

A photon counting ground receiver for free-space optical communications

Advanced Photon Counting Techniques XVIII

Jennifer N. Downey

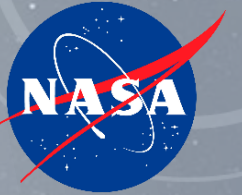
NASA Glenn Research Center

Cleveland, Ohio

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Introduction

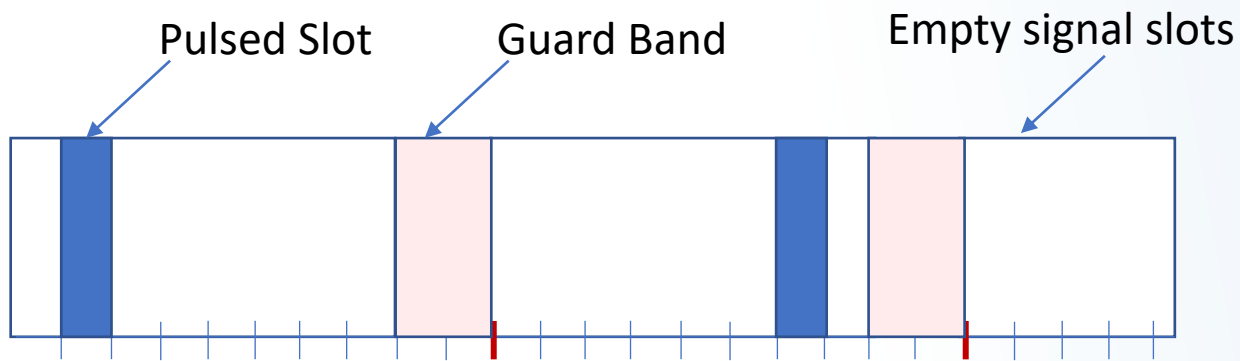


- **NASA Glenn is building a fiber-coupled photon-counting ground receiver compliant with the Consultative Committee for Space Data Systems (CCSDS) Optical Communications High Photon Efficiency (HPE) standard.**
 - PPM: 4, 8, 16, 32, 64, 128, 256
 - Slot widths: 512 ns - 125 ps
 - Maximum data rate: ~2 Gbps
- **CCSDS HPE Modes currently implemented:**
 - PPM: 16-32
 - Code rates: 1/3, 1/2, 2/3
 - Slot widths: 2 ns, 1 ns, 0.5 ns
 - Convolutional channel symbol interleaver with $N=84$, $B = \{0, 540, 2160, 4140\}$
- **Goals:**
 - Utilize commercial off the shelf (COTS) components
 - Demonstrate with Optical Artemis-II Orion (O2O) at the NASA Goddard Low Cost Optical Terminal (LCOT) ground station
 - Release CCSDS HPE VHDL code internationally
 - Enable technology infusion in missions

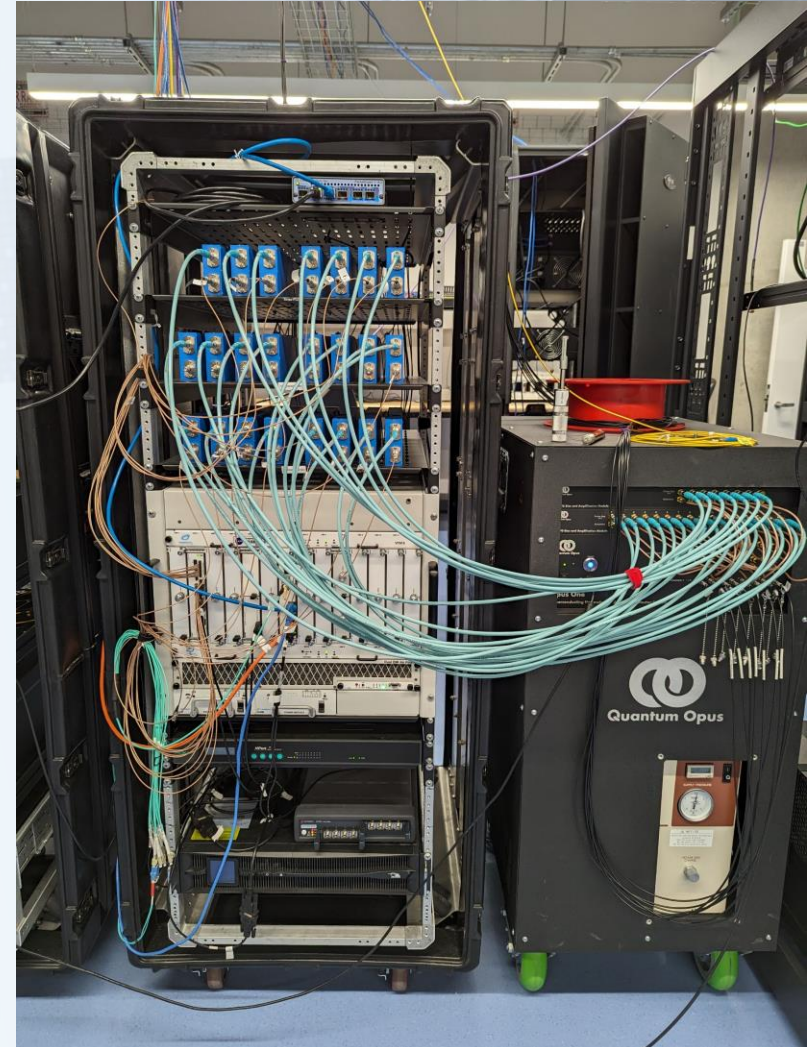
Receiver for pulse position modulation (PPM)



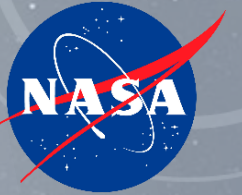
- **PPM: Power efficient modulation designed for low-photon flux regime, such as deep space**
- **<1 photons per bit received**
- **Direct detection, photon counting receiver**



PPM-8: 8 signal slots, 2 guard band slots

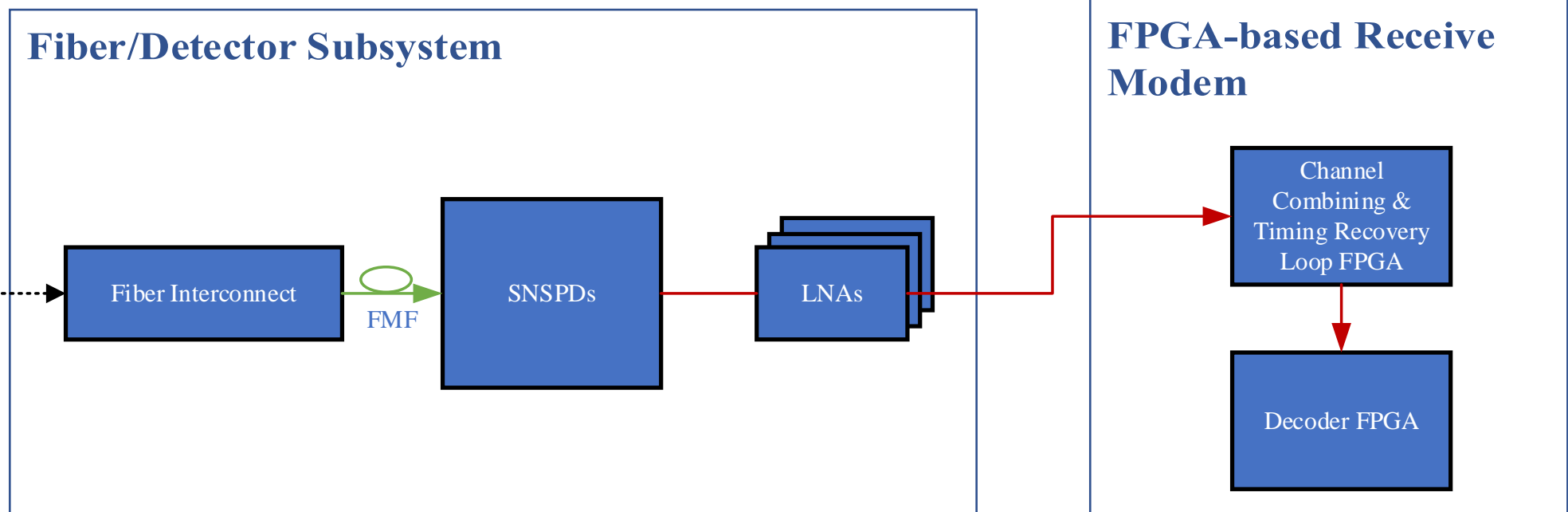


Receiver System

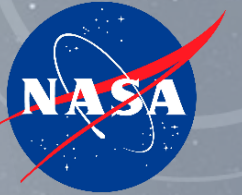


- Fiber Interconnect
- Superconducting nanowire single photon counting detectors (SNSPDs)
- FPGA-based receive modem

Real Time Optical Receiver



Few Mode Fiber (FMF) and SNSPD Array Architecture

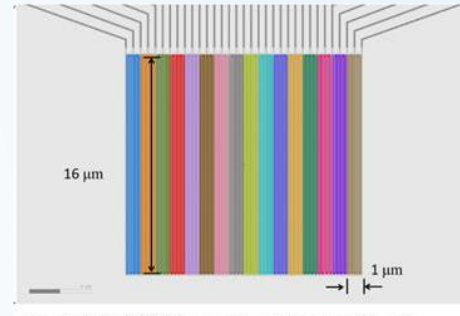


Fiber Interconnect:

- 10-mode, 25 μm , graded index, FMF

Detectors:

- 15-element array
- $1/e$ reset time: 5-8 ns
- $< \sim 80$ M counts per second per channel



Optical input

Fiber coupler

6LP FMF

20 m

$T = 300$ K

SNSPD array

$T = 2.5$ K

Fiber splice
4LP FMF

50 Ω

50 Ω

50 Ω

50 Ω

50 Ω

50 Ω

1

2

3

15

Output electrical pulses

Photonic Lantern and 7 Single Pixel Architecture

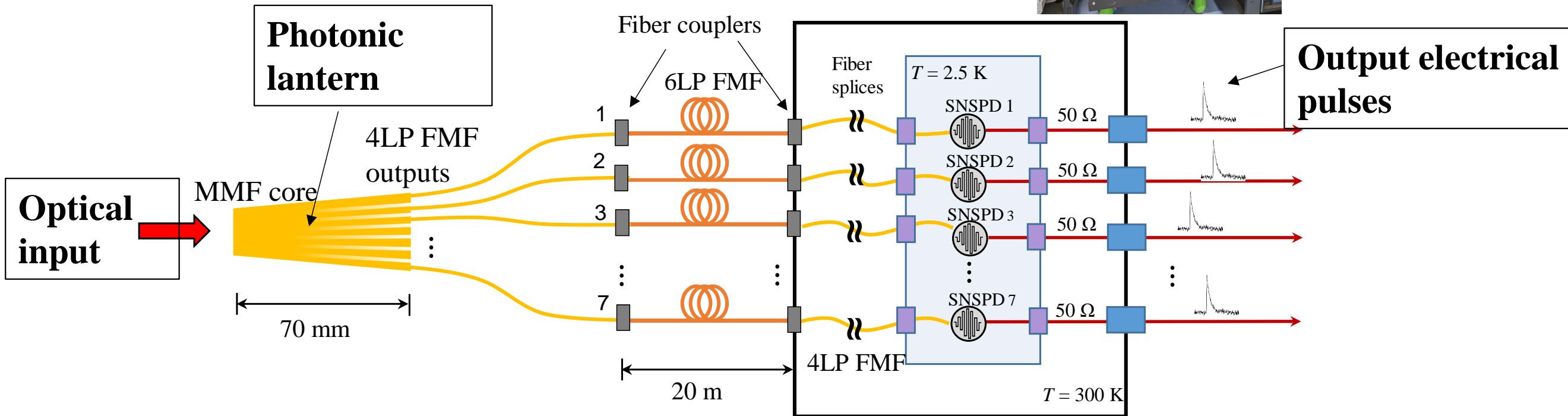
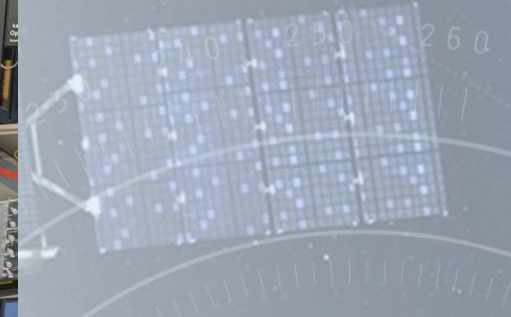
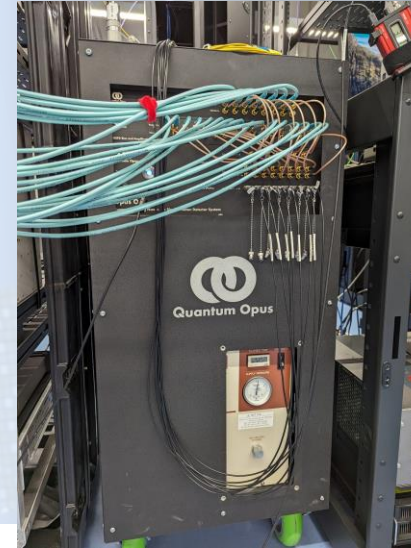


Fiber Interconnect:

- Photonic lantern: 70-mode, 55 μm input core, 25 μm , graded index FMF outputs

Detectors:

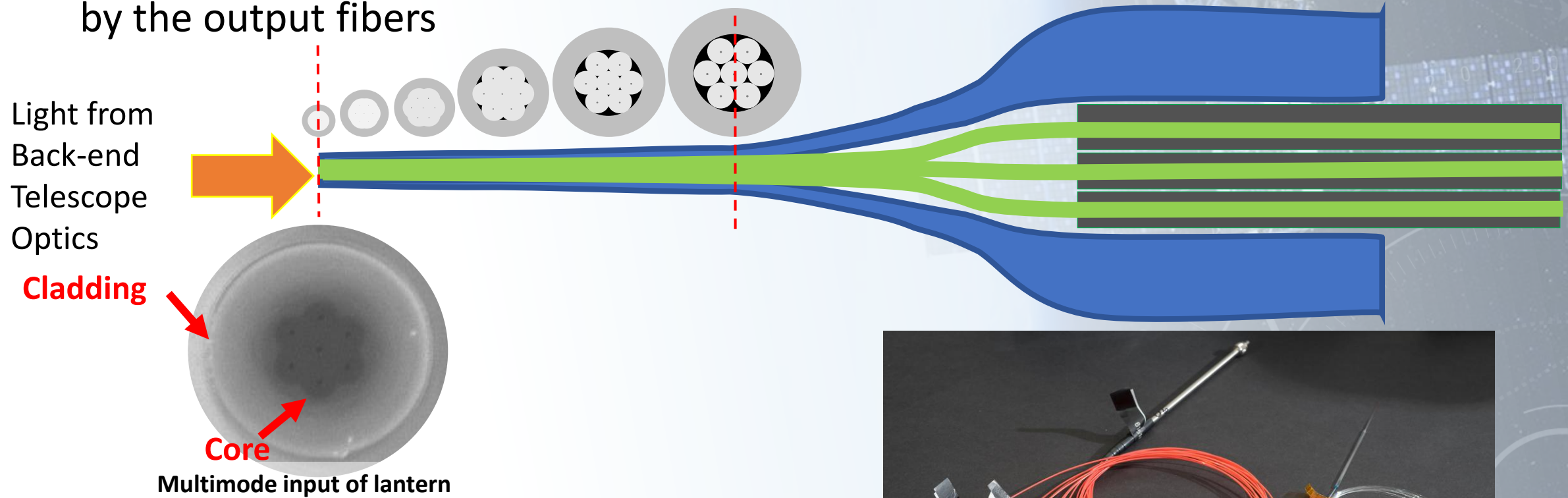
- 7 single-pixel
- $1/e$ reset time: 15 ns
- $< \sim 30$ Mcps per channel



Photonic Lantern



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



Fully packaged photonic lantern, next to bare photonic lantern

Fiber/Detector Subsystem Architecture Summary



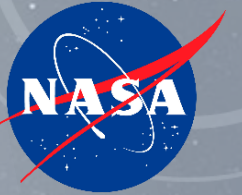
Photon Lantern + 7 Single Pixels

- Input couples 70 spatial modes
- Fiber coupling loss (D/r0 4-9):
 - 4.2 – 6.6 dB
- Number of Detectors: 7
- Detector Reset Time: 15 ns

FMF + 15 Channel Array

- Input couples 10 spatial modes
- Fiber coupling loss (D/r0 4-9):
 - 4.1 – 9.6 dB
- Number of Detectors: 15
- Detector Reset Time: 5-8 ns

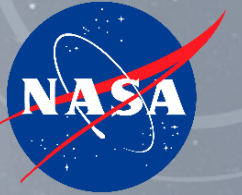
FPGA-based Receiver



- COTS MicroTCA development platform
- 2 field programmable gate arrays (FPGAs)
- Command/telemetry interface is through HTTP interface built on Space Telecommunications Radio System Architecture



FPGA-based Receiver



Timing Recovery FPGA

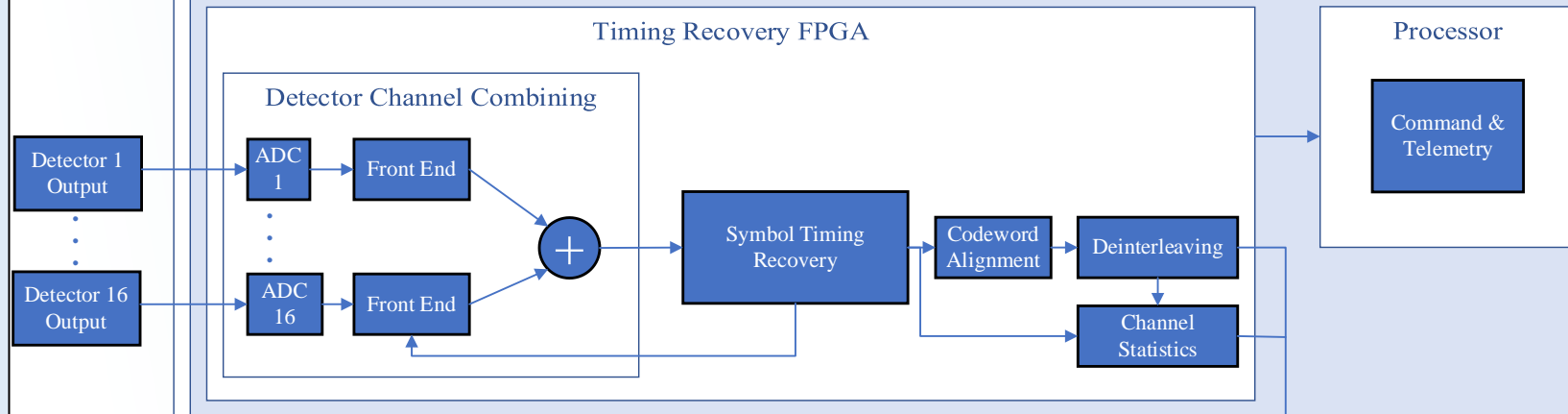
- Symbol timing recovery
- Codeword alignment
- Convolutional deinterleaving

Decoder FPGA

- Iterative decoding
- Derandomization
- Deframing

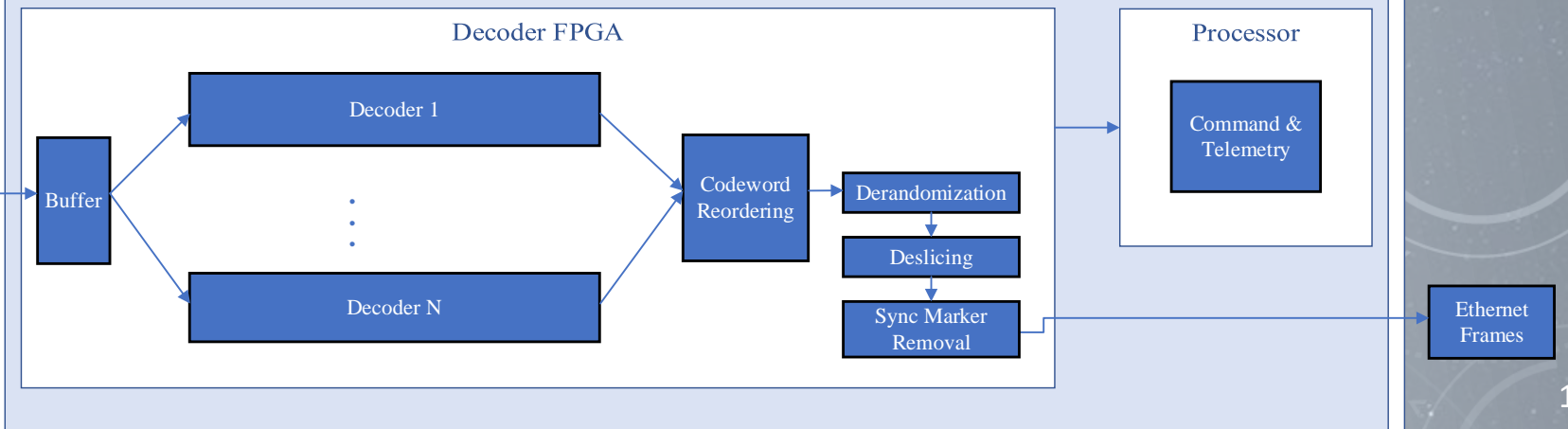
FPGA-based Receiver: MicroTCA Chassis

Timing Recovery FPGA Card

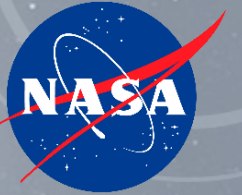


Backplane: High-Speed Serial Link

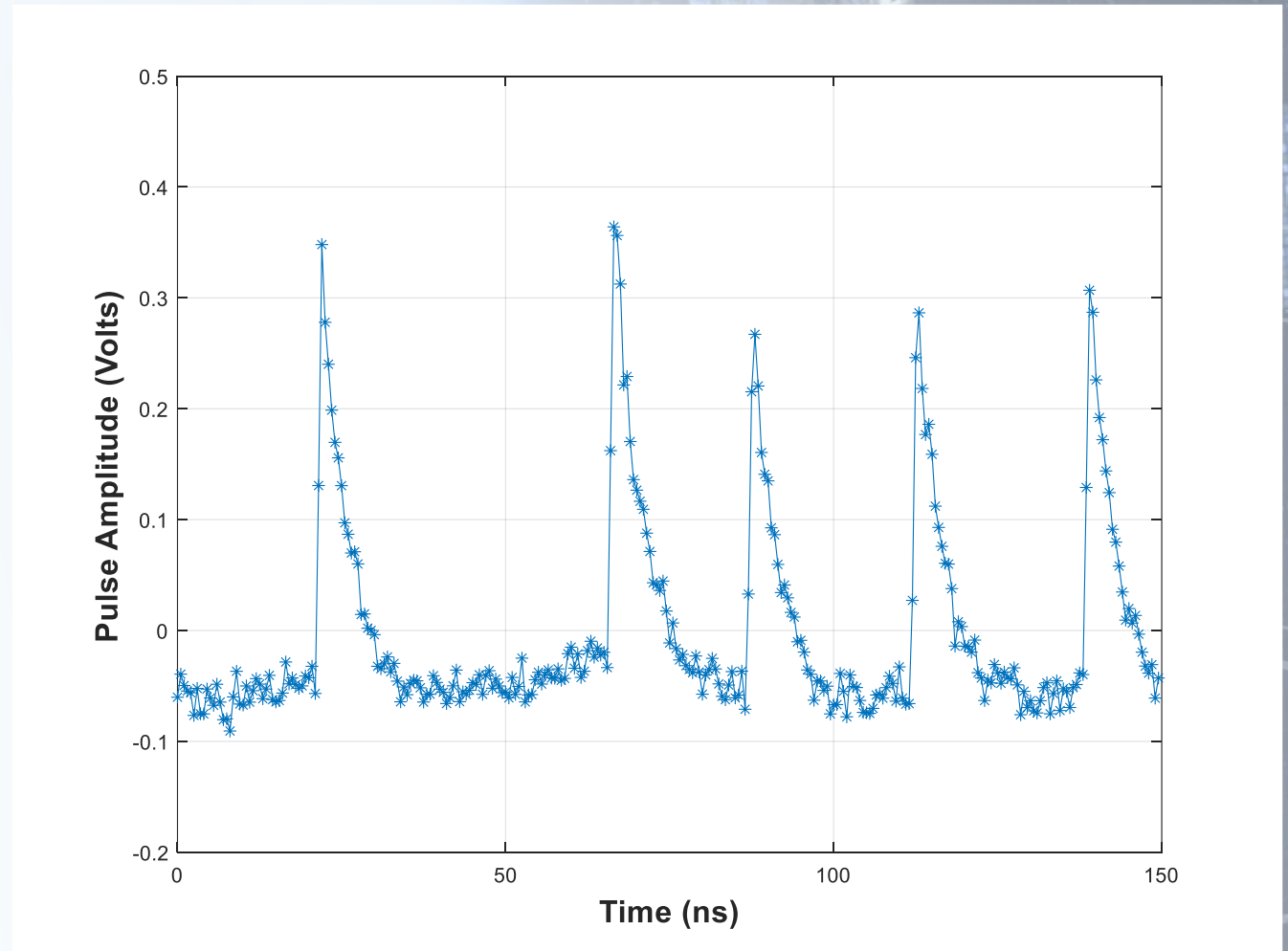
Decoder FPGA Card



Photon Counting



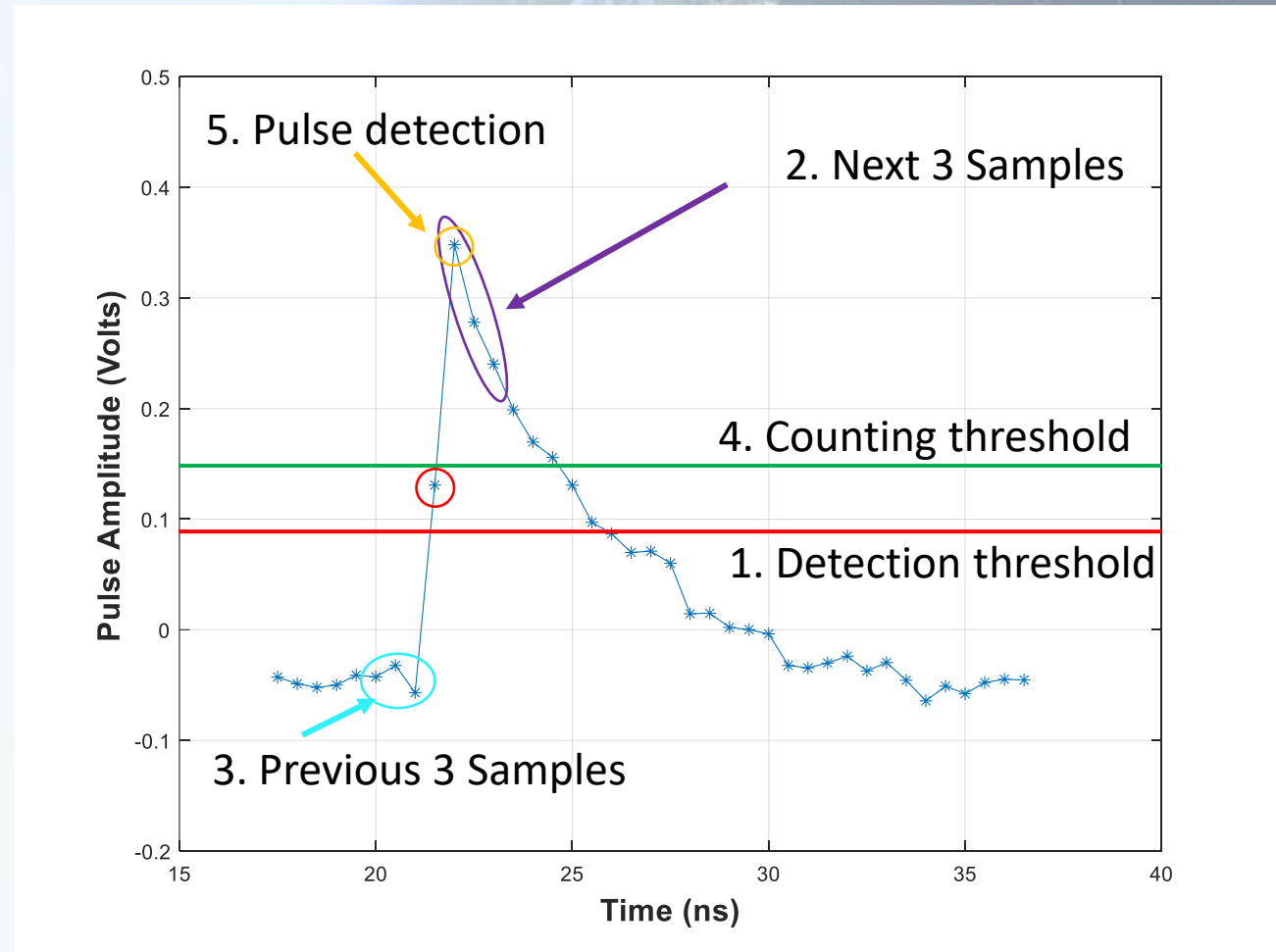
- Performed in the Timing Recovery FPGA
- Xilinx Radio Frequency System on a Chip FPGA (RFSoc)
 - 16 analog to digital convertors (ADCs)
 - Sample rate per channel:
 - > 2 G samples/s
- Count rate per channel:
 - 200 Mega counts per second (Mcps)
- Single FPGA count rate:
 - 3.2 Gcps
- Pulse amplitudes vary, especially at higher count rates, detector pulse walk is caused when using a constant threshold
 - Detection jitter



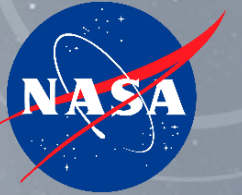
Photon Counting Method



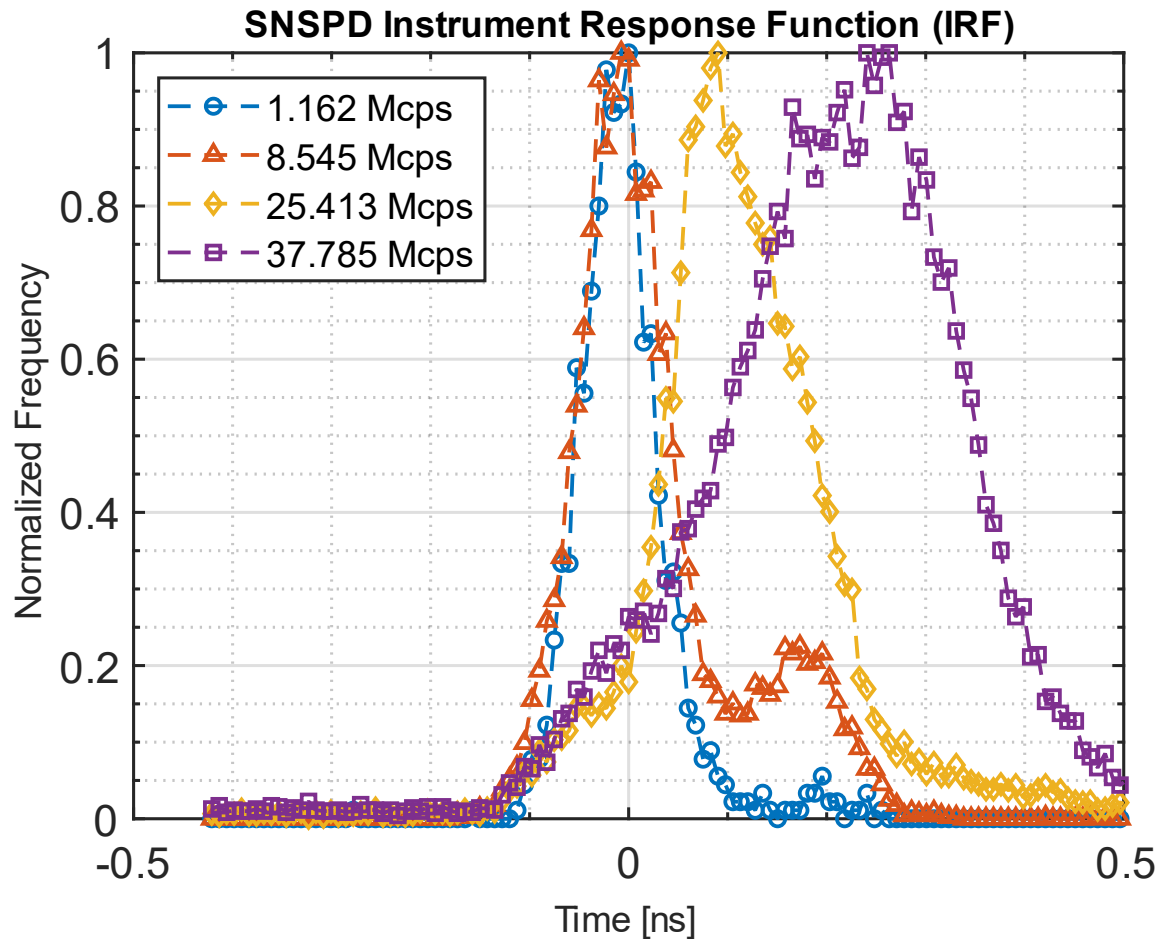
1. A pulse is detected when a sample passes the detection threshold
2. The maximum sample is found from the crossing sample and the next 3 samples
3. The minimum sample is found from the crossing sample and the previous 3 samples
4. The counting threshold is set at 50% of the pulse amplitude
5. The pulse is detected at the first sample to cross the counting threshold



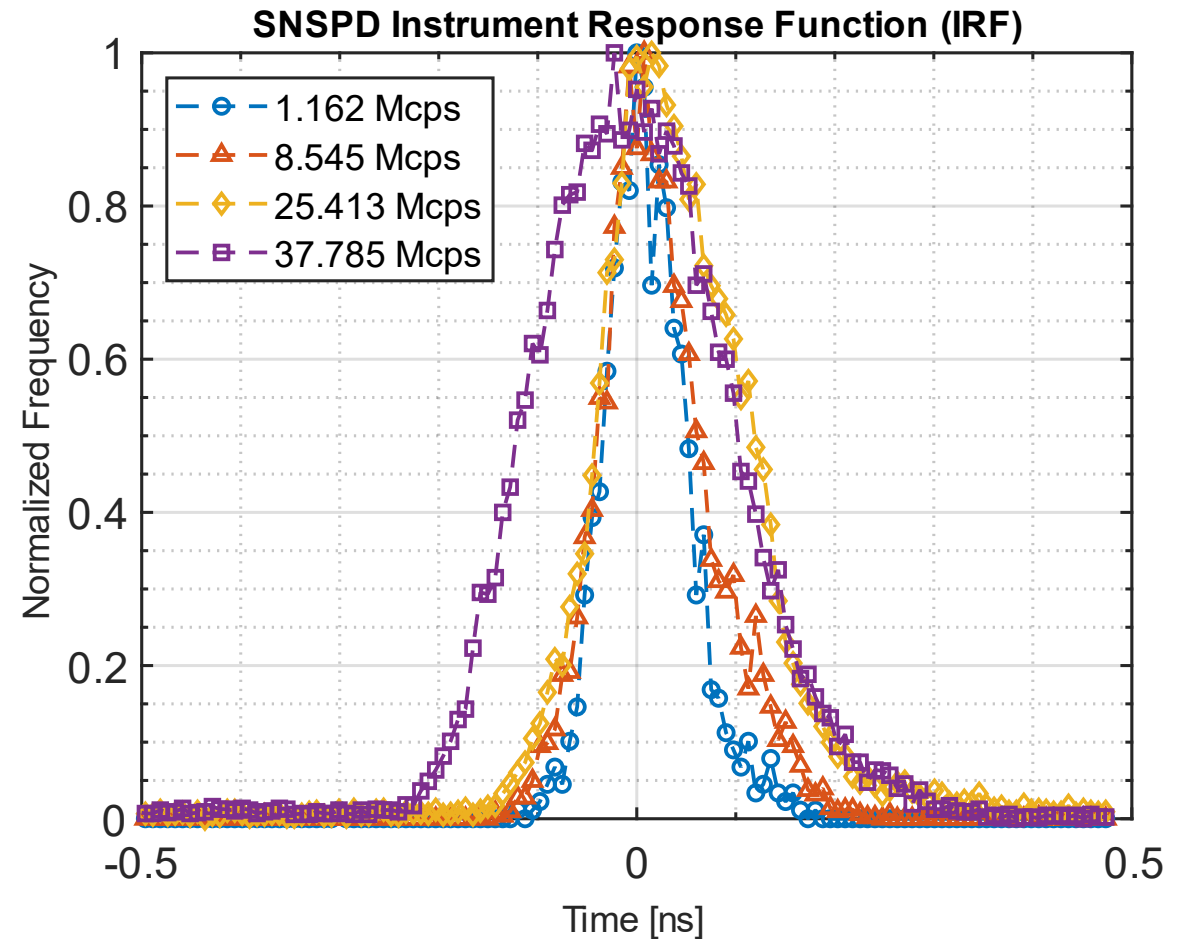
Photon Counting Results



Fixed Threshold



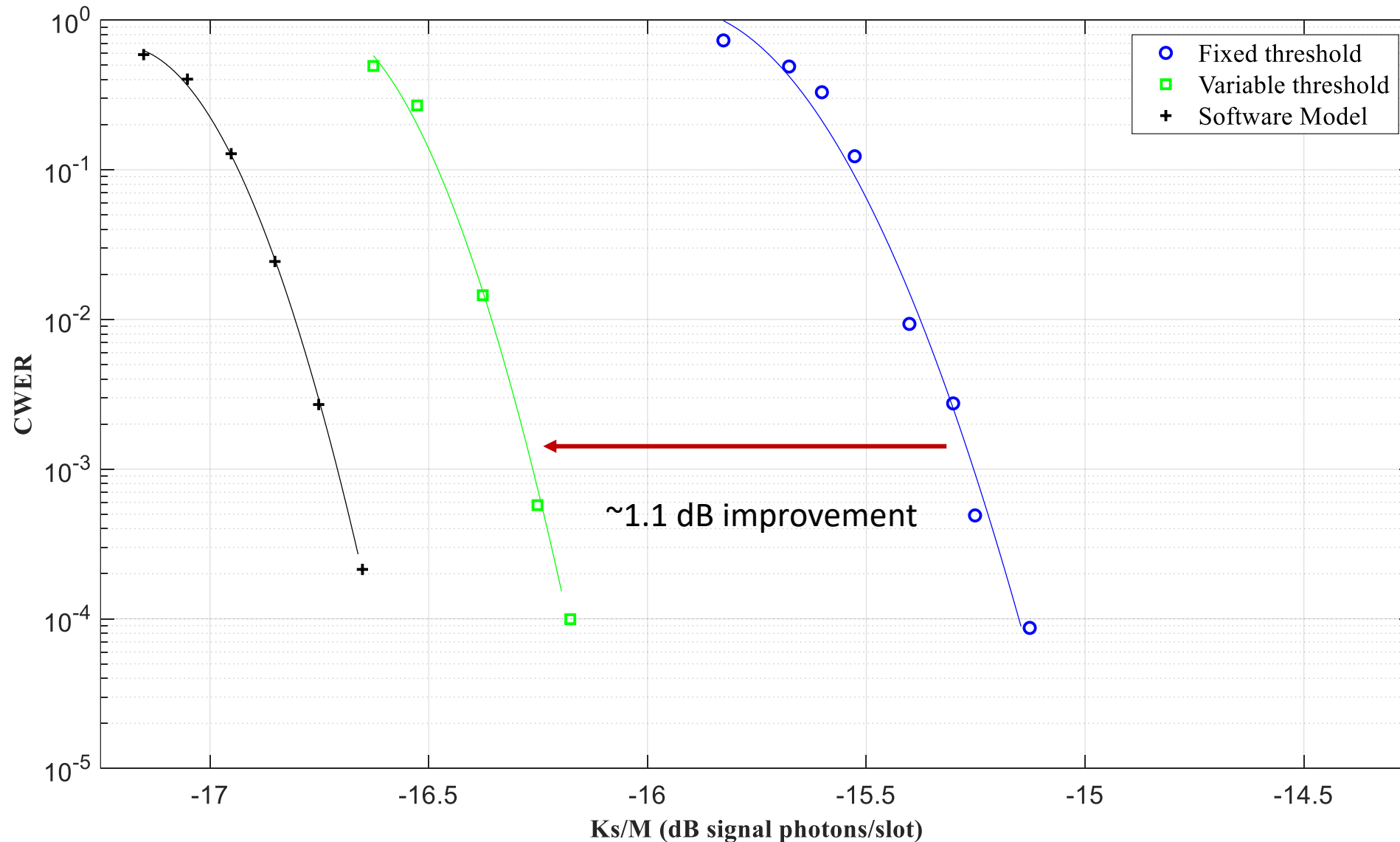
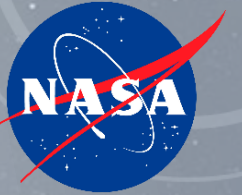
Variable Threshold



- Measured SNSPD instrument response functions (IRF) at 20 Gbps.
- Input: 70 fs mode-locked fiber laser at 50 MHz repetition rate, attenuated from ~ 0.01 to 1 photon per pulse.

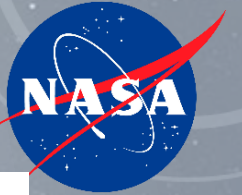
Receiver Results - 7 single pixel detectors

CCSDS Mode: PPM-16, Code Rate 1/3

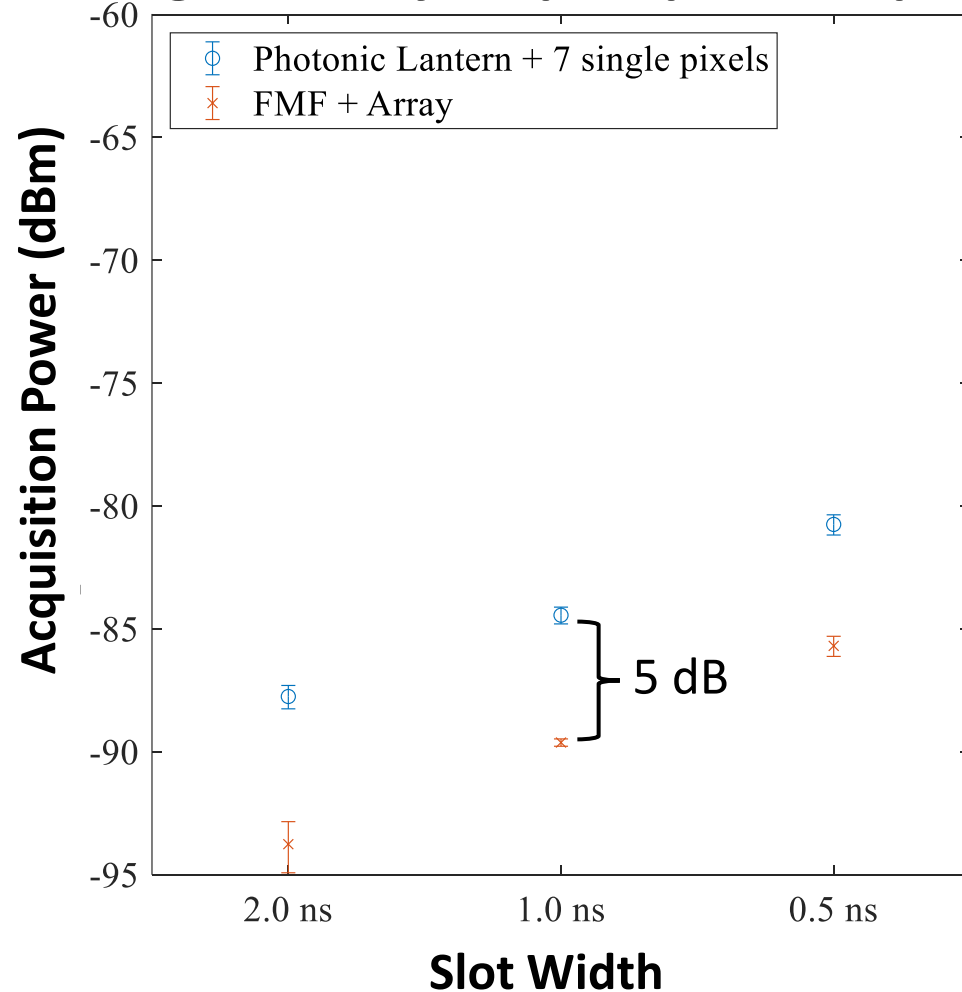


Receiver Baseline Performance Without Fading

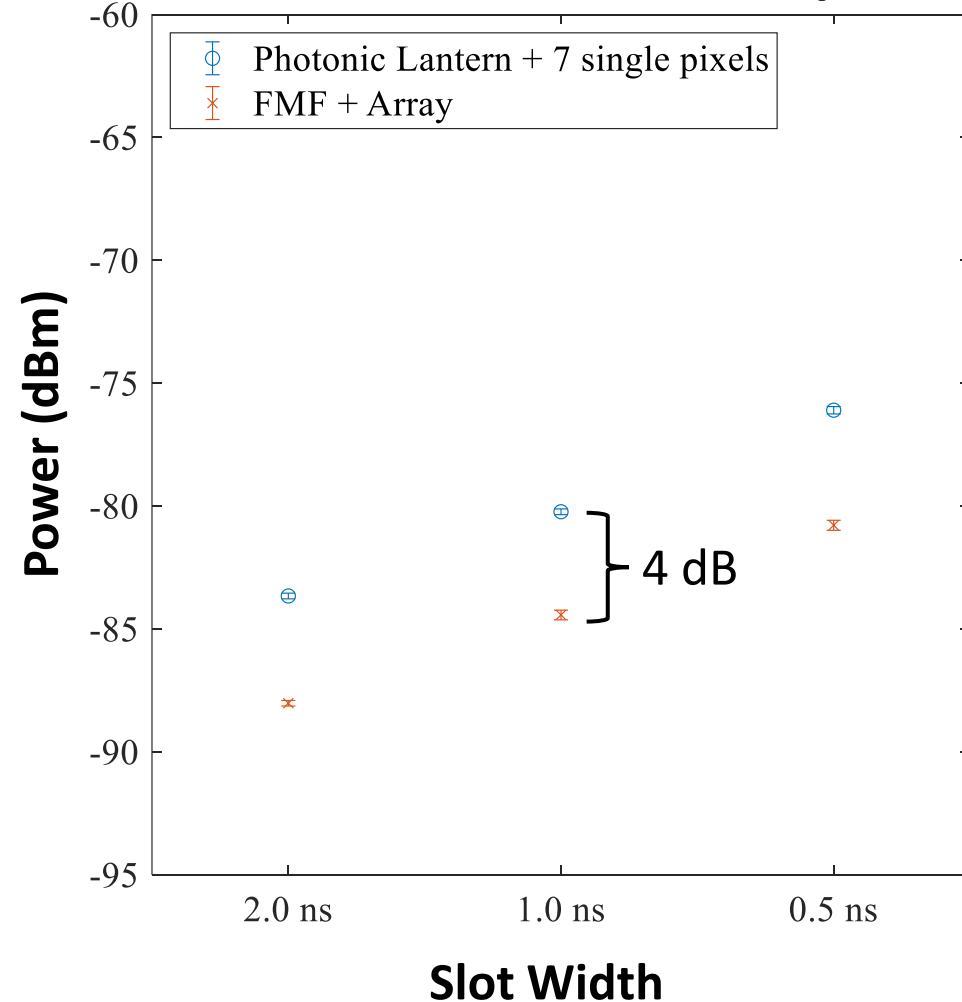
PPM-32 Modes



Timing recovery loop acquisition power

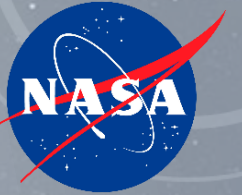


Codeword error rate 10^{-4} power

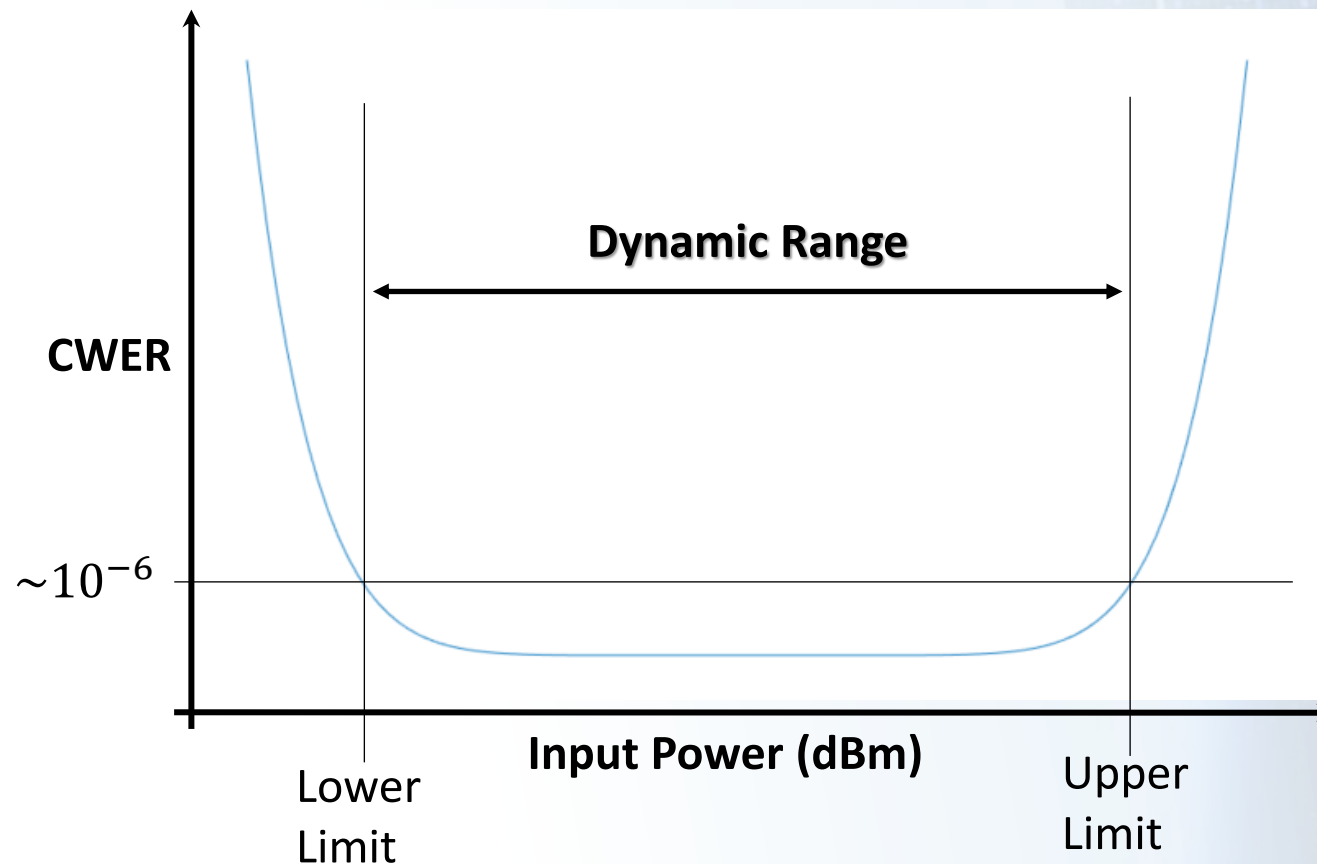


Photonic lantern and 7 single pixel architecture requires 4-5 dB more power.

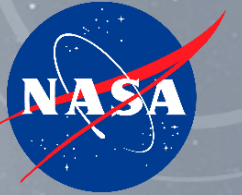
Receiver Dynamic Range



Dynamic range: Ratio between the upper and lower input power limits of the receiver system



Dynamic Range – Results



- Lower limit: limited by the performance of forward error-correction code
- Upper limit: limited by poor SNR at higher input photon flux rates and detector reset time

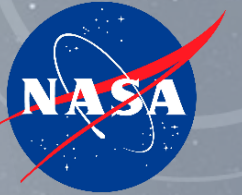
FMF + 15 pixel array

Ts (ns)	PPM	Code Rate	Data Rate (Mbps)	Dynamic Range (dB)
2.0	32	1/3	21	33
1.0	32	1/3	42	28
0.5	32	1/3	83	37
0.5	16	1/3	133	39
0.5	16	1/2	200	33
0.5	16	2/3	267	21

Photonic Lantern + 7 single pixels

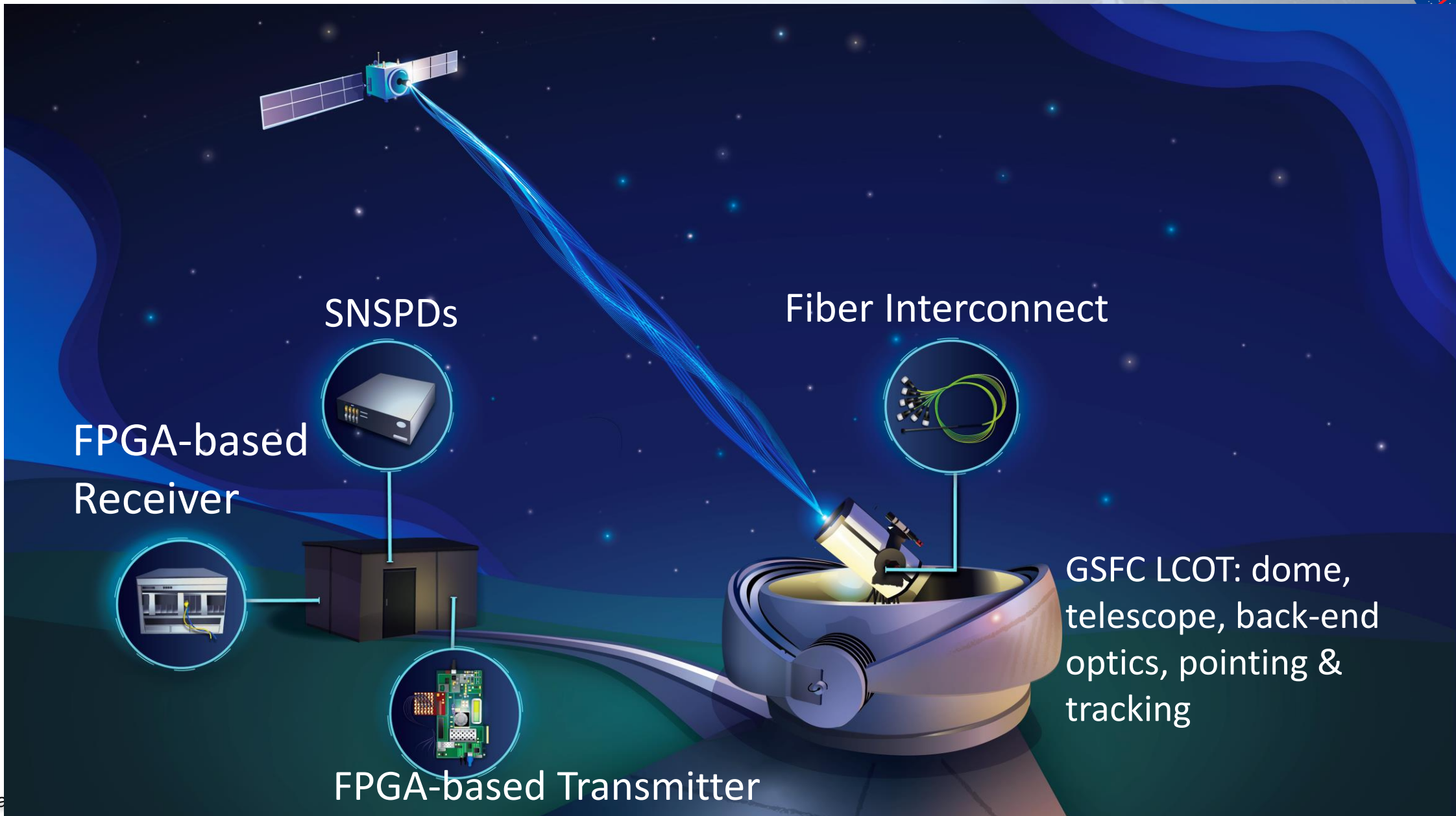
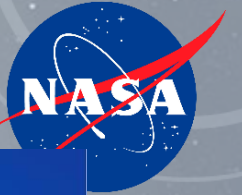
Ts (ns)	PPM	Code Rate	Data Rate (Mbps)	Dynamic Range (dB)
2.0	32	1/3	21	29
1.0	32	1/3	42	25
0.5	32	1/3	83	13

Conclusion



- **Two architectures for a fiber-coupled photon-counting ground receiver have been developed.**
- **FMF + 15-channel array has a 4-5 dB advantage in PPM-32 modes without fades.**
 - **2x detectors each with 1/2 reset time**
- **Architectures perform similar when including fiber coupling loss.**

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



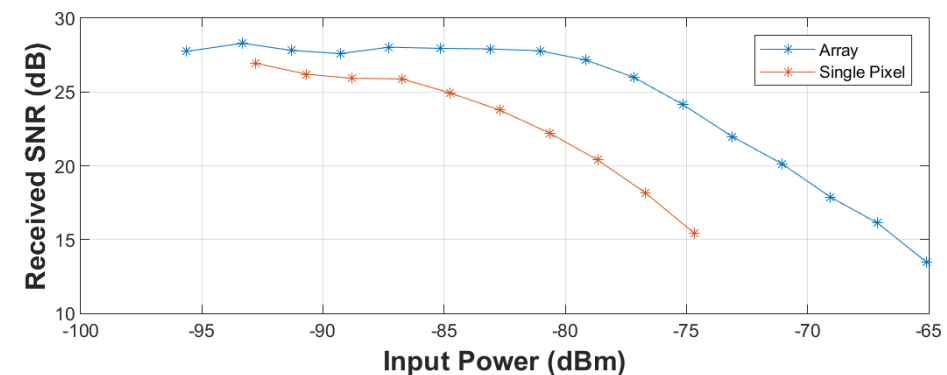
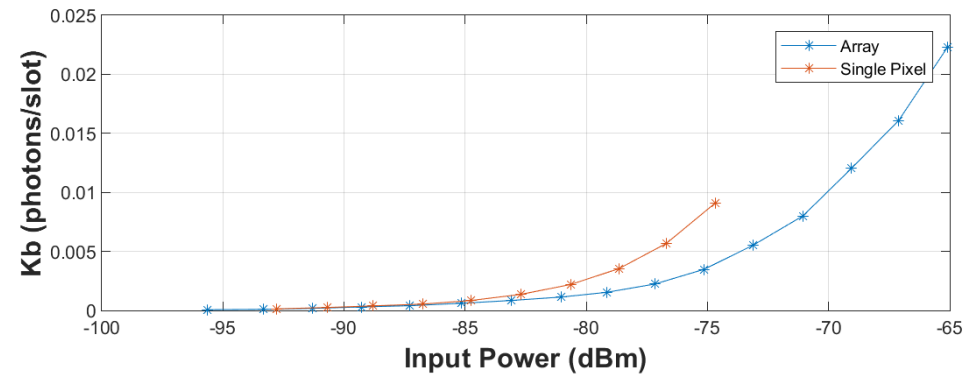
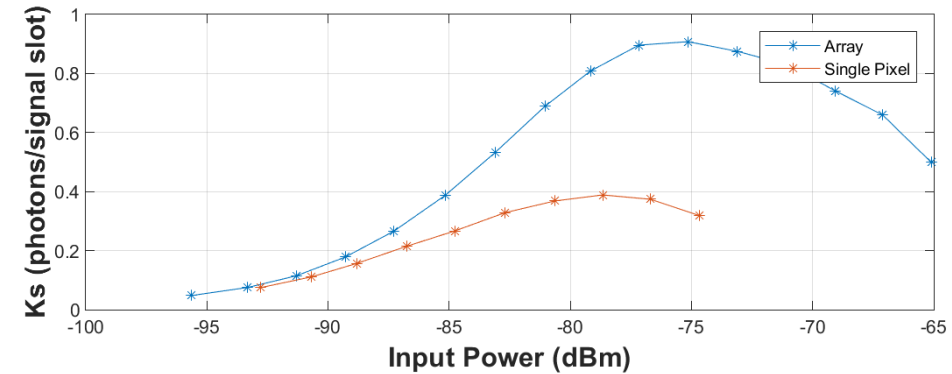
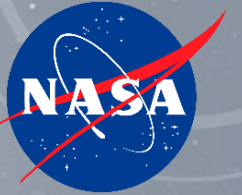
Future Work

Combined Architecture

- Currently working on an architecture which uses both detector systems
- Challenges:
 - Array detectors and single pixel detectors have different ranges of operation
- Advantages:
 - Lower coupling loss with photonic lantern
 - Increased speed from arrayed detectors

Fade Testing

- Utilizing a spatial light modulator and an acoustic optic modulator in real time to emulate fades:
 - Pointing
 - Scintillation
 - Fiber coupling





Thank You!

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