Near Infrared Enhanced Detectors for 20- to 50-Mbps Deep Space Communications Links

a laboratory demonstration

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Outline

- Deep space link detector requirements
- Detector selection for lab demo – NIR PMT
- NIR PMT Characterization
- 20 – 50 Mbps PPM optical comm demonstration
- Conclusions

Deep Space Link Scenario (1)

- Deep space operation calls for operation of a "photon starved" link

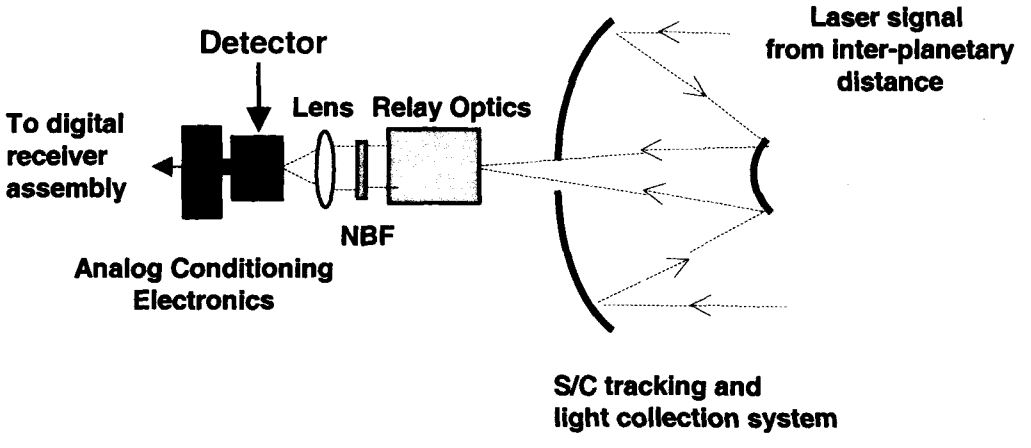
average laser power, bits/second, photon energy

$$P_{avg} = \frac{B_{bit} h \nu N_{photons/bit}}{\eta_{link} \eta_{detector}}$$

link loss, quantum efficiency

  - large receiver (telescope) apertures are required to minimize link losses
  - must maximize detector efficiency the minimize the required photons/bit
  - many tradeoffs between transmit laser, atmospherics, link losses, bandwidth, and detector QE at transmit wavelength

- Must minimize laser transmitter average power! Need a good detector…



Deep Space Link Scenario (2)

- Operation near 1 μm is attractive
  - efficient Nd laser wavelengths
  - however, edge of Si detector absorption band
- "Photon counting" direct detection offers highest potential sensitivity
  - optical preamplification adds excess noise and "thermalizes" photon statistics
  - need good AO for coherent detection through large (ground-based) receive apertures
  - quantum noise of coherent state limits phase measurements to $\Delta\varphi \cong 1/2\sqrt{\langle n \rangle}$
  - quantum noise of coherent state limits photon number measurements to $\Delta n \cong 1/\sqrt{\langle n \rangle}$

Detector Class	Examples	Photon Capacity Limit
phase insensitive amplifier	parametric amplifier, Raman amplifier, laser amplifier	1.44
dual quadrature sensitive	coherent heterodyne	1.44
single quadrature sensitive	coherent homodyne, degenerate parametric amplifier	2.88
photon counting	photomultiplier tube, cooled avalanche photodiode, hot electron superconducting	$h\nu/2kT\ln 2$ (for instance, 69 bits /photon at 1μm & 150K)

Photon Counting Detectors

- Detector cooling allows operation as a photon counter
  - reduces dark current continuum to "dark count rate"
  - detector cooling may be limited at some point by "carrier freezout"
  - loss of QE near band edge can also limit cooling
- Internal detector gain is required to overcome internal and external noise sources
  - kTC charge uncertainity in detector
  - additive Gaussian noise from post-detector electronics

technology	cooling	QE @ 1064 nm	t_p	wavelength	dark rate	gain	area (mm^2)	notes
NIR-PMT	77K	8%	9 ns	300-1700 nm	20-200 Kcps	1E6	>20	2 μA anode current limit
hybrid-PMT	<300K	15%	1 ns	900-1300 nm	50 Kcps	12E3	1	
SSPM	<10K	1% front 20% edge	3 ns	0.4-28 μm	7 Kcps	20E3	1	no excess noise, 3E7 max rate
Si APD (Geiger mode)	<280K	18%	<10 ns	0.35-1 μm	250 cps	∞	0.2	requires pulse quenching
Si APD (gain mode)	<200K	40%	2 ns	0.35-1 μm	10 Kcps	>1E3	9	
InGaAs APD (gain mode)	150 – 200K	60%	1 ns	0.9-1.5 μm	500 Kcps	20E3	.01	
hot-electron NbN	4 – 10K	2%	30 ps	0.4-2 μm	0.1 cps	3E2	.0001	polarization sensitive

Deep Space Detector Requirements

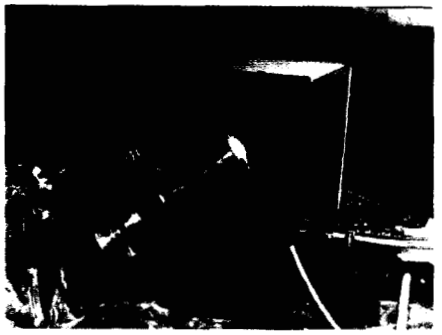
- ✓ High Quantum Efficiency
  - inverse linear relationship to required laser transmitter power
- ✓ High Bandwidth
  - to support of high data rates
  - allows trade of channel capacity for channel efficiency
  - minimizes optical backround contributionsHi
- ✓ High Internal Device Gain
  - minimize affect of kTC noise
  - minimize affect of post-detector electronics noise
- ✓ Low Noise
  - want minimum dark event rate
  - want minimal additive noise
  - want minimal gain variance ("excess" noise)
- ✓ Proportional Response
  - allows efficient and large high-level coding gains
- ✓ Large Area
  - match detector area to blur circle at focal plane of receiver antenna
  - inherently in conflict with bandwidth and noise requirements

PMT Selection

detector requirement	NIR PMT	Si APD (Geiger mode)	InGaAs APD (gain mode)
High QE	- 8%	- 18%	✓ 60%
High Bandwidth	✓ 100 MHz	- > 10 MHz (requires quenching)	✓ > 100 MHz
Hign Internal Gain	+ 10^5 to > 10^6	✓ > 10^5	✓ > 10^4
Low Noise	✓ 25 Kcps dark rate	+ < 100 cps dark	- > 200 Kcps dark
Proportional Response	+ yes	- no	+ yes
Large Area	+ yes, >10 mm^2	✓ ~ 1 mm^2	- no, << 1 mm^2

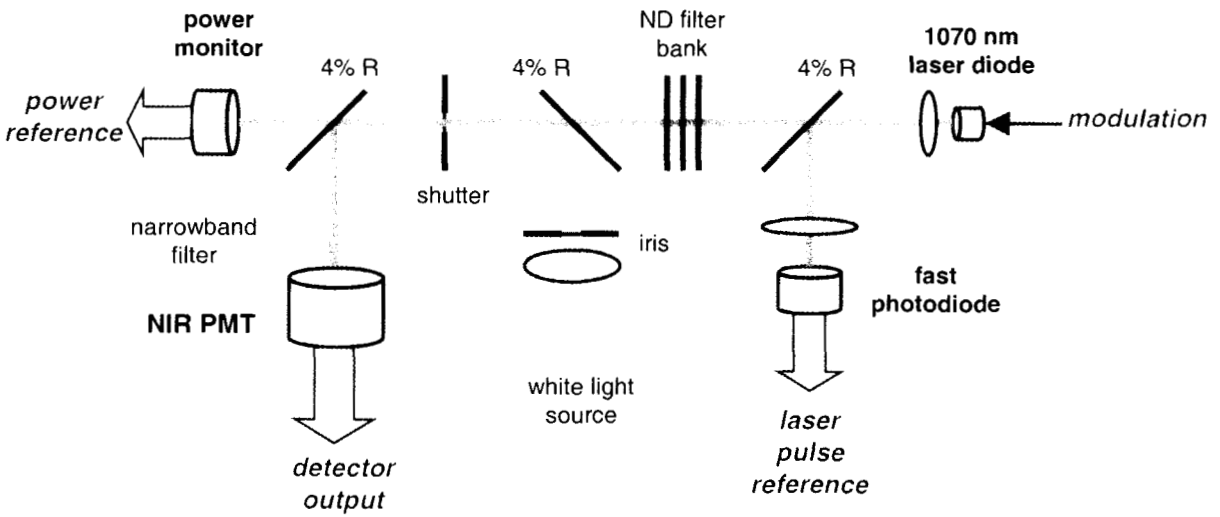
- NIR PMT selected as good choice for demonstration of photon counting detector for deep space optical comm link
  - reasonable bandwidth for high data rate demo
  - high internal gain simplifies post-detector electronics
  - large area simplifies experimental set-up
  - low QE is acceptable for initial lab demo
- Commercial device selected: Hamamatsu R5509-42
  - "hand selected" tube with 8% QE

Optical Setup



LN2 cooled PMT assembly

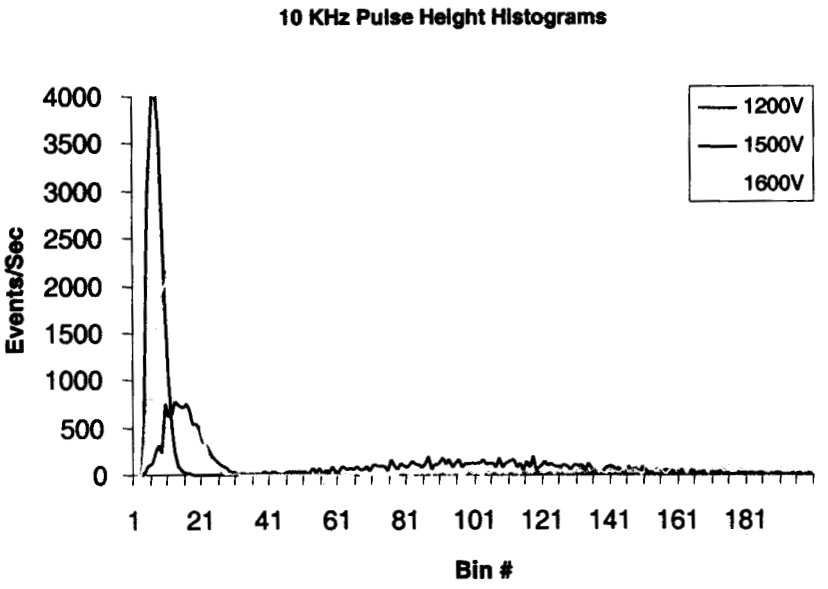
Optical Schematic



- NIR PMT (InAlAs/InGaAs photocathode) is LN2 cooled to 80K to minimize dark count rate
- Laser source is a directly modulated 1070 nm diode. ND filters attenuate the signal to "photon starved" levels
- White-light source can add photon "background" noise (through 10 nm optical filter)
- DSO acquires comm data (8 M data points per acquisition record). Post-detector LNA (10-100X) minimizes noise contribution from DSO vertical preamplifier.
- Custom 10 MHz MCA acquires continuous pulse height histograms for low rep-rate pulse sequences (<100 KHz)

MCA Histogram Acquisition

Low-noise amplifier with
10 MHz multi-channel analyzer



- MCA forms true "pulse-height" histograms
- Custom JPL design with 10 MHz maximum count rate, 260 KHz average count rate limit
- Bipolar op-amp based LNA front end

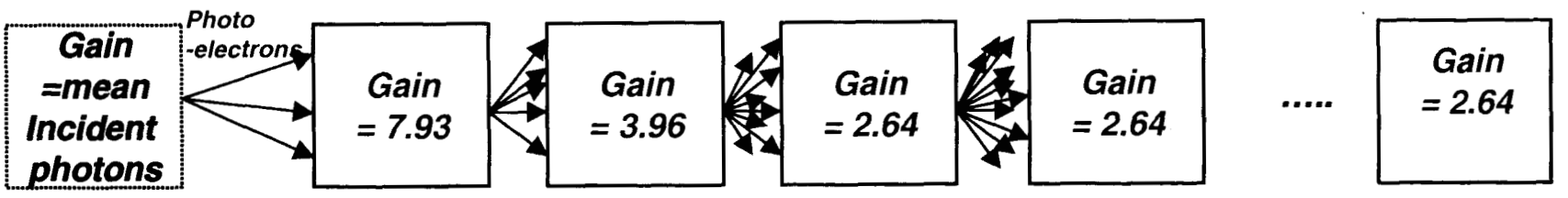
Polya Statistics

- PMT multi-dynode statistics can be well described by the (discrete) Polya distribution
  - can model multi-photon inputs as virtual first stage with Poisson distribution for coherent state input field
  - Subsequent stages can be modeled as Poisson with a shape parameter
    - Shape parameter varies from 0 (Poisson) to 1 (exponential)

- Consider the PMT operating at 1300 V the mean gain is 2E5 but distributed across the dynode stages as shown below

K	B	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	P
	→	→	→	→	→	→	→	→	→	→	→	→
	X	3	1.5	1	1	1	1	1	1	1	1	1

- A sequence of Poisson stages with different gains was used to calculate the probability distribution of secondary electrons emitted from the anode



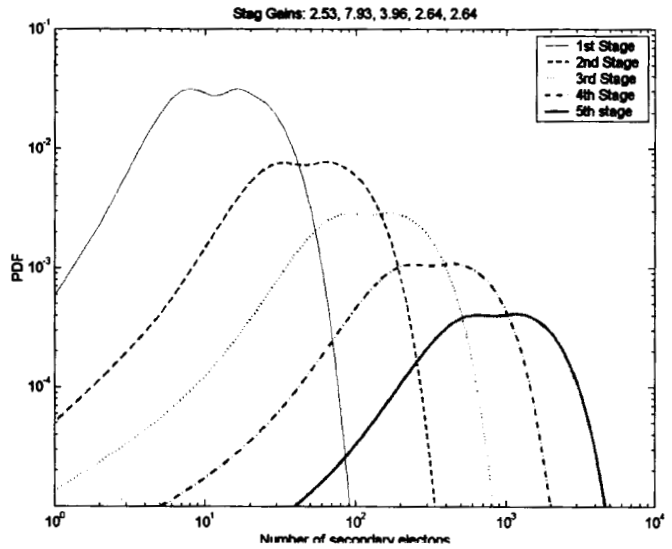
The variance after any 2-stages is given by Where μ_i and σ_i is mean gain and standard deviation

$$\sigma_{12}^2 = \mu_2^2(\sigma_1^2) + \mu_1(\sigma_2^2)$$

Polya Statistics (cont'd)

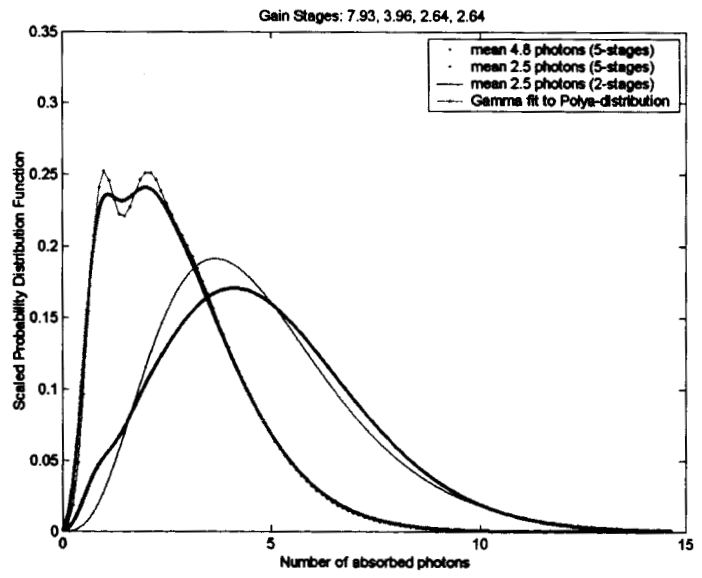
Computed Polya distribution for the incidence of 2.5 photons

Log-log representation shows mean secondary electrons Increasing with number of stages

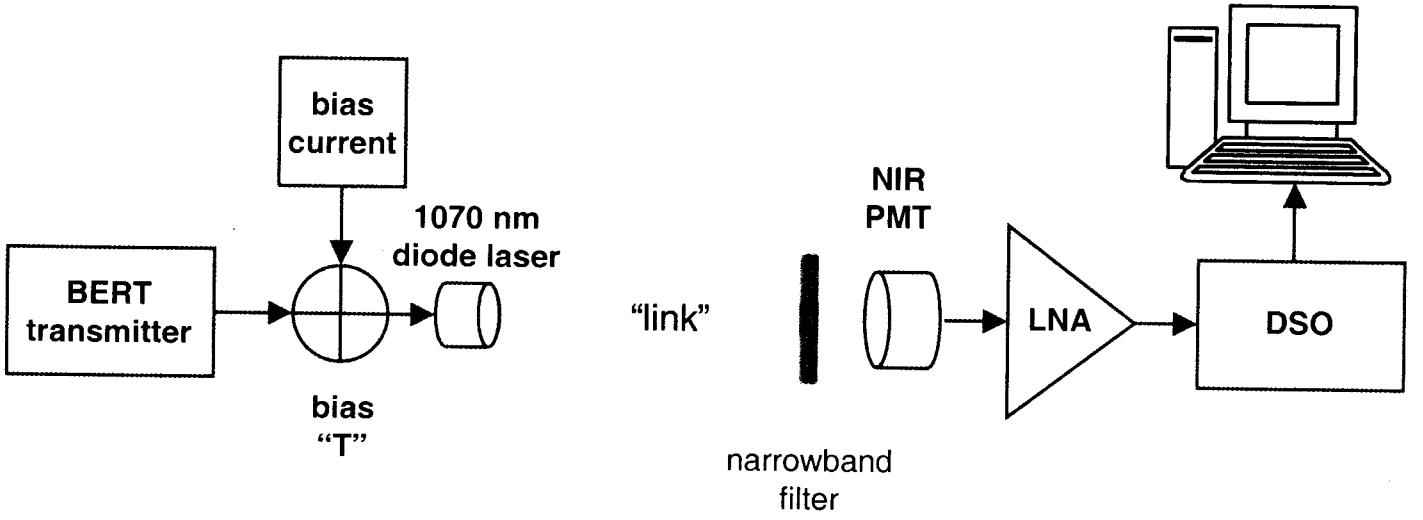


Observed rapid convergence of probability distribution Function (PDF) due to dominance of high gain stage

Observed a dip near peak of distribution
- *attribute this to the discrete nature of the Polya distribution*
- *Gamma fit to Polya-distribution also shown*



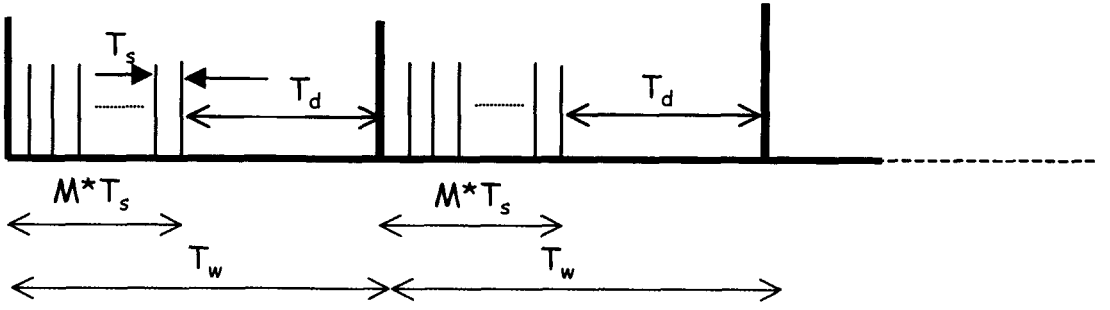
Photon Starved Optical Link Demo



- Goal: demonstrate photon starved link with NIR PMT at 20 – 50 Mbps using pulse position modulation (PPM) encoding
- Problem: PMT anode current limit is exceeded at high data rates

Pulse Position Modulation (PPM) Review

T_s	Slot Width
T_w	Frame (word) Time
T_d	Dead Time
M	Alphabet Size
T_p	Laser Pulse Width
PRR	Max. Laser Repetition Rate
R_b	Bit Rate



$T_p < T_s$, $T_w = T_d + MT_s$, $R_b = (\mathrm{Log}_2 M)/T_w$, $PRR = 1/(T_d+T_s)$

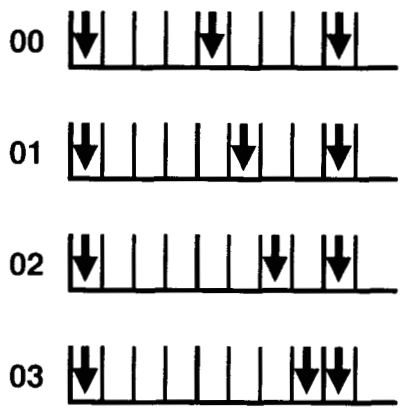
- PPM encodes data value by pulse position (= slot) within a word frame.
- PPM encoding allows efficient use of channel capacity
  - trades link bandwidth for reduced link power requirements
  - good match to photon counting direct detection
  - required channel bandwidth is reciprocal of slot time
  - set capacity "modes per photon" equivalent to *M*-ary slots

$$C = B\left[\log_2\left(1+\frac{1}{M}\right)+\frac{1}{M}\log_2(1+M)\right] \xrightarrow{PPM\,encoding} C = \frac{B}{M}\log_2 M$$

from Brillouin's "negentropy principle"

Link Setups

Tube Voltage	1500 V	1300 V
Gain	1.0E6	3.0E5
Max. Cathode e-	20.8E6	125.E6
Mean photons/pulse	1 - 6.2	1.5 - 9
Max. pulse rate	7.8 MHz	15.6 MHz
Word Time	128 ns	64 ns
Slot Width	12 ns	16 ns
Encoding	PPM32	PPM4
Data Rate	23 Mbps	31 Mbps

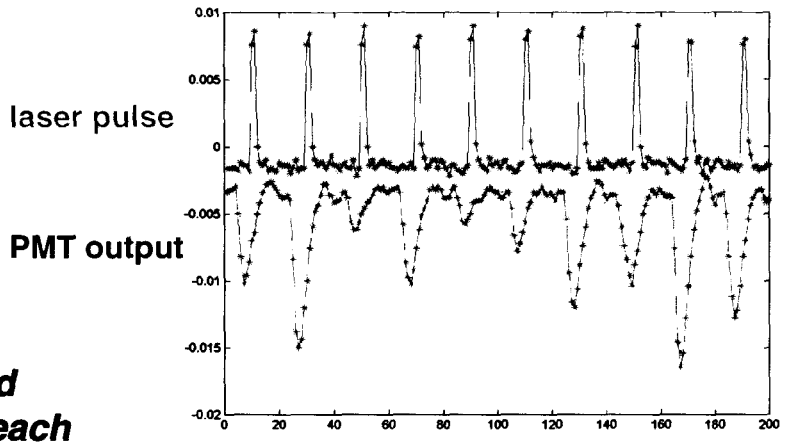


PPM4 Test Patterns

- Set laser pulse width to ½ slot width
- PMT anode current limit sets maximum PPM frame rate
- Generated PPM4 and PPM8 test patterns with BERT transmitter
- Set DSO sampling rate to harmonic of slot rate

Link Data

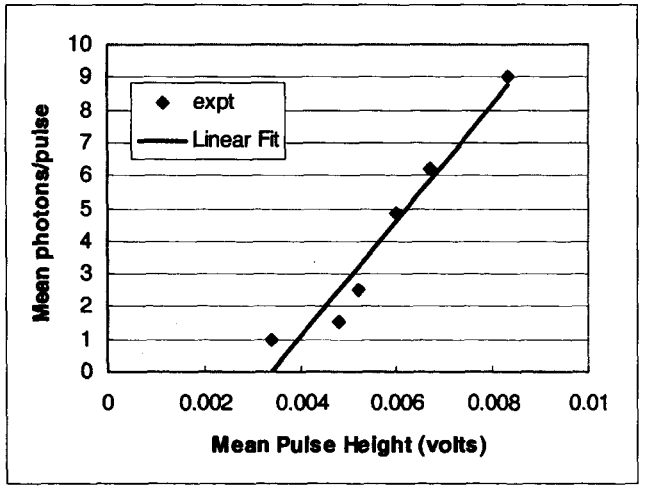
Logged two channels of data with 4E6 records each
On digital storage oscilloscope
- *1st channel has timing reference data*
- *typical sampling was 250 MS/sec*



Read stored data and use simple maximum likelihood algorithm to determine slot with maximum signal in each frame

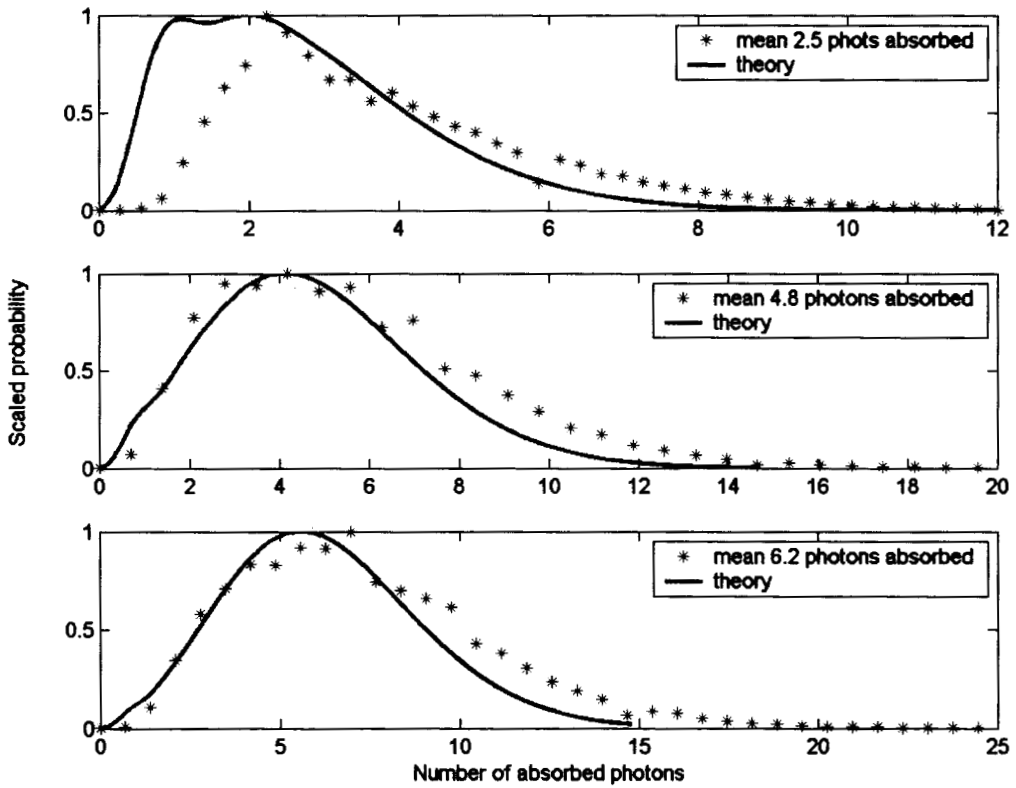
Compare maximum slot with the known slot position based upon timing reference data stream and obtain symbol error rate

Obtain pulse height statistics



Link Data (cont'd)

Comparison of the Polya distribution and experimental pulse height distribution



Reasonable fits were obtained using a pure Poisson model introducing shape fitting parameter >0 may improve fit, will investigate in future

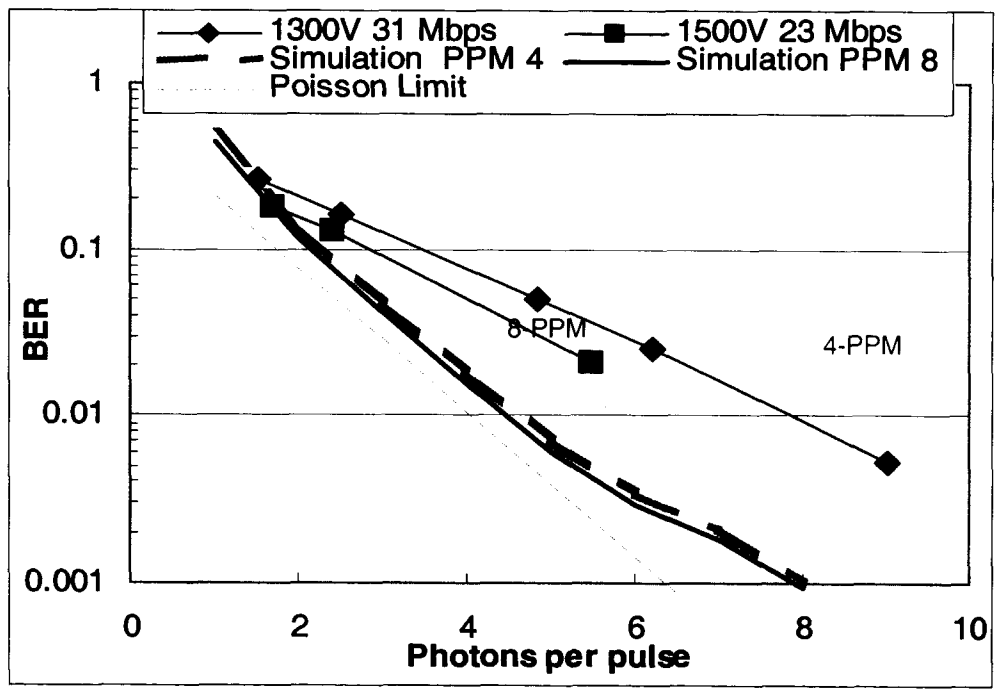
BER Results

- **Demonstrated photon counting scheme with 3-4 detected photons/bit**
  - achieved 20-30 Mbps @ 1E-2 bit-error rate (BER)

- PMT detection limited by:
  - anode current limit
  - bandwidth
  - quantum efficiency
  - under realistic spacecraft power constraints PMT will support
  - 1- 5 Mbps links from Mars at maximum range

- improved over 20-30 detected photons/bit demonstrated with Si avalanche photodiode (APD)
  - overcoming additive thermal noise provides improvement
  - linear mode photon counting with APD desired ground detector

BER curve using Polya distribution has not been derived yet, expect better fit to data



Conclusions

- NIR PMT can successfully realize a "photon counting" detector for a high data rate photon starved optical comm link
- NIR PMT is a good device to test cascaded gain stage noise models and impact on link BER and coding models
- Low photocathode QE limits usefulness as a deep space detector
- Low anode current limitation limits usefulness at high data rates and high background illumination levels. Gain loss near saturation is problematic. Low tube life is expected.