Photon Counting Detectors for Laser Communications and Interplanetary Light Science

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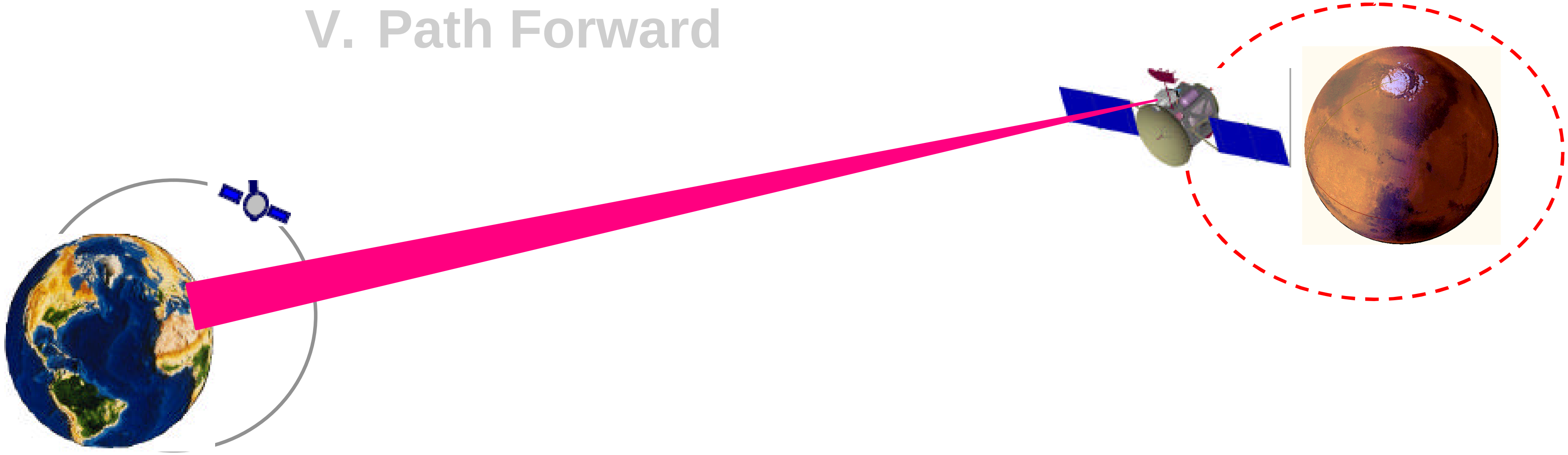
I. **Laser Communications**

II. SPCDs for Laser Comm

III. SPCD Characterization for Laser Comm

IV. Interplanetary Light Science

V. Path Forward



Deep Space Communications Capability

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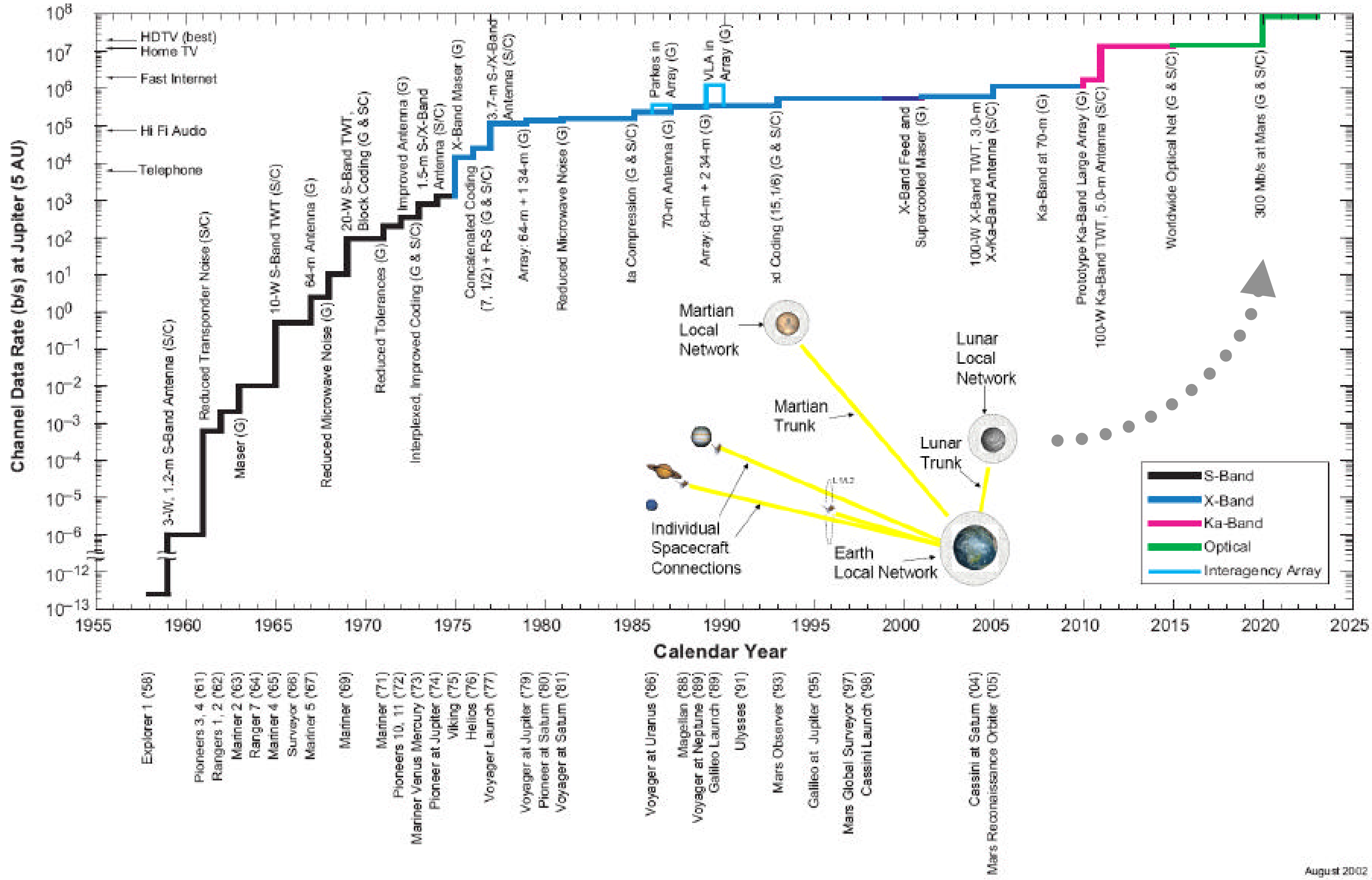
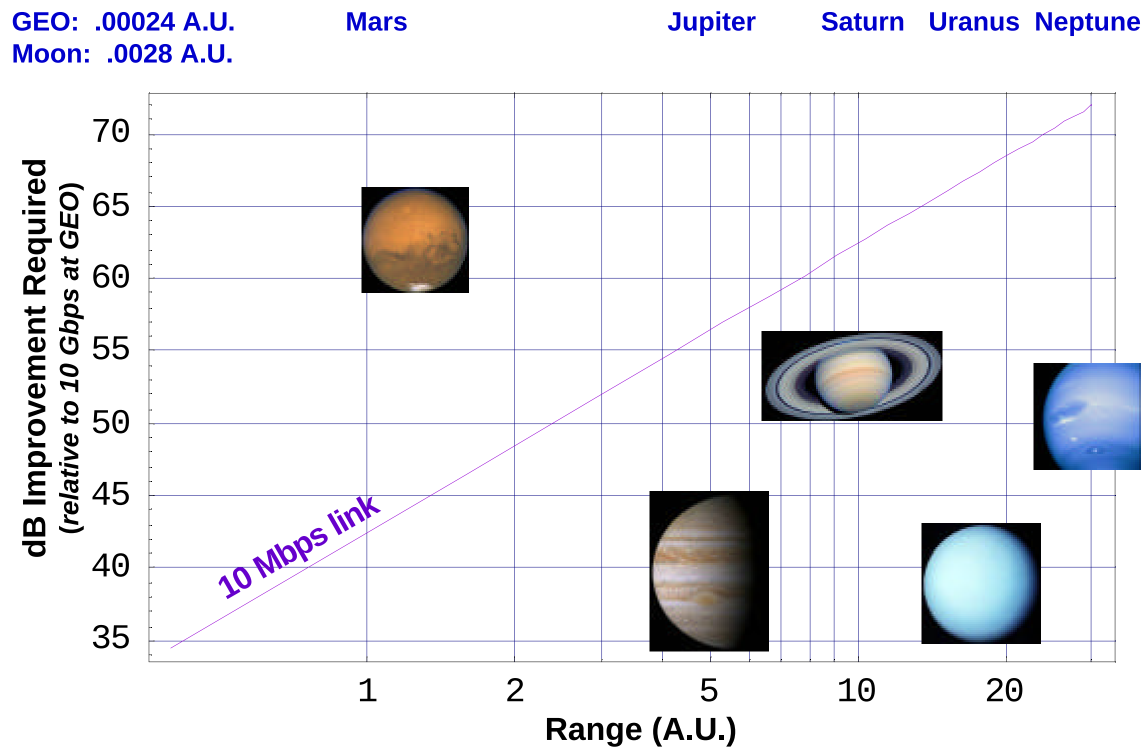


Interplanetary Laser Communications

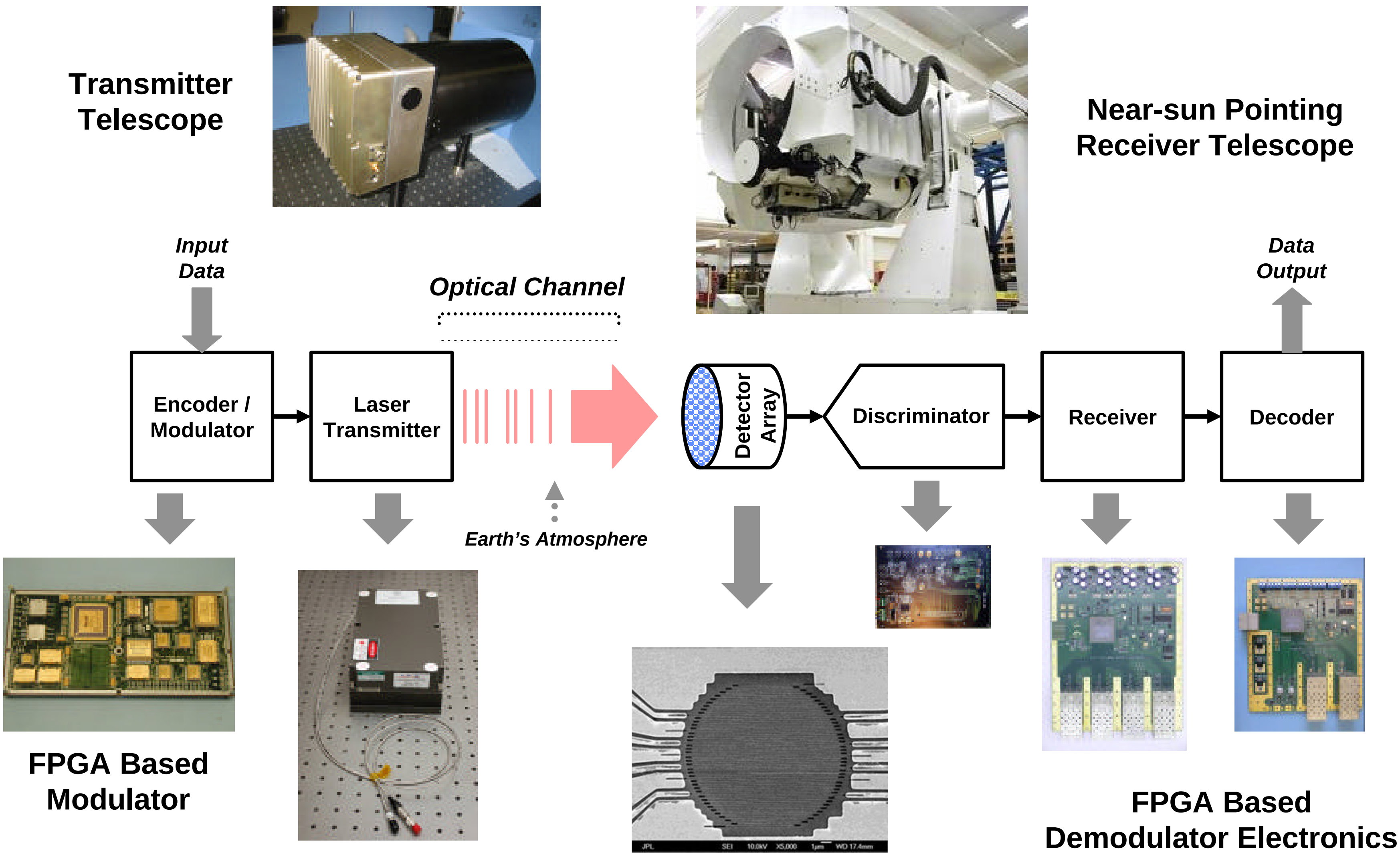
- **Optical communications must provide cost effective higher *data rate per kilogram* and *per Watt* than RF systems to be accepted for operations**
- **Reduction of spacecraft burden is the overriding concern**
  - Mass, power, delta-V limits
- **Result is a *photon starved* communications channel**



- **Deep space optical communications technology targets gains through:**
  - **Pointing**: High carrier frequency allows narrow beams from small transmit apertures
  - **Coding**: GigaHertz bandwidth traded for high bits per photon efficiency at lower data rates
  - **Detection**: Efficient and high rate photon counting

Count every photon and make every photon count!

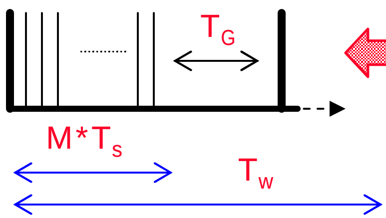
Laser Communications Link



Data Modulation for Interplanetary Comm

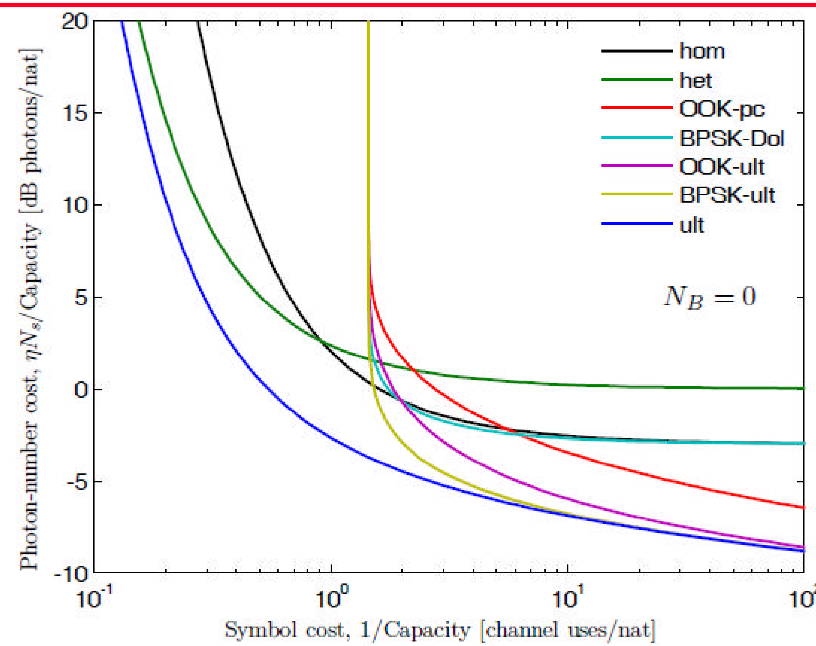
- **Present emphasis on Pulse Position Modulation (PPM) and phase insensitive detection with Single Photon Detectors**
  - GHz bandwidths and up to ~3 bits per detected photon efficiency at 1 to 1.6 μm
  - Requires high peak-to-average power lasers

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



Detector Class	Examples	Capacity Limit *bits/photon*
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, Geiger mode APD, NbN nanowire	**hn/2kTln2** (~ 69 @ 1 μ m, 150K)

- **Binary Phase Shift Keying (BPSK) modulation could provide "quantum-optimum" performance**
  - Receivers operating above the atmosphere would be desired for this
  - BPSK would eliminate the present high peak-to-average power technology driver
  - *However*, no one knows how to build the "optimal receiver" yet, although it will likely require phase sensitive single photon detectors



Ultimate capacity of a pure-loss channel and the capacities of structured transmitter and receivers

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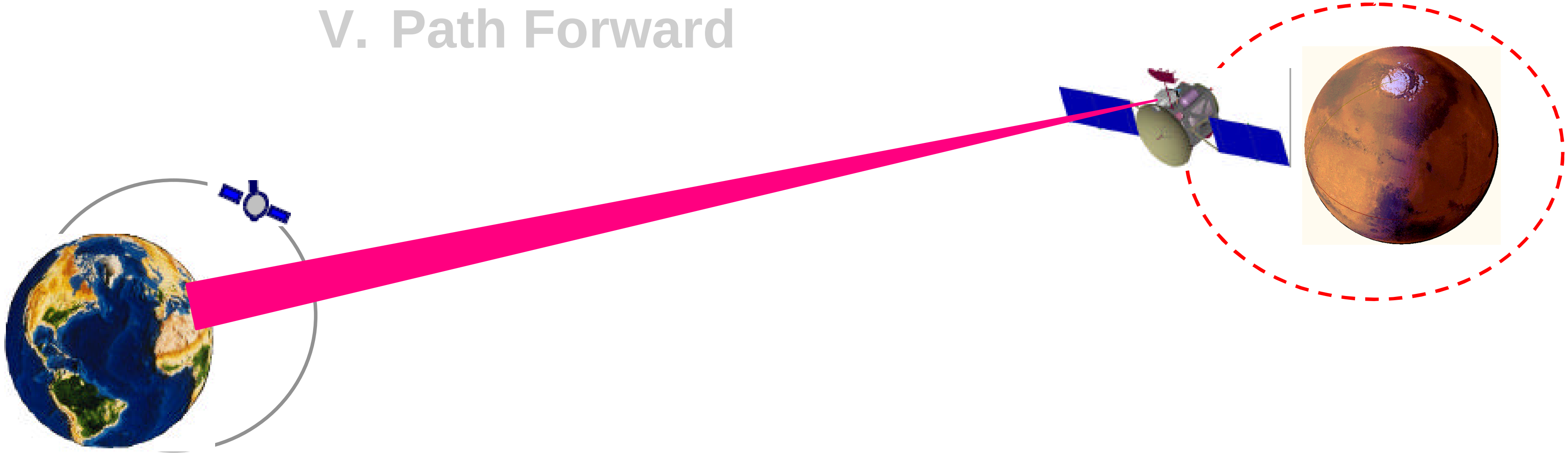
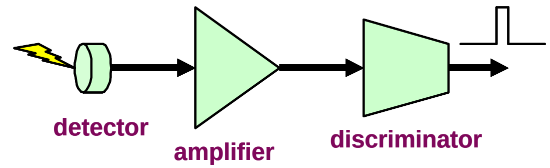


Single Photon Counting Detectors (SPCD)

- **Single photon counting detectors (SPCD) are the most sensitive detectors for electromagnetic radiation**
  - But the ideal single photon detector with 100 % detection efficiency zero dark count rate and after-pulsing, zero timing jitter, high bandwidth and dynamic range does not exist



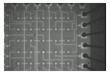
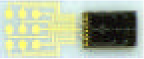
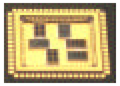
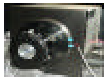
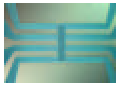
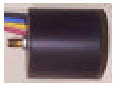
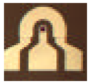
Easy → *Difficult*

	Spectroscopy *Fluor., Raman, …*	**TCSPS**	**Quantum** *QKD, computing, …*	**Imaging** *Scint., low-light, …*	**Lidar**	**Communications** *Photon starved*
Detection Efficiency	M	L	H	M	L	H
Dark Rate	L	M	L	L	M	H
Dynamic Range	L	L	L	M	L	H
Bandwidth	M	H	H	L	H	H
Jitter	H	L	L	H	L	L

Parameter		**Description**	**Units**
Quantum Efficiency	QE	Ratio of generated primary photocarrier rate to incident photon rate	% (*unitless*)
Detection Efficiency	DE	Ratio of rate of distinguishable electrical output pulses to incident photon rate	% (*unitless*)
Dark Count Rate	DCR	Rate of distinguishable electrical output pulses (at a given DE operating point) with no optical input	Hz
After-Pulsing Ratio	APR	Ratio of correlated secondary distinguishable electrical output pulses to primary distinguishable electrical output pulses (at a given DE point)	% (*unitless*)
Single Photon Jitter	SPJ	Timing uncertainty between arrival of incident photons to distinguishable electrical output pulses	s
Recovery Time		Time after a photon detection event for the DE to recover to a specified fraction of the limiting (low rate, maximum) DE value	s
Saturation Rate		Mean rate of distinguishable electrical output pulses under continuous wave (Poission) illumination for which apparent SPDE drops to a specified fraction of its limiting (low rate, maximum) value	Hz

High Bandwidth and low Single Photon Jitter are essential requirements for high rate photon counting for efficient laser communications

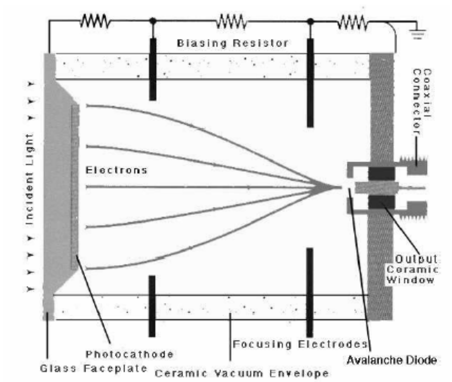
Some Vis/NIR SPD's Characterized in JPL's Optical Communications Detector Calibration Facility

	Device	Wavelength (nm)	DE	Dark Rate (Hz/mm2)	Rise Time (ns)	1-s Jitter (ps)	Dia. (mm)	Temperature (K)	Saturation (0.5 dB)	Comment
	Si GM-APD	400 .. 1060	20-40%	1.E6	0.2	1200	0.03	270 .. 300	5 MHz	large jitter contribution from decay tail
	Si:As (VLPC)	400 .. 850	> 50%	1.E5	0.5	600	1	6 .. 9	17 MHz	> 90% DE at peak
	Pt:Si:As (NIPC)	400 .. 2000	<1 %	1.E5	0.5		1	6		high noise from positive feedback at Pt:Si interface
	InGaAsP Near-Infrared PMT	900 .. 1300	8%	2E4	3	800	3 x 8	190	200 KHz	Low DE, bandwidth and saturation
	InGaAs(P) GM-APD	900 .. 1600	55%	2.E8	0.3	270	< .02	220 .. 300	100 KHz	requires detector array with active reset and microlens array for high rate comm.
	Nb(Ti)N Nanowire	<400 .. >1600	20 - 80%	100	0.1	50	<.02	2 .. 4.2	5 MHz	Saturation is DE and size dependant
	InGaAs(P) Hybrid Photodiode	900 .. 1600	40%	1.E6	0.2	70	1	220 .. 300	> 200 MHz	Presently the best choice for large area, high rate NIR photon counting
	Si NAF	450 .. 800	20%	3.E4	< 0.2	3700	0.5	260 .. 300	50 MHz	tested devices intolerant of overbias
	InGaAs/InP NAF	900 .. 1600	22%	5.E8	0.3	240	0.03	80 .. 300	6 MHz	Early development; lower jitter and DE to >40% viable

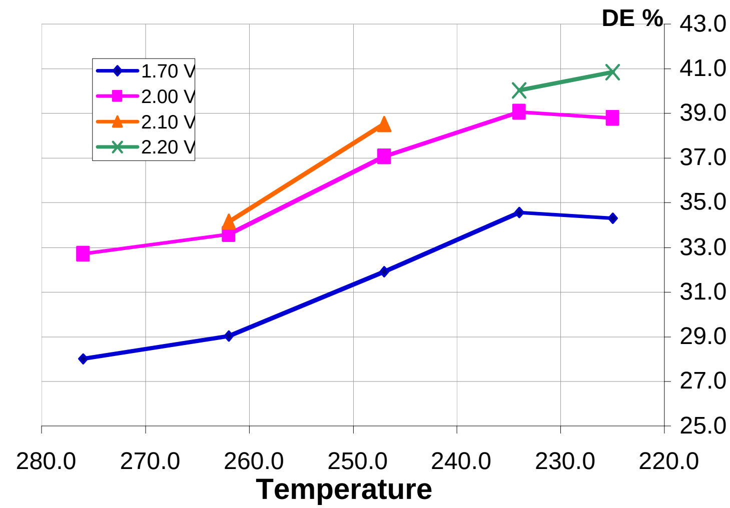
Note: table values are "characteristic" of well performing devices

Intensified Photodiode Detectors

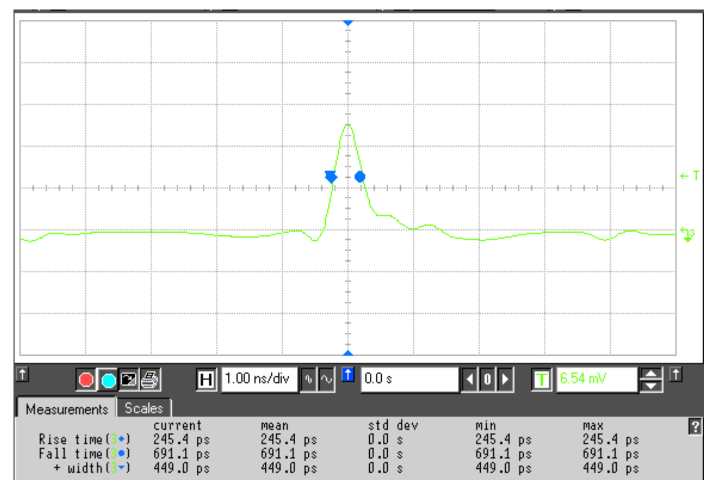
- **The Intensified Photodiode (IPD) offers the best combination of high detection efficiency, high count rate, and large detector area**
  - The IPD uses a two-stage gain process to achieve single photon sensitivity:



    - Ultra-low noise multiplication on the order of 10^3 via energetic impact of kinetic (8 KV typical) electrons onto a GaAs semiconductor anode
    - Avalanche multiplication with gains on the order of 10 within a high-field region of the semiconductor anode (avalanche diode)
  - Both single pixel and multi-pixel (array) configurations are available
- **Using the IPD, JPL has demonstrated emulated Mars links at 47 Megabits/s and efficiencies over 2.8 bits per detected photon**



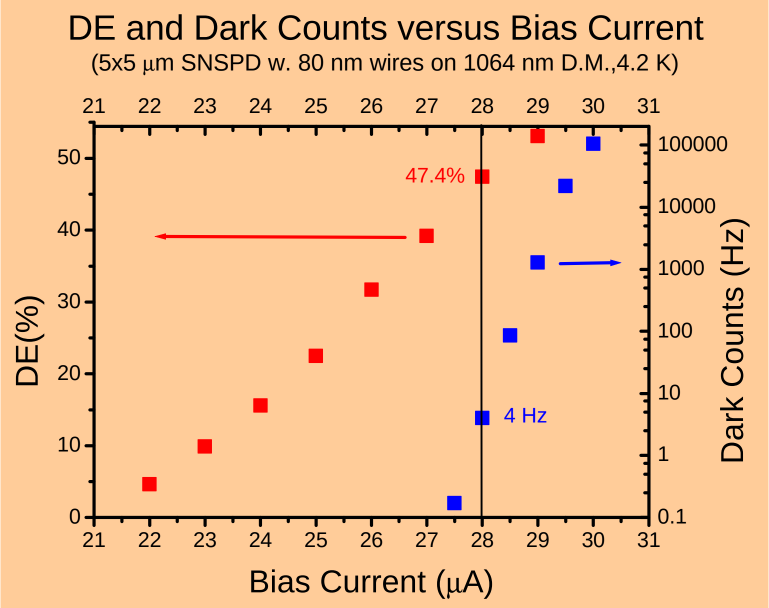
InGaAs IPD Detection Efficiency at 1064 nm

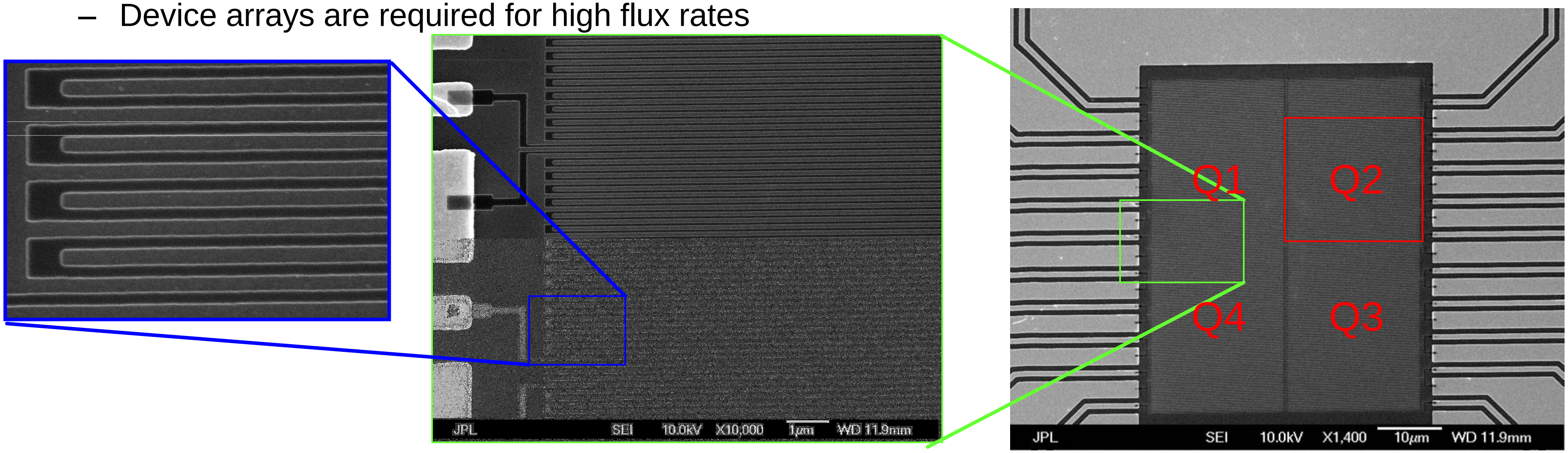


InGaAs IPD 500 ps FWHM Single Photon Response

NbN Superconducting Nanowire Detector

- **Nb(Ti)N Superconducting Nanowire Single Photon Detectors (SNSPD) can have high detection efficiency coupled with low dark rate**
  - Detection efficiencies > 80% observed at ~2K
  - Best devices fabricated at JPL to date have <1 Hz dark rates (100 μm^2) at detection efficiencies of 40%
- **Low single photon jitter is an attractive feature of this technology**
  - Down 20 ps 1-σ for a 5 x 5 μm device
  - 50 ps 1-σ typical for 10 x 10 μm devices
- **Kinetic inductance limits device speed**
  - < 200 ps risetimes, few ns recovery times
  - Device arrays are required for high flux rates

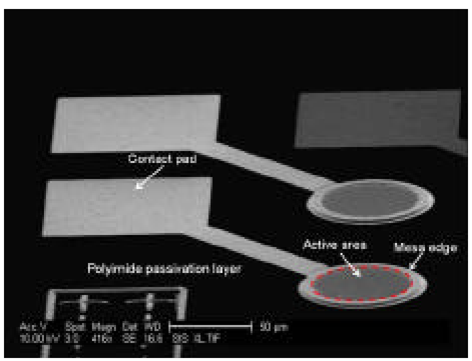




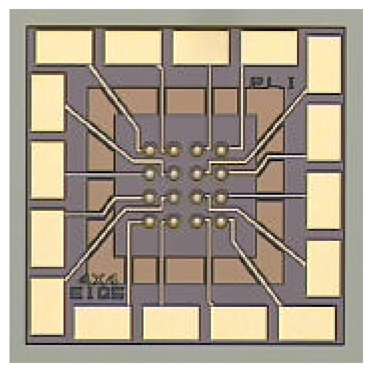
Negative Avalanche Feedback Detectors

- **Single photon detectors incorporating Negative Avalanche Feedback (NAF) operating at 1550 nm are simple two terminal devices requiring only DC bias and a low cost RF amplifier for single photon sensitivity**
  - High sensitivity and low noise can be achieved with simple thermoelectric cooling.
  - Free-running and self-resetting, NAF APDs can saturate at rates 100 X higher than Geiger mode APDs
- **JPL has collaborated with three partners (to date) to develop these novel InGaAs APDs**

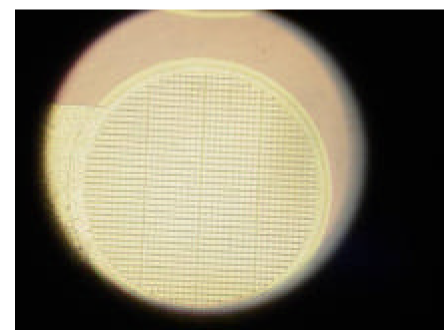
	TCB	NFAD	DAPD	Note
SPDE	14%	22%	8.5%	measured at 1534 nm
DCR	6 MHz	0.1 MHz	3 MHz	at highest SPDE
APR	*not measured*	30%	50%	at highest SPDE
SPDJ	850 ps	240 ps	13.5 ns	1-σ at highest SPDE
recovery	60 ns	20 ns	1 ns	at highest SPDE
saturation	3 MHz	8 MHz	5 MHz	1 dB loss; function of detector area



UCSD Transient Carrier Buffer Single Photon Detector



PLI Negative Feedback APD 16 Element Array

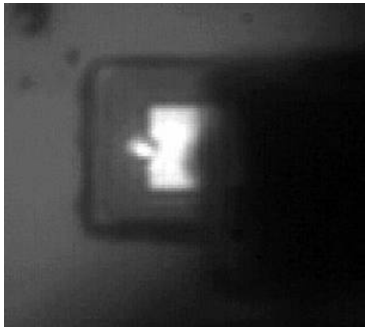


ATI Discrete Amplification Photo-Detector

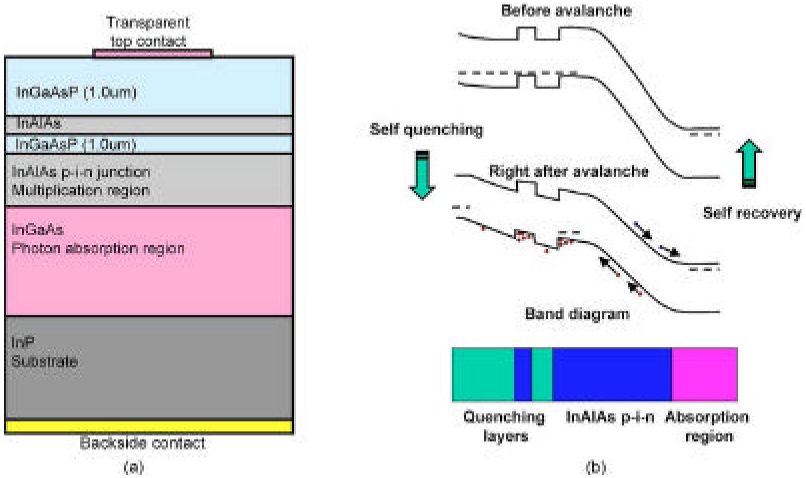
2004	2005	2007	2008
Validated ATI Si NAF	*UCSD InGaAs on Si NAF*	*UCSD TCB InGaAs NAF*	*PLI & ATI InGaAs/ NAF*

InGaAs/InP Negative Avalanche Feedback APD

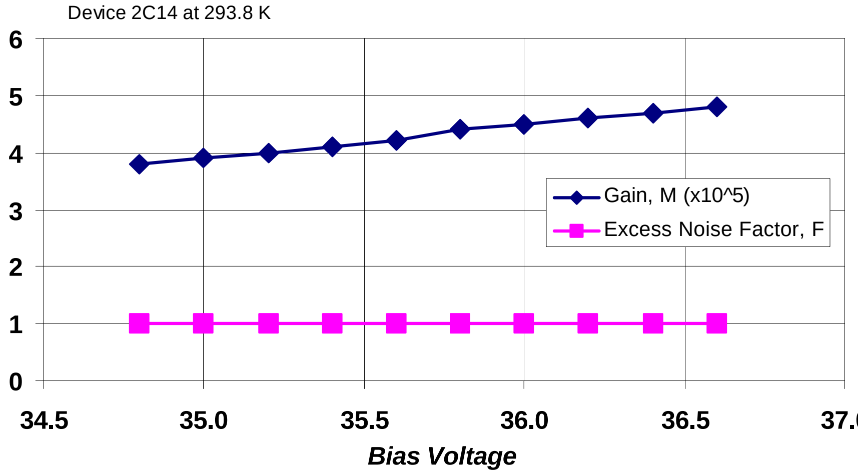
- **In 2007, JPL and UCSD demonstrated the first ever near-infrared photon counting with an InGaAs Negative Avalanche Feedback (NAF) detector**
  - Non-Geiger mode 1.5 μm photon counting at 295K
  - NAF eliminates the need for complicated Geiger mode readout circuitry as the device avalanche is gain limited and self resetting
    - Gain bandwidth product is greater than 10 THz
  - Negative feedback was achieved through a “Transient Carrier Buffer” design



Focused 1.5 mm spot on 10 μ m Device



**(a) Schematic diagram of InGaAs–InAlAs SPCD layer structure.
(b) Concept of operation for the InGaAs–InAlAs SPCD showing the self-quenching and self-recovery processes.**



TCB Gain and Excess Noise Dependence on Bias Voltage

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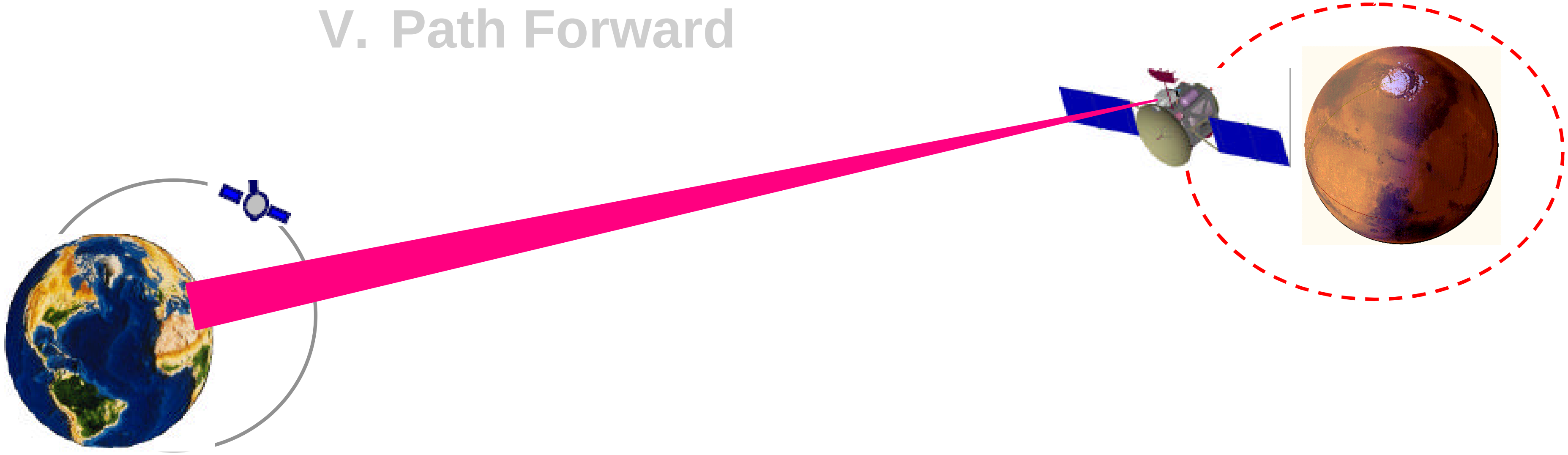
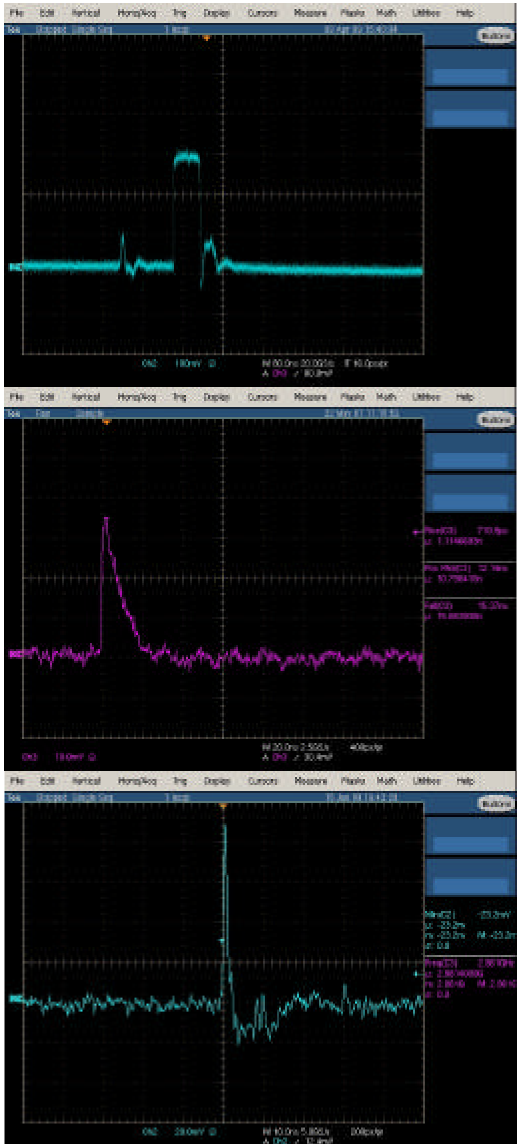


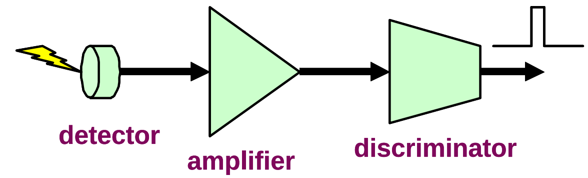
SPD Output Pulses

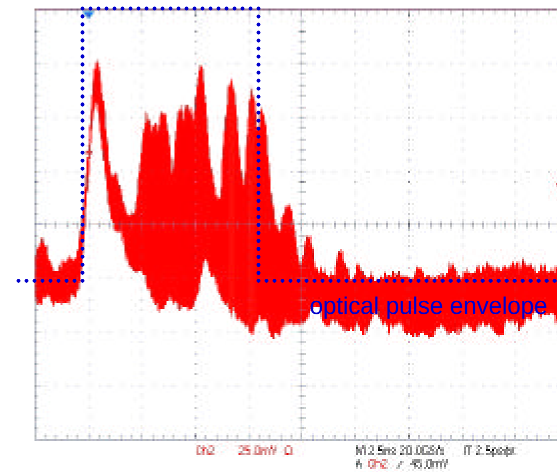


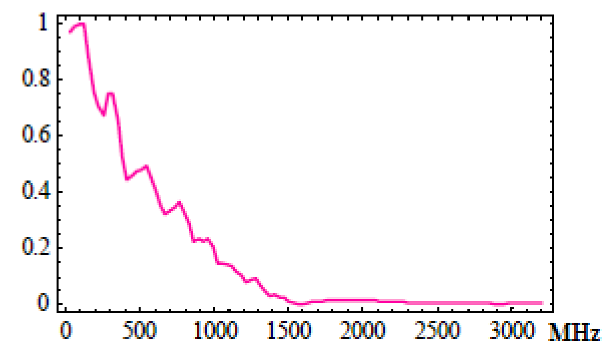
- Geiger mode SPD’s can be considered to incorporate a “virtual discriminator” after the internal gain mechanism; external reset is required, followed by a recovery (“dead”) time

- A Superconducting Nanowire SPD (SNSPD) has a fast leading edge, but kinetic inductance (proportional to nanowire length) limits recovery time

- Linear mode photon counters (Photo-Multiplier Tube (PMT), Intensified PhotoDiode (IPD) and Negative Avalanche Feedback (NAF) SPDs generate short pulses; recovery time is essentially the device pulse width.

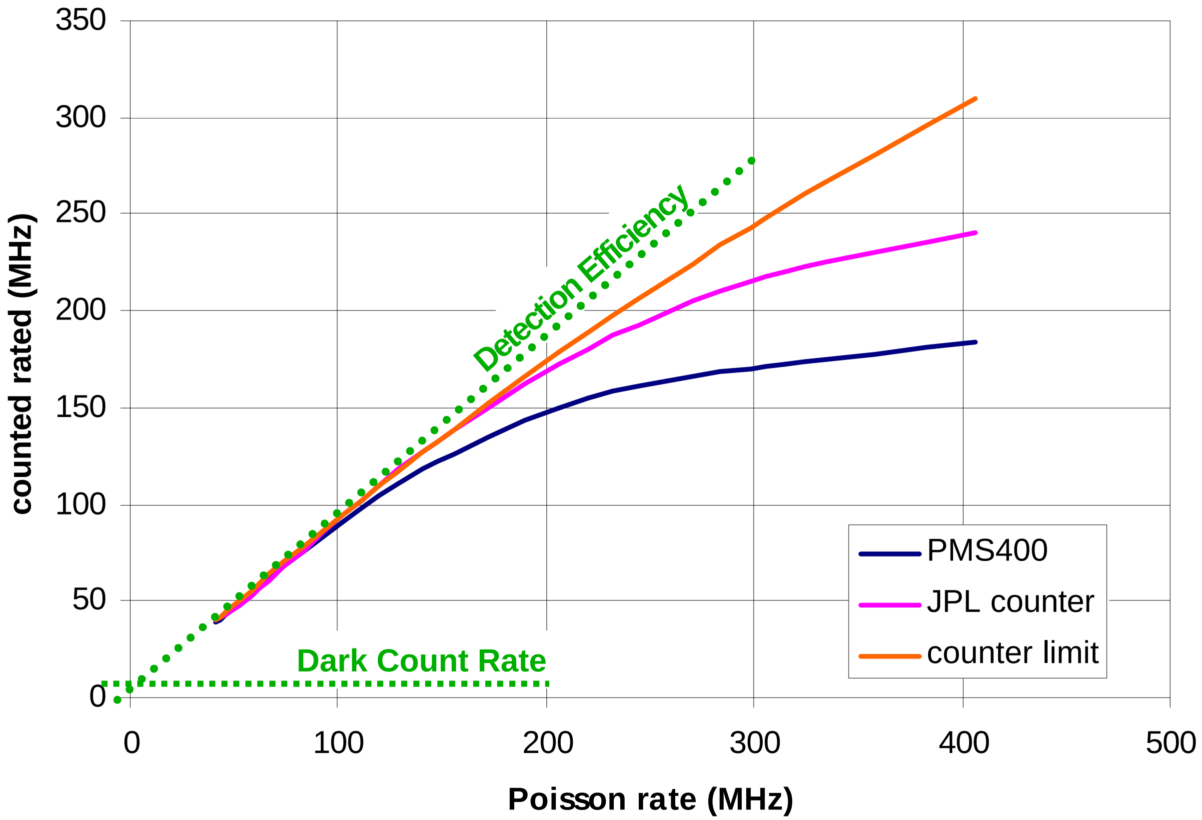


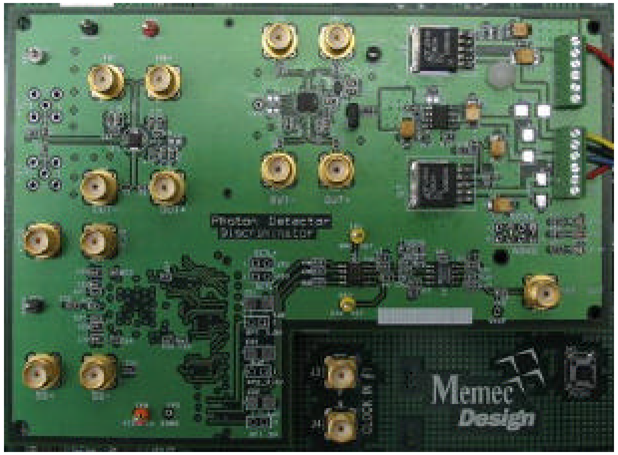




DE, DCR, and Saturation

- **DE and saturation rates for optical communications applications are best characterized using continuous illumination**
  - Thermal emitter (noise) or greatly attenuated laser (signal) well approximate a Poisson source
  - Finite pulse widths and SPCD recovery times lead to undercounting at high flux rates
    - *Recovery time greater than SPCD output pulse width is sometimes referred to as "dead" time*
  - Undercounting losses can be recovered by splitting the input optical signal across multiple detectors



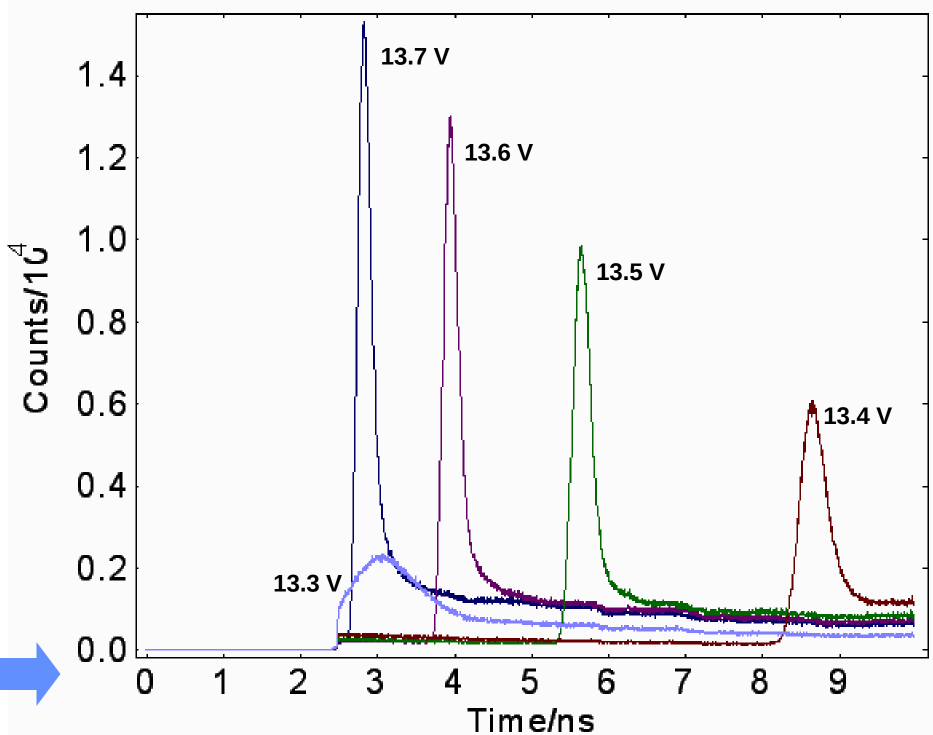


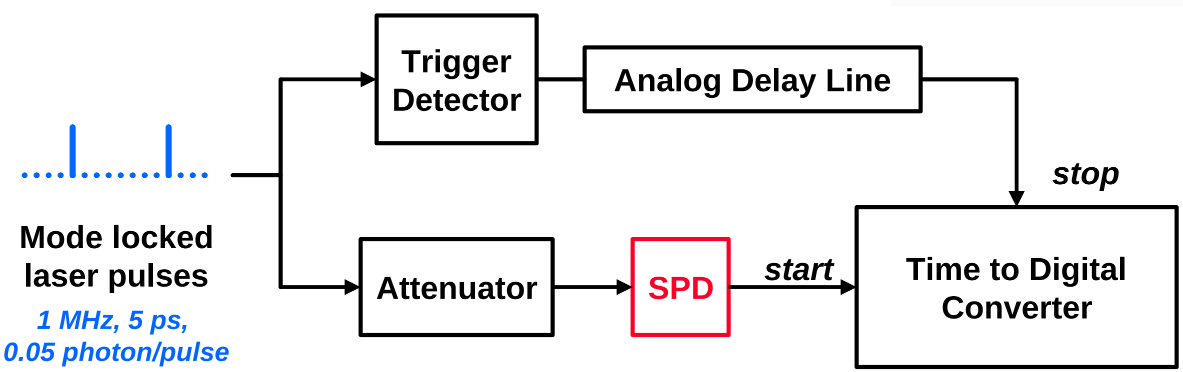
JPL 10 GHz photon counting receiver board outperforms best available commercial boards

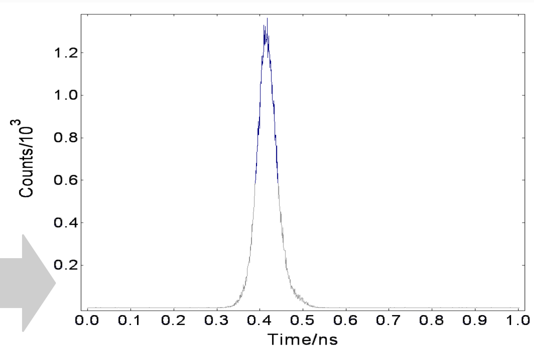
Single Timing Photon Jitter

- **Timing jitter limits ultimate SPD bandwidth**
  - Effects of finite pulse width and recovery time may be mitigated by use of edge detection and arrays, *but not timing jitter*
- **Single photon jitter can be directly characterized using a mode-locked laser source attenuated to a Poisson mean of less than 0.05 photon per pulse**
  - Probability of a two photon pulse < 1%
- **Single Channel Analyzer (SCA) technique records the delay time between the trigger pulse and the first electrical pulse above threshold out of the SPD**
- **Single photon timing jitter may be temperature and applied bias dependant**

Observed Si GM-APD Bias Dependant Single Photon Jitter



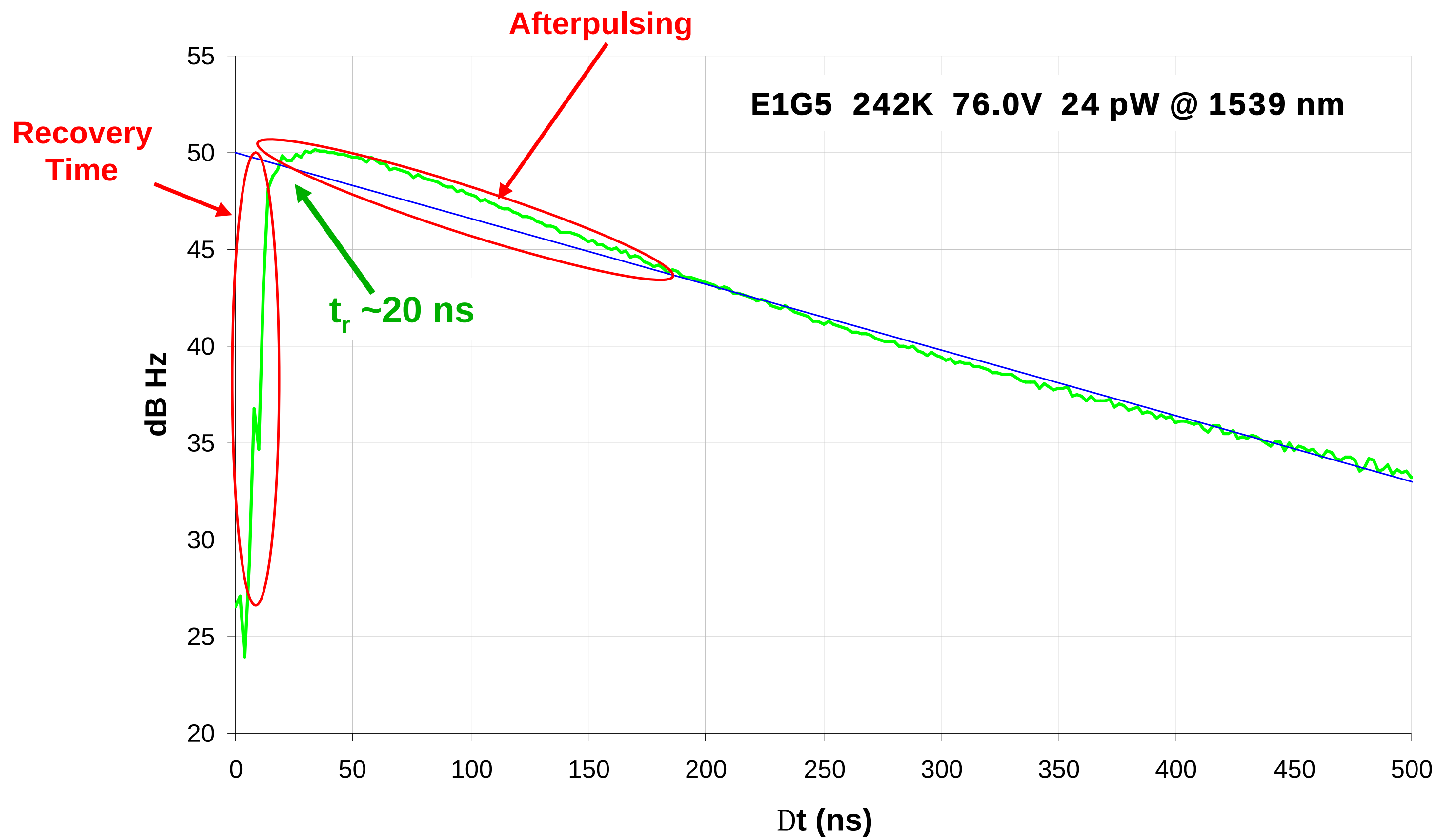




Single Channel Analyzer Histogram

Recovery Time and After-Pulsing Rate

- **As overlapping pulses will be counted as a single photon arrival event, maximum count rate is primarily a function of SPCD output pulse width and recovery time**
  - For an optical source with Poisson statistics, the interarrival times follow an exponential distribution and a semi-log plot of the pulse interarrival times should show a linear slope.
  - Response below the linear slope represents decreased effective DE for that inter-pulse interval.
  - Response above the linear slow represents after-pulsing effects that give a false high DE.



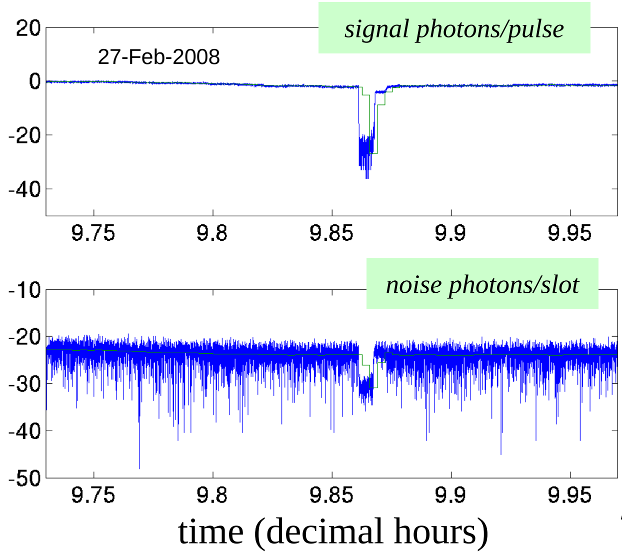
Poisson source statistics:

$$p(k) = \frac{(l\,t)^k}{k!}\, e^{-l\,t}$$

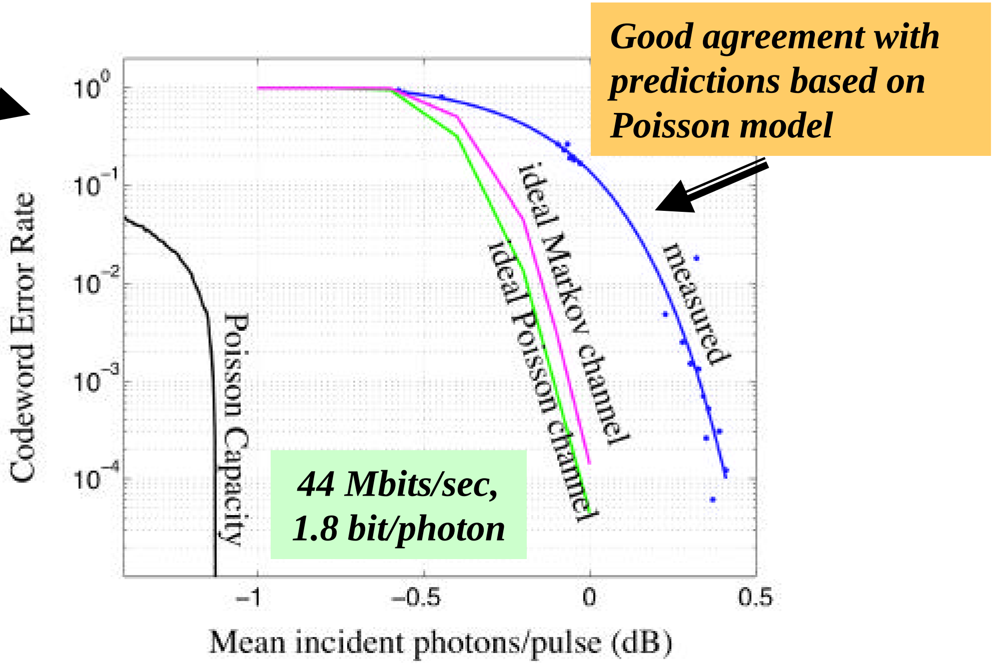
Poisson interarrival time distribution:

$$f(t) = l\,e^{-l\,t}$$

Emulated Interplanetary Optical Links



- A real-time end to end test-bed logs time-tagged optical receiver and decoder performance metrics as well as independent measures of sky radiance, transmit laser power, received laser power, and total detected photon flux rate
- Actual versus predicted photon starved link performance is quantified



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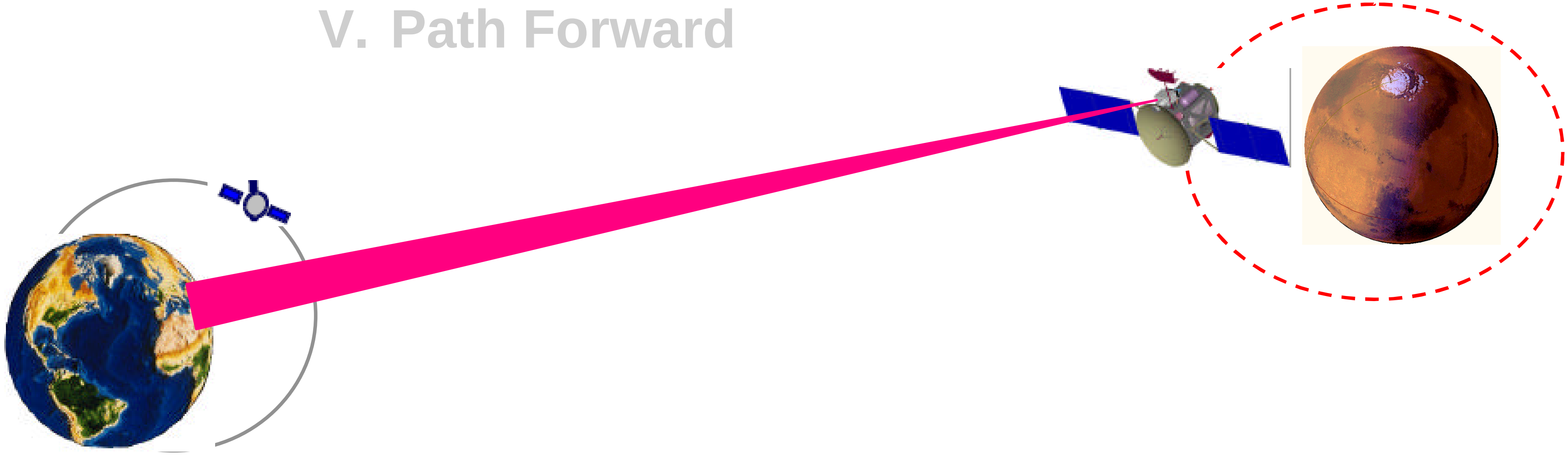
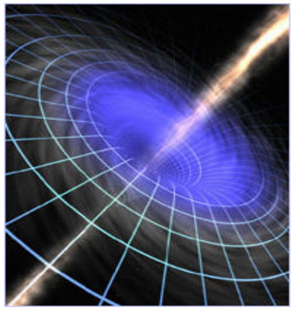


Laser Communications Light Science

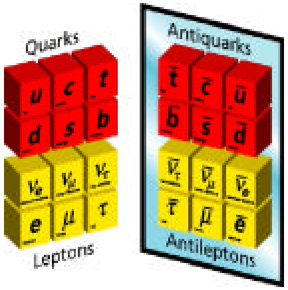
- **A deep space laser accesses very long interaction paths!**
  - Higher power•length products than accessible in laboratory or near Earth environments

- **Available measurements with the transmit laser of an optical communications transceiver:**
  - Time-of-flight
  - Wavelength dispersion
  - Nonlinear effects
    - In interplanetary media or vacuum
  - Anisotropy
    - Including linear birefringence
  - Circular (isotropic) Birefringence



- **Interplanetary Ranging for tests of Gravitation and Relativity**
  - Tests of Parametric Post-Newtonian gravitational theories
  - Tests of strong and weak equivalence principles

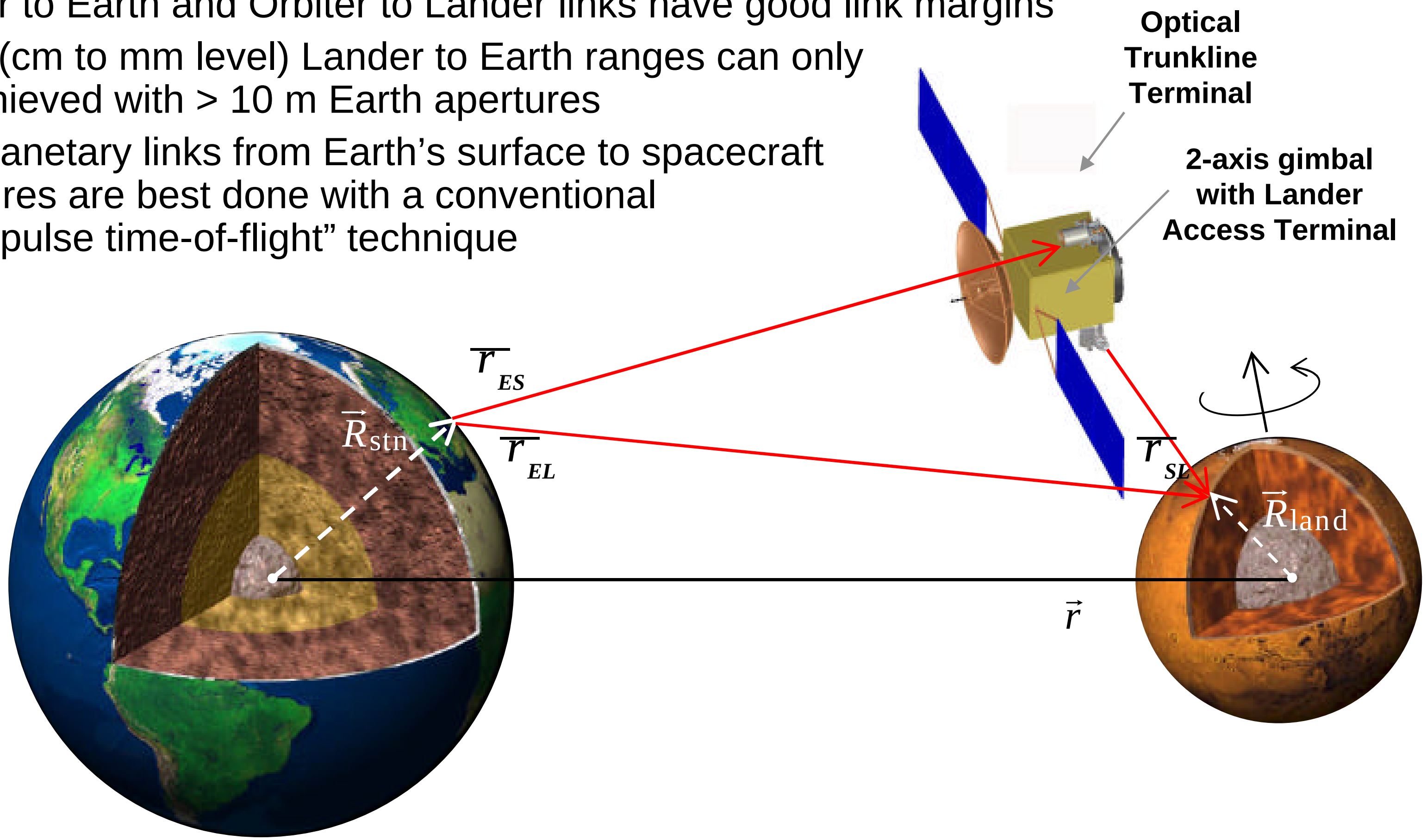
- **Interplanetary Ranging for determination of planetary interiors**



- **Tests of Fundamental Physics**
  - Physics beyond the standard model
  - Tests of time variation of fundamental physics constants

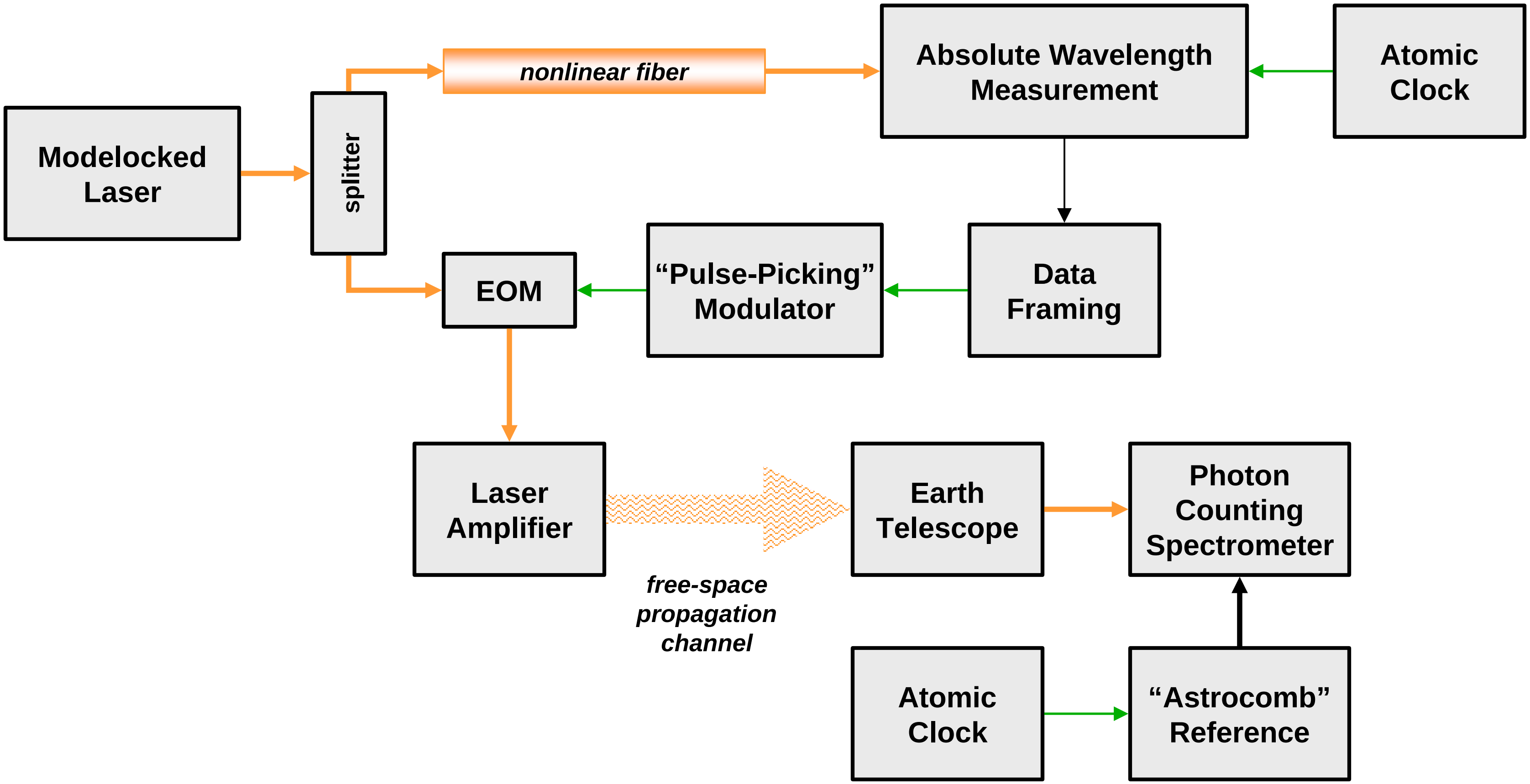
Planetary Ranging using LaserComm Terminals

- **Paired one-way ranging using asynchronous active transponders**
  - An optical communications transceiver can measure time-of-flight from timing synchronization of data encoding symbol and frame boundaries
  - Orbiter to Earth and Orbiter to Lander links have good link margins
  - Good (cm to mm level) Lander to Earth ranges can only be achieved with > 10 m Earth apertures
  - Interplanetary links from Earth's surface to spacecraft apertures are best done with a conventional "giant pulse time-of-flight" technique



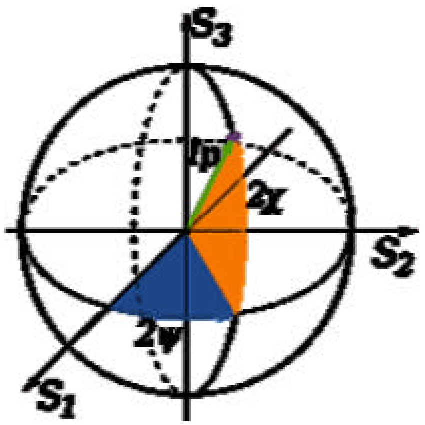
Absolute Laser Frequency Metrology

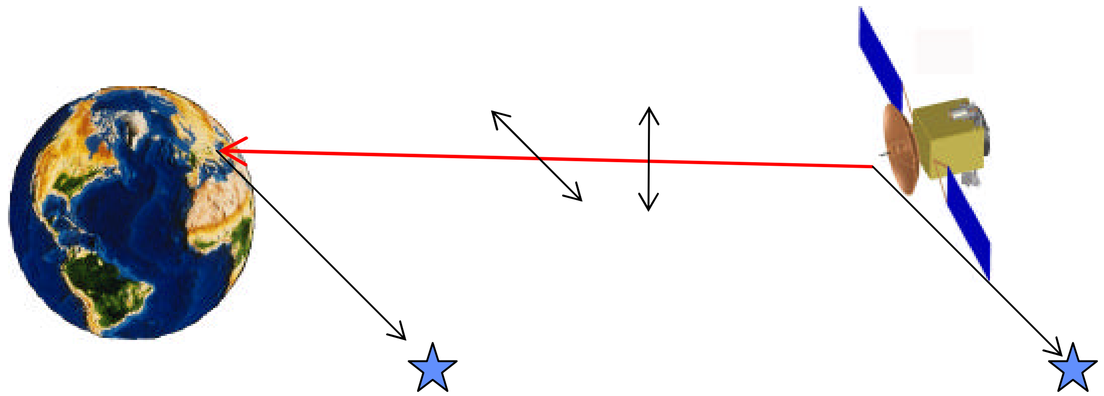
- **Octave spanning femtosecond combs combined with precision ultrastable clocks on ground and in flight can provide absolute laser frequency metrology**
  - Measure the laser frequency independently on spacecraft and at Earth, then compare



Polarization Measurements

- **Circular polarization is the preferred output from an interplanetary laser transmitting to a receiver on Earth's surface**
  - This allows rejection of at least 3 dB of background light during daytime operations, and that can as much as double the link capacity
- **Polarization measurements can come almost "for free"**
  - Can find the magnitude and orientation of any linear birefringence by transmitting circularly polarized light
    - Requires a common coordinate system for directions in space.
  - Compare state of polarization of received light when to state when transmitted.
    - Propagation vector of light defines one direction
    - Full Jones matrix (or Mueller matrix if looking for attenuation) requires another reference direction
      - Can use a star to determine orientation angle about the propagation vector, then can measure circular birefringence and anisotropic absorption





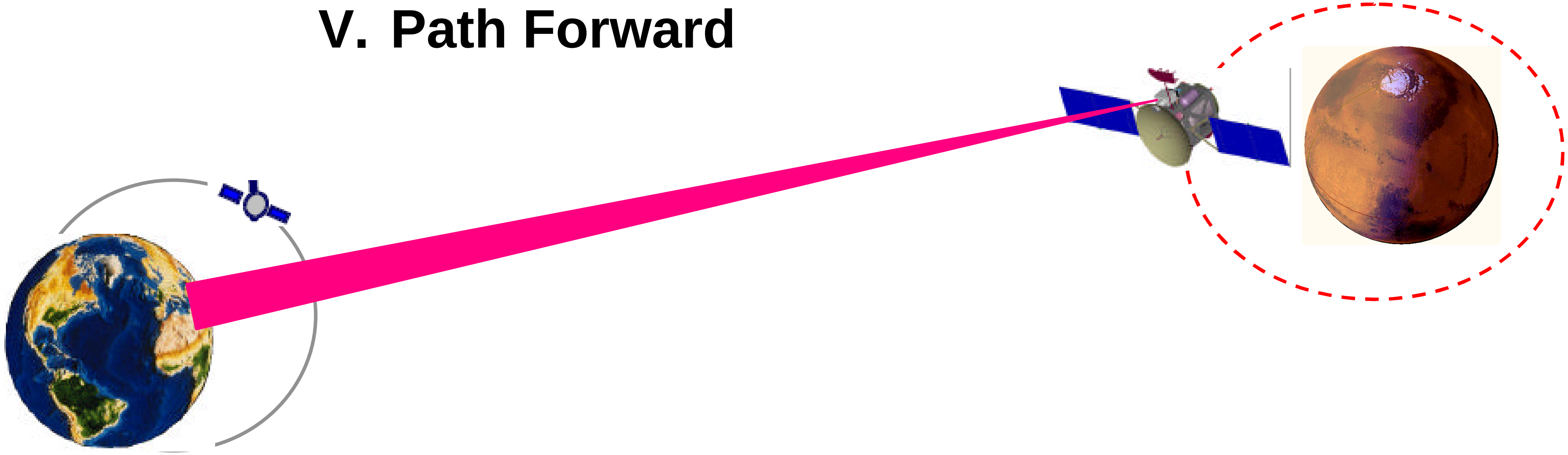
I. Laser Communications

II. SPCDs for Laser Comm

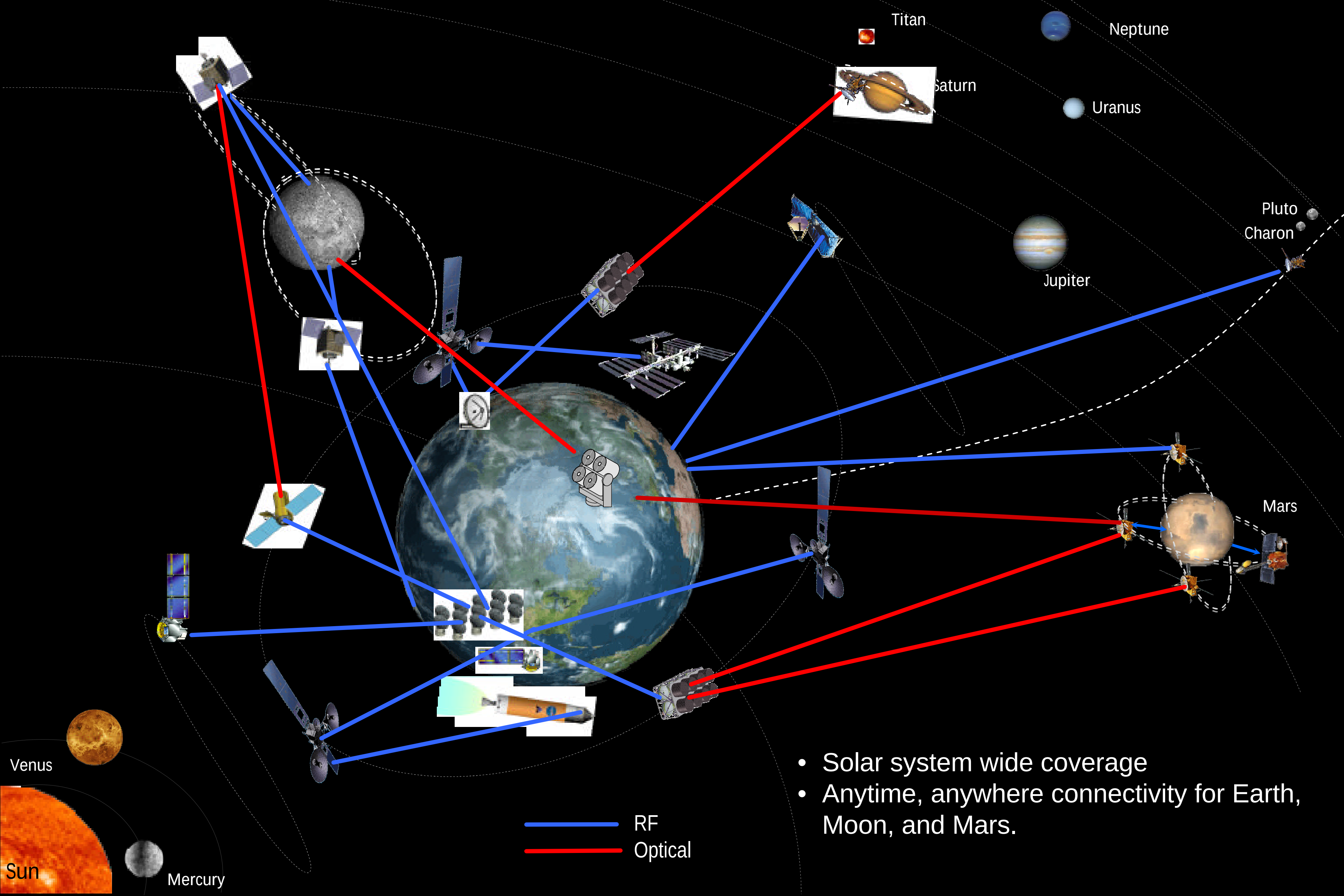
III. SPCD Characterization for Laser Comm

IV. Interplanetary Light Science

V. Path Forward



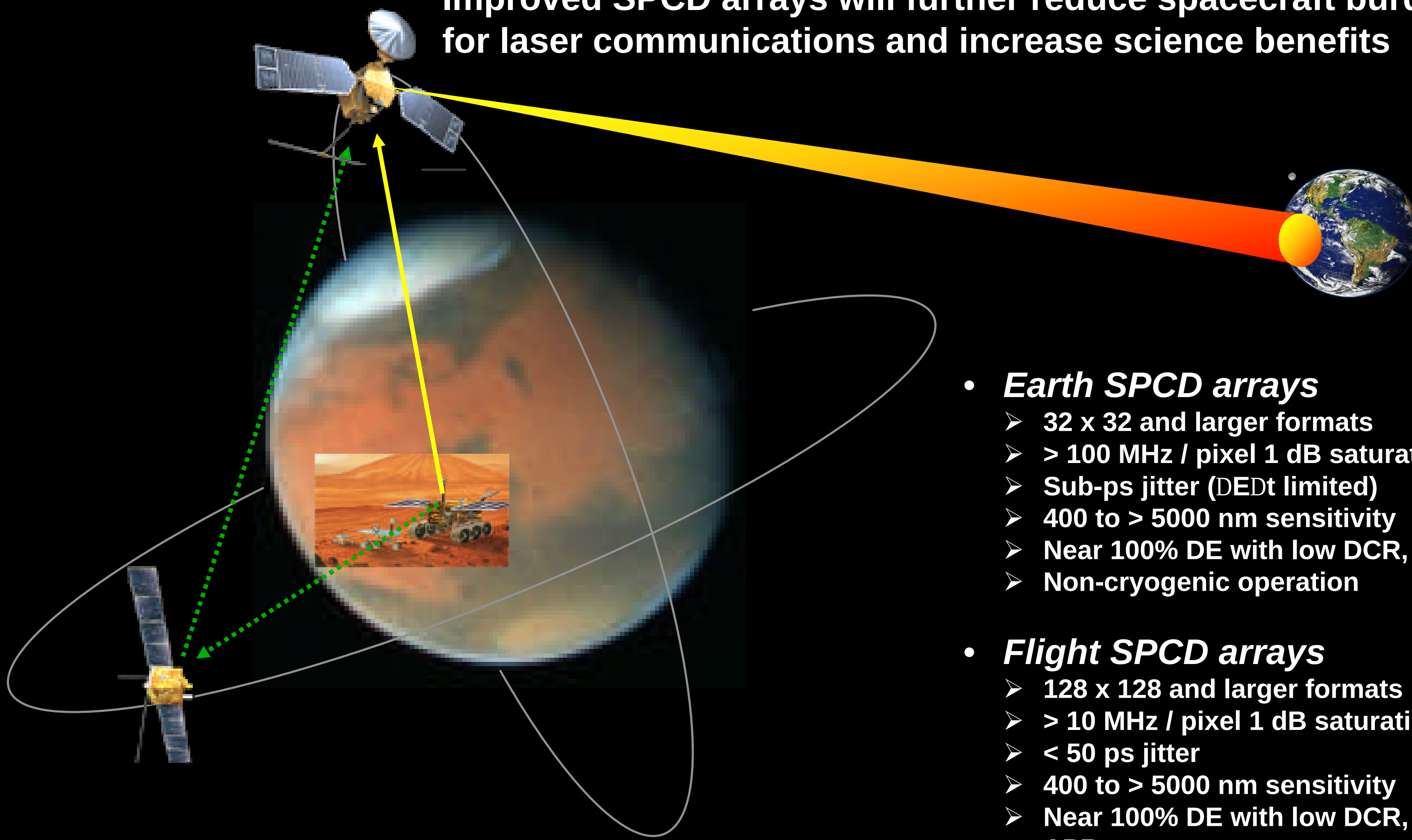
NASA Communication Architecture in 2025 Timeframe



- Solar system wide coverage
- Anytime, anywhere connectivity for Earth, Moon, and Mars.

SPCD "Needed" Developments for LaserComm

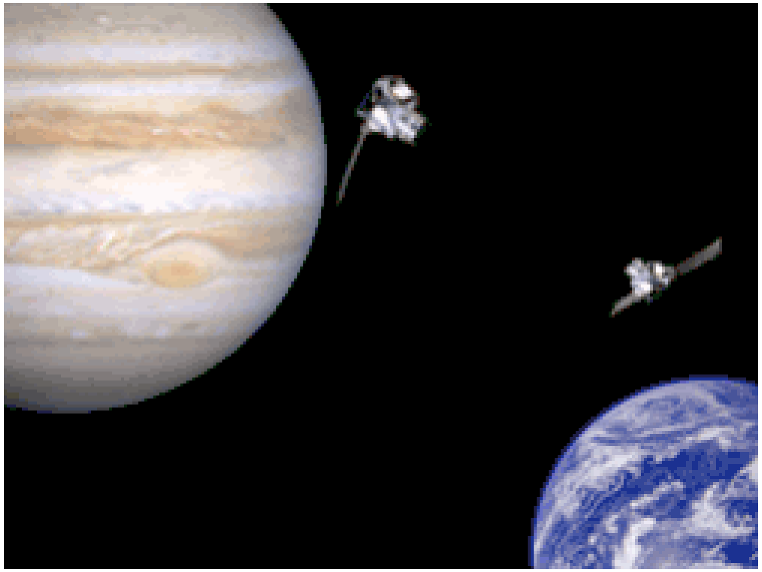
Improved SPCD arrays will further reduce spacecraft burden for laser communications and increase science benefits



- ***Earth SPCD arrays***
  - **32 x 32 and larger formats**
  - **> 100 MHz / pixel 1 dB saturation**
  - **Sub-ps jitter (DEDt limited)**
  - **400 to > 5000 nm sensitivity**
  - **Near 100% DE with low DCR, APR**
  - **Non-cryogenic operation**
- ***Flight SPCD arrays***
  - **128 x 128 and larger formats**
  - **> 10 MHz / pixel 1 dB saturation**
  - **< 50 ps jitter**
  - **400 to > 5000 nm sensitivity**
  - **Near 100% DE with low DCR, APR**
  - **Non-cryogenic operation**
  - ***Radiation Hard***

Summary

- **Expansion of telecommunications capabilities and architecture is a part of NASA's ongoing exploration activities**
  - **Optical communications capabilities are a significant component of NASA's future network architecture for both near Earth and interplanetary communications**
- ***Single photon detectors with high timing resolution, high efficiency, and low noise are an essential part of interplanetary laser communications***
- **"Dual use" laser communications systems providing increased data return volumes with reduced spacecraft burden plus *new and enhanced science* data products will be very attractive**



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