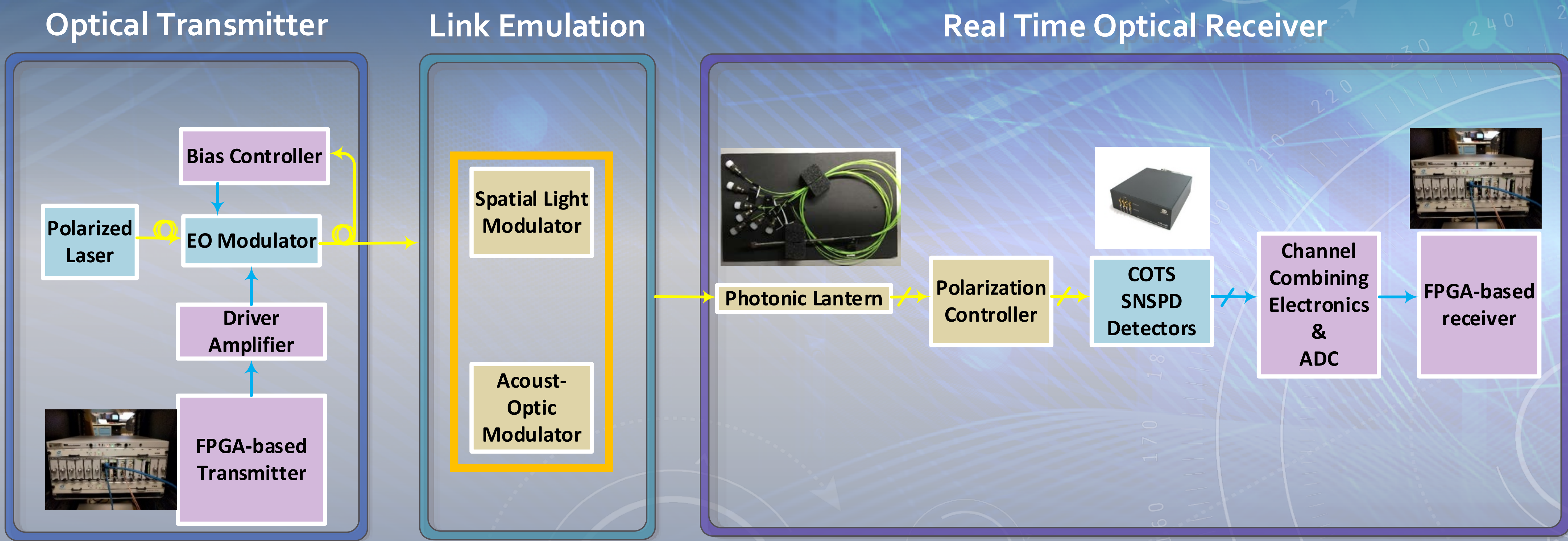
CCSDS Optical Communications High Photon Efficiency Telemetry Signaling Transmit Waveform VHDL/Verilog

> **Released internationally CCSDS High Photon Efficiency Telemetry Signaling Transmit Waveform January 2020 including:**
  - **VHDL/Verilog source code**
  - **Bitfiles and Vivado project for Xilinx VC707 commercial off the shelf development board**

> https://software.nasa.gov/software/LEW-20090-1

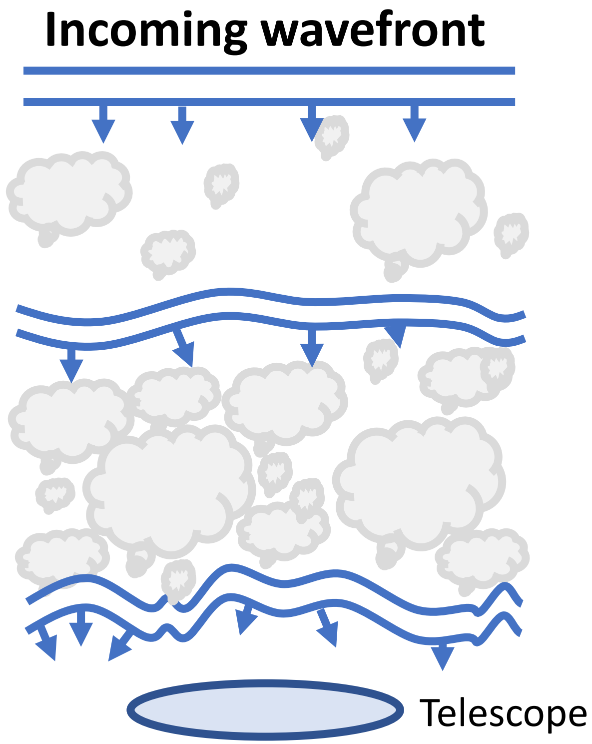
Code release enables user to have an HPE signal transmitted out the VC707 FPGA with no development.

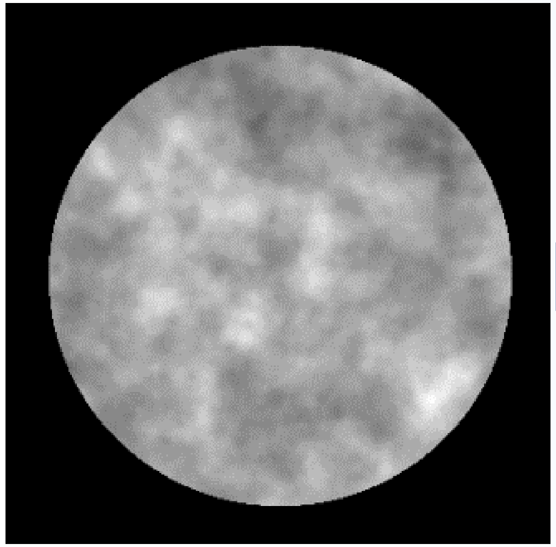
Link emulation



Creation of wavefront emulated atmospheric conditions

Simulation

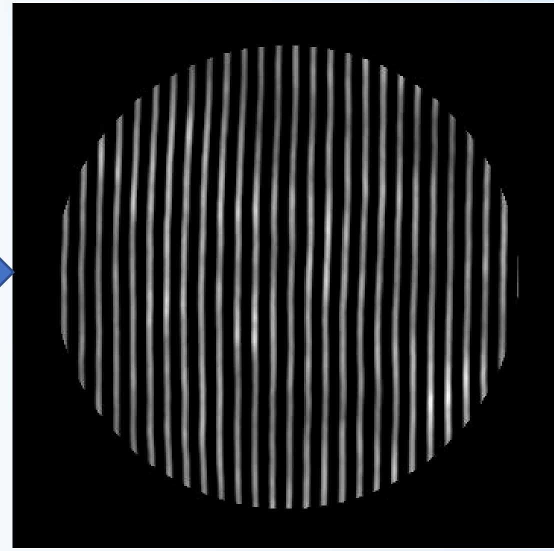




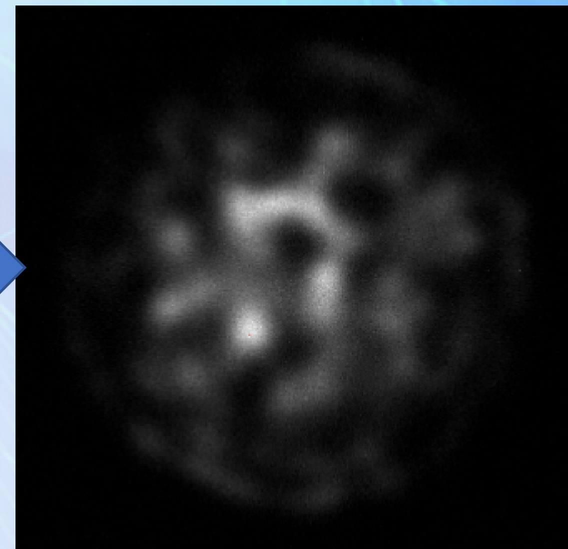
Simulated Intensity

- **Optical turbulence is modeled with phase screens distributed based on the Hufnagel-Valley turbulence strength profile.**
- **Simulation model verified.**
- **Details in: Chahine et al,** "Beam propagation through atmospheric turbulence using an altitude-dependent structure profile with non-uniformly distributed phase screens", **Tuesday poster session.**

Emulation



Phase Hologram



Emulated intensity

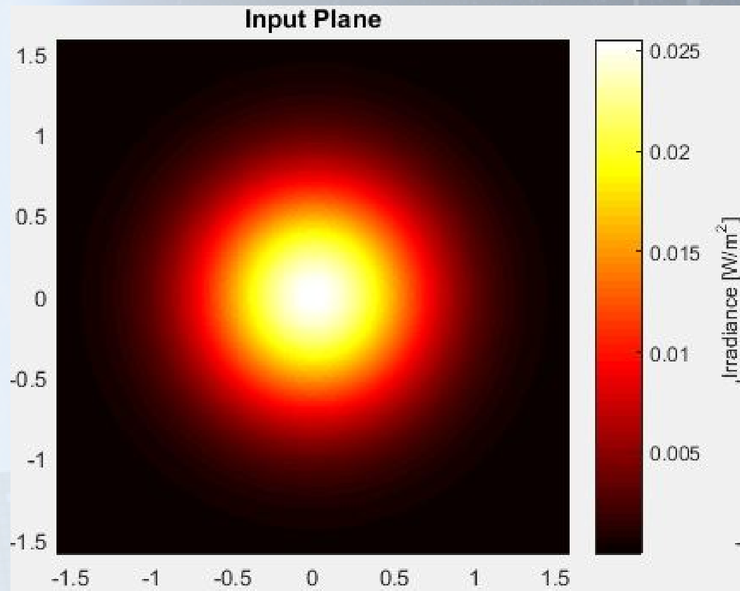
- **Complex amplitude phase hologram created from simulated wavefront.**
- **Hologram applied to beam with spatial light modulator generates emulated wavefront.**
- **Emulation accuracy not fully verified**
- **Results preliminary**

Fade Emulation

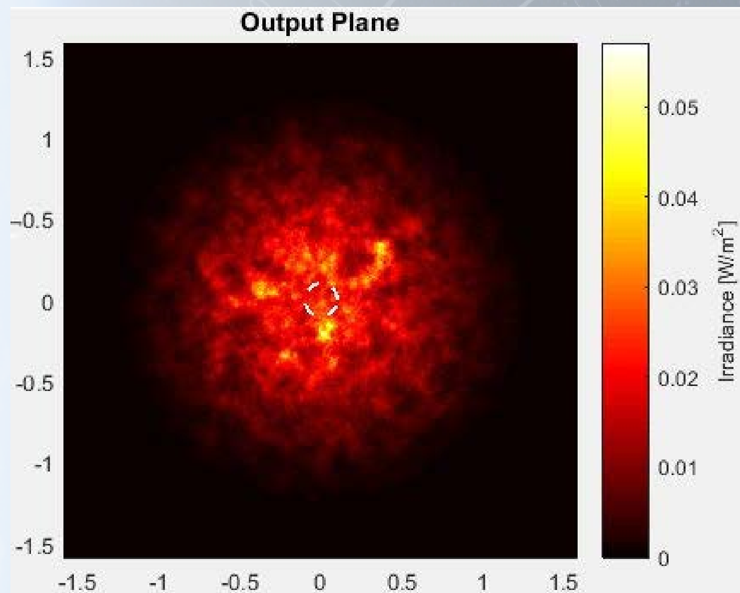
Purpose\Impact:

- Enable laboratory tests of ground receiver and components with emulated atmosphere effect of fade.

Acousto-Optic Modulator (AOM): 45 dB max extinction ratio, max frequency 55 MHz



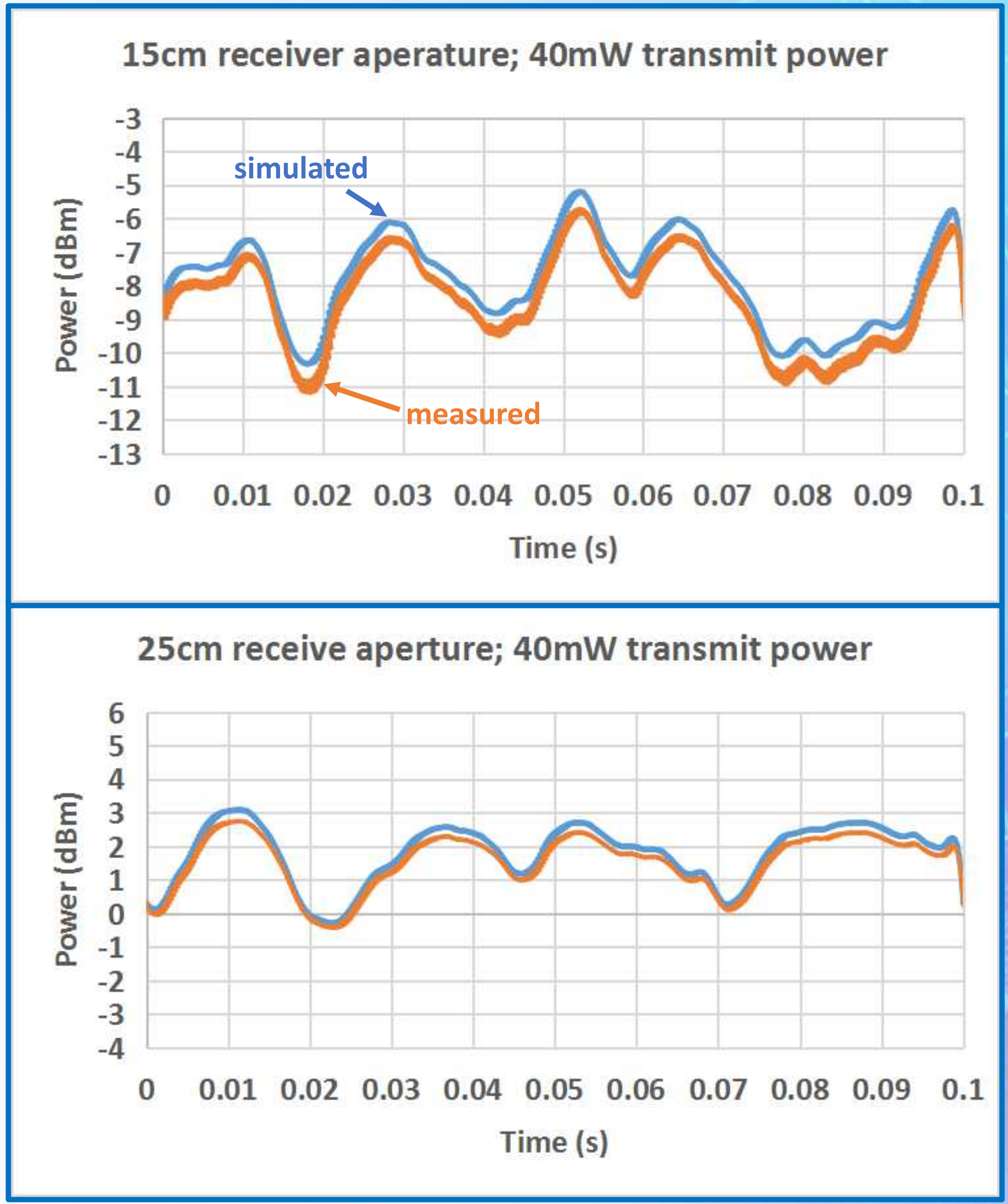
Simulated beam profile at transmitter; 1m beam radius



Simulated beam profile at receiver. Fade simulated using Hufnagel Valley C_n^2 model with 20 cm diameter aperture.

Fade Generation with Acoustic Optical Modulator

Parameter	Value
Atmosphere model	Hufnagel Valley
Beam wavefront	Gaussian
Wavelength	1550 nm
Diameter of source aperture	infinite
Beam radius	1 m
Beam curvature	Infinite (collimated beam)
Cn^2 at ground	$1.7*10^{-14}$
RMS wind speed	21 mps
Source altitude	24 km
Receiver altitude	122 m
Visibility	Infinite (at 550 nm)



Fade profile generated by AOM matches the input fade profile within 0.5 dB.

Receiver Subsystems Under Development

Free-space to Fiber Coupling:

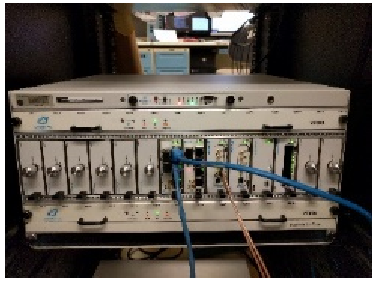
- Photonic lantern (one multimode fiber input to 7 FMF outputs)
- Input fiber core size, number of outputs, and output fiber core size scalable to application
- In house prototyping capability; development partnership with University of Sydney; commercialization through Chiral Photonics.

Single Photon Detector:

- COTS Quantum Opus detectors, portable, rack-mounted
- Array of single-pixel detectors sharing one cryostat; couple to SMF or FMF
- Continuous operation, includes amplifier electronics, 60-80% efficient

Detector Channel Combining:

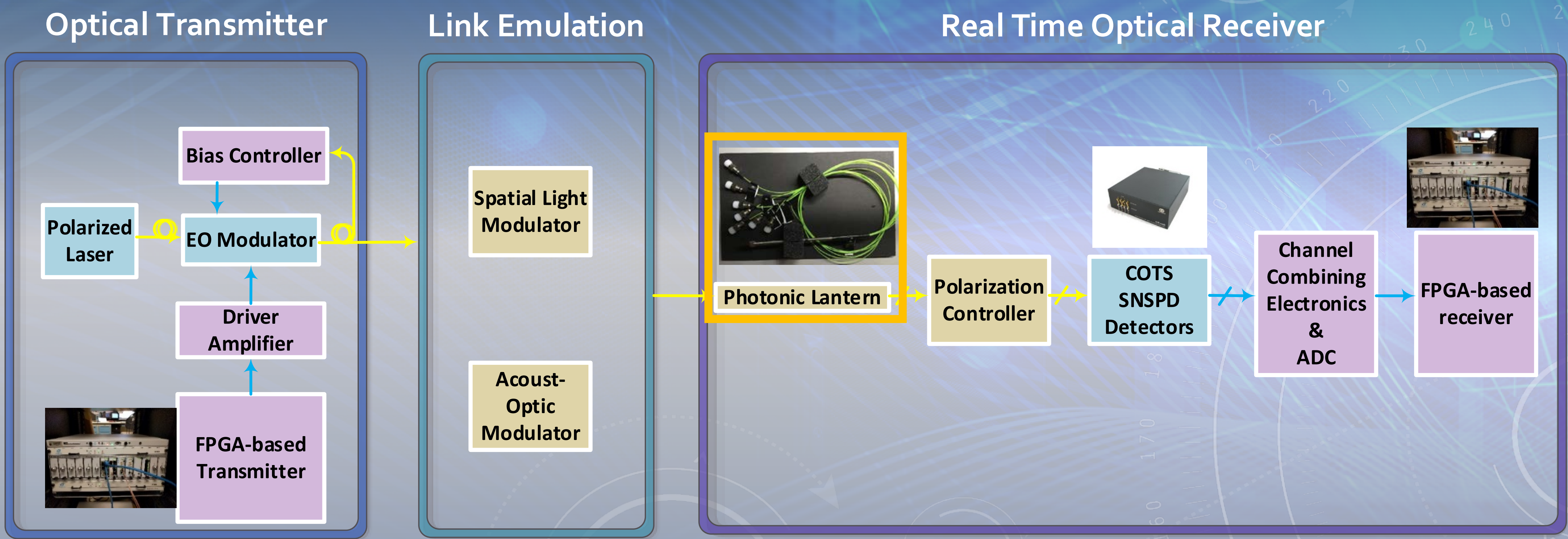
- 1 ADC per detector channel; digital combining



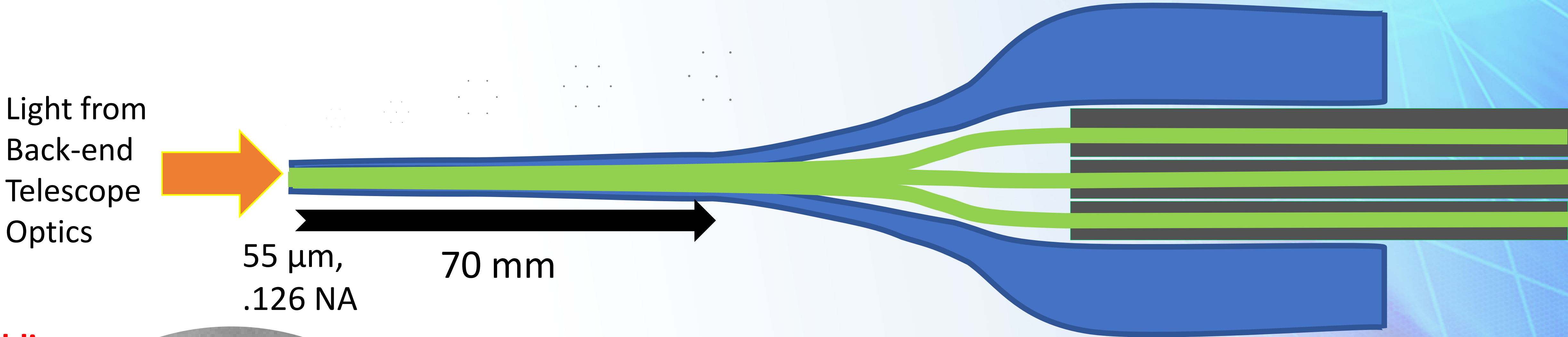
FPGA-based Receiver:

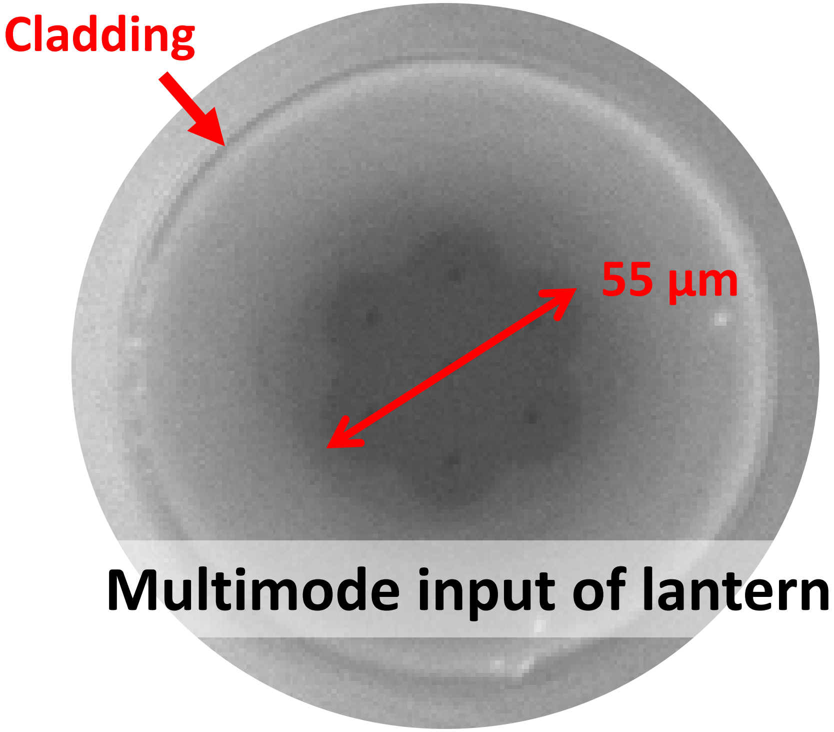
- Real Time processing; COTS Vadatech platform
- Transmit and receive compatible with CCSDS downlink optical waveform (high photon efficiency)
- FPGA VHDL/Verilog code will be released

Photonic lantern



7:1 Few-Mode Fiber Photonic Lantern

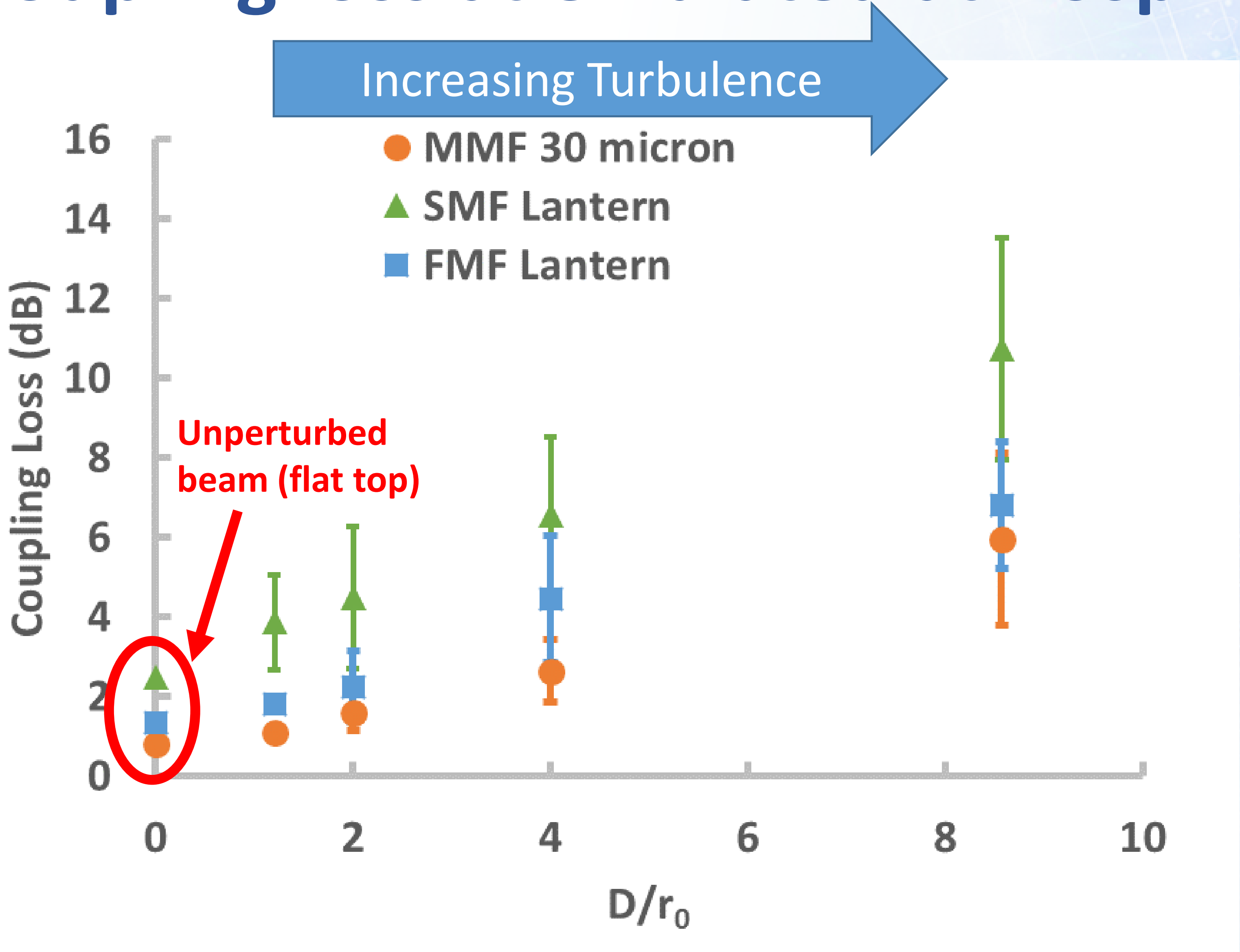




Multimode input of lantern

- **Purpose: efficiently deliver atmospheric distorted light to 7 single pixel fiber-coupled COTS detectors**
- **Made at NASA GRC**
- **Developed in collaboration with Univ. of Sydney**

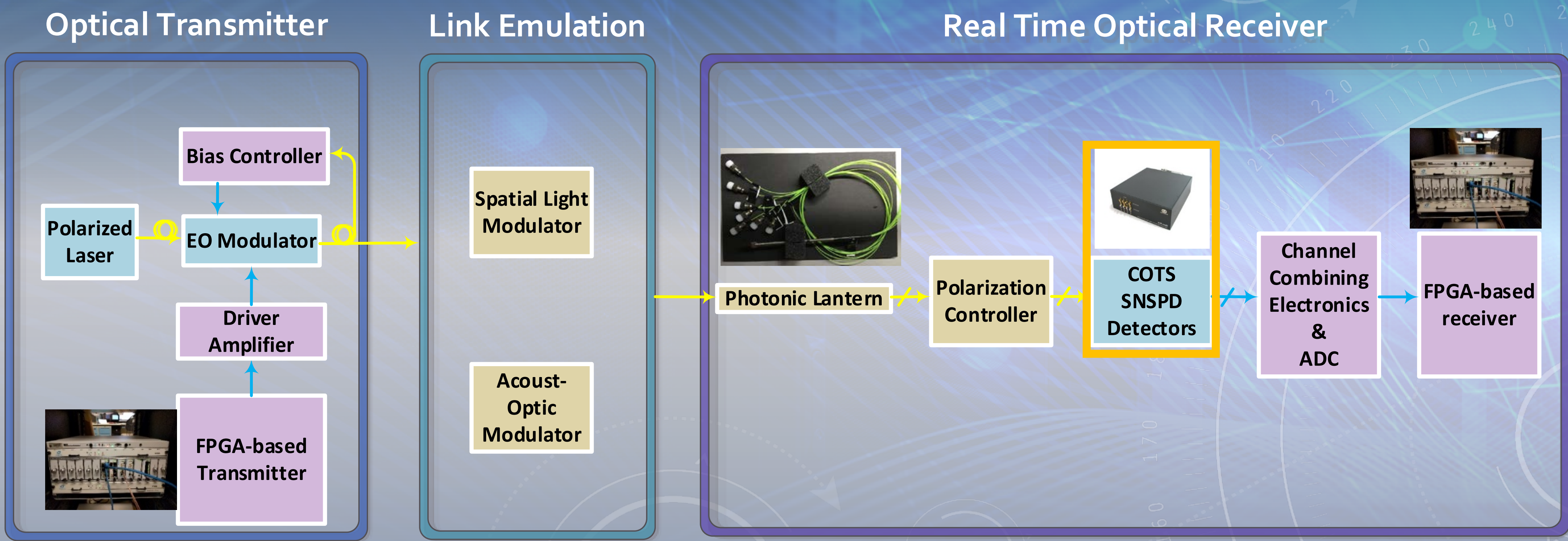
Coupling loss at emulated atmosphere conditions



D/r_0	Loss Relative to the GI-MMF (dB)
8.6	0.86
4.0	1.83
2.0	0.66
1.2	0.69
0	0.53

Current FMF lanterns offer similar performance in atmospheric conditions to MMF previously used in optical ground stations. (~0.9 dB loss on average)

Superconducting Nanowire Single-Photon Detector System



Quantum Opus SNSPD Detector System Description

Opus One™ from Quantum Opus, LLC

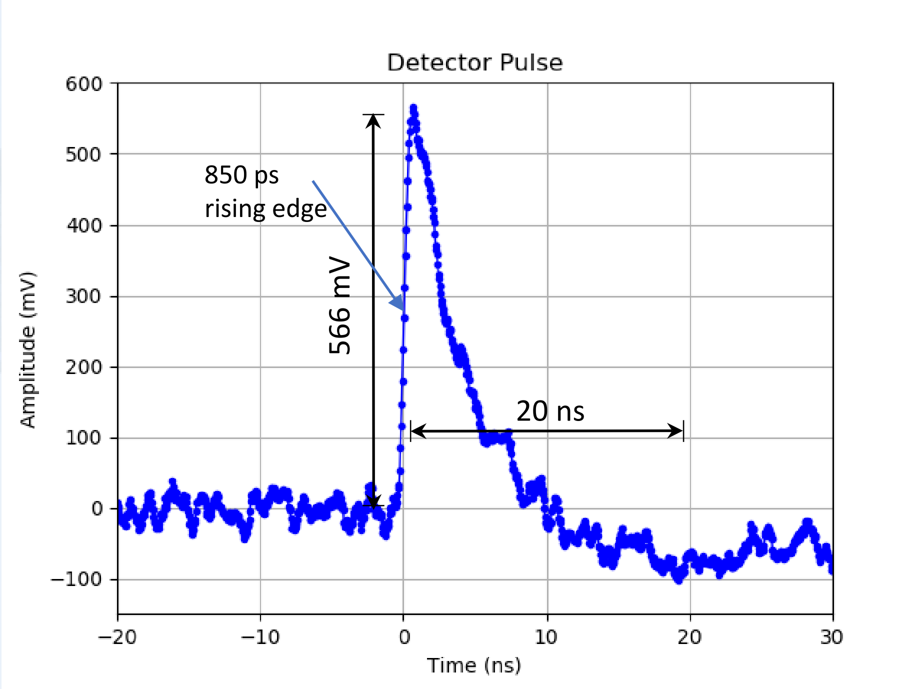
System Parameters	Previous Specs	Current Specs
Wavelength	1550 nm	1550 nm
Fiber coupling	SMF	FMF
Dark counts	< 100 cps	< 10 kcps
Reset time	50 ns	20 – 30 ns
Jitter (SNSPD + Amp)	< 100 ps	≈ 50 ps (min)
Electronics	Room temp amplifiers, 500 MHz, AC-coupled	Room temp amplifiers, 500 MHz, DC-coupled

All detectors are few mode fiber (FMF)-coupled with blackbody dark count reduction coatings, and DC-coupled, i.e. *RL* filter to ground and increased feedback resistance to obtain higher count rates.

Quantum Opus SNSPD and electronics

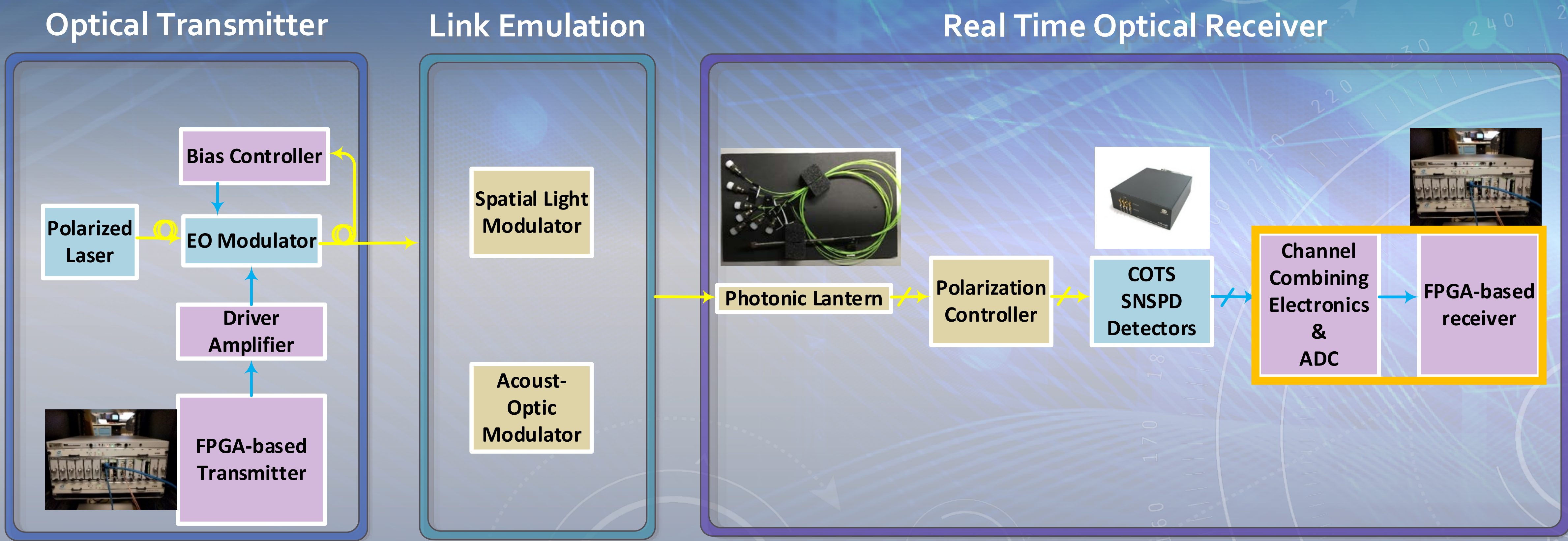
Helium compressor

Typical output pulse



Parameter	Measured
Reset time (90/10)	20 – 30 ns
Pulse height	≈ 600 mV
Rising edge	850 ps

FPGA-based receiver



Receiver

Current Capability:

- **Receiver demonstrated in laboratory with post processing software receiver:**
  - **Supports up to 130 Mbps with 4 detectors**

Future Capability:

- **To be demonstrated with the real-time receiver:**
  - **260 Mbps with 7 detectors**
- **Timing recovery and decoder implementation in FPGA VHDL/Verilog code in progress**

For further details see following publications:

- Downey, J., Vyhnalek, B., Tedder, S., and Lantz, C. “Detector channel combining results from a high photon efficiency optical communications link test bed”, Proceedings of SPIE, Free-Space Laser Communications XXXII (2020).
- Nappier, J., Vyhnalek, B., Tedder, S., and Lantz, C. “Characterization of a Photon Counting Test Bed for Space to Ground Optical Pulse Position Modulation Communications Links”, Proceedings of SPIE, Free-Space Laser Communications XXXI (2019).
- Vyhnalek, B., Downey, J., and Tedder, S. “Single-Photon Counting Detector Scalability for High Photon Efficiency Optical Communications Links” , Proceedings of SPIE, Free-Space Laser Communications XXXII (2020).
- Vyhnalek, B. E., Tedder, S. A., and Nappier, J. M. “Performance and Characterization of a Modular Superconducting Nanowire Single Photon Detector System for Space-to-Earth Optical Communications Links”, Proceedings of SPIE, Free-Space Laser Communications XXX (2018).
- Vyhnalek, B., Tedder, S., Katz, E., and Nappier, J. “Few-Mode Fiber Coupled Superconducting Nanowire Single-Photon Detectors for Photon Efficient Optical Communications”, Proceedings of SPIE, Free-Space Laser Communications XXXI (2019).
- Tedder, S. A., Vyhnalek, B. E., Leon-Saval, S., Betters, C., Floyd, B., Staa, J., and Lafon, R. “Single-Mode Fiber and Few-Mode Fiber Photonic Lanterns performance evaluated for use in a Scalable Real-time Photon Counting Ground Receiver “, Proceedings of SPIE, Free-Space Laser Communications XXXI (2019).
- Tedder, S. A., Floyd, B., Chahine, Y. K., Croop, B., Vyhnalek, B. E., Betters, C., Leon-Saval, S. “Measurements of few-mode fiber photonic lanterns in emulated atmospheric conditions for a low earth orbit space to ground optical communication receiver application”, Proceedings of SPIE, Free-Space Laser Communications XXXII (2020).

For more information, please contact:

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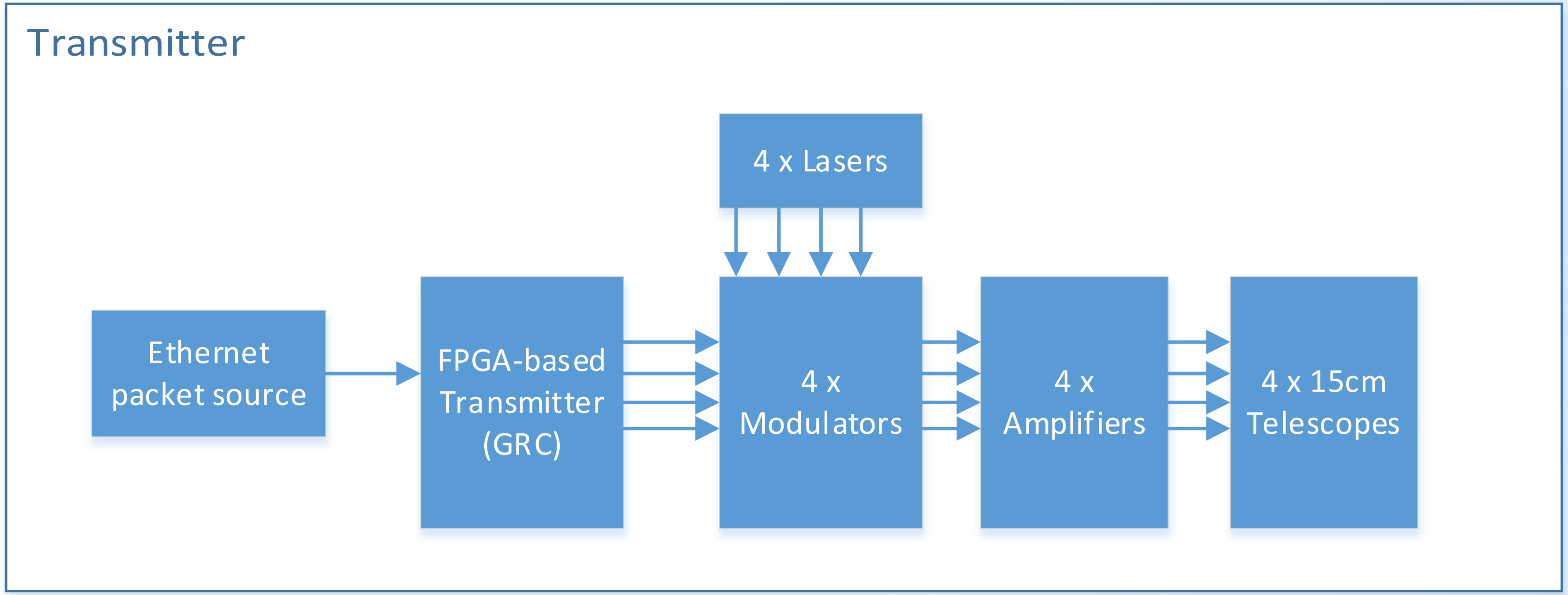
Backup

High Photon Efficiency Ground Station Transmitter Diagram



The FPGA-based transmitter currently supports all O2O waveform modes

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Proposed Collaboration with ANU for High Photon Efficiency Transmitter

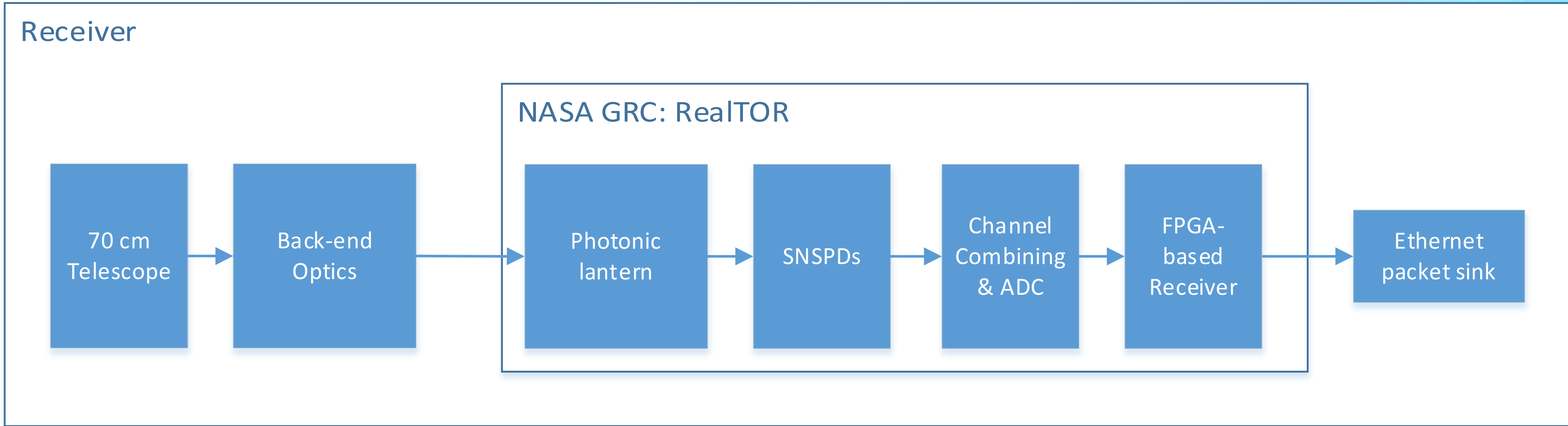
ANU to provide

> Transmitter telescope(s)
> Lasers, modulators
> FPGA electronics

NASA GRC RealTOR to provide:

> Details of system design and assembly
> Support of assembly and testing (remotely and directly)
> Specifications and sources to purchase FPGA electronics
> FPGA VHDL/Verilog code for CCSDS transmitter:
  > Available at https://software.nasa.gov/software/LEW-20090-1

High Photon Efficiency Ground Station Receiver Diagram



Current Capability:

Receiver demonstrated in laboratory with post processing receiver:

- **Supports up to 130 Mbps with 4 detectors**

Future Capability:

To be demonstrated with the real-time receiver:

- **260 Mbps with 7 detectors**

Proposed Collaboration with ANU for High Photon Efficiency Receiver

ANU to provide

- **Pad and dome including electrical and plumbing needs, telescope**
- **Back end optics design to support photonic lantern or other fiber solution.**
- **Detector, FPGA electronics, channel combining electronics**

NASA GRC RealTOR to provide:

- **Details of system design and assembly**
- **Support of assembly and testing (remotely and directly)**
- **Specifications and sources to purchase COTS components:**
  - Detectors
  - Fibers/Fiber device
  - Channel combining electronics
  - FPGA electronics
- **FPGA VHDL/Verilog for CCSDS receiver (future release)**
- **Design of photonic lantern for University of Sydney to fabricate**