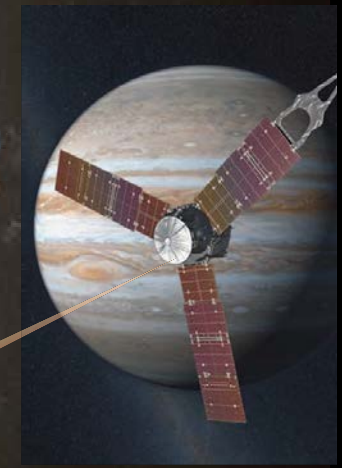
Jet Propulsion Laboratory
California Institute of Technology

13 Bits per Incident Photon Optical Communications Demonstration



YOU ARE HERE

William Farr, John Choi, Bruce Moision

Jet Propulsion Laboratory
California Institute of Technology

SPIE Photonics West
February 2013

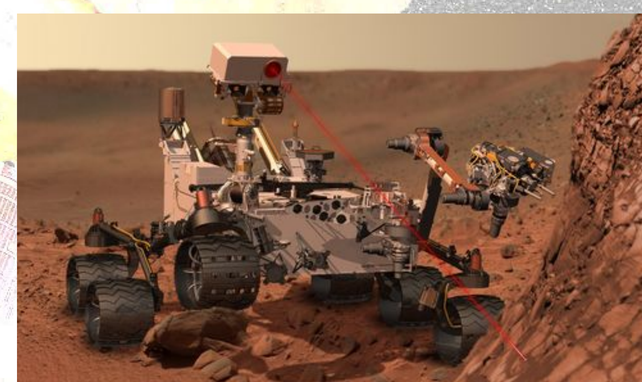
Photon Starved Optical Communications

- ***Objective*: Optical communications technology to vastly improve (10 to 100X) the data return volumes for NASA missions**
  - Benefits include increased science data return, human mission support, virtual presence across the solar system and enhanced public engagement
- ***To be competitive with existing RF deep space systems, operate in a photon starved regime***
  - **How many bits can you fit on a photon?**

10X Increased Imaging Resolution for Astrophysics

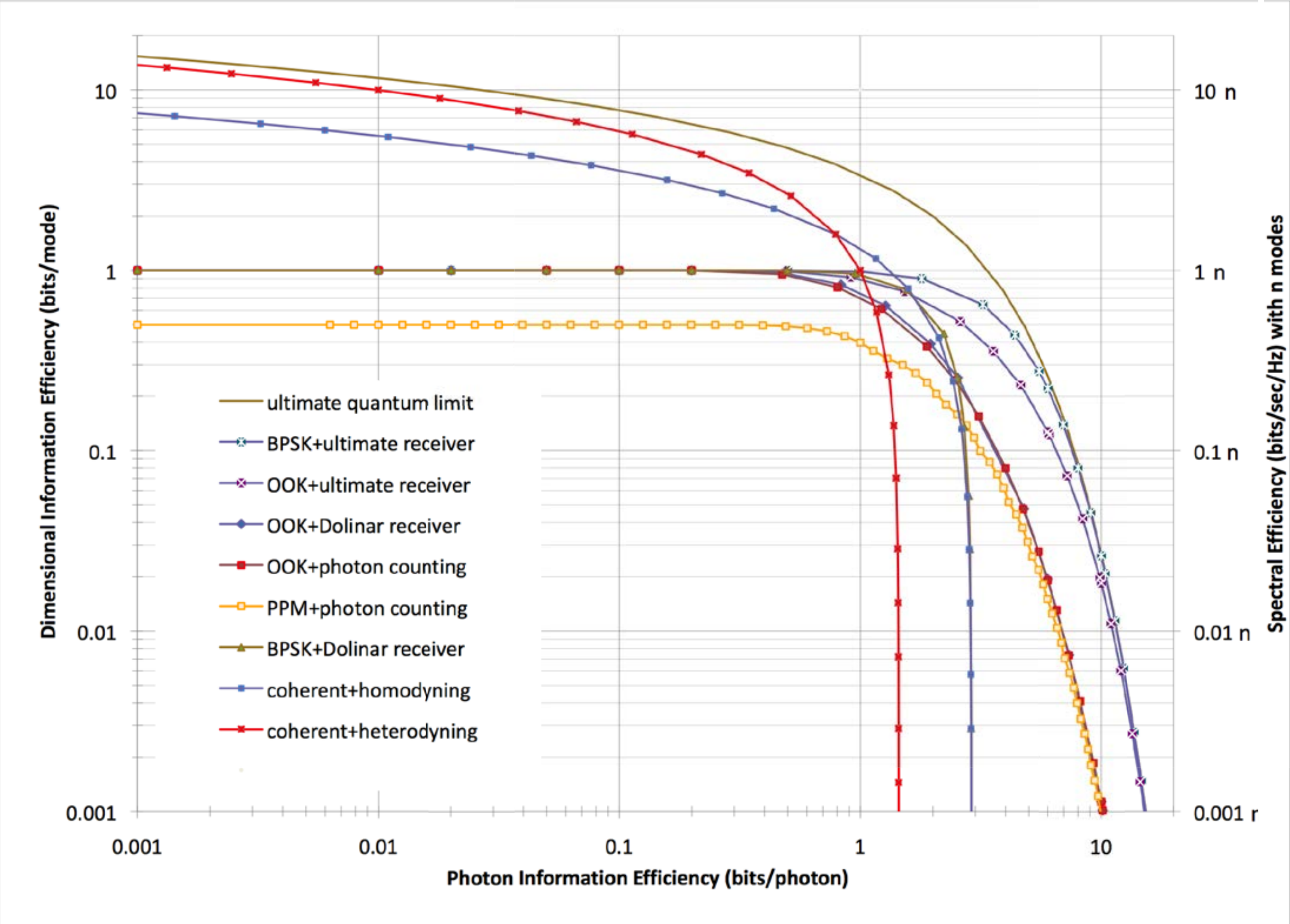
Human Exploration Beyond Low-Earth Orbit

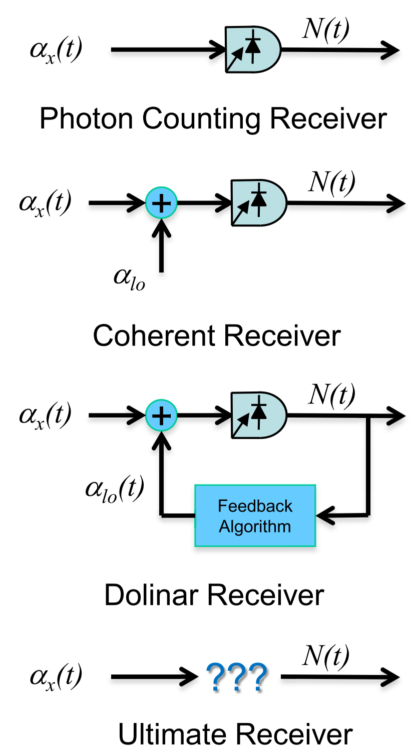
Future Advanced Instruments



Tele-Presence with Live HiDef Video

Single-mode Free-space Capacity Limits





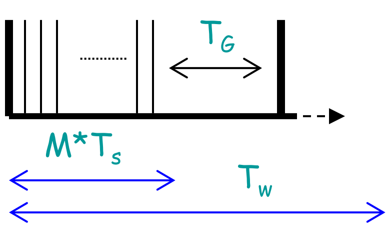
- Efficiencies in terms of the average number of photons per dimension E at the Holevo limit :

$$c_d = (E+1)\log_2(E+1) - E\log_2 E \qquad c_p = c_d/E$$

Pulse Position Modulation (PPM)

- **Pulse Position Modulation (PPM, a form of generalized OOK) of a laser transmitter in combination a photon counting receiver is a near-optimal configuration for high PIE**
  - "Poisson channel" model applies
  - Trades low dimensional for high photon efficiency
  - Uses high peak-to-average power lasers
  - ✓ **Photon Counting – Direct Detection (PC-DD) is easy to implement**
  - ✓ **Forward Error Correction codes are known that approach within 1 dB of capacity**
- **In PPM, a single laser pulse in one of M symbol slots encodes $\log_2 M$ information bits**
  - Additional non-signal (guard time) slots may be appended to the PPM symbol to allow for slot clock recovery at the receiver and/or pulsed laser reset time

M Alphabet size
T_s Slot Width
T_w Symbol Time
T_G Guard Time



- With no minimum slot width constraint in place, the capacity of the Poisson channel may be bounded as:

$$C \le C_{\text{ook}} = \frac{1}{\ln 2}\big((\lambda_s + \lambda_b/M)\ln(1+\lambda_b/(M\lambda_s)) + ((M-1)/M)\lambda_b \ln(\lambda_b/(M\lambda_s)) - (\lambda_s+\lambda_b)\ln((1+\lambda_b/\lambda_s)/M)\big) \text{ bits/sec}$$

Where
- λ_s = mean signal photons/second
- λ_b = mean noise photons/second

High bits/photon Experimental Challenges

- **High bits/photon is achieved at high PPM order**
- **Need a ultra-low probability of a (false) detection event in any of the (many) empty slots in each symbol**
  - *Need a very high ratio of slot rate to dark rate*

$$c_p \lessapprox \log_2\left(\frac{1}{e^4 l_d T_s}\right) \text{ bits/photon}$$

  - *Need a very high extinction ratio of signal light*

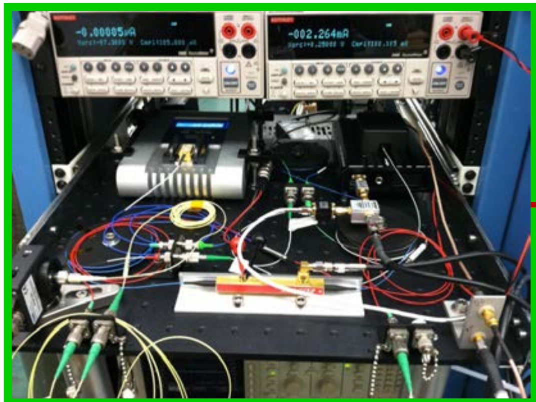
$$c_p \lessapprox \log_2(\alpha) - 1/\ln(2) \text{ bits/photon}$$

- **Need to capture large (up to multi-Tbyte) data volumes at high (up to few GHz) bandwidth to characterize the channel**

c_p = photon information efficiency, PIE (bits/photon)

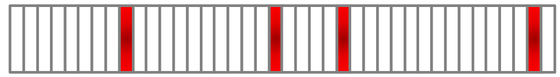
Experimental Demonstration

High Extinction Ratio Laser Transmitter

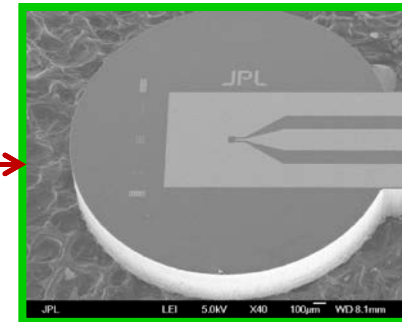


700 MHz BW,
> 70 dB ER

Optical PPM Pulses

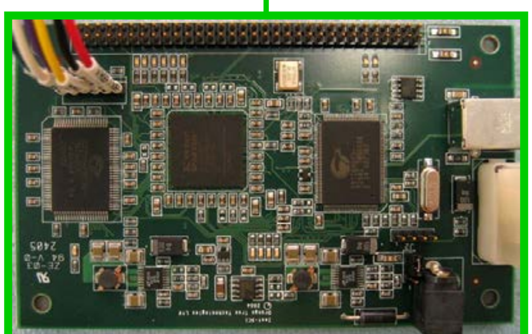


Single Photon Detector



Electrical PPM Pulses

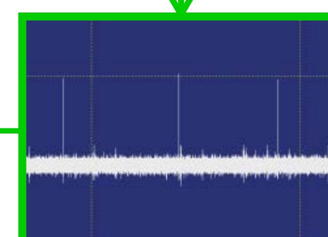
Data Acquisition Subsystem



PPM Test Data Generator

PPM 2^4 to 2^{20}, 2.4 GHz max. slot rate

2-channel, 1.4 Gsa/s, 48 TSa storage

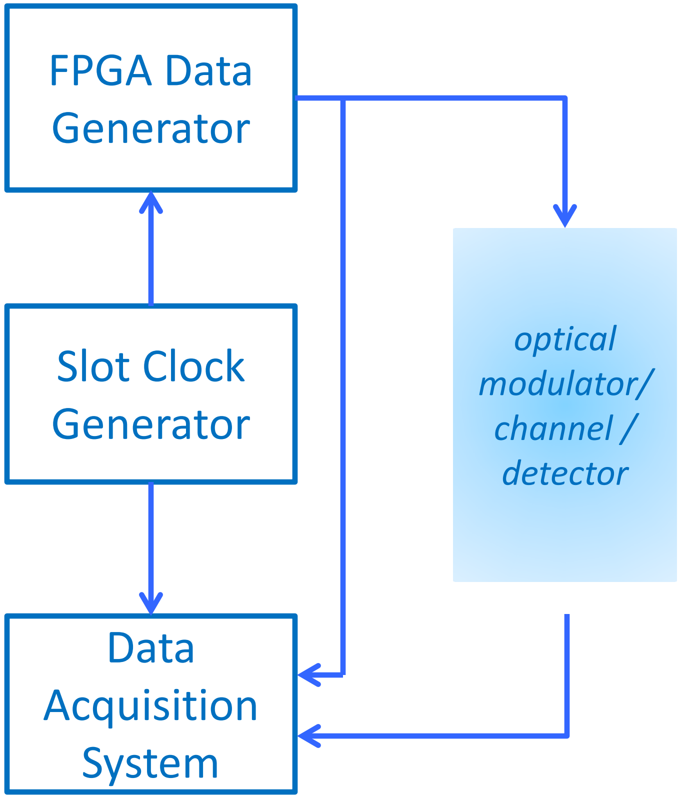


Analog Signal Processing

Test Data Generation

- **Implemented 2^{14} to 2^{20} PPM with Pseudo-Noise (PN) data pattern in FPGA hardware**
- **Verified PPM modulation and Data Acquisition System (DAS) by capture of > 60 min digital data stream at 1 GHz and post-processing verification of PN sequence**
  - DAS sampling is at either 1X or 2X slot clock rate

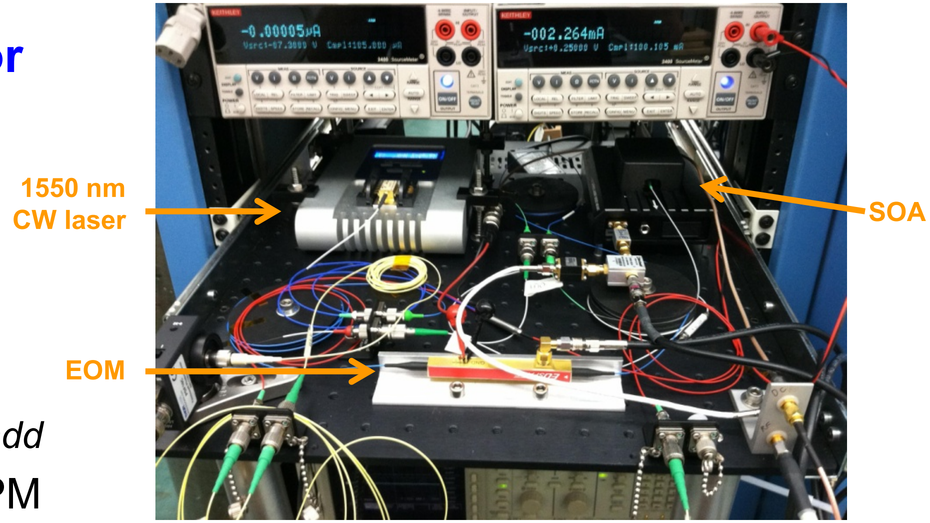
PPM 2^{14} to 2^{20} PN
Slot rate ≤ 2.4 GHz



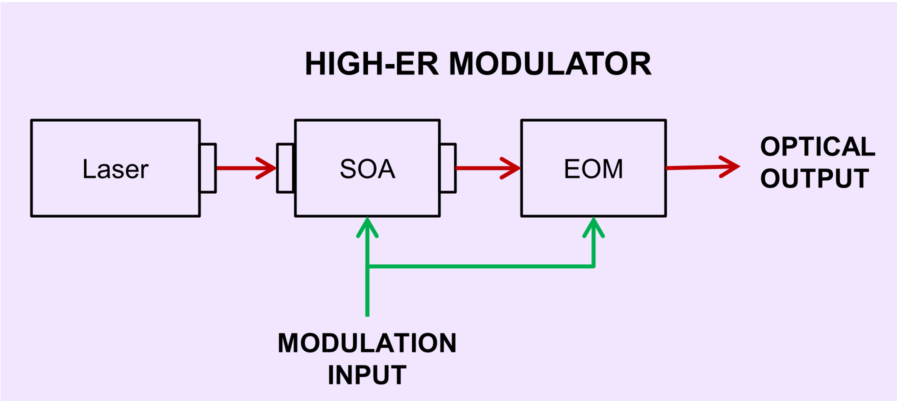
8-bit ADC
Sampling Rate ≤ 3GHz
Data Rate ≤ 1.4 GB/s per channel (1 or 2)
48 TB RAID Array
60 min = 3.3 TB data @ 1GHz

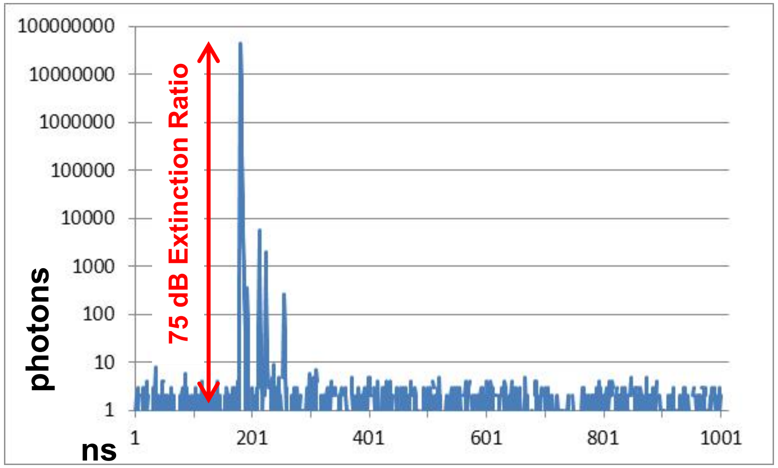
High Extinction Ratio PPM modulator

- **Utilized new topology laser modulator for Pulse Position Modulation (PPM)**
  - Combines a gain-switched semiconductor optical amplifier (SOA) with an electro-optical modulator (EOM) stage.
    - *Demonstrated 75 dB extinction ratio (ER), as compared to 30 dB ER of EOM alone.*
    - *Unlike cascaded EOMs, extinction ratios directly add*
  - New topology enabled practical high-order PPM (2^{14} to 2^{20} slots per PPM symbol) for > 10 bits per photon efficiencies



Laboratory Prototype Modulator





Temporally Resolved Extinction Ratio

Experiment Design for 10^+ bits/photon

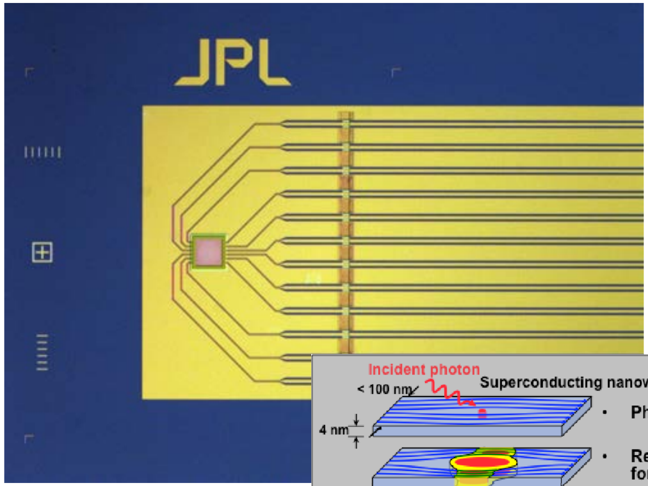
- Designed & selected operating parameters for a single-mode experiment to achieve 10^+ bits per ***detected*** photon in the laboratory, using a single-pixel ***NbN nanowire detector***.
- Two operating points were targeted, at 10 and 12 bits per ***detected*** photon, using PPM orders 2^{13} and 2^{15}, respectively.
- Our new modulator enabled PPM orders up to 2^{20} (theoretically targeting a photon efficiency of ~17 bits/***detected*** photon), and our first experiment was done at this operating point.

Parameter	Design Value	
Extinction Ratio	76 dB	
Slot width	0.4 ns	
Jitter (std dev)	60 ps	
Background rate	<< 2 Hz	
Dark rate	2 Hz	
Detector efficiency	50%	
Code efficiency	0.5 dB	
	10 bits / detected photon	**12 bits / detected photon**
PPM order	$8192 = 2^{13}$	$32768 = 2^{15}$
Code rate	2/7	1/5
Data rate	1 Mbps	0.2 Mbps
Spectral efficiency	.0005 bits/slot	.0001 bits/slot

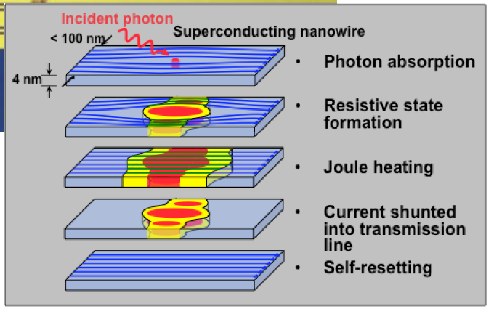
$W_xSi_{(1-x)}$ Superconducting Nanowire Detectors

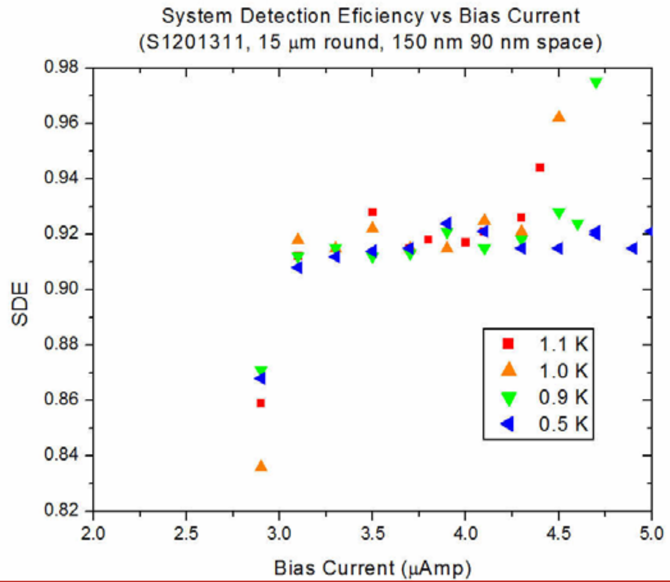
- ✓ **Demonstrated record setting 93% system single photon detection efficiency with 15 μm diameter single pixel detectors coupled to single-mode fiber**
  - Measured detection efficiencies include fiber and detector coupling losses
  - Detection efficiency is independent of bias current over wide range

Collaborative development between JPL and NIST



12 pixel, 66 μm active dia. WSi array



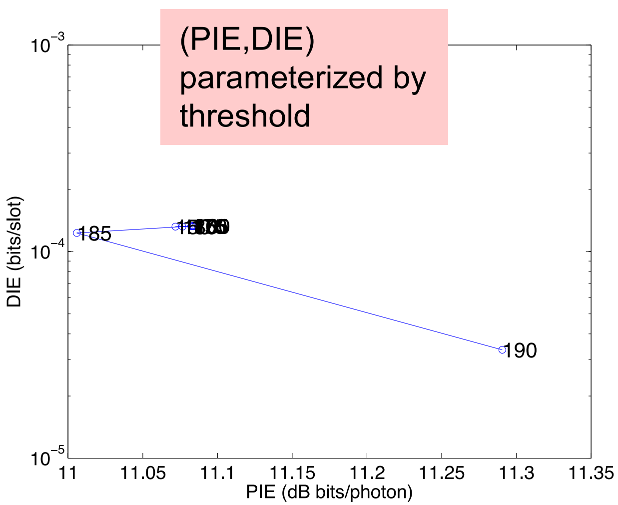


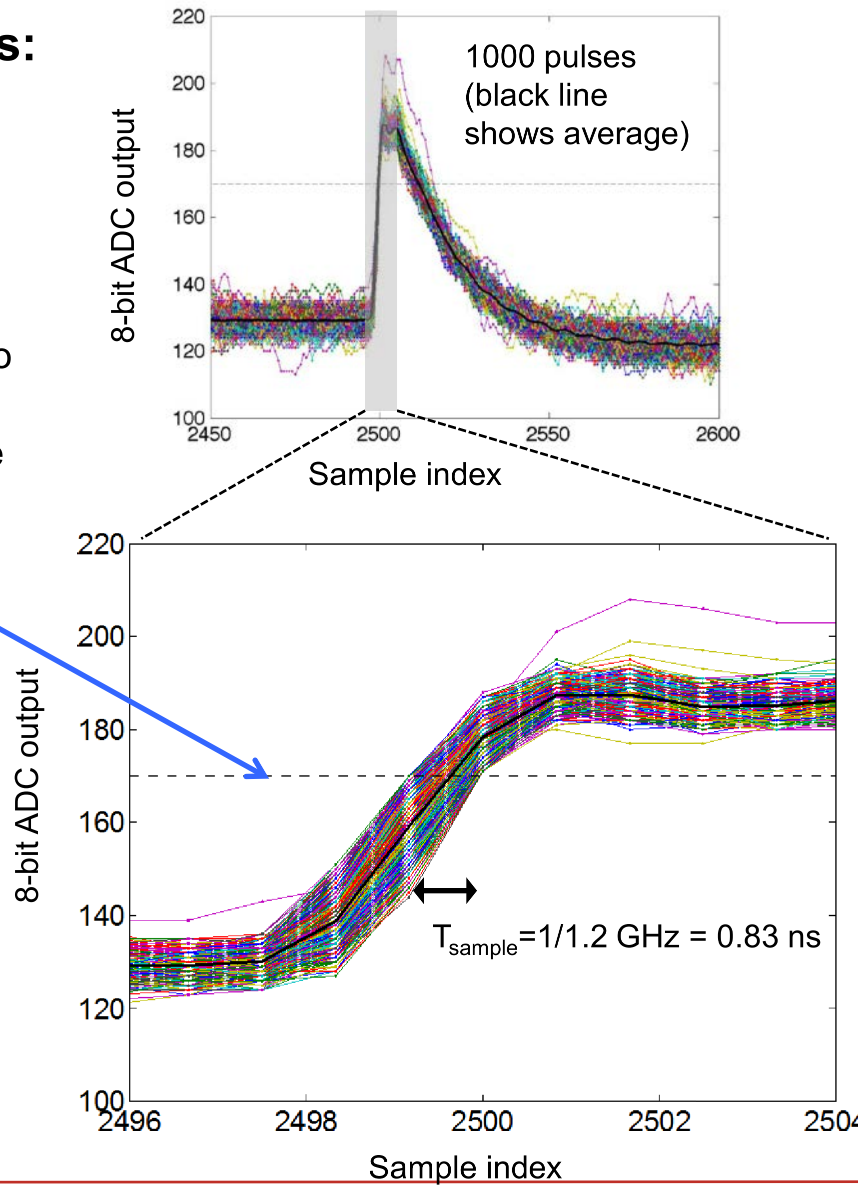
- **Amorphous Tungsten Silicide (WSi) Superconducting Nanowire Single Photon Detectors (SNSPDs) *are a "game changer"* for deep space optical ground receivers**
  - *>90% efficiency and high yield for arrays with > 100X the area of older NbN technology*

Estimating pulse arrival times

Converting ADC output to photon counts:

- $T_{slot} = 2T_{sample} = 1.67$ ns
- 8-bit sampled output was compared to a threshold to declare pulse arrival time.
- Short run-lengths were filtered out to effect edge-detection.
- Threshold (invariant over a wide region) was chosen to optimize (PIE, DIE).
- $T_{slot} = T_{sample}$ may be achieved with matched-filter edge detection.





Parameter Estimation

Parameter	Value	Methodology
Dark Rate	17 Hz	Measured rates with laser unplugged
Noise Rate	18—28 Hz (varies with signal power)	Count rate in non-signal samples (assumes no more than one arrival in sample duration)
Average Signal rates	0.7—5 kHz	Computed from erasure rate (avoids under counting multiple photons)
Extinction Ratio	70—75 dB	(noise rate – dark noise rate)/peak signal rate

$$\hat{l}_d = \frac{\text{total counts in T with laser unplugged}}{T}$$

$$\hat{l}_n = \frac{\text{total counts in non-pulsed slots (laser modulation on)}}{\text{duration of noise slots}}$$

$$P\text{erasure} = \exp\left(-(\hat{l}_s + \hat{l}_n)MT_{slot}\right)$$

$$\hat{\alpha} = \frac{\hat{l}_n - \hat{l}_d}{\hat{l}_s M}$$

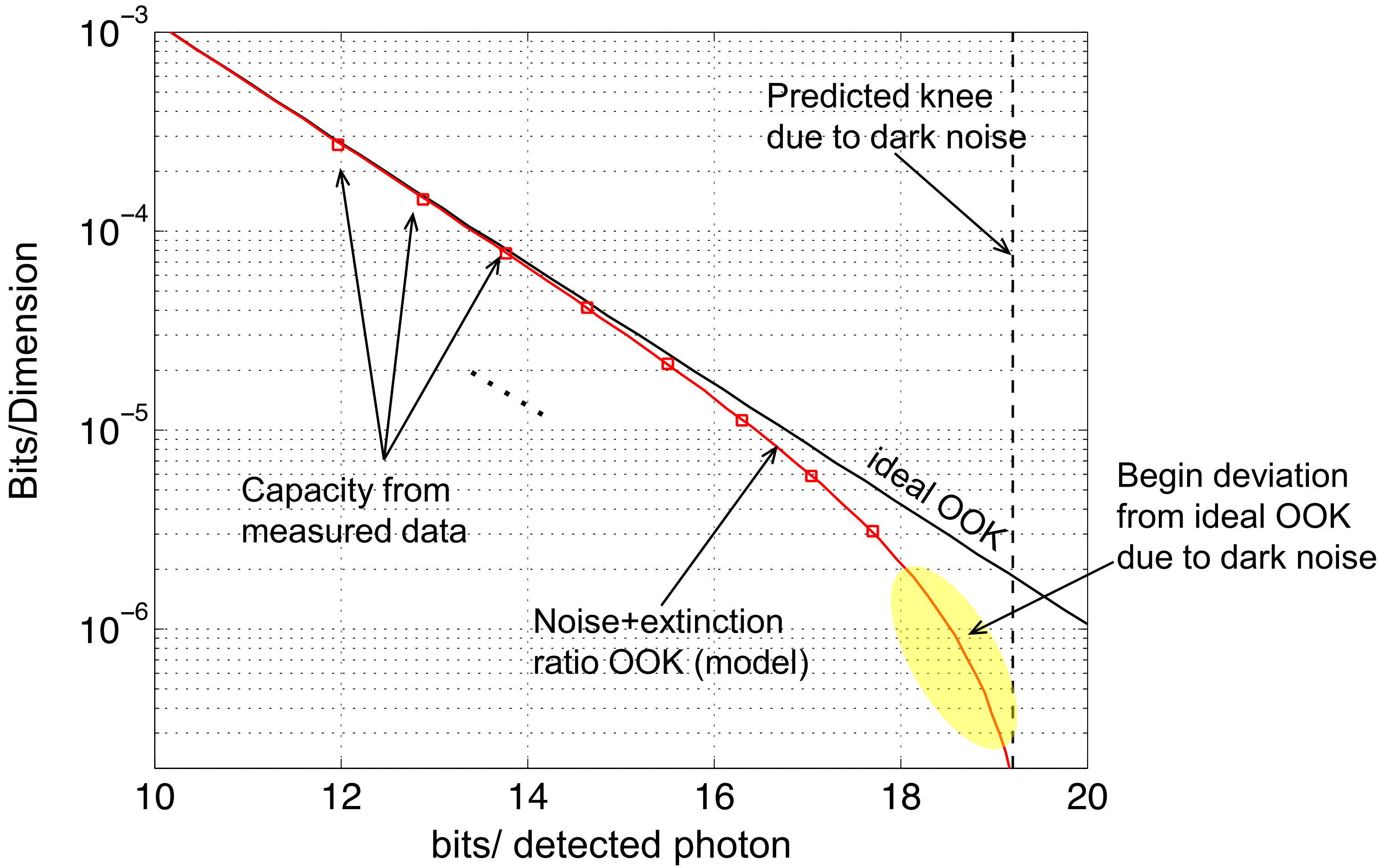
Parameter estimates (dark rate, extinction ratio) were consistent over all observed trials

Experiment Measured Parameters

Parameter	Design Target		Measured Value							
Slot width	0.4 ns		1.67 ns							
Jitter	60 ps		60 ps							
Background	<< 2 Hz		<< 17 Hz							
Dark rate	2 Hz		17 Hz							
Detector Efficiency	0.5		0.86							
Extinction Ratio	76 dB		74 dB	75 dB	77 dB	77 dB	77 dB	74 dB	75 dB	78 dB
PPM order	2^{13} … 2^{16}		2^{13}	2^{14}	2^{15}	2^{16}	2^{17}	2^{18}	2^{19}	2^{20}
PPM symbols collected	---	---	$2^{20.5}$	$2^{19.5}$	$2^{18.5}$	$2^{17.5}$	$2^{16.5}$	$2^{15.5}$	$2^{14.5}$	$2^{13.5}$
PPM symbol erasure rate	---	---	0.8298	0.8314	0.8305	0.8292	0.8298	0.8282	0.8221	0.8100
PPM symbol error rate	---	---	0.0009	0.0011	0.0015	0.0024	0.0046	0.0071	0.0154	0.0275

Noisy Poisson Channel Capacity

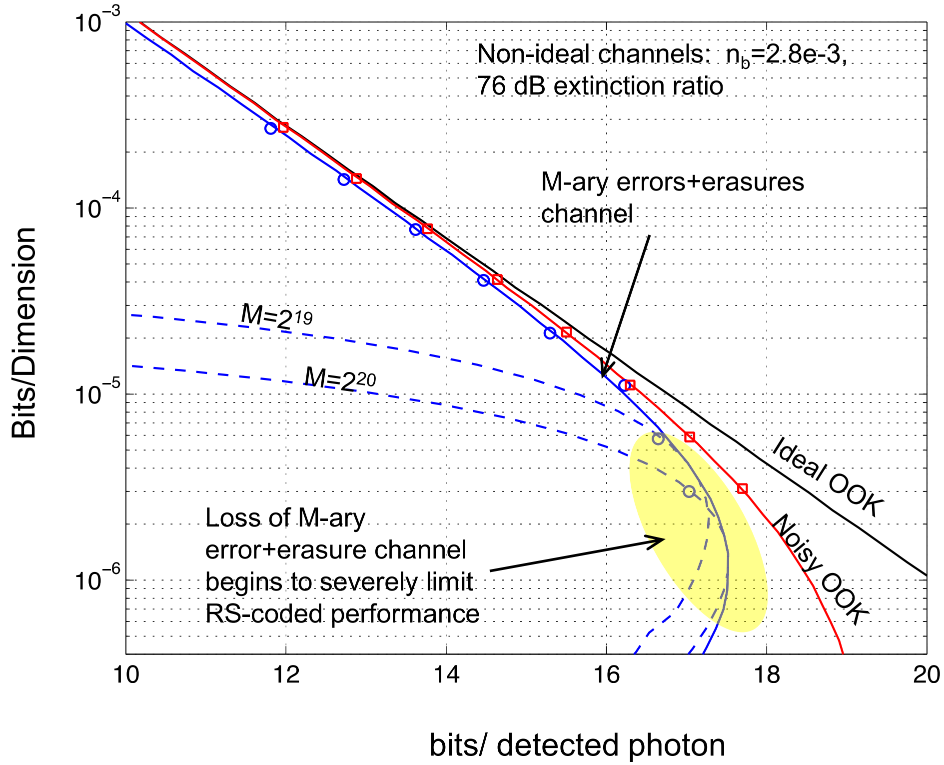
$n_{b,dark}$=2.8 x 10^{-8} e/slot
extinction ratio = 76 dB

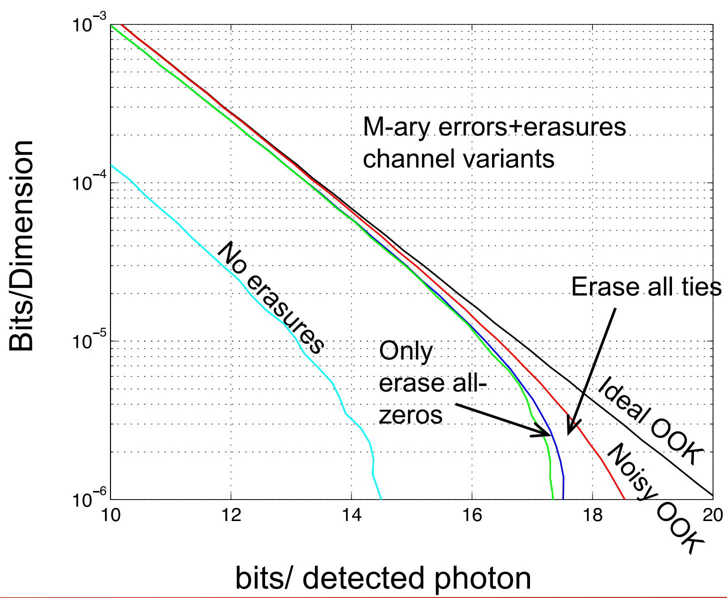


Capacity of *M*-ary errors + erasures channel

The *M*-ary Errors+Erasures Channel

- Reed-Solomon codes (used as our baseline code for analyzing the experimental data) operate on ternary-outcome hard decision output (error, correct, erasure).
- What's the ***capacity loss*** in mapping Poisson output to the *M*-ary errors & erasures channel?
  - Loss increases as we approach noise threshold.
  - Small loss (~0.15 dB) at target operating points.





What if we see multiple counts in a symbol (a tie)? Should these be resolved or declared an erasure?

- Small gain (0.05 dB) in erasing all ties relative to erasing only all-zeros

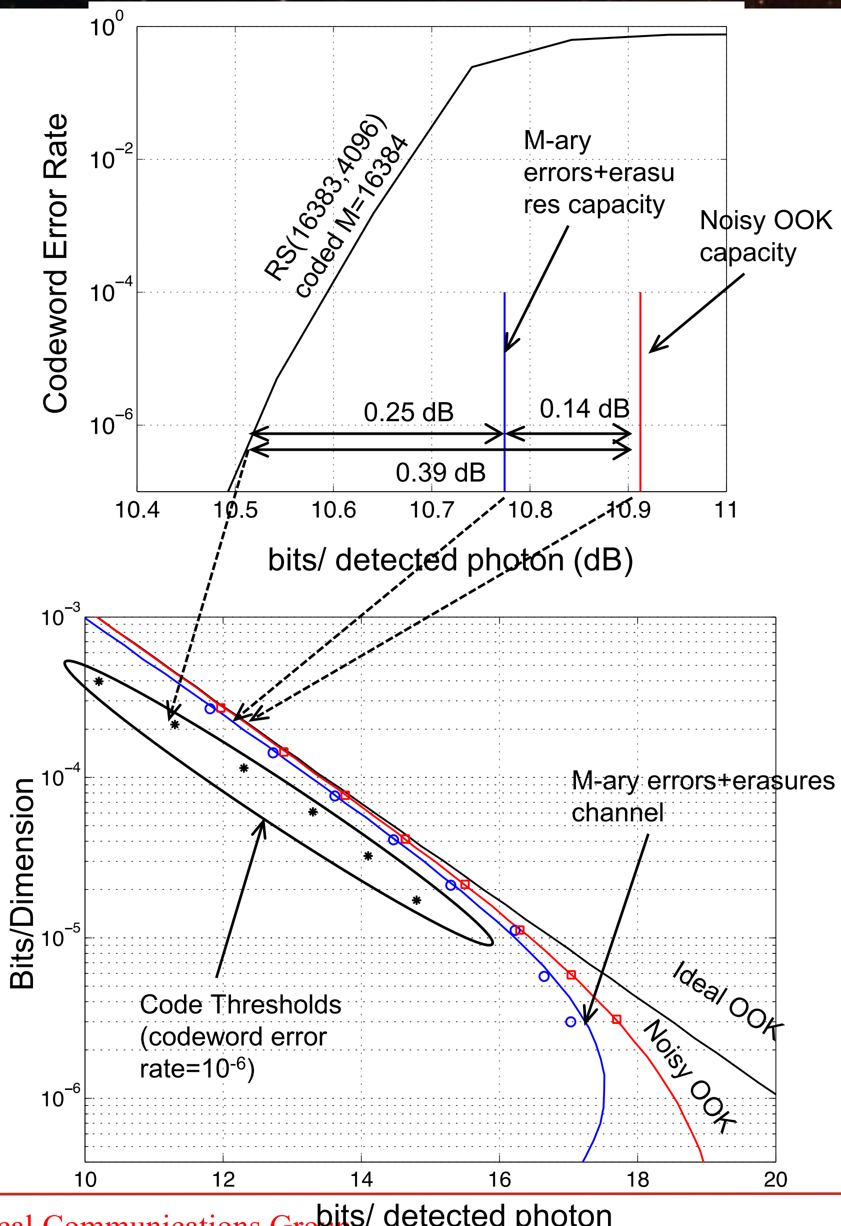
Performance with Reed-Solomon Coding

Reed-Solomon (RS) Codes

- RS codes with symbols over GF(M) are optimal on the pure erasure channel (i.e., they correct the largest number of erasures for a code of a given block-length)
- Errors & erasures RS decoders operate on a ternary output channel (error, erasure, correct)
- From the data we observed

  $\#_{erasures}/\#_{errors}$ ranged from 974 @ $M = 2^{13}$ to 29 @ $M = 2^{20}$
- With large M on this "near-erasure" channel, RS codes provide very good performance (~0.5 to 0.25 dB gap-to-capacity)
- We don't expect significant gains over RS codes until errors become significant

  However, in this region, any code will be limited by the rapidly decreasing capacity of OOK



Achieved photon & spectral efficiencies

Parameter	Design Target		Measured Value							
PPM order	2^{13}	2^{15}	2^{13}	2^{14}	2^{15}	2^{16}	2^{17}	2^{18}	2^{19}	2^{20}
RS code length	$2^{13}-1$	$2^{15}-1$	$2^{13}-1$	$2^{14}-1$	$2^{15}-1$	$2^{16}-1$	$2^{17}-1$	$2^{18}-1$	$2^{19}-1$	$2^{20}-1$
RS code rate	2/7	1/5	~1/4	~1/4	~1/4	~1/4	~1/4	~1/4	~1/4	~1/4
Code efficiency (dB)	0.5 dB		0.52	0.39	0.32	0.26	0.26	0.31	0.43	0.70
Data Rate (kbps)	1000	200	238	128	68.7	36.6	19.4	10.3	5.44	2.86
Bits/slot (DIE)	5.0e-4	1.0e-4	3.97e-4	2.14e-4	1.14e-4	6.10e-5	3.24e-5	1.72e-5	9.06e-6	4.77e-6
Bits/detected photon (PIE/d) @ Poisson capacity	---	---	11.5	12.4	13.2	14.1	15.0	15.8	16.6	17.3
Bits/detected photon (PIE/d) @ errors & erasures capacity	---	---	11.1	12.0	12.8	13.6	14.4	15.1	15.8	16.2
Bits/detected photon (PIE/d) @ 10^{-6} CWER (RS)*	10	12	10.2	11.3	12.3	13.3	14.1	14.8	15.0	14.7
Bits/incident photon (PIE/i) @ 10^{-6} CWER (RS)*	5	6	8.8	9.7	10.6	11.4	12.1	12.7	12.9	12.6

*Threshold for Reed-Solomon (RS) codeword error rate (CWER) of 10^{-6} of was interpolated from higher and lower values of calculated CWER, using a Poisson model for the variation of errors and erasures with signal power.

State-of-the-Art Performance

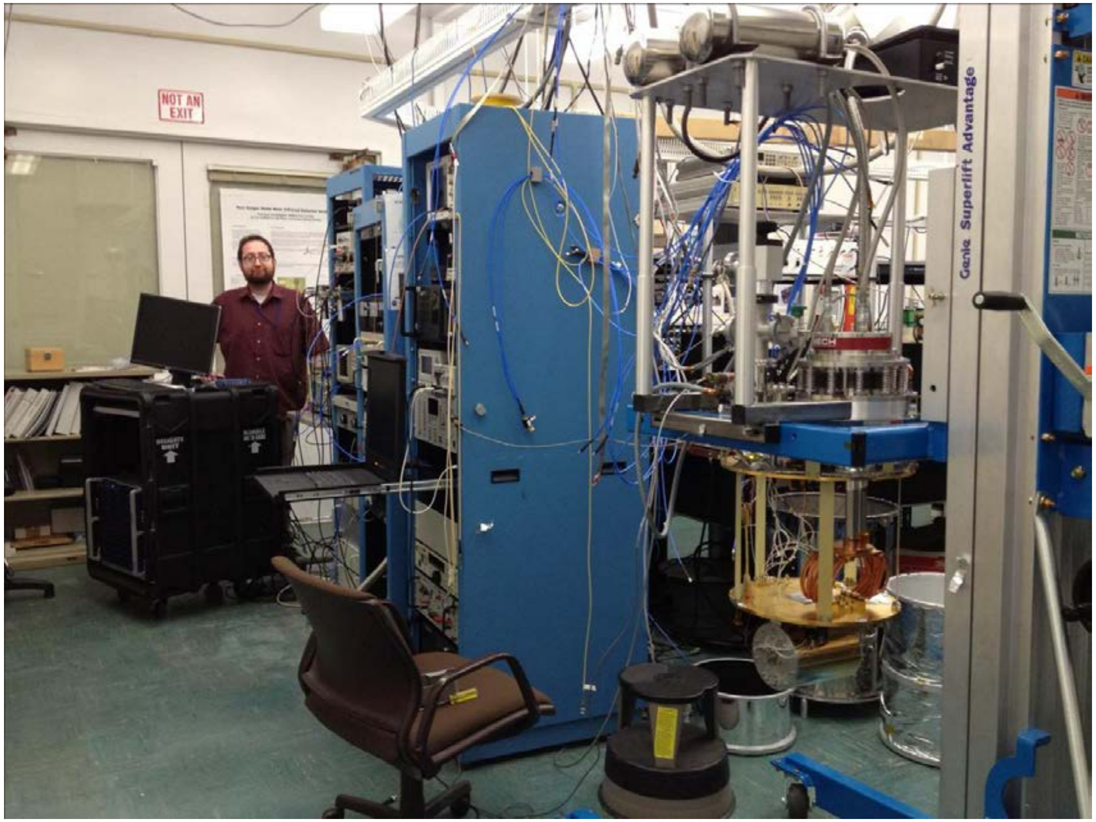
- **Prior state-of-the-art in highly energy-efficient communication comprises pulsed systems using pulse-position-modulation (PPM) and a direct detection receiver**
  - State-of-the-art systems only achieved energy efficiencies of 2 to 3 bits/ *detected* photon, and low spectral efficiencies not much more than 0.1 bit/sec/Hz
- **JPL's demonstration for the DARPA InPho program smashed existing records for high bits/photon demos**
  - 10.2 to 15.0 bits/detected photon
  - 8.8 to 12.9 bits/incident photon
- **This breakthrough was possible due to advances in critical technologies:**
  - Low dark rates (< 20 Hz)
  - High detection efficiencies (> 0.83)
  - Large extinction ratios (> 70 dB)
  - Large bandwidths (600 MHz)

Photon and Spectral Efficiencies per Detected (d) or Incident (i) Photon

PIE bits/photon	SIE Bits/sec/Hz	Bits/sec	By	Technology
1.8d	0.125	44 x 10^6	Birnbaum, … JPL 2009	IPD; includes real-time implementation losses
2.5	0.0234	0.1 x 10^6	Lesh, … JPL 1981	Projected performance with PMT
2.3 d 1 i	0.0469	0.1 x 10^6	Robinson, … MIT-LL 2005	GM-APD
1.7 d 0.91 i	0.0781	0.78 x 10^9	Robinson, … MIT-LL 2007	SNSPD as emulated array detector to mitigate blocking
0.83 d 0.14 i	0.25	2.5 x 10^9		
1.9 d 0.0063 i	0.0781	0.78 x 10^9	Dauler, … MIT-LL 2006	SNSPD
1.48 d 0.006 i	0.125	1.25 x 10^9		
0.71 i	0.0273	5.5x 10^6	Grein, … MIT-LL 2007	GM-APD + sum-frequency conversion
0.67 i	0.5	0.16 x 10^9	Stevens, … MIT-LL 2008	PSK with homodyne detection
2.3 d 0.125 i	0.0781	0.39 x 10^9	Robinson, … MIT-LL 2008	SNSPD
1.98 d 0.05 i	0.0781	0.78 x 10^9		

JPL InPho Team

- Sam Dolinar
- Baris Erkmen
- Bruce Moision
- Dariush Divsalar
- Kevin Birnbaum
- William Farr
- John Choi
- Gary Gutt
- Jeffrey Stern
- Matthew Shaw



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) for the DARPA InPho Program