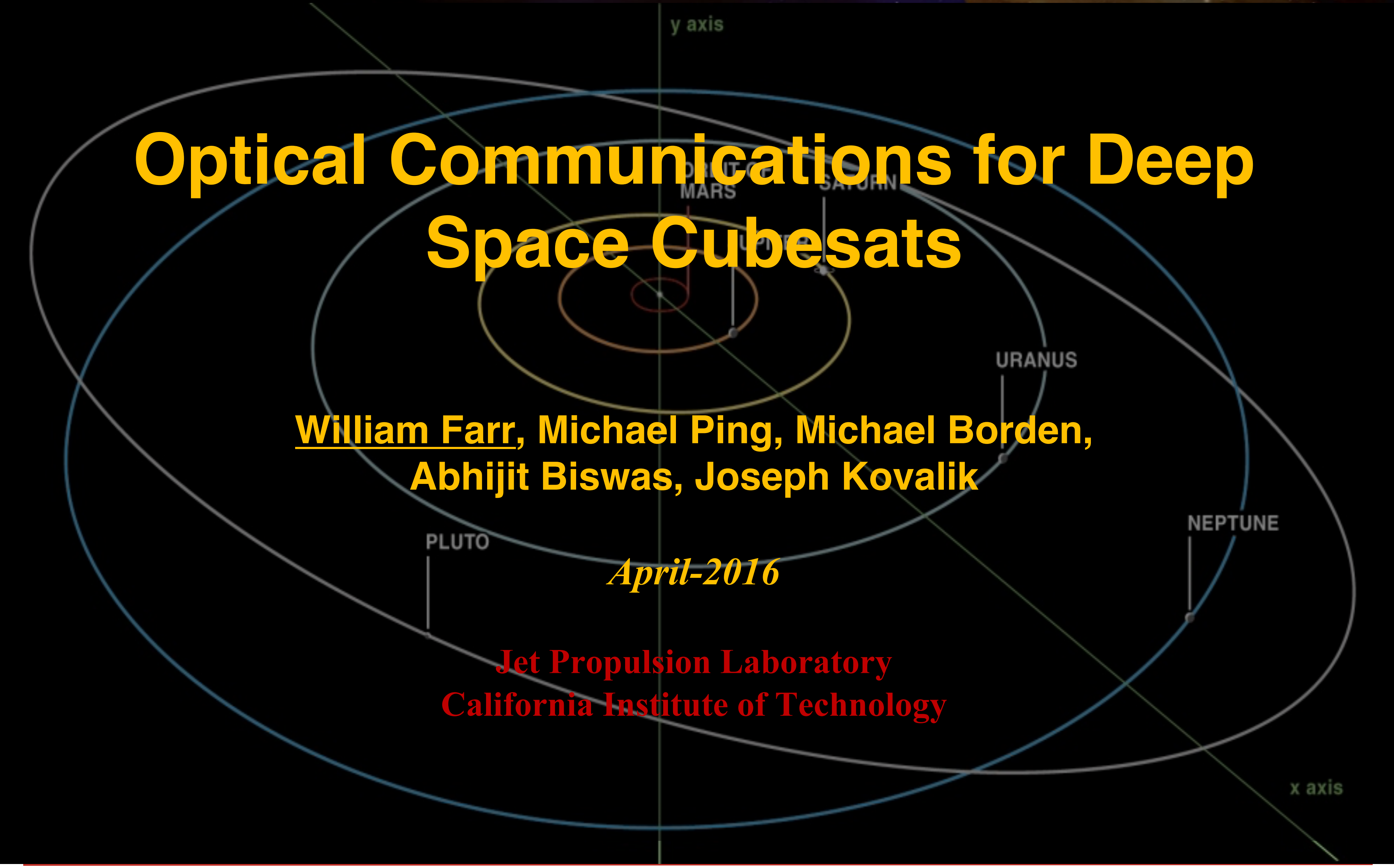

Optical Communications for Deep Space Cubesats

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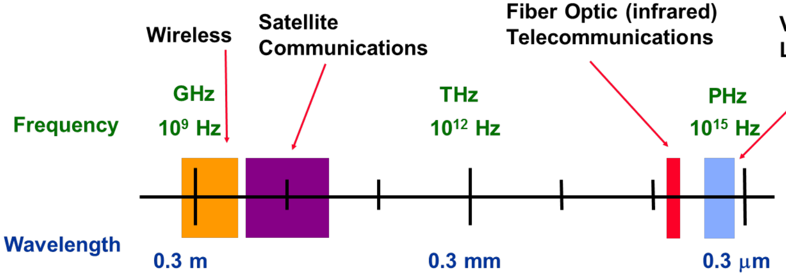
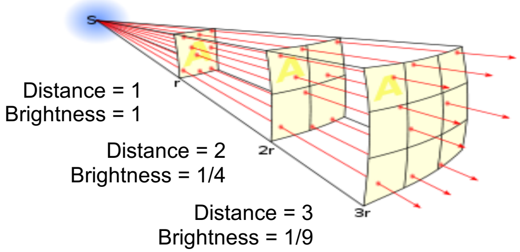
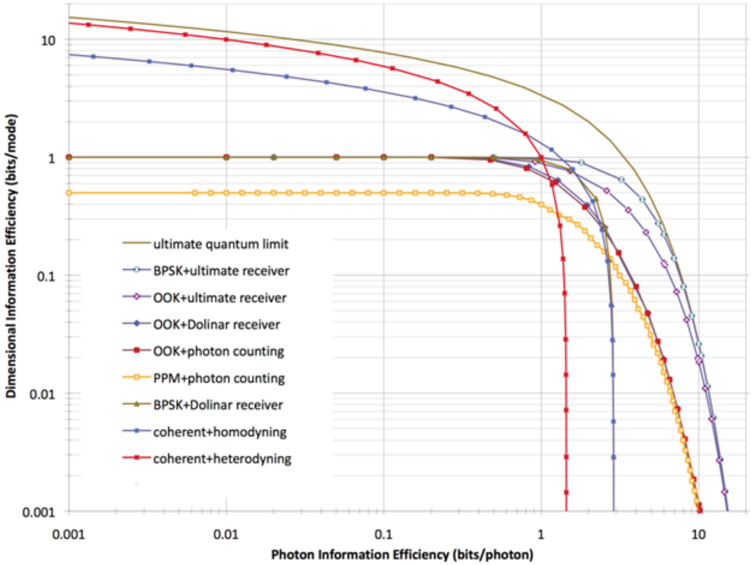
Why consider optical for cubesat telecom?

Versus RF telecommunications:

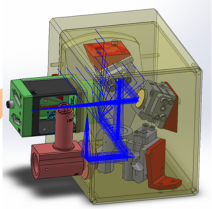
- **Freedom from spectrum regulations**
  - Limited spectral allocations limit data rates
  - Long lead times for RF licenses
- **Smaller beam divergences from small transmitter apertures**
  - Higher Equivalent Isotropic Radiated Power (EIRP)
    - ➢ *Beam width = wavelength / antenna diameter*
  - ***In a well-designed system data rate is proportional to received power***
- **Fewer photons per bit required for direct detection than coherent detection**
  - Limit of 1.44 bits per photon for heterodyne
  - Limit of 2.89 bits per photon for homodyne
  - Unlimited bits per photon for direct detection
    - ➢ *17 bits per detected photon demonstrated at JPL*





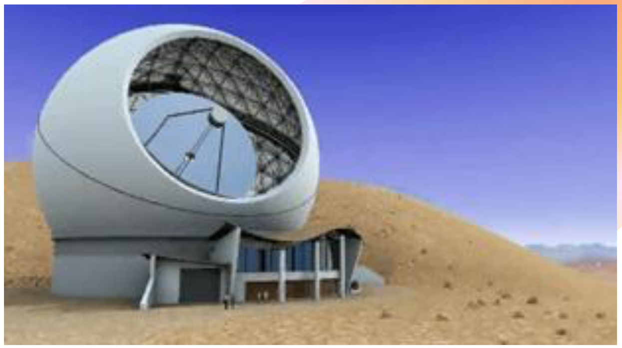


Challenge of Deep Space Telecom



- **International Telecommunication Union definition of deep space for RF spectrum allocation purposes is 2 million km**
  - The moon is about 0.4 million km away
  - The Earth-Sun L1 and L2 points are about 1.5 million km away
- ***However*, interplanetary distances are much larger than that**
  - Mars at typical *closest* range is 60 million km
    - **3.6 billion times larger signal loss than LEO**
  - Venus at typical *closest* range is 40 million km:
    - **1.6 billion times larger signal loss than LEO**

Range (R)		Additional 1/R^2 Loss Factor at 1 AU	Round-trip Light Time
LEO (1000 km)	6.7×10^{-6} AU	2.25×10^{-10}	3.3 msec
GEO	.00024 AU	17,400,000	0.24 secs
Moon	.0028 AU	128,000	2.79 secs
Earth-Sun L2	.01 AU	10,000	10 secs
Deep Space	1 AU	1	16.6 mins



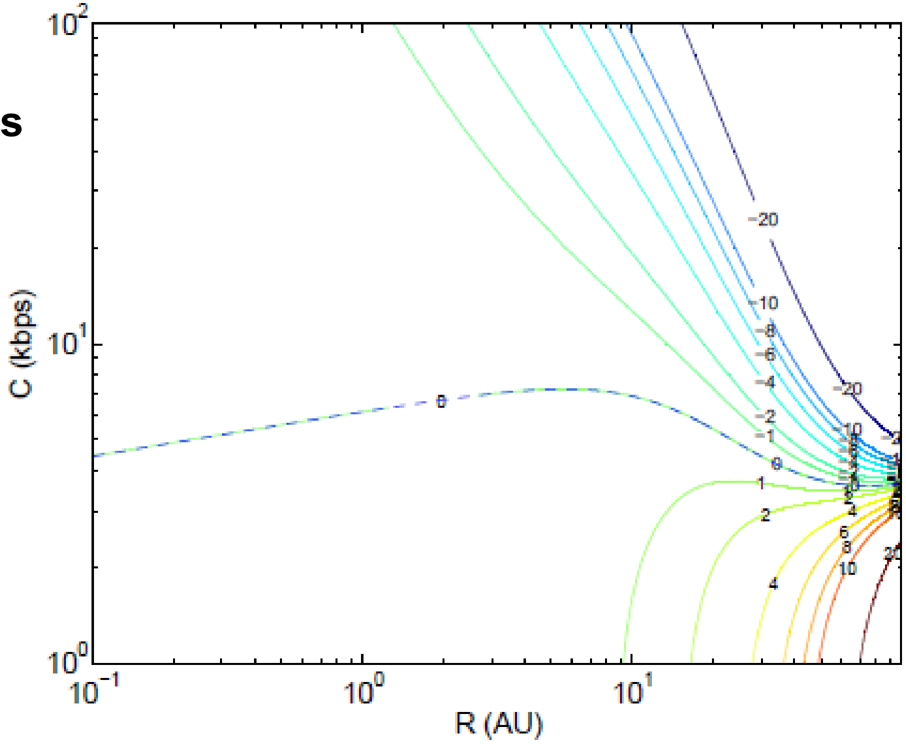
Telecom under mass & power constraints

- **Although optical outperforms RF at high data rates, RF can outperform optical at large ranges and under high background conditions**
  - With photon counting direct detection the capacity goes as $1/R^2$ for $P_r > 2\,P_b \ln M/M$, and as $1/R^4$ for $P_r < 2\,P_b \ln M/M$
    - *with M as the peak-to-average power ratio of a symbol*

$$C_{RF}(W) = W \log_2 \left(1 + \frac{P_r}{N_0 W}\right) \text{bps}$$

$$\begin{aligned} C_{opt} &= \left((P_r + P_b/M) \log_2(1 + M P_r/P_b) \right. \\ &\left. -(P_r + P_b) \log_2(1 + P_r/P_b)\right) / E_\lambda \text{ bps} \end{aligned}$$

  - This also implies a maximum effective diameter for optical ground-based receivers
    - *Beyond this limit, doubling the antenna diameter only increases the achievable data rate by √2*



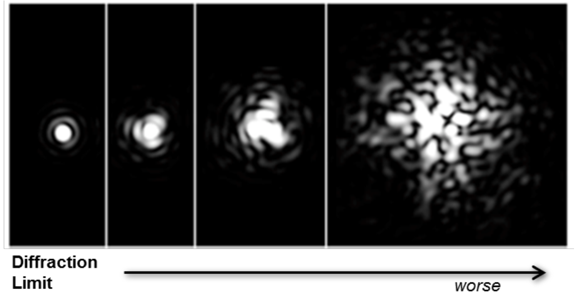
Example mass difference contours, ($m_{(o)} - m_{(r)}$) (kg), to achieve specified (R,C). Positive (negative) contours denote the kg gain of an RF (optical) terminal.

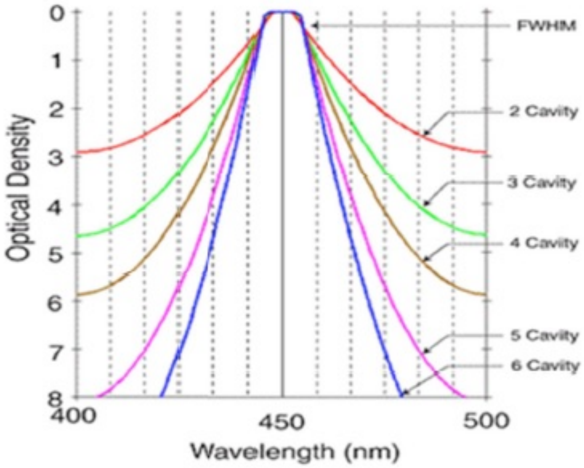
Capacity

- Is the *maximum information rate* achievable across a channel with arbitrarily small probability of error
- Represents the *maximum mutual information* between the channel input and channel output
- Examples of units of capacity are *bits per second* and *bits per channel use*

Optical Noise Rejection Challenge

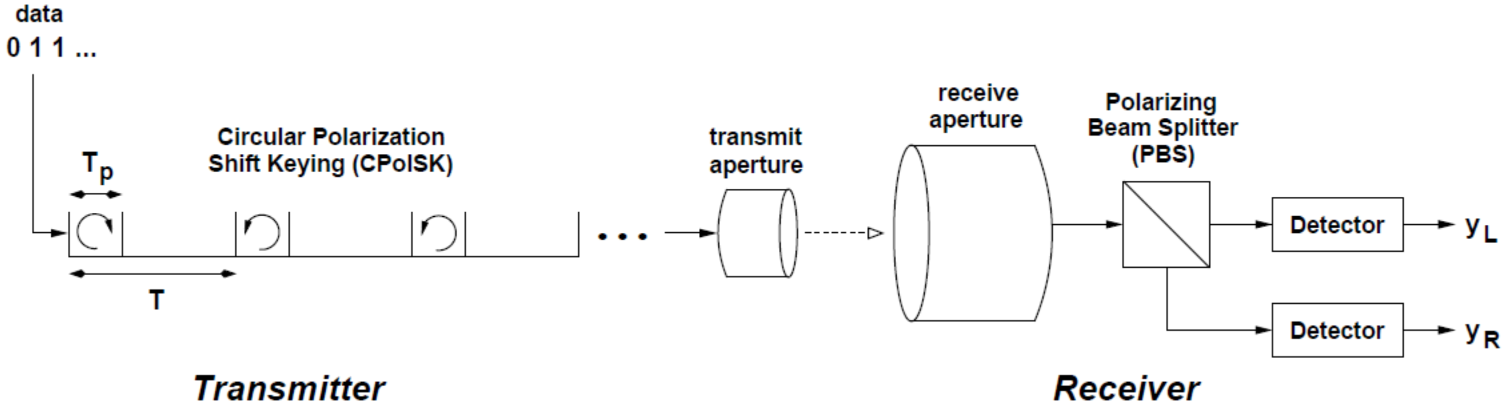
- **When noise power dominates, capacity *C* scales as P_s^2/P_b**
  - *In this regime, data rate scales as $1/R^4$, and optical communications advantage from a narrower transmit beam are quickly lost*
- **Background light in the optical receiver is traditionally rejected by either limiting the field-of-view or by optical bandpass filtering.**
  - An optical receiver located in the Earth's atmosphere has a field-of-view limited by atmospheric turbulence, characterized by the Fried parameter r_0, unless adaptive optics (complex, bulky, and costly) is utilized.
    - r_0 (few cm worst case, typically) represents the optical coherence length and the maximum receiver aperture diameter that can achieve a diffraction limited field of view.
  - Narrowband optical interference filters with low transmission loss (< 1 dB) have tens of gigahertz bandwidths or greater.
    - Alternate filter technologies such as atomic line filters and ring resonators have severe implementation challenges with respect to not only transmission loss, but also Doppler and/or effective field of view.





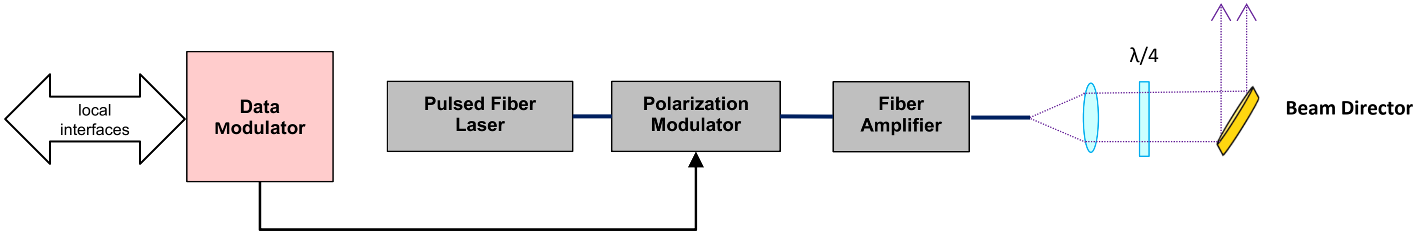
Noise Rejection in the Time Domain

- **With photon-counting direct detection optical background can also be rejected in the time domain**
  - Time-of-arrival of every individual detected photon at the receiver is tagged with sub-nanosecond precision
- **Simplest scheme: polarization modulate a fixed-rate pulsed laser**
  - For instance, right-hand circular polarization to represent "0" and left-hand circular polarization to represent "1“
  - Single "tone" of direct detection signal allows time-gated rejection of non-signal photons
  - Signal can still be acquired under high loss conditions, then forward error correction coding gains applied



Circular Polarization-Shift-Keying Terminals

- **Circular-Polarization-Shift-Keying (CirPolSK) laser transmitter is low complexity with small diameter aperture (few mm to few cm)**
  - Pulsed laser transform-limit bandwidth should be matched to receiver optical filter bandwidth



local interfaces

Data Modulator

Pulsed Fiber Laser

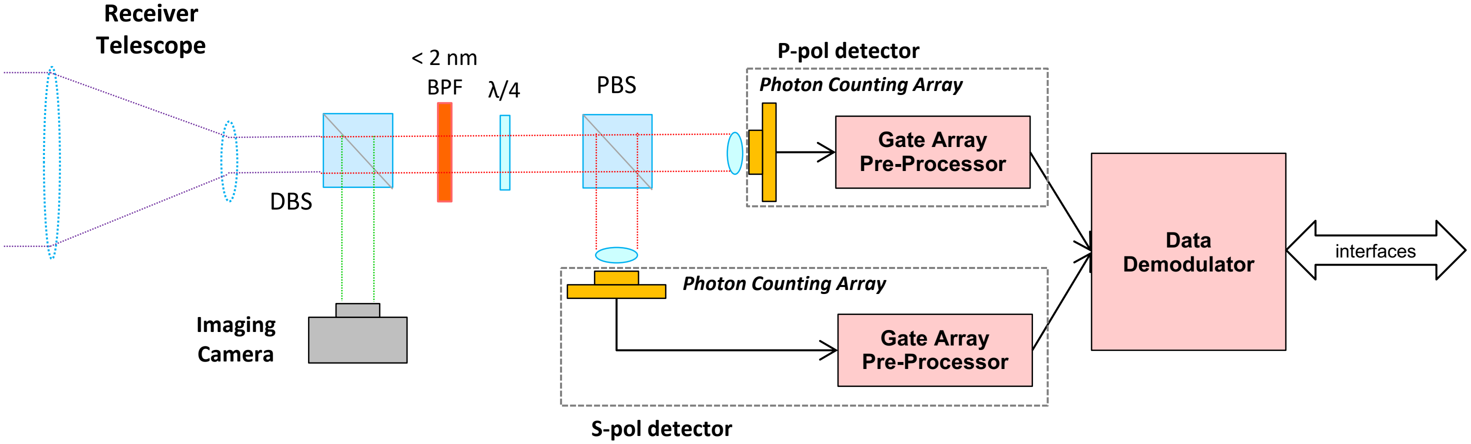
Polarization Modulator

Fiber Amplifier

λ/4

Beam Director

- **Background rejection performance of the Photon Counting Detector (PCD) CirPolSK receiver is set by optical filter bandwidth and timing resolution of photon arrivals**
  - New generation near-infrared PCD arrays with readout can operate with <200 ps timing uncertainty, > 50% efficiency, and near-zero intrinsic noise rates



Receiver Telescope

DBS

Imaging Camera

< 2 nm BPF

λ/4

PBS

P-pol detector

Photon Counting Array

Gate Array Pre-Processor

Photon Counting Array

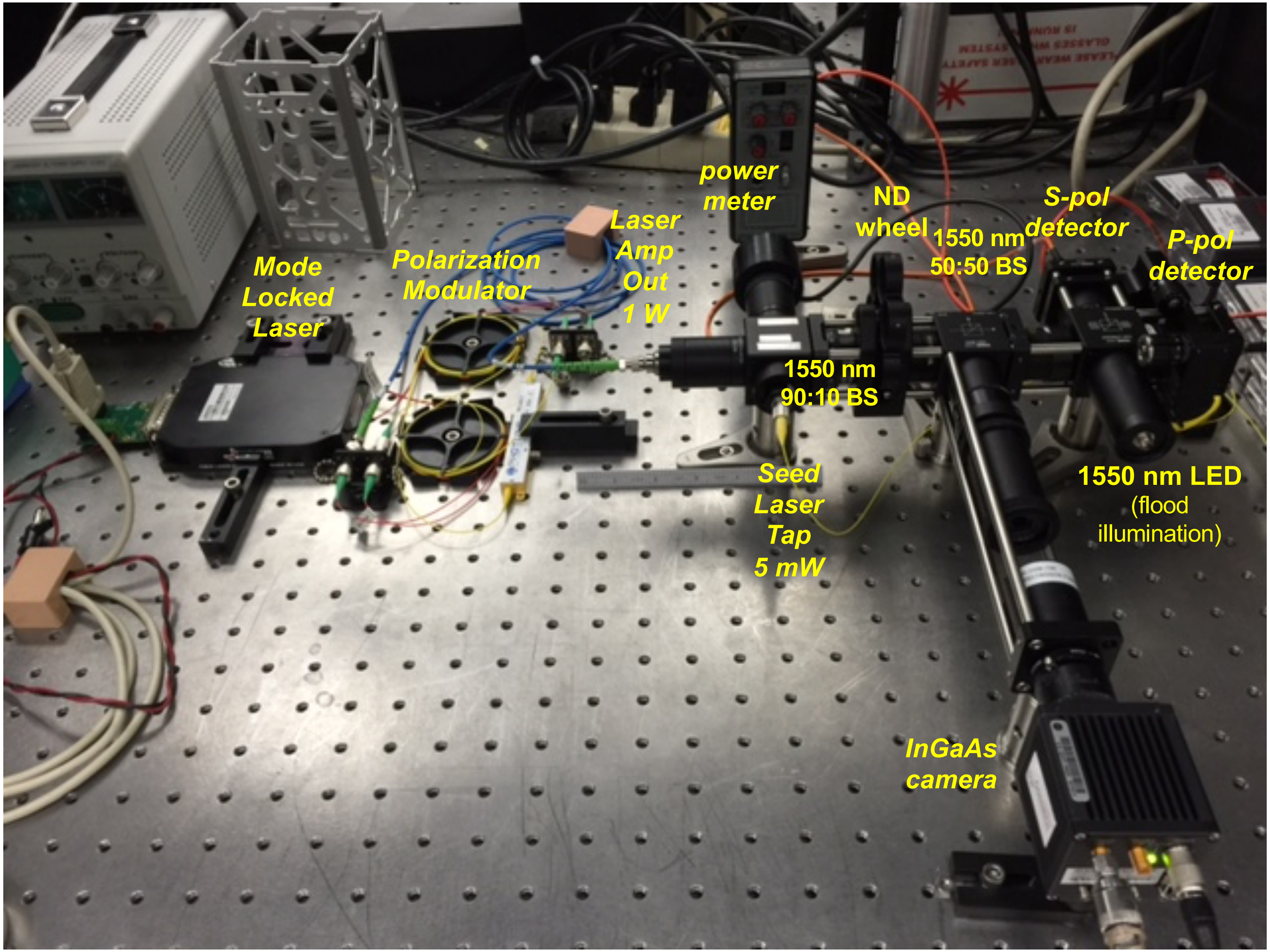
Gate Array Pre-Processor

S-pol detector

Data Demodulator

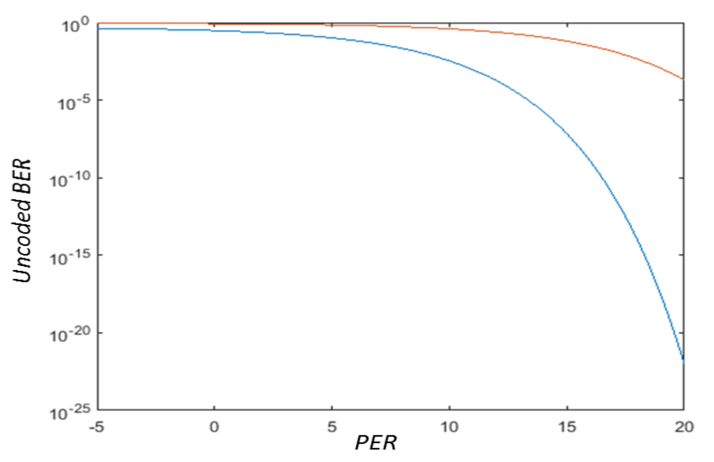
interfaces

CubeSat PolSK Testbed

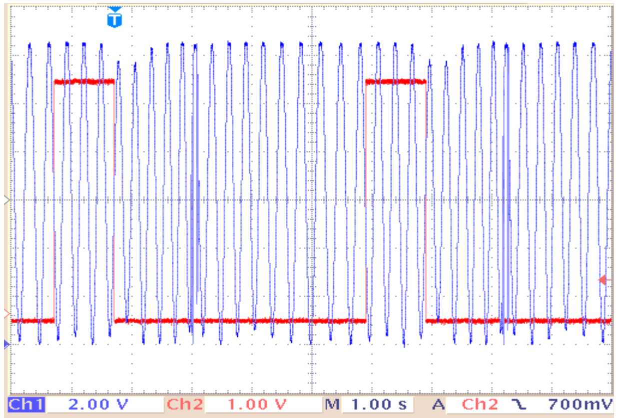


Initial PolSK Results

- **Measured performance > 8dB worse than theory due to poor polarization extinction ratio (PER) after the polarization modulator**
  - Obtained only 6 dB PER after modulator with mode locked laser pulses, versus measured 16.5 dB PER before modulator
  - Measured 24 dB PER at modulator output with CW laser input
- **Established that low PER is the result of group velocity dispersion (GVD) in the polarization modulator**
  - The polarization modulator was implemented in a waveguide $LiNbO_3$ technology with 5V Vπ switching voltage
  - Confirmed issue by scanning a narrowband laser signal below/above 1560 nm and observing the amplitude of a single polarization



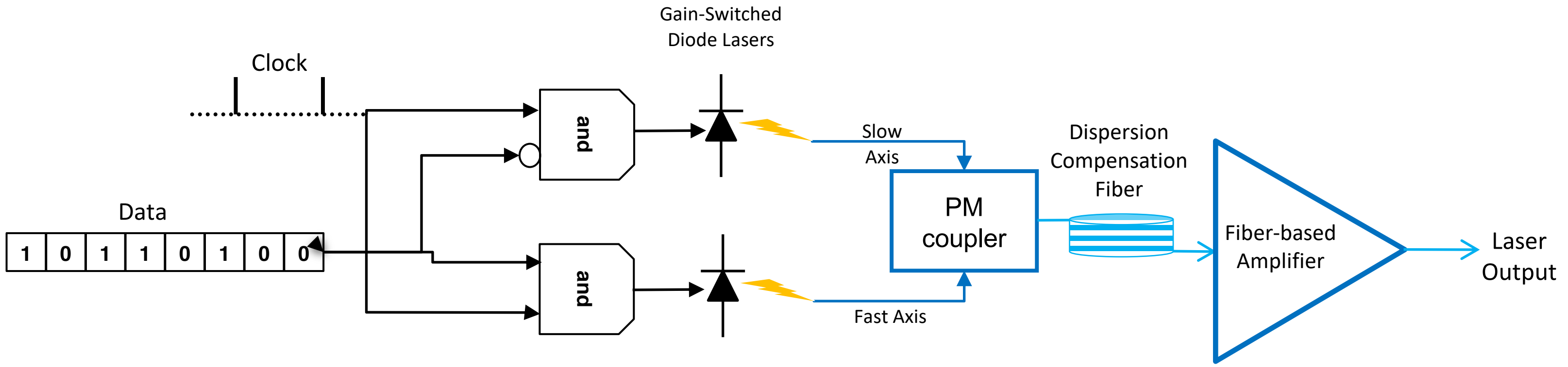
Modeled BER for ideal versus measured PER. Performance is degraded by >8 dB at 10^{-3} BER



Measured polarization modulation by scanning narrowband CW laser. Full polarization switch occurs with a frequency shift of 0.3 nm. Measured FWHM of mode-locked laser was 0.24 nm.

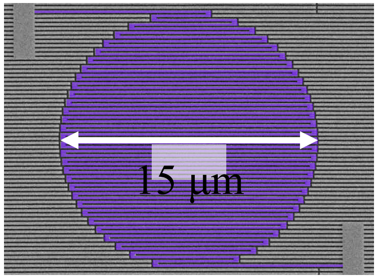
Simplified PolSK Transmitter

- **Developed simplified laser transmitter with improved pulse rate flexibility by using "gain-switched" laser diodes (GS-LD)**
  - PolSK can be achieved by alignment of polarization axis of one laser to the "slow" axis of an output polarization maintaining fiber, and the other to the "fast" axis
  - Simple non-linear transmission line circuit converts logic-level input pulses to sub-nanosecond, ~100 mA drive pulses with 10's of mW average power dissipation
  - Provides some redundancy in the event of a diode failure
- **Unlike a fixed rate mode-locked laser, can change pulse repetition frequency to accommodate different loss/background conditions**
  - Rate is set by external electronics
  - Can also implement Pulse-Position Modulation (PPM) with demonstrated pulse rates from < 10 KHz to > 500 MHz

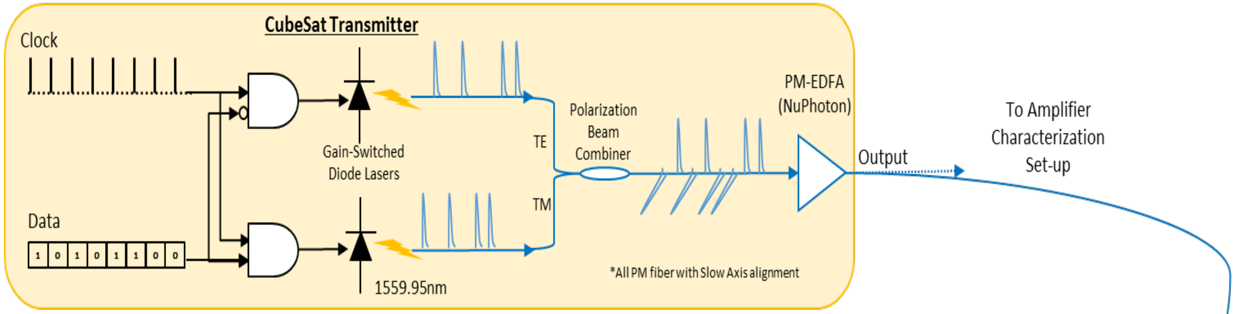


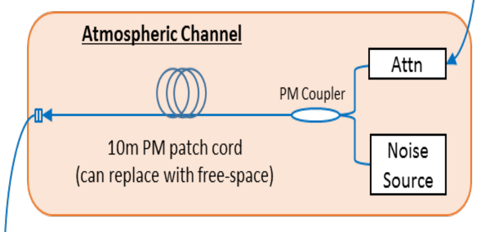
Improved PolSK Testbed

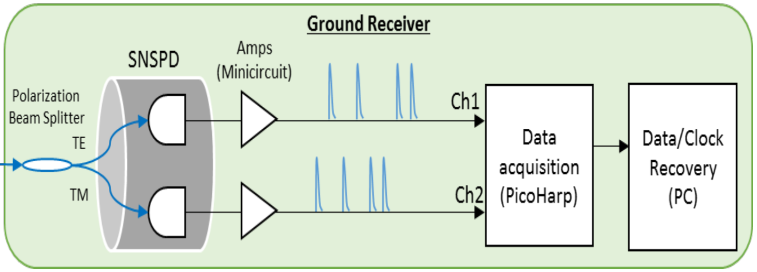
- **New testbed is distributed over lab, but allows more accurate emulation of expected link conditions and support use of state-of-the-art WSi superconducting single photon detectors**

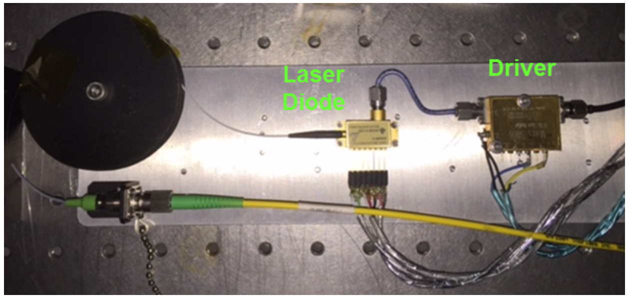


Superconducting Nanowire Single Photon Detector (SNSPD). ~4 nm by ~100 nm superconducting wire biased just below the critical current. Absorbed photon creates a hot-spot: drop in current is read out as a voltage across a load resistor. Rise time is sub-ns, fall time is a few ns due to kinetic inductance. A meander placed in an optical cavity increases the detector area and probability of photon absorption. Arrays to 64 pixels and 320 µm diameter have been fabricated to date.





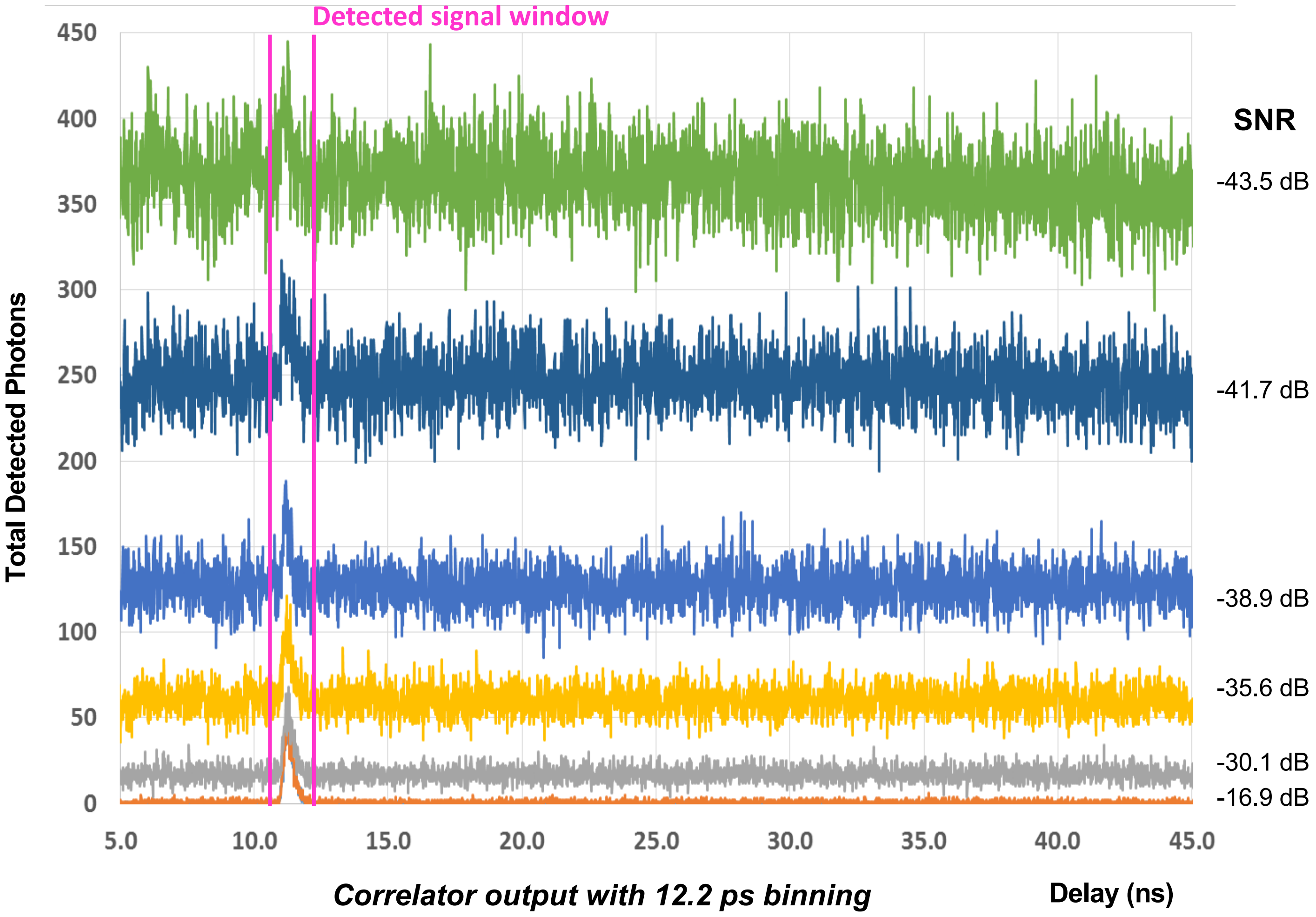




Gain switched laser diode. Version shown uses a electro-optic modulator driver to test wide range of pulse widths and repetition rates. <100 ps output pulse with Full Width Half Maximum spectral width of 0.1 nm at 35 dB extinction ratio.

Negative SNR Photon Counting Acquisition

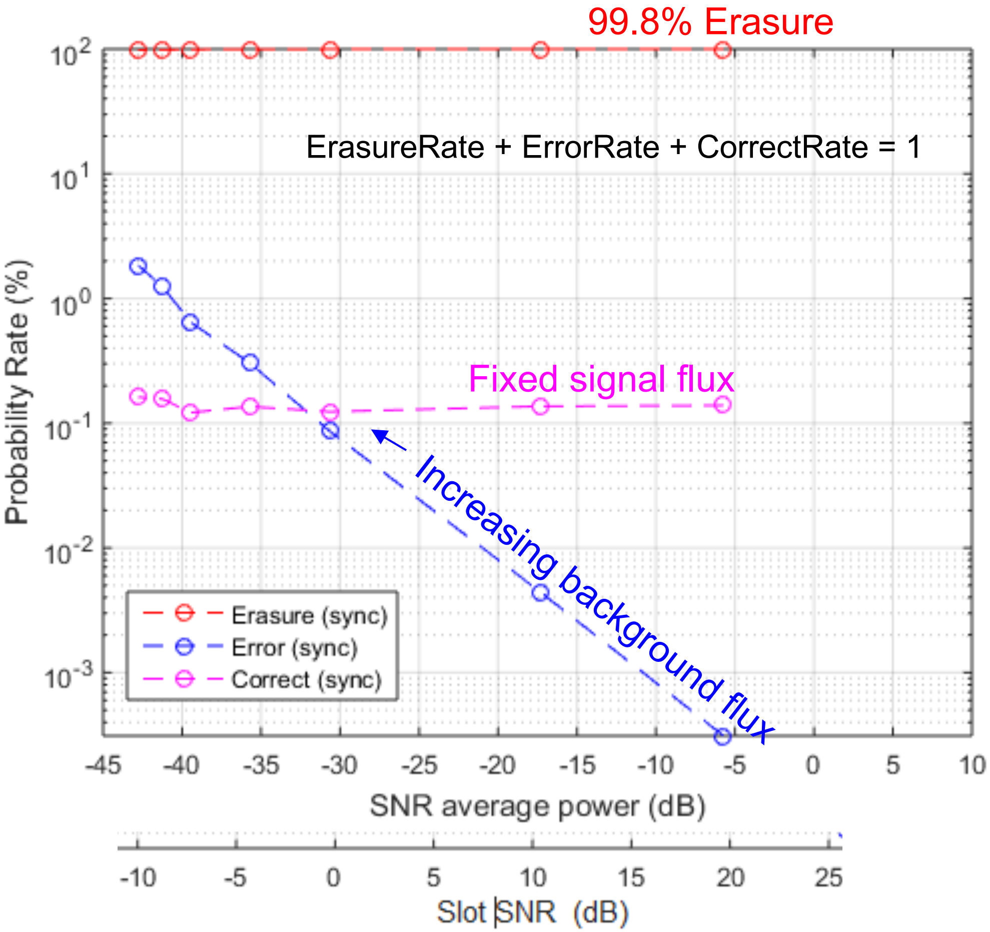
- **Demonstrated signal acquisition at -43.5 dB average signal power to average noise power ratio at 1550 nm using GS-LD at 1 MHz symbol rate and single pixel WSi SNSPD**
  - Signal acquisition window was 600 ps for a symbol period of 1000 ns
    - *32 dB background counts rejection*
  - Measured clock stability sufficient for100 ms integration
  - Mean signal in acquisition window at 100 ms integration exceeds noise variance by 3.2 standard deviations.



Correlator output with 12.2 ps binning

Estimated Error and Erasure Rates

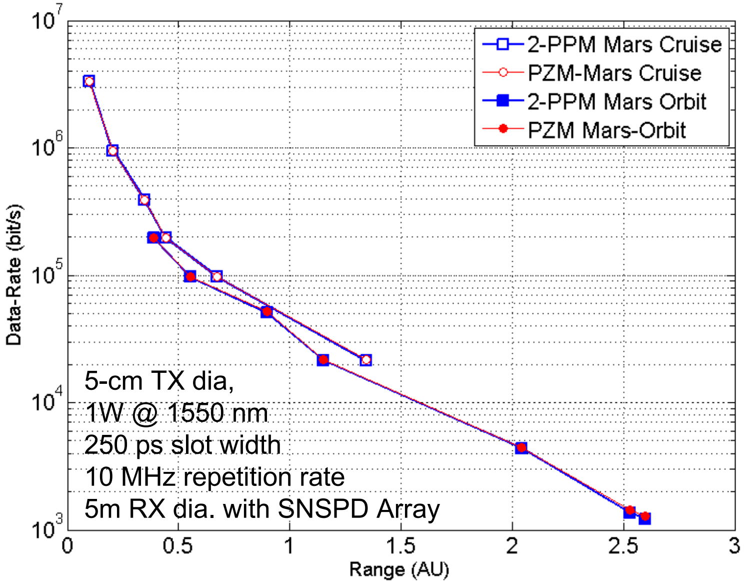
- **Case for previous slide with fixed signal and increasing background**
  - Error rate is a bound estimated from a single detector for a PolSK system



High error and erasure rates will require combination of low-rate (<1/10) forward error correction codes along with spreading sequences

Summary

- **Polarization modulation of a high peak-to-average power laser transmitter combined with photon counting direct detection can support deep space cubesat optical telecom links**
  - Pointing remains a dominant challenge
- **Acquisition in highly negative average signal power to average noise power regimes has been demonstrated**



5-cm TX dia,
1W @ 1550 nm
250 ps slot width
10 MHz repetition rate
5m RX dia. with SNSPD Array

- **Demonstration of low-rate forward error correction codes and spreading sequences for this channel is the next step**
  - Protograph-based Raptor-like (PBRL) codes or punctured-node protograph-based Raptor-like (PN-PBRL) codes?
  - Simple repeats or pseudo-noise spreading codes?

The work described here was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA)