

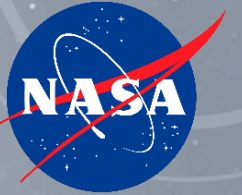
Detector channel combining results from a high photon efficiency optical communications link test bed

Jennifer N. Downey, Brian E. Vyhnalek, Sarah A. Tedder, and Nicholas C. Lantz

NASA Glenn Research Center

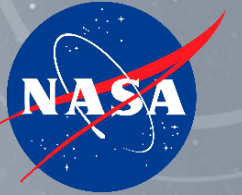
Cleveland, Ohio

Introduction



- **NASA is using the CCSDS Optical Communications High Photon Efficiency (HPE) waveform on future missions: Optical Artemis-2 Orion, Psyche**
- **Superconducting nanowire single-photon detectors (SNSPDs) are required to receive this waveform on the ground in low photon flux conditions**
- **The received photon flux rate is limited by detector blocking**
- **Previous results indicated that 1 detector could receive a data rate of 40 Mbps**
 - **Detector arrays are necessary to enable higher data rates**

Test Setup



Transmitter:

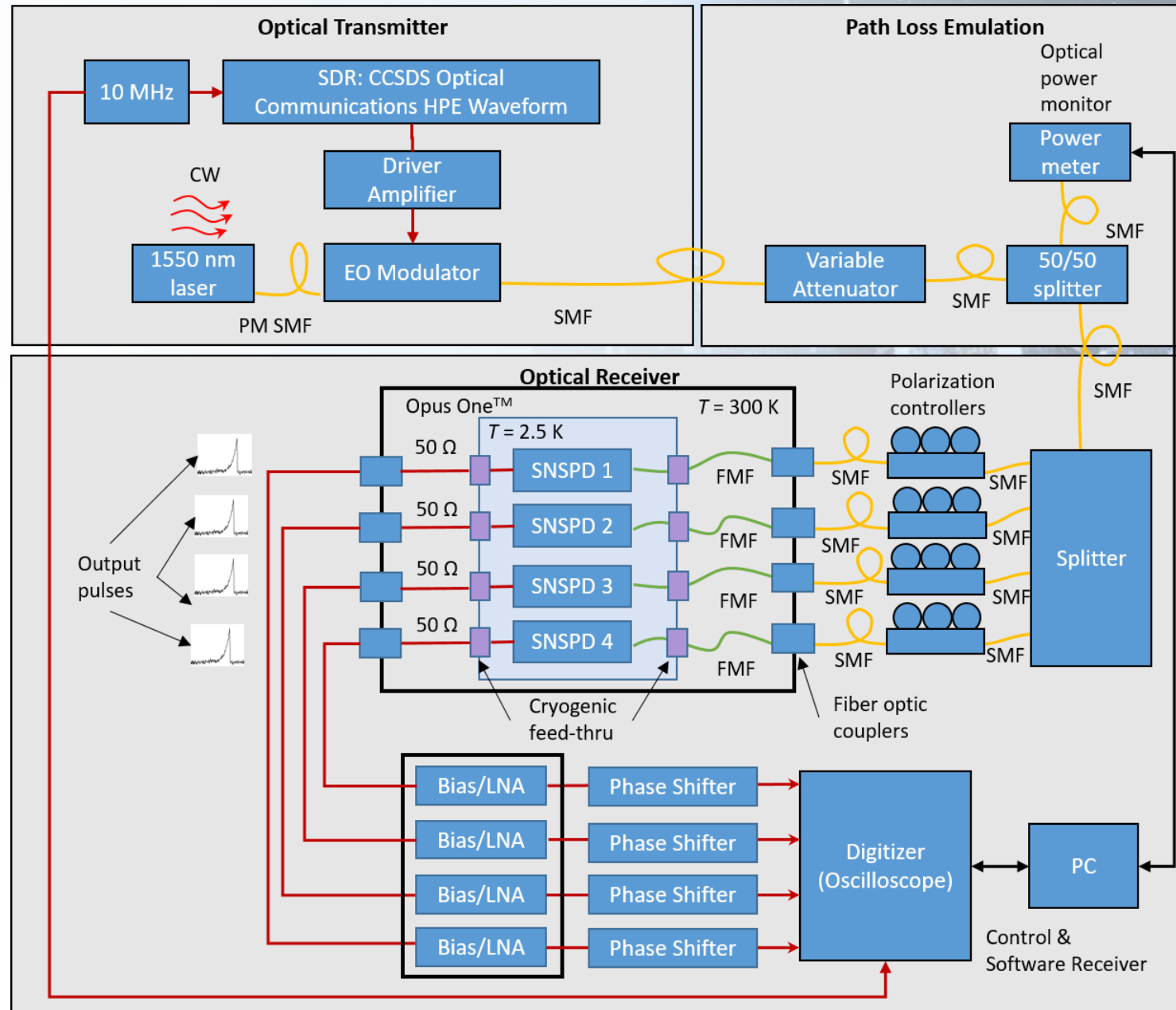
- **CCSDS Optical Communications HPE Waveform**
 - <https://software.nasa.gov/software/LEW-20090-1>

Path Loss Emulation:

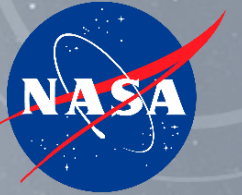
- **Variable attenuator**

Receiver:

- **4 SNSPD channels**
- **Post processing receive waveform**



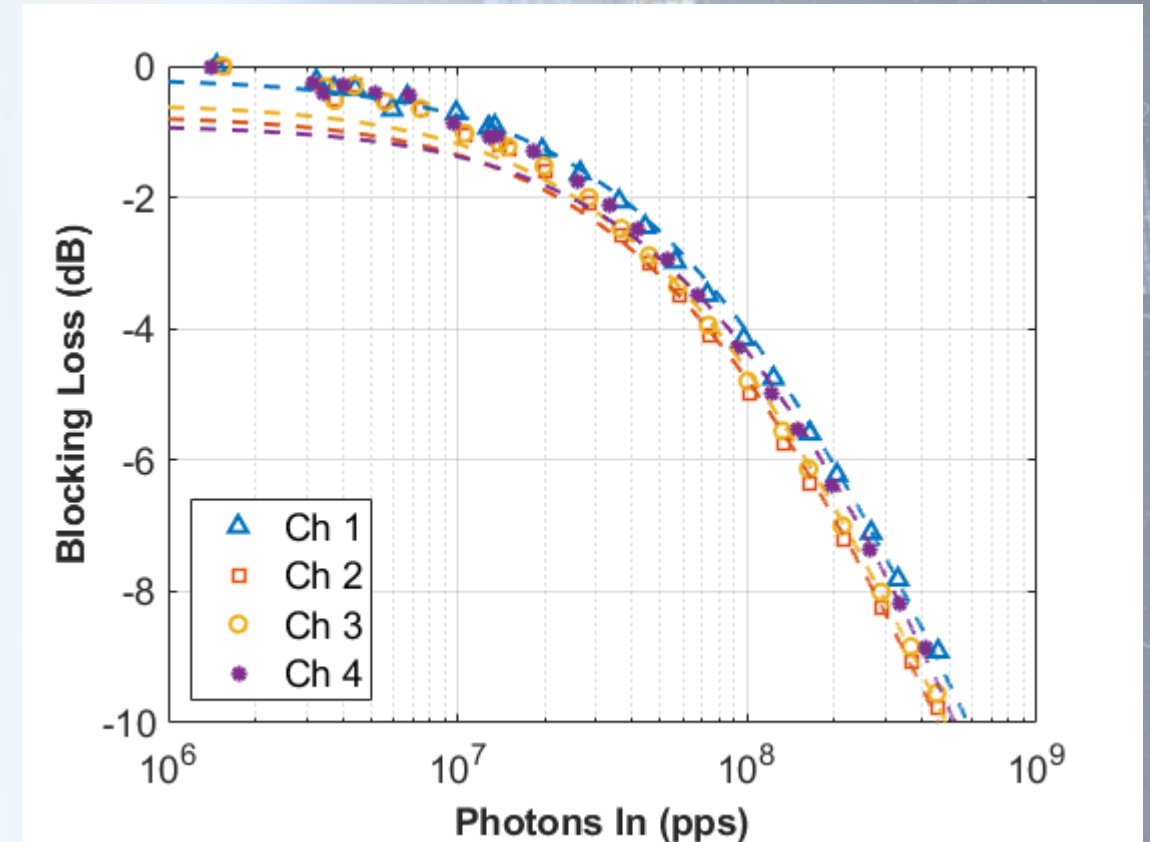
SNSPD Characterization



4 single-pixel SNSPDs from Quantum Opus

Detector performance characterization results¹:

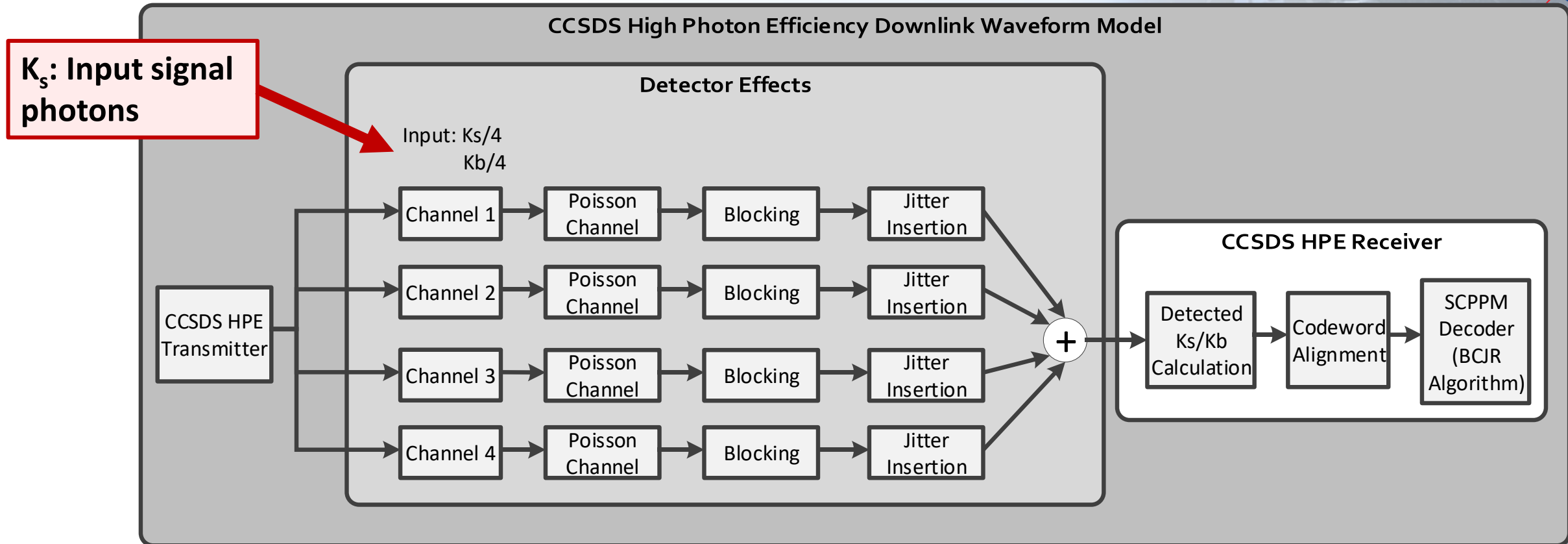
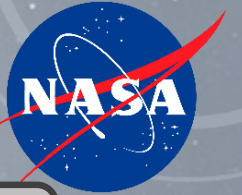
- Pulse rise time: 850 ps (90/10)
- Reset time: 25 ns
- Blocking loss
- Jitter:
 - Ch1 = 45.6 ps RMS
 - Ch2 = 46.2 ps RMS
 - Ch3 = 40.2 ps RMS
 - Ch4 = 48.6 ps RMS



Total receiver system jitter ~60 ps RMS

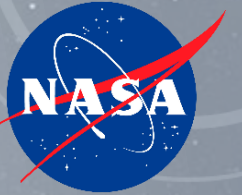
1. Vyhnalek, B., Downey, J., and Tedder, S. "Single-photon counting detector scalability for high photon efficiency optical communication links," Proc. SPIE Free-Space Laser Communication and Atmospheric Propagation XXXII 11272 (2020).

Simulation Model

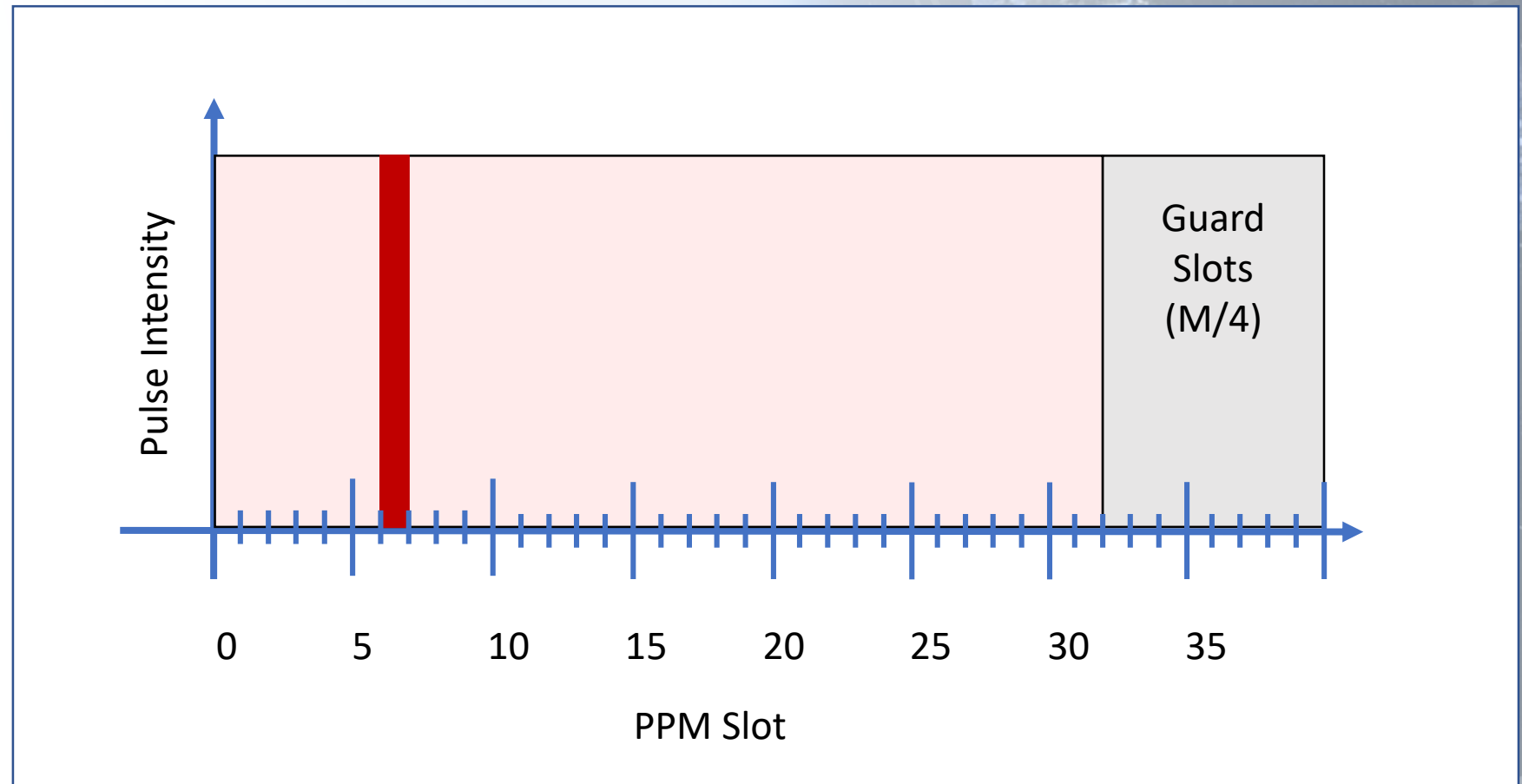


- CCSDS HPE transmit waveform model
- Poisson channel model
- Detector effects:
 - 4 detectors, 25 ns blocking, 60 ps RMS jitter
- CCSDS HPE receive waveform model

Slot and Symbol Phase Estimation

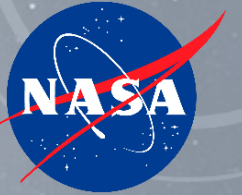


- Each symbol contains M slots in which there is one signal pulse and an additional $M/4$ guard slots in which there is never a signal pulse.
- This feature enables symbol and slot synchronization in the receiver
- Photon counts are summed over many symbols, resulting in a histogram of counts per slot²



2. Rogalin, R. and Srinivasan, M. "Synchronization for optical PPM with inter-symbol guard times," The Interplanetary Network Progress Report 42-209 (2017).

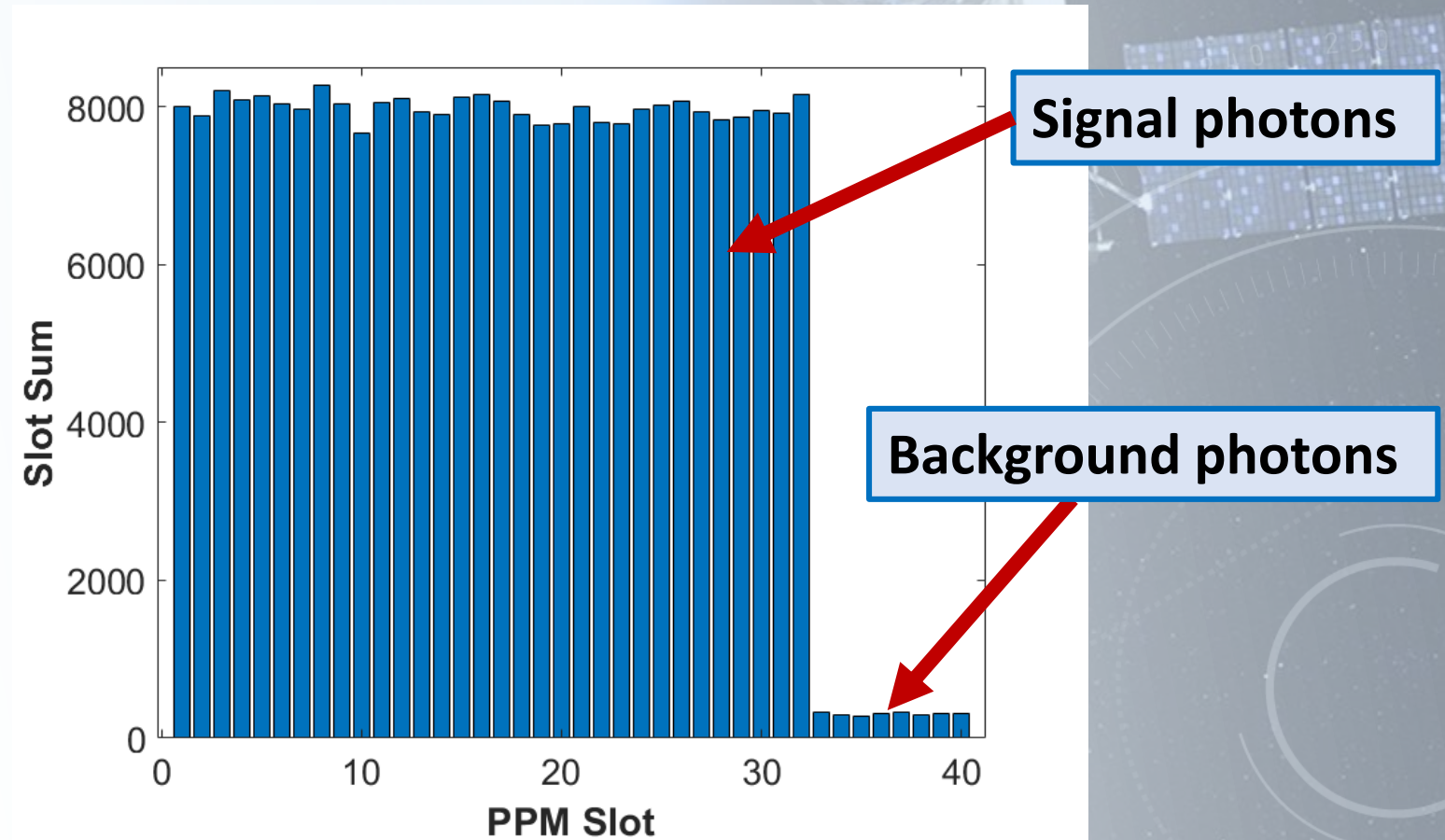
Slot Phase Estimation Histogram Baseline

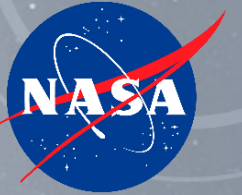


Waveform mode:

- PPM-32
- Code rate 1/3
- 0.5 ns slot
- Photons per signal slot, $K_s=0.8$
- Background photons per slot $K_b=0.001$

100 Codewords





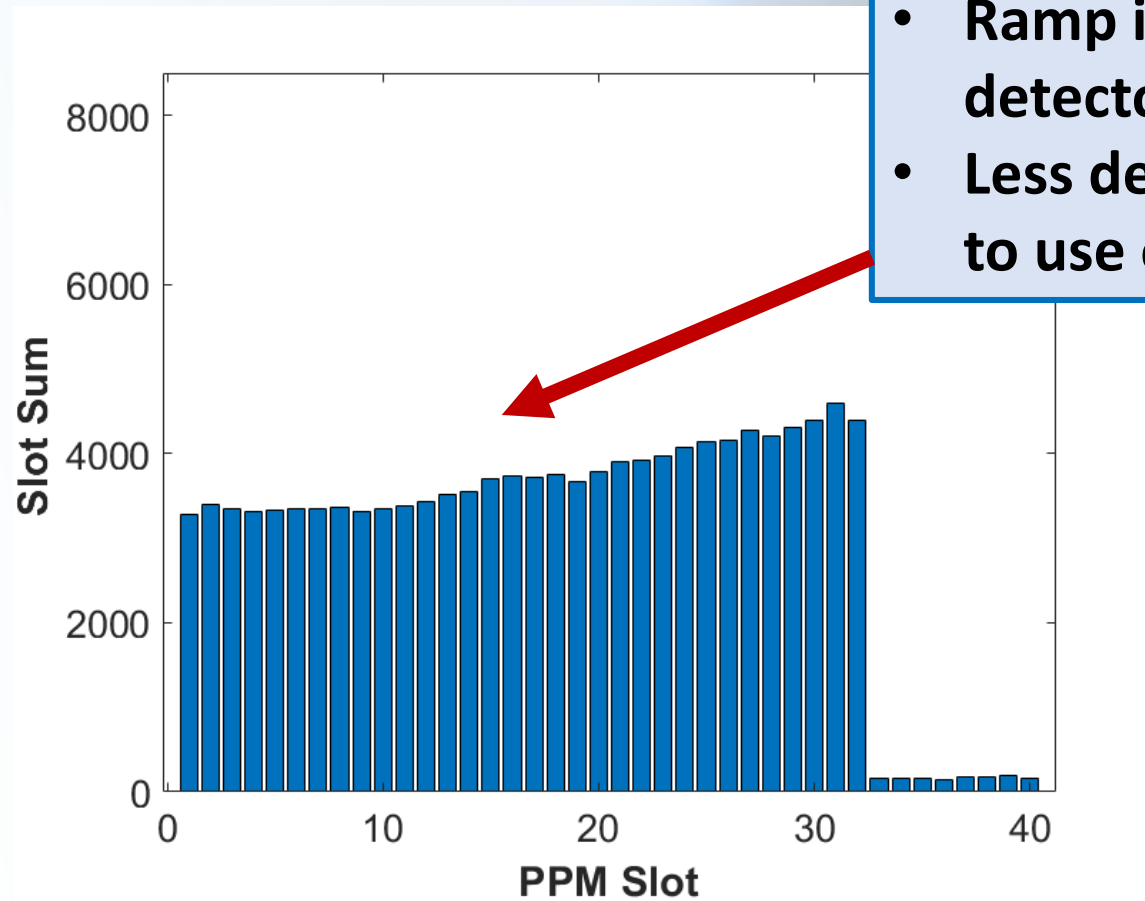
Slot Phase Estimation Histogram

1 detector, 25 ns detector blocking

Waveform mode:

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100 Codewords



- Ramp is due to detector blocking
- Less detections due to use of 1 detector



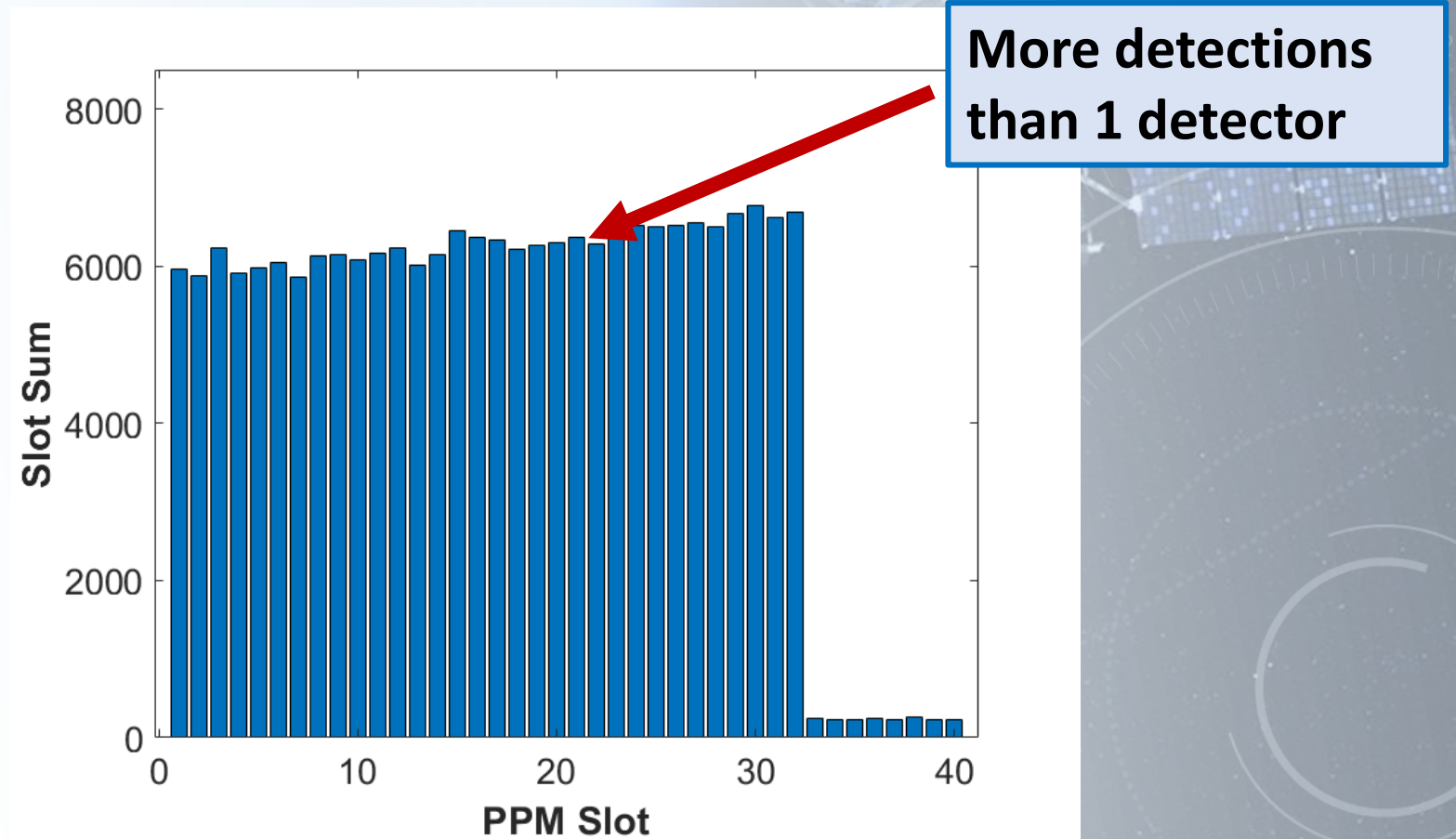
Slot Phase Estimation Histogram

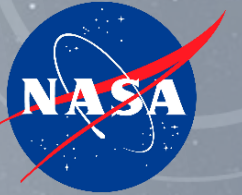
4 detectors, 25 ns detector blocking

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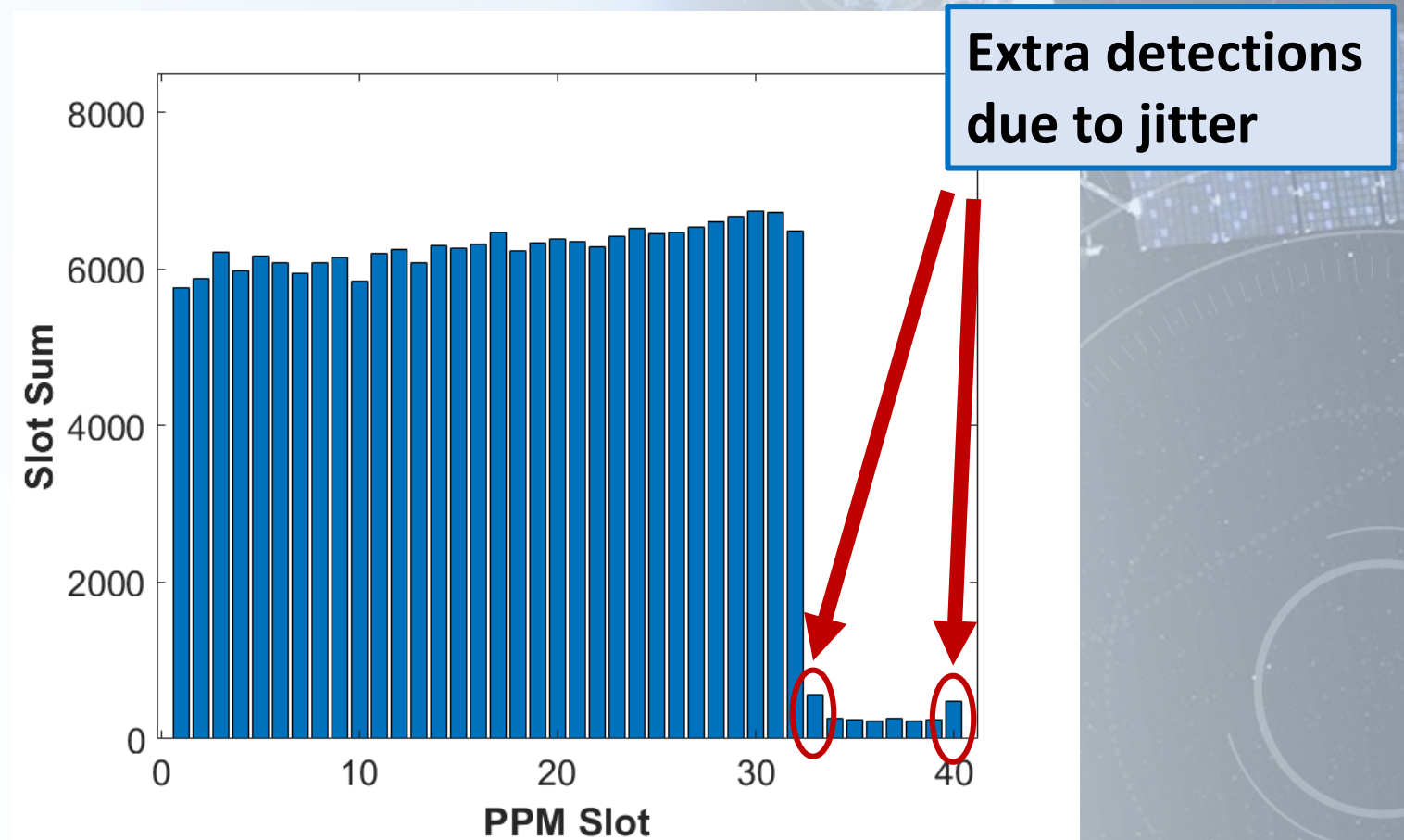
Slot Phase Estimation Histogram

4 detectors, 25 ns detector blocking, 60 ps jitter

Waveform mode:

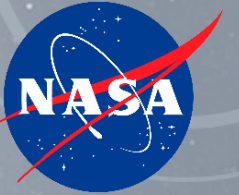
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100 Codewords



Slot Phase Estimation Histogram

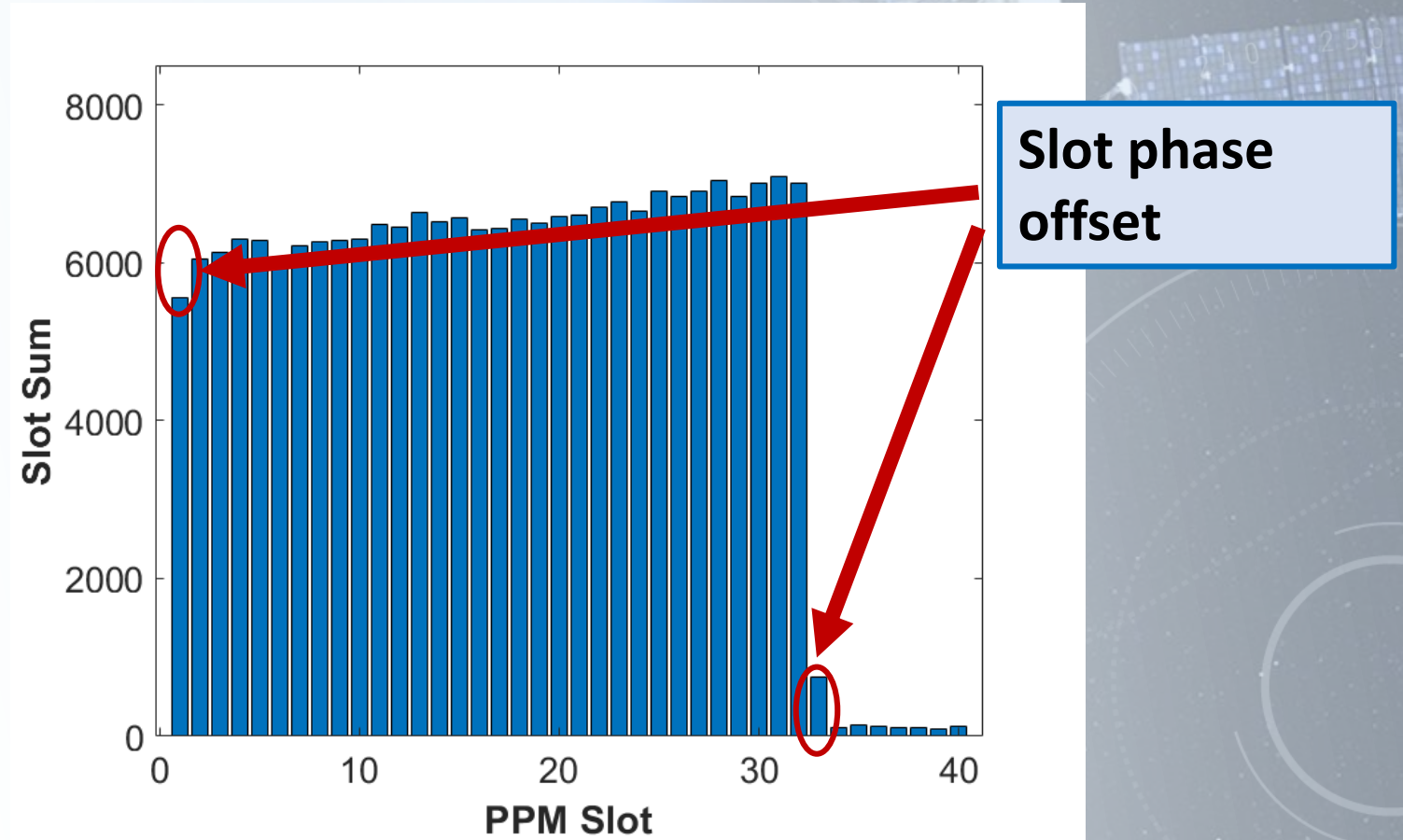
4 detectors, 25 ns detector blocking, 60 ps jitter, slot phase offset



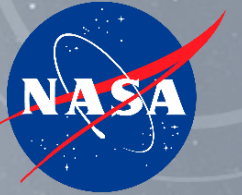
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100 Codewords

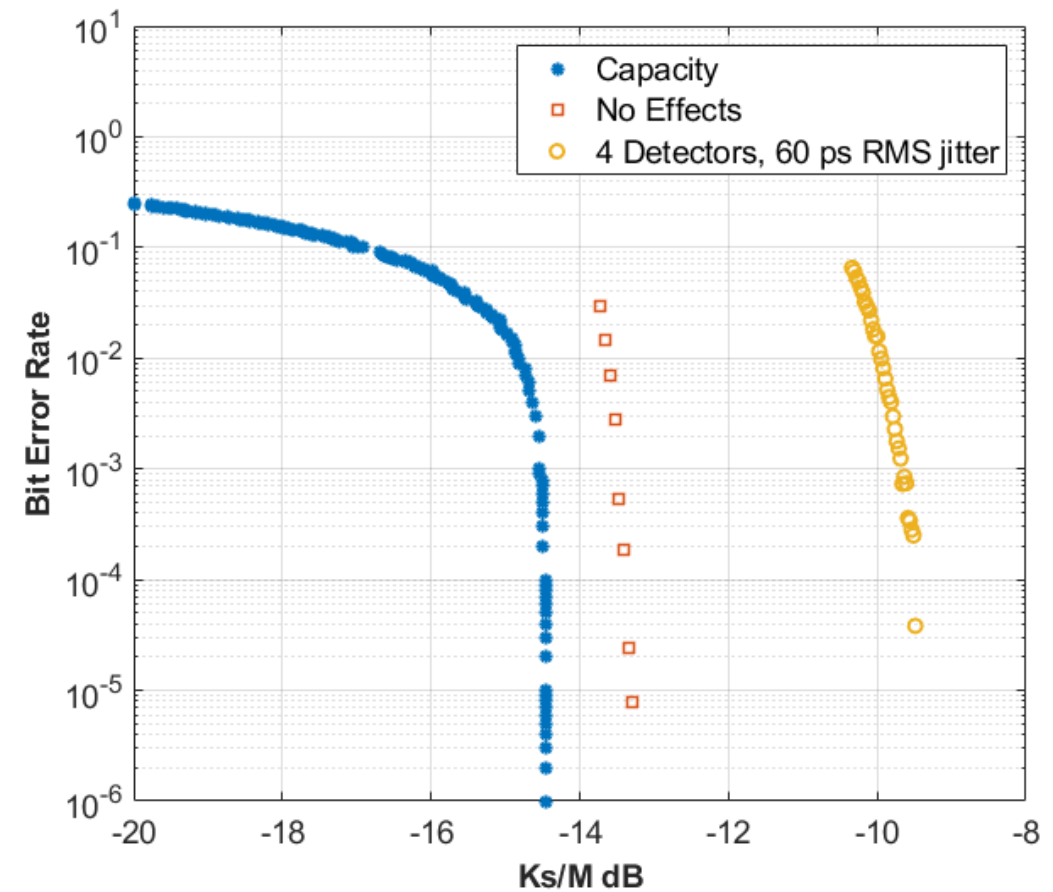
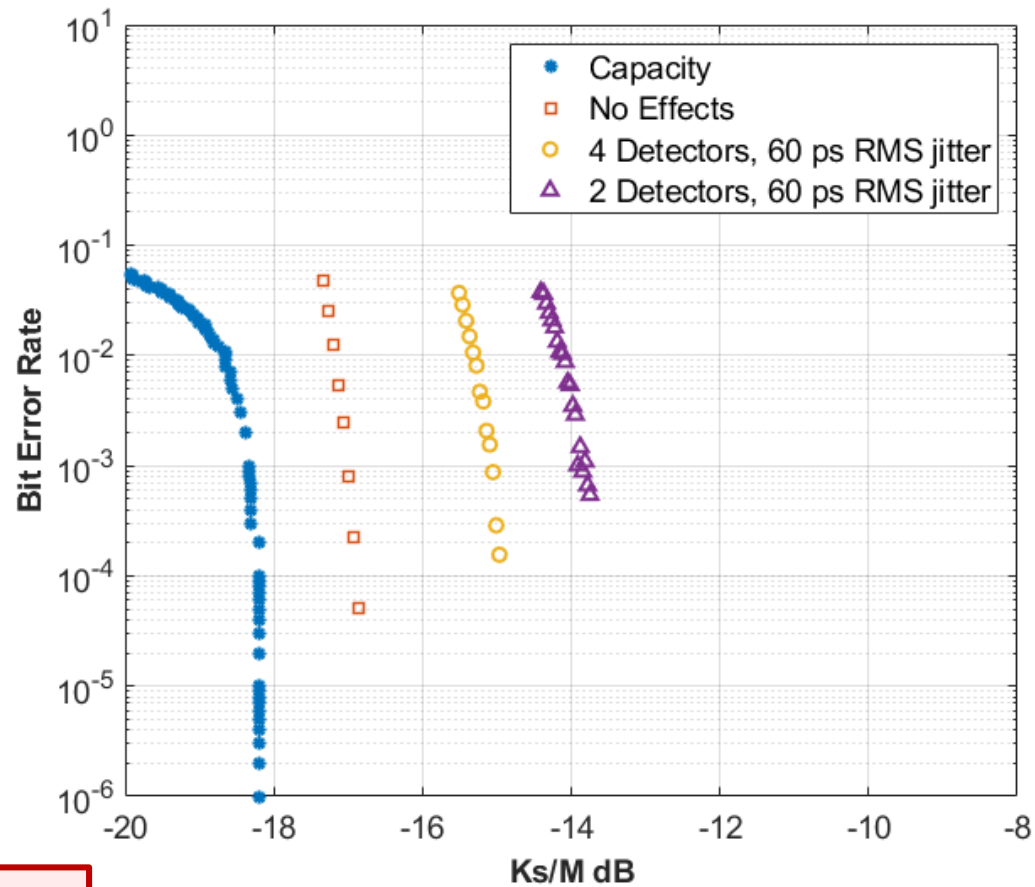


Bit Error Rate Simulation Results



PPM-32, code rate 1/3, 0.5 ns slot,
81 Mbps mode; $K_b=0.001$

PPM-16, code rate 1/3, 0.5 ns slot,
130 Mbps mode; $K_b=0.01$

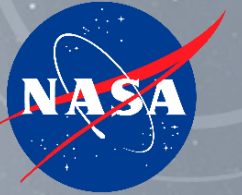


K_s : Input
signal
photons

Link should close with 2 channels

Link should close with 4 channels

Receive Waveform



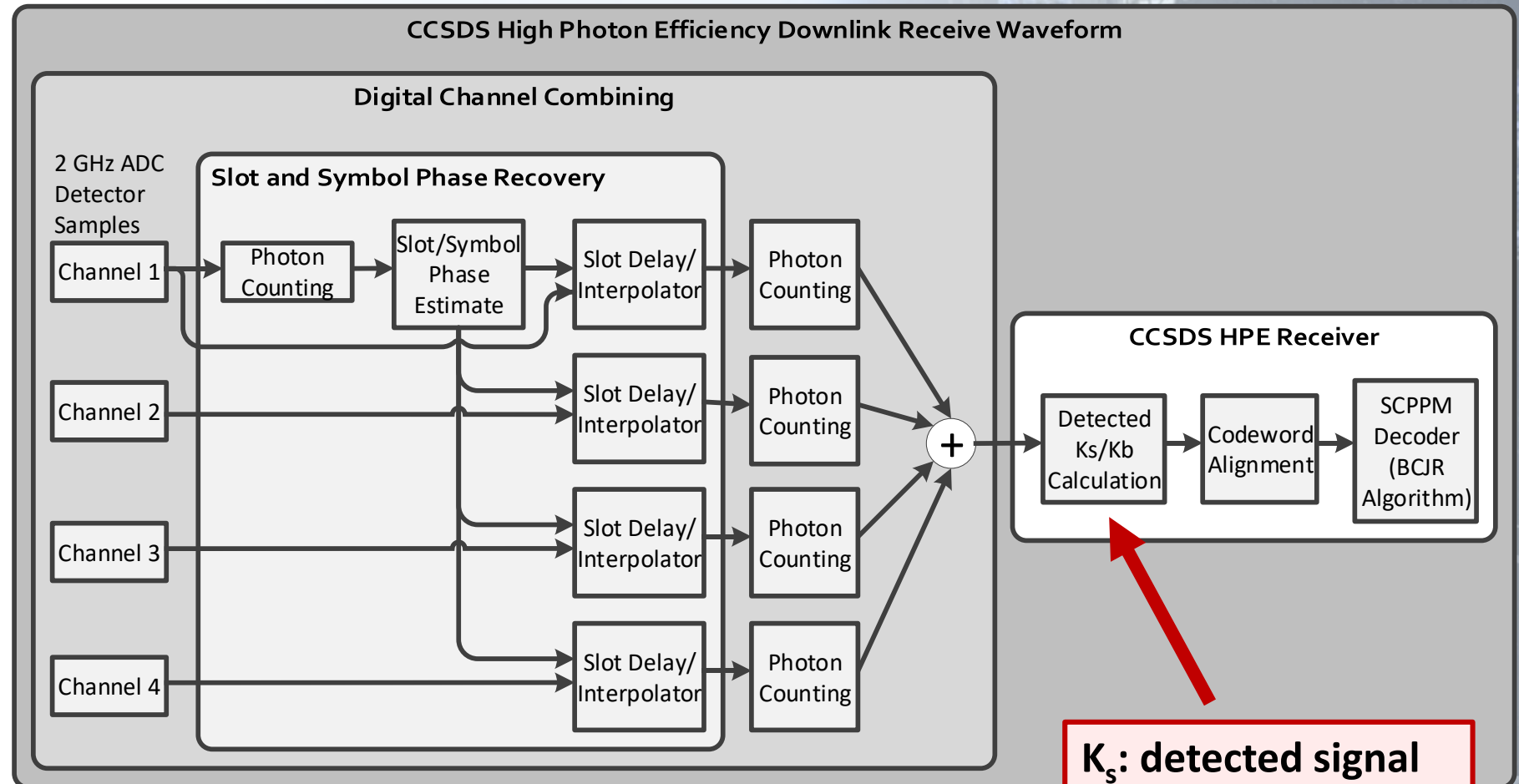
Digital Channel Combining:

- Count photons in each slot
- Estimate slot and symbol phase
- Linearly interpolate detector samples at symbol/slot boundary
- Count photons in each slot using the interpolated signal

Calculate K_s , K_b

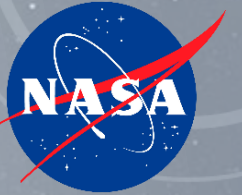
Align codewords

SCPPM decoder



K_s : detected signal photons calculated by the receiver

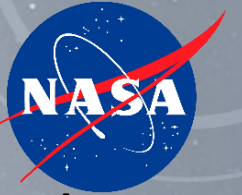
Channel Combining Results



- **BER Curves completed with 4 detector channels:**
 - PPM-32, 81 Mbps mode
 - PPM-16, 130 Mbps mode
- **Channel Alignment:**
 - PPM-32, 81 Mbps mode: 10% of slot (50 ps)
 - PPM-16, 130 Mbps mode: 14% of slot (70 ps)
- **Detector Efficiency:**
 - PPM-32, 81 Mbps: ~70%
 - PPM-16, 130 Mbps: ~30%

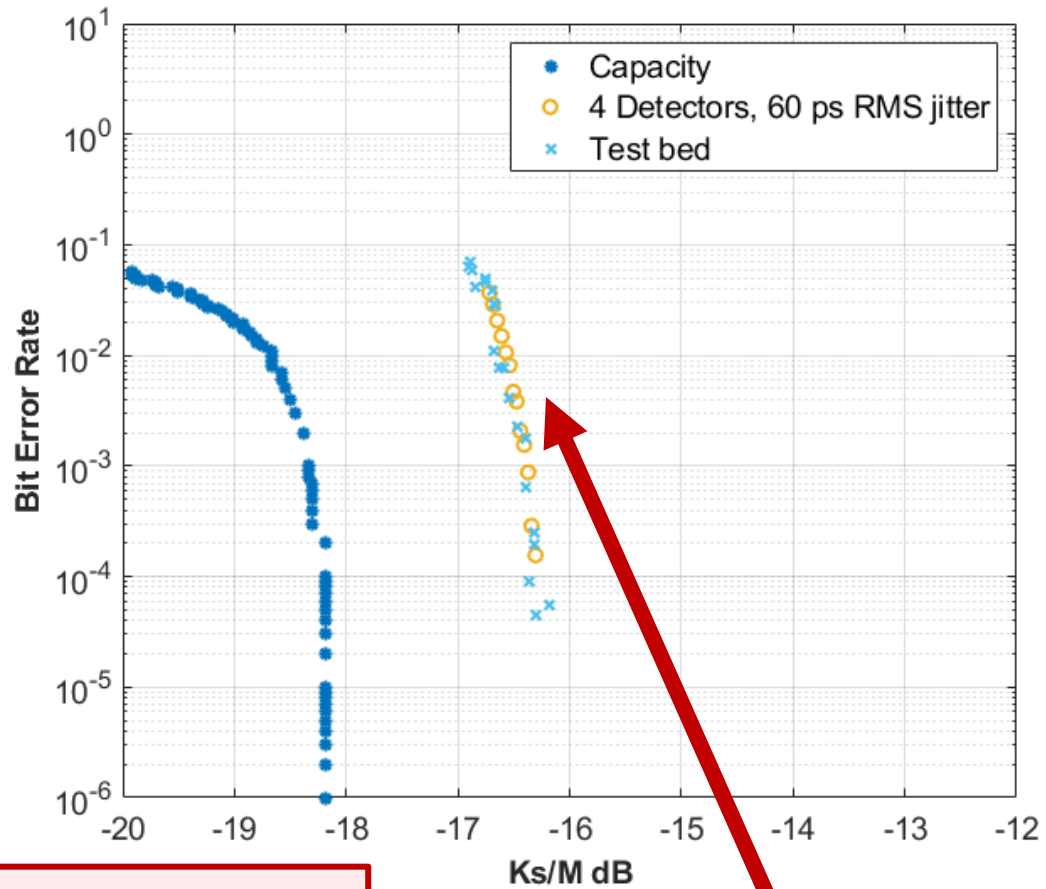
High photon flux, nonlinear regime of operation

Channel Combining BER Curve Results



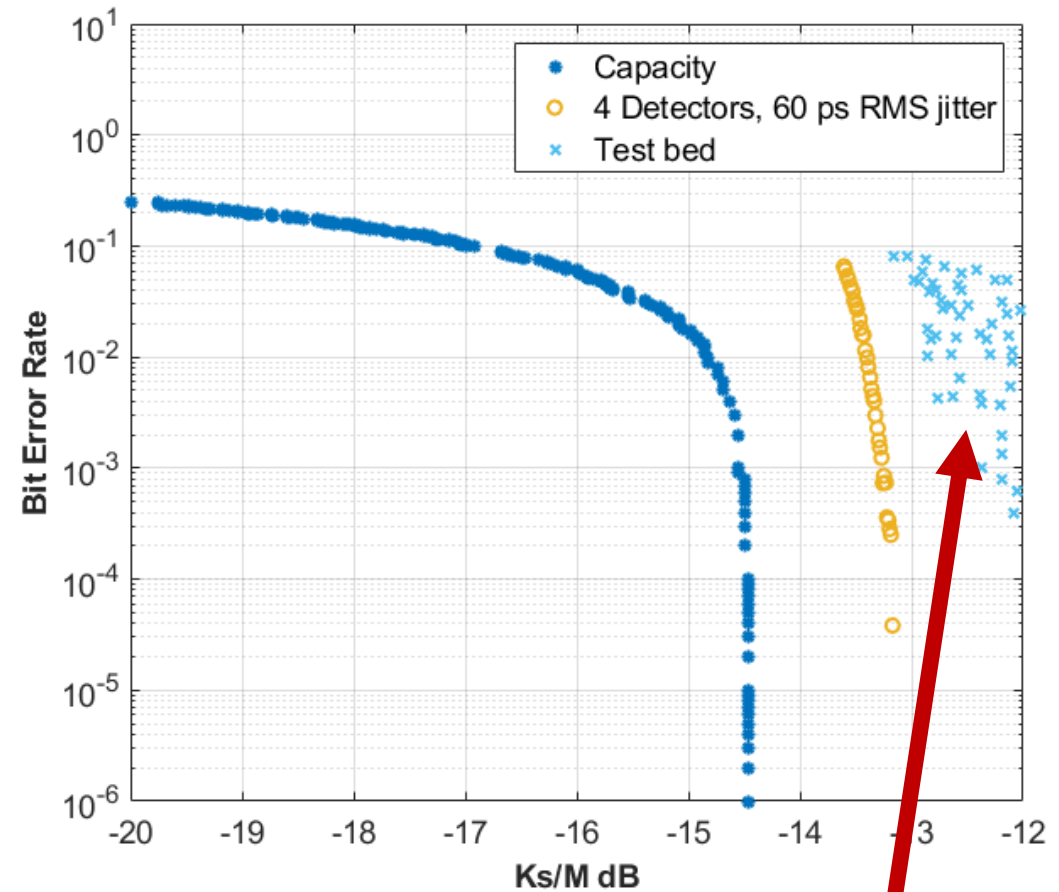
PPM-32, code rate 1/3, 0.5 ns slot, 81 Mbps mode

PPM-16, code rate 1/3, 0.5 ns slot, 130 Mbps mode



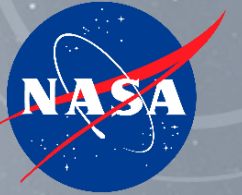
K_s : detected signal photons calculated by the receiver

Test bed results match simulation results

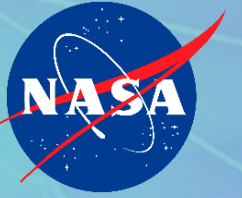


Cause of spread is detector pulse walk

Summary

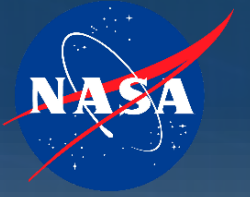


- **A data rate improvement from 40 Mbps with 1 detector to 130 Mbps with 4 detectors has been demonstrated in hardware.**
- **Simulation results indicate:**
 - **At least 2 detectors are needed to receive the PPM-32, code rate 1/3, 0.5 ns slot, 81 Mbps mode**
 - **At least 4 detectors are needed to receive the PPM-16, code rate 1/3, 0.5 ns, 130 Mbps mode**
- **PPM-16, 130 Mbps waveform requires operating the 4 detectors in the high photon flux, nonlinear regime.**
- **Methods for correcting the signal for detector pulse walk in the high photon flux regime will be researched in the future.**



Acknowledgements

This work was funded by the Space Communications and Navigation Program at NASA.



Thank You!

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