Binary polarization-shift-keyed modulation for interplanetary CubeSat optical communications

Michael Peng, William Farr, Michael Borden,
Abhijit Biswas, Joseph Kovalik

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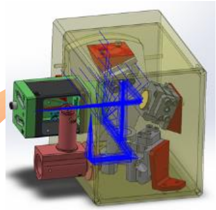
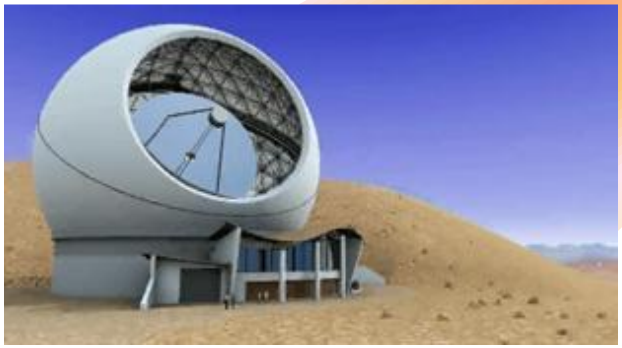
Jet Propulsion Laboratory
California Institute of Technology

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)		$1/R^2$ Loss (rel. to LEO)	Round-trip Light Time
LEO (1000 km)	6.7×10^{-6} AU	1	3.3 msec
GEO	.00024 AU	7.8×10^{-4}	0.24 secs
Moon	.0028 AU	5.7×10^{-6}	2.79 secs
Earth-Sun L2	.01 AU	4.5×10^{-7}	10 secs
Deep Space	1 AU	4.5×10^{-11}	16.6 mins



Telecom under mass & power constraints

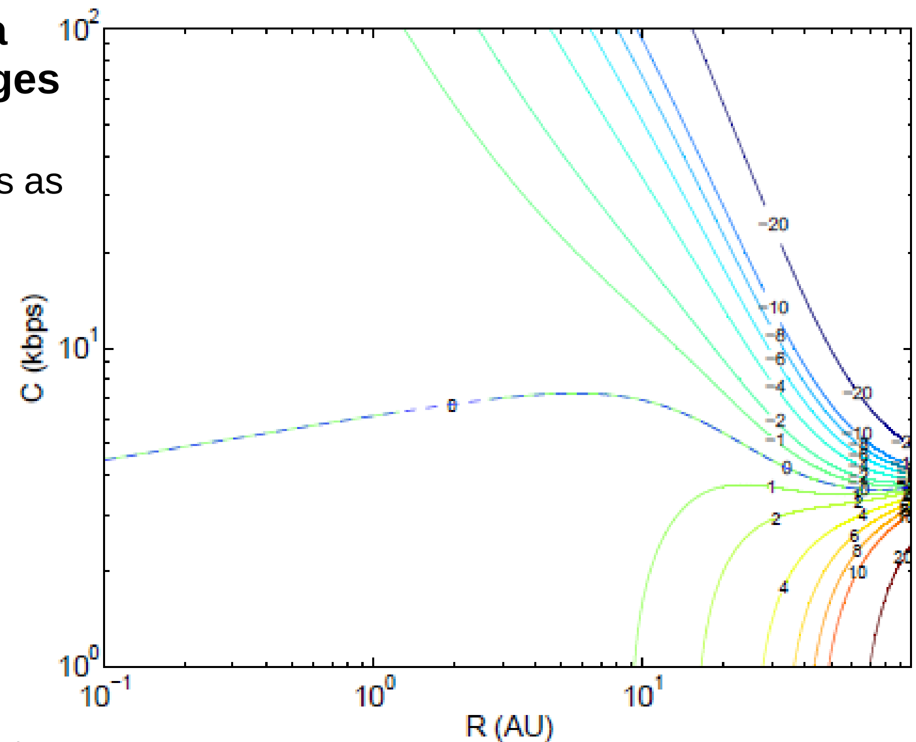
Although optical outperforms RF at high data rates, RF can outperform optical at large ranges and under high background conditions

- Capacity for photon-counting direct detection goes as
  - $1/R^2$ for $P_r > 2\, P_b \ln M/M$
  - $1/R^4$ for $P_r < 2\, P_b \ln M/M$
    - *M: peak-to-average power ratio of a symbol*
    - *P_r: received signal power*
    - *P_b: background noise power*

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

$$C_{opt} = \left((P_r + P_b/M)\log_2(1 + MP_r/P_b) - (P_r + P_b)\log_2(1 + P_r/P_b)\right)/E_\lambda \text{ bps}$$

- 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*



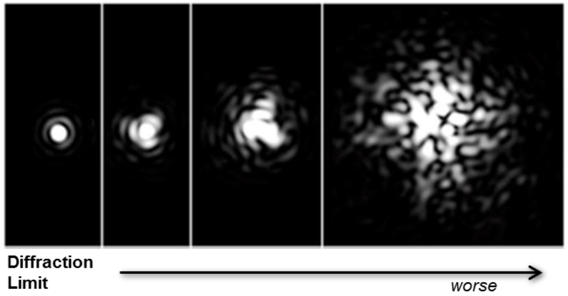
Example mass difference contours, ($m_{(o)} - m_{(r)}$) (kg), to achieve specified (R,C). Positive (negative) contours denote the kg gain of an RF (optical) terminal.

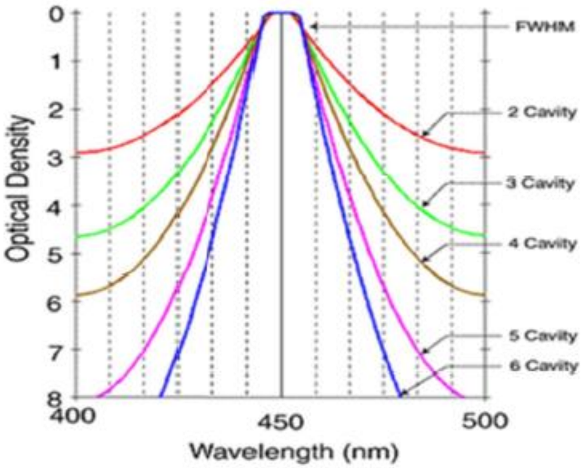
Capacity

- 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 <u>*bits per second*</u> and <u>*bits per channel use*</u>

Optical Noise Rejection Challenge

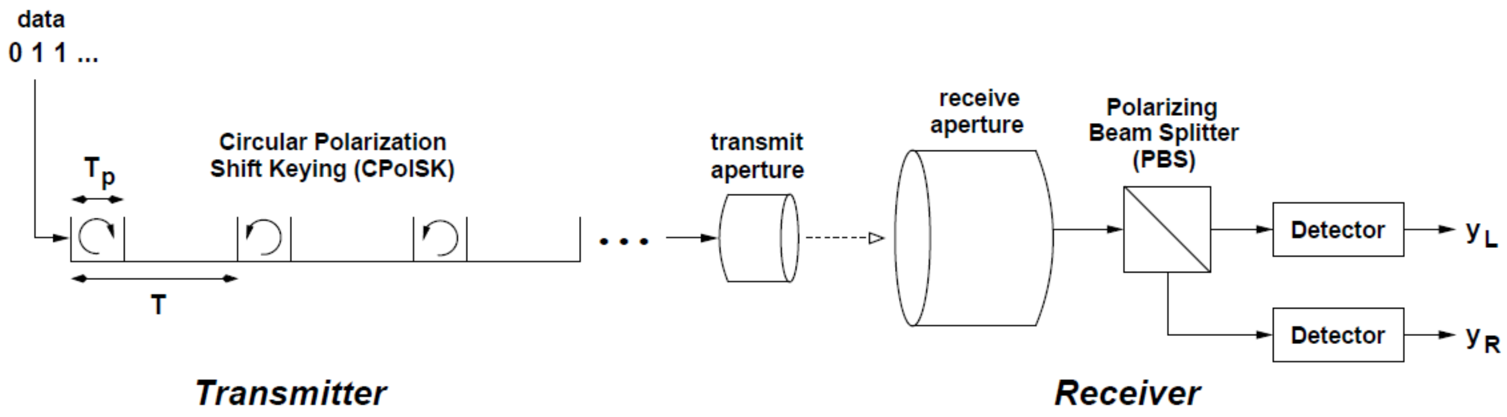
- **When noise power dominates, capacity *C* scales as P_r^2/P_b**
  - *In this regime, data rate scales as $1/R^4$, and optical communications advantage from a narrower transmit beam are quickly lost*
- **Background light in the optical receiver is traditionally rejected by either limiting the field-of-view 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 sever implementation challenges with respect to not only transmission loss, but also Doppler and/or effective field of view.





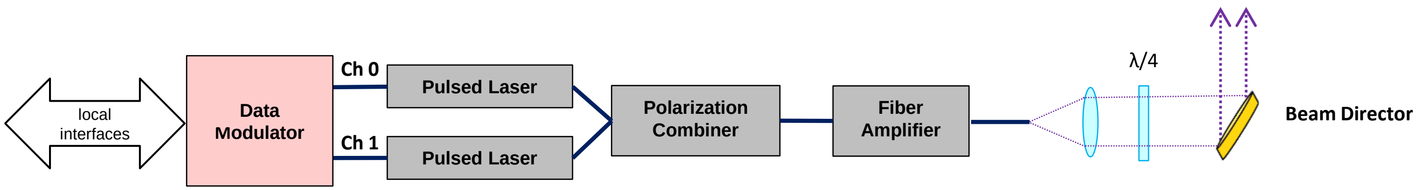
Noise Rejection in the Time Domain

- **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

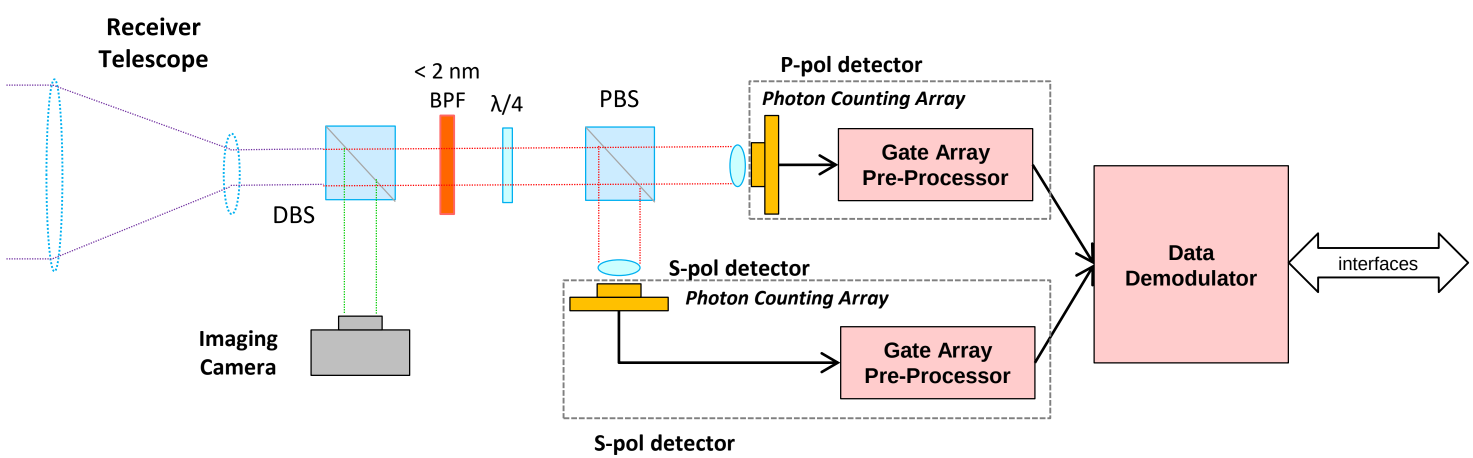


Binary Polarization-Shift-Keying Terminals

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

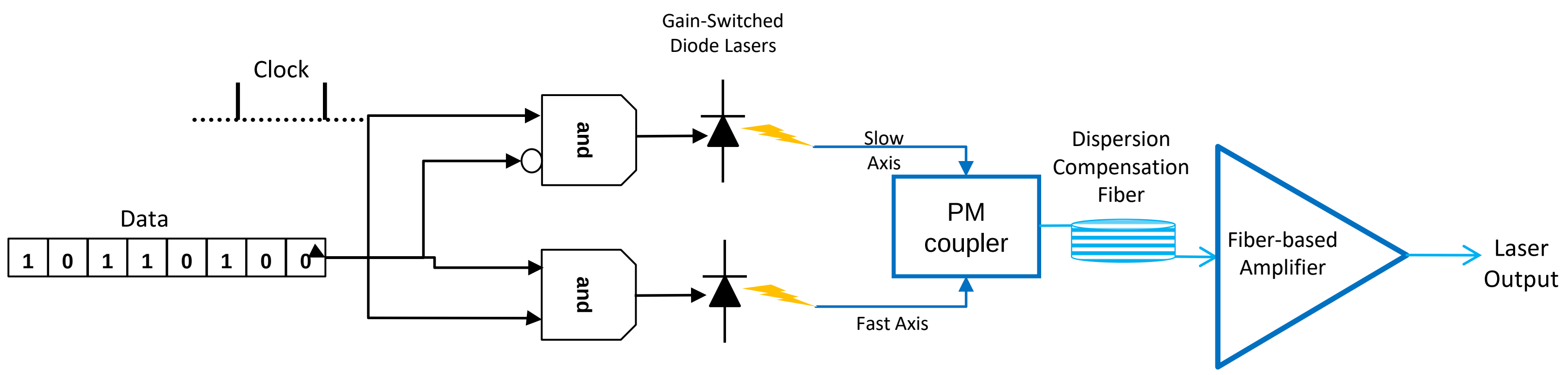


- **Background rejection performance of the Photon Counting Detector (PCD) BPolSK receiver is set by optical filter bandwidth and timing resolution of photon arrivals**
  - New generation near-infrared PCD arrays with readout can operate with <200 ps timing uncertainty, > 50% efficiency, and near-zero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

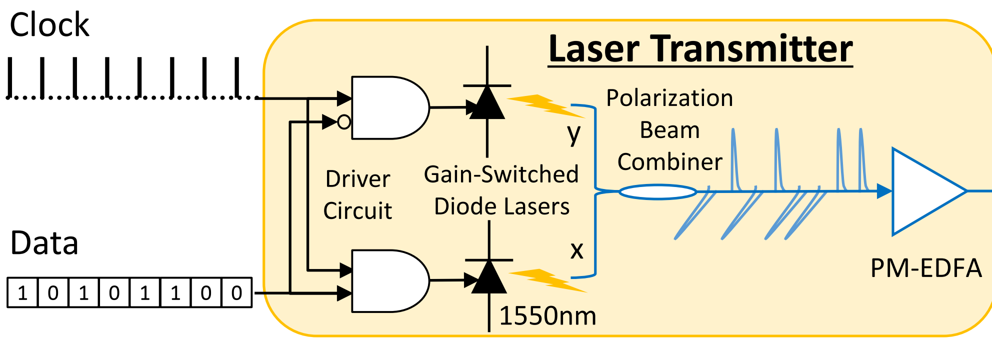


Simplified PolSK Transmitter

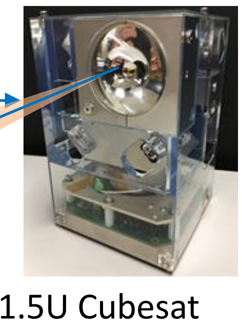
- **Developed simplified laser transmitter with improved pulse rate flexibility by using "gain-switched" laser diodes (GS-LD)**
  - PolSK can be achieved by alignment of polarization axis of one laser to the "slow" axis of an output polarization maintaining fiber, and the other to the "fast" axis
  - 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



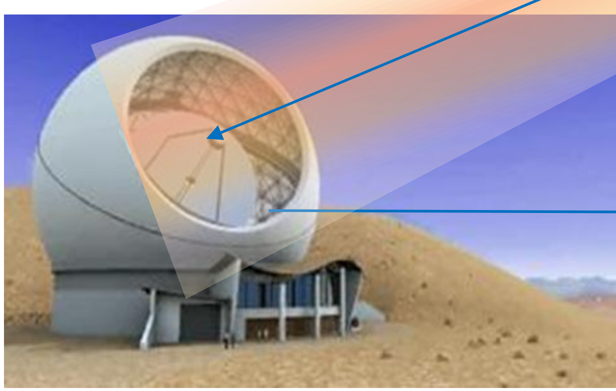
Direct-to-Earth Link Architecture

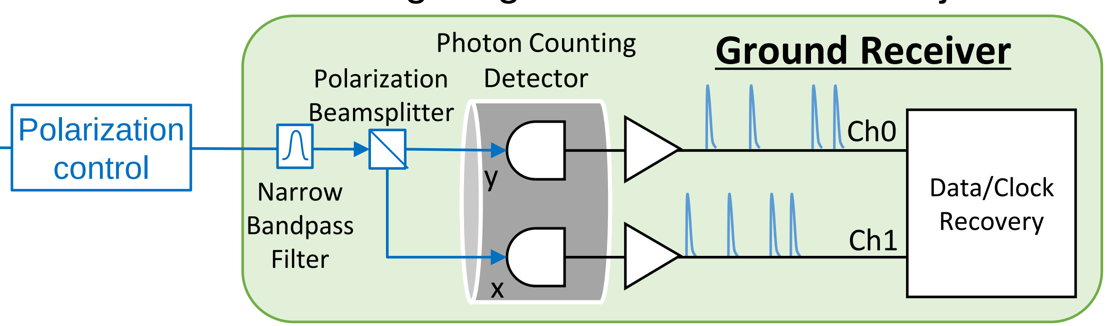


- Direct modulation via gain-switching
- Compact, all-fiber implementation



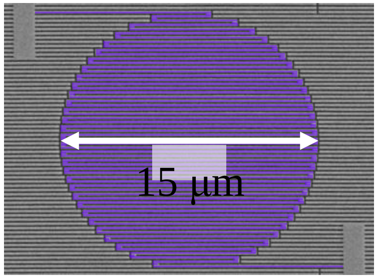
- Simple FFT clock recovery algorithm
- Time-gating for additional noise rejection



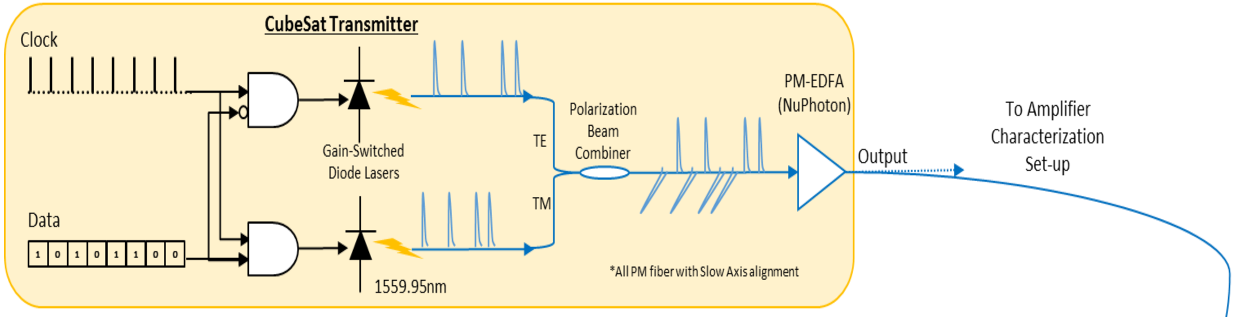


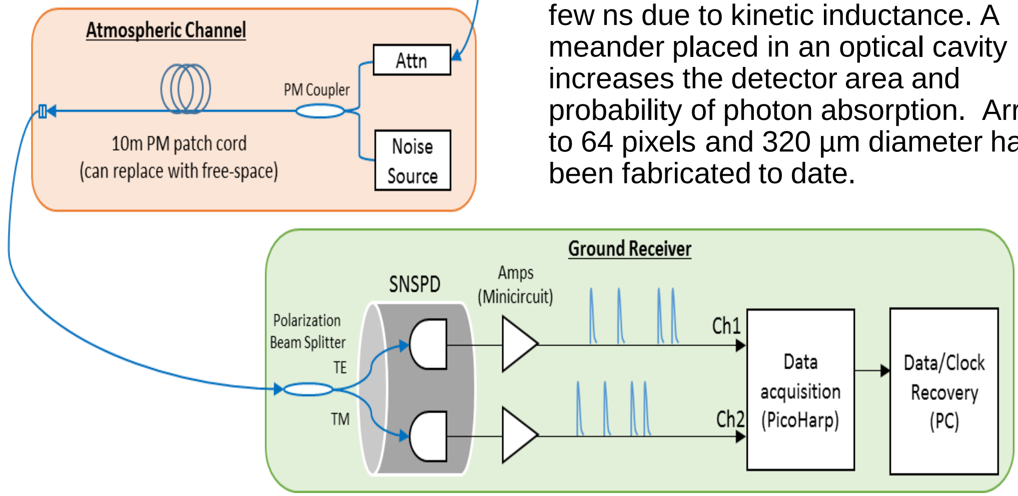
End-to-End Link Testbed

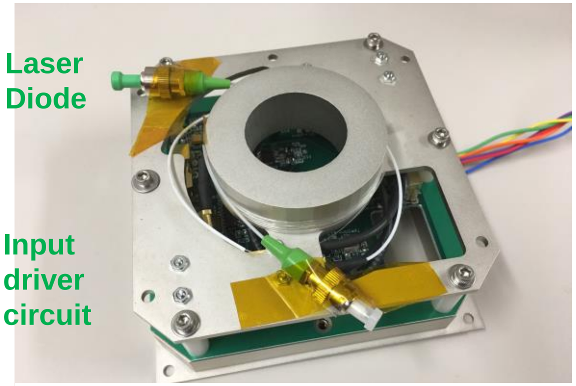
- **Developed end-to-end link testbed to emulate expected link conditions at extremely low SNR**



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.

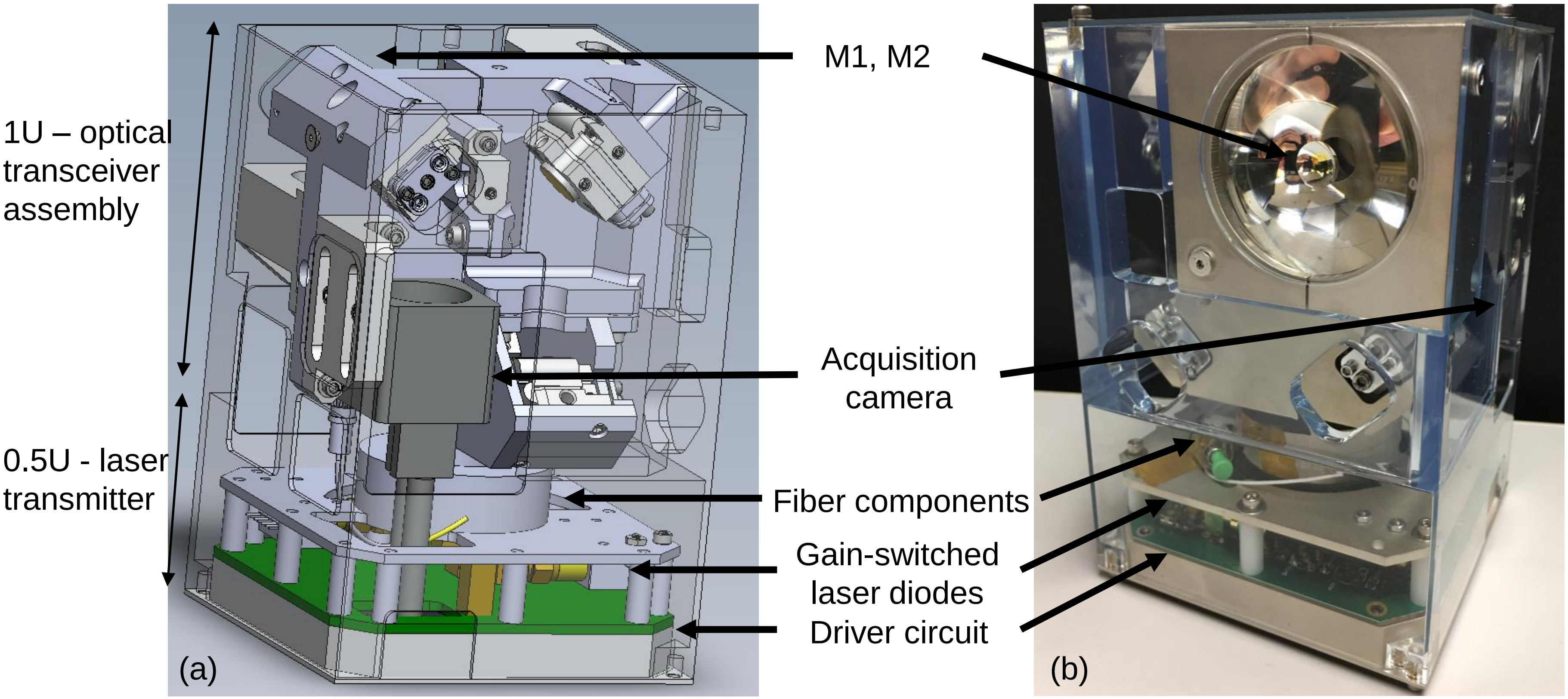






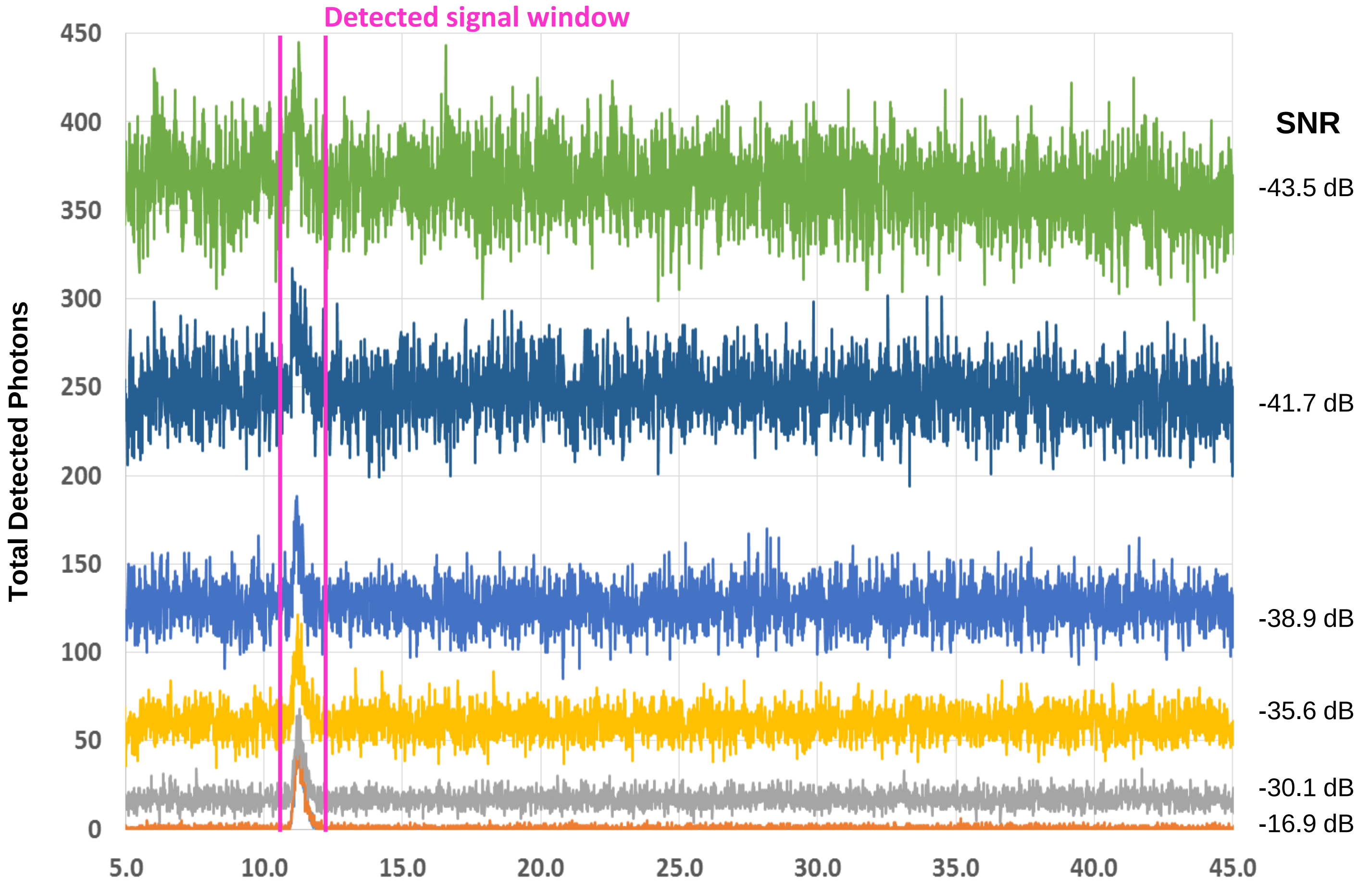
Gain switched laser diode.
<100 ps output pulse
0.1 nm FWHM spectral width
35 dB extinction ratio.

1.5U CubeSat Prototype



Negative SNR Photon Counting Acquisition

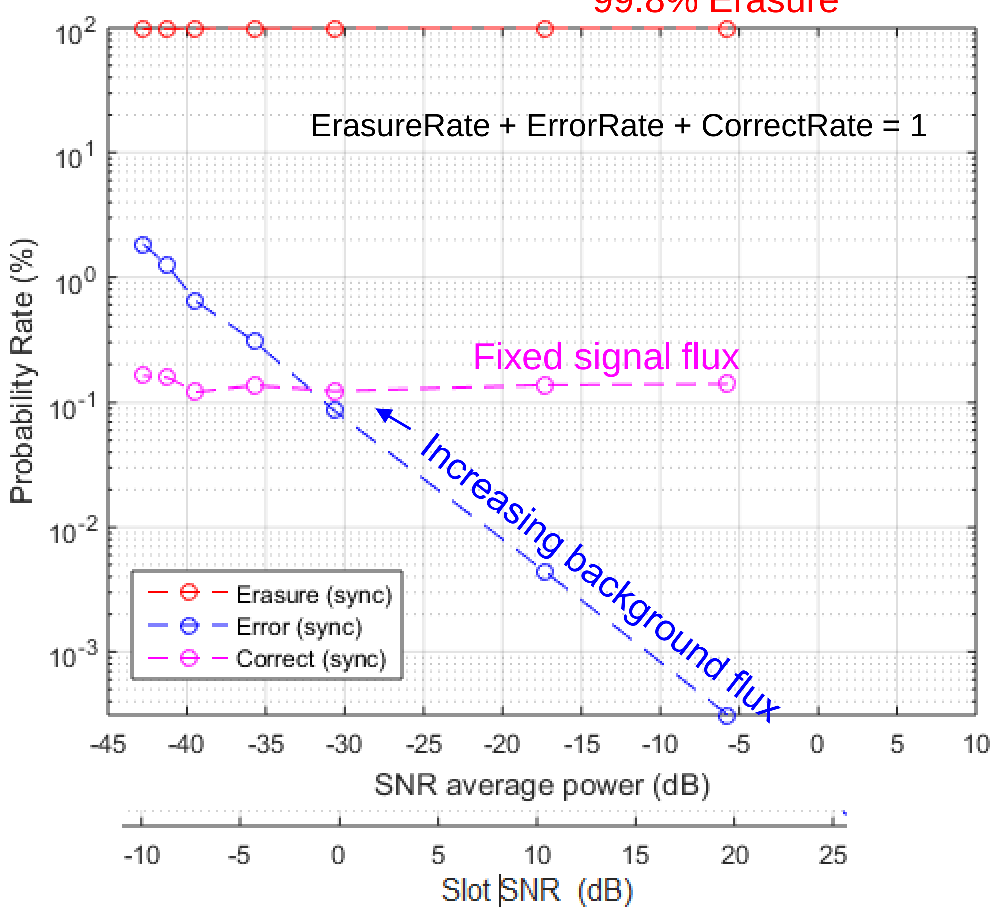
- **Demonstrated signal acquisition at -43.5 dB average signal power to average noise power ratio at 1550 nm using GS-LD at 1 MHz symbol rate and single pixel WSi SNSPD**
  - Signal acquisition window was 600 ps for a symbol period of 1000 ns
    - *32 dB background counts rejection*
  - Measured clock 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

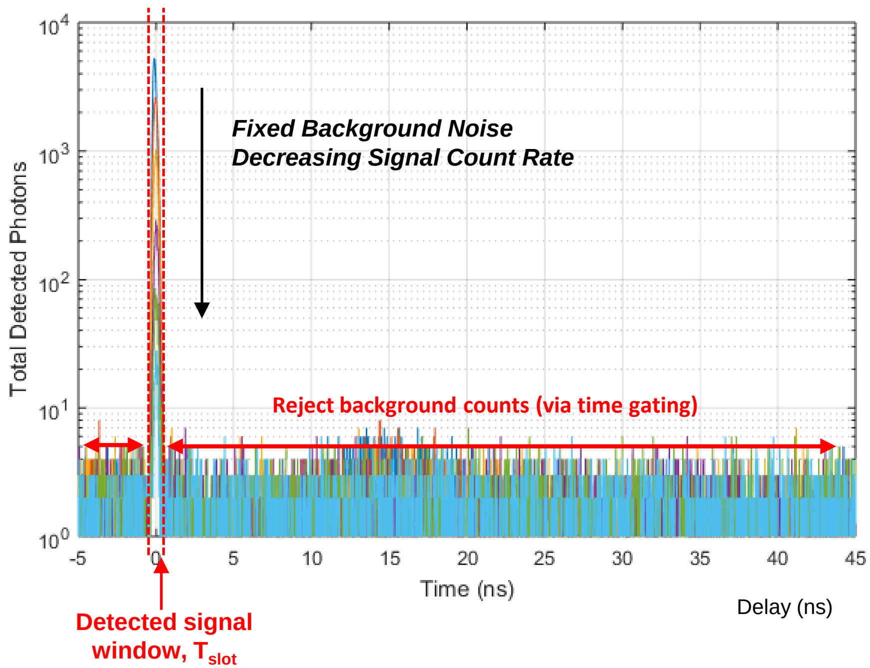


High error and erasure rates will require combination of low-rate (<1/10) forward error correction codes along with spreading sequences

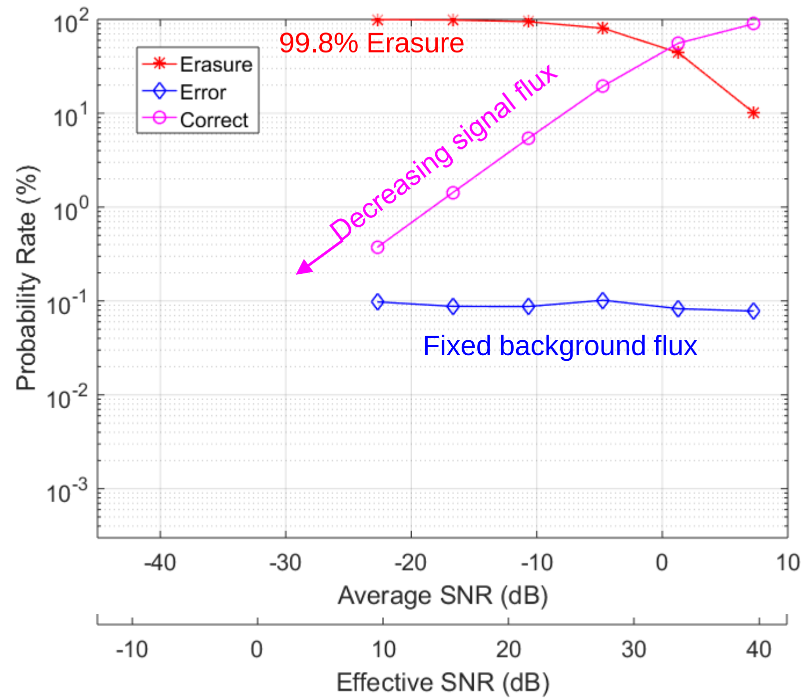
Clock Recovery

- **Demonstrated clock recovery at -23 dB SNR at 1550 nm using GS-LD at 1 MHz symbol rate and a pair of WSi SNSPDs**
  - Clock recovery limited by relative clock drift between transmitter and receiver

(a) Pulse Arrival Time Histogram



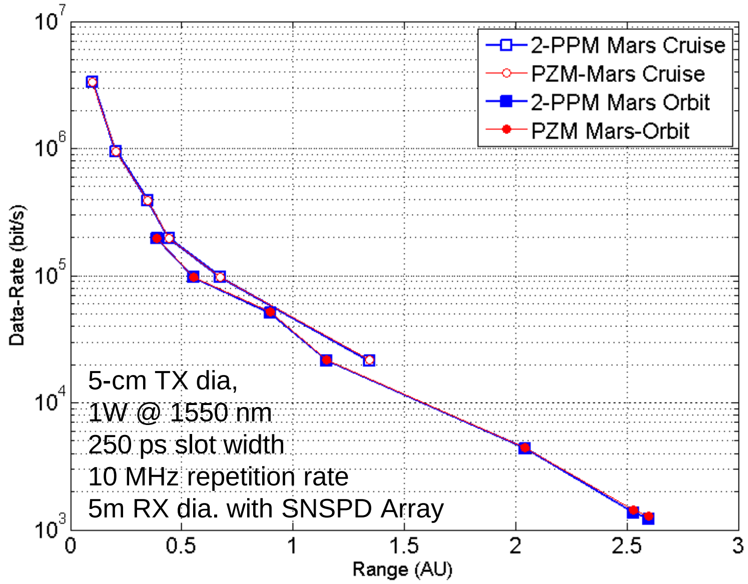
(b) Uncoded modulation performance



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**



- **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)