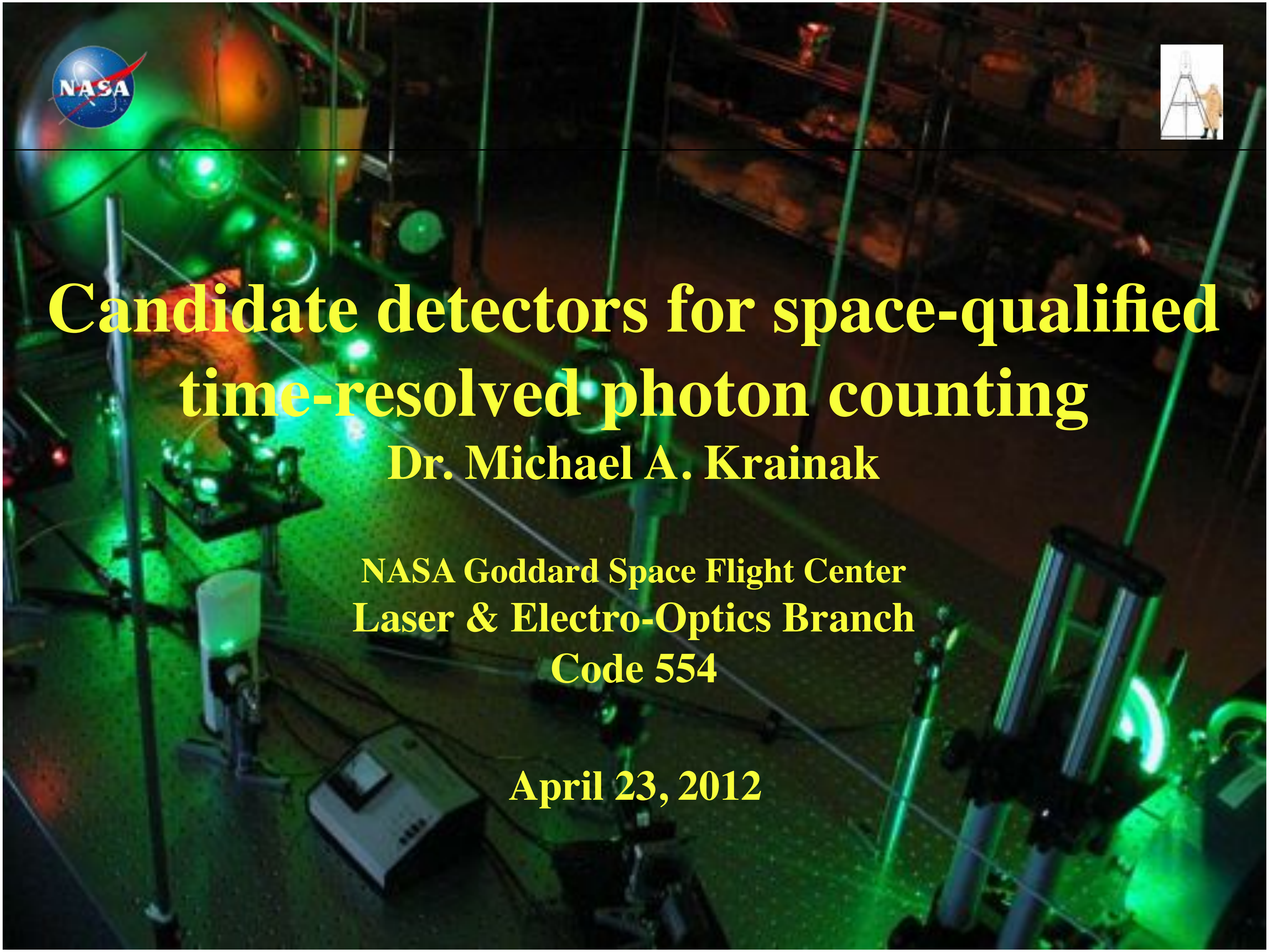


Candidate detectors for space-qualified time-resolved photon counting

Dr. Michael A. Krainak

NASA Goddard Space Flight Center
Laser & Electro-Optics Branch
Code 554

April 23, 2012

AGENDA

I. NASA LASER INSTRUMENTS

II. DETECTOR REQUIREMENTS

III. CANDIDATE DETECTORS

IV. SUMMARY

AGENDA

I. NASA LASER INSTRUMENTS

II. DETECTOR REQUIREMENTS

III. CANDIDATE DETECTORS

IV. SUMMARY

NASA Laser Instruments Methodologies

Space laser instrument techniques:

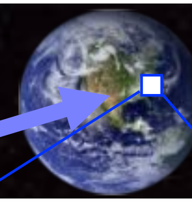
1. Time of flight with waveform processing for cm scale altimetry and atmospheric lidar
2. Tunable, multiwavelength laser spectroscopy
3. Narrow linewidth lasers for coherent (interferometric) nanometer scale laser ranging
4. Laser communications - pulse position modulation and error correcting codes with multiple bits per symbol with photon counting
5. Doppler shift for wind (not discussed in this presentation)

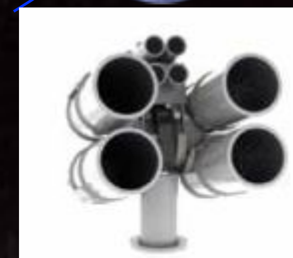
NASA Laser Instruments
Planned Missions with Photon Counting

NASA Mission	Photon Counting Detector
Lunar Laser Communication Demonstration (LLCD) on LADEE (2013)	GROUND-based: Super Conducting Nanowire Detector Array, Hybrid PMT
Laser Communication Relay Demonstration (LCRD) (2016)	GROUND-based: Super Conducting Nanowire Detector Array, Hybrid PMT
Ice, Cloud and Land Elevation Satellite (ICESat-2) Advanced Topographic Laser Altimeter System (ATLAS) (2016)	Hamamatsu PMT
Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) (2022)	HgCdTe APD, Hamamatsu PMT
The Aerosols-Clouds-Ecosystem (ACE) (2025)	Silicon APD
LIdar Surface Topography (LIST) (2028)	HgCdTe APD, Silicon APD
3D-Winds (Demo) (2030)	Silicon APD

Lunar Laser Communication Demonstration (LLCD)

LLCD on Lunar Atmospheric Dust Environment Explorer (LADEE)-Built by MIT-LL

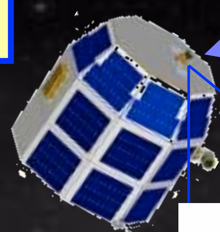




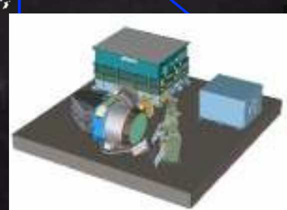
Orbiter-to-Earth Laser Communications
- 622 Mbps downlink (O-E)
- 16 Mbps uplink (E-O)
- Sub-cm ranging

400,000 km

LADEE



Terrestrial Photon-Counting Array Rx



Orbital terminal
- Inertial-stabilization
- Fully-gimbaled
- Low size, weight, & power design

2013 Launch - Wallops Island, VA

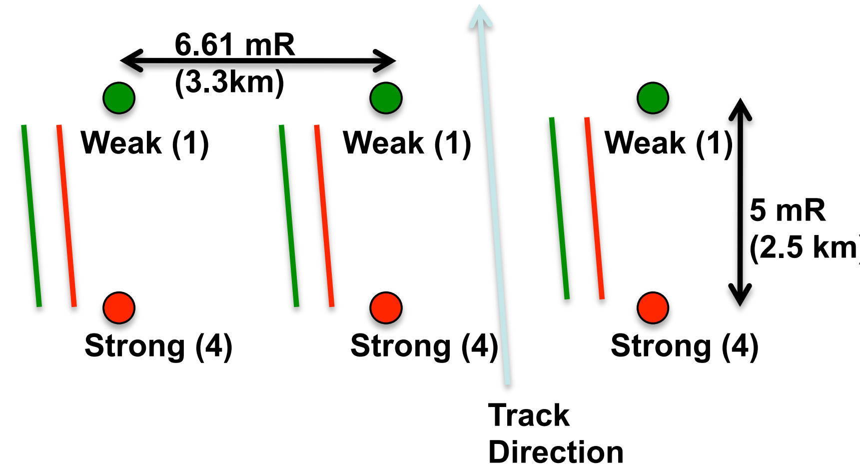
D. Boroson, "Overview and status of the Lunar Laser Communications Demonstration,"
Paper 8246-11 of Conference 8246
Date: Wednesday, 25 January 2012; Time: 3:30 PM – 3:50 PM

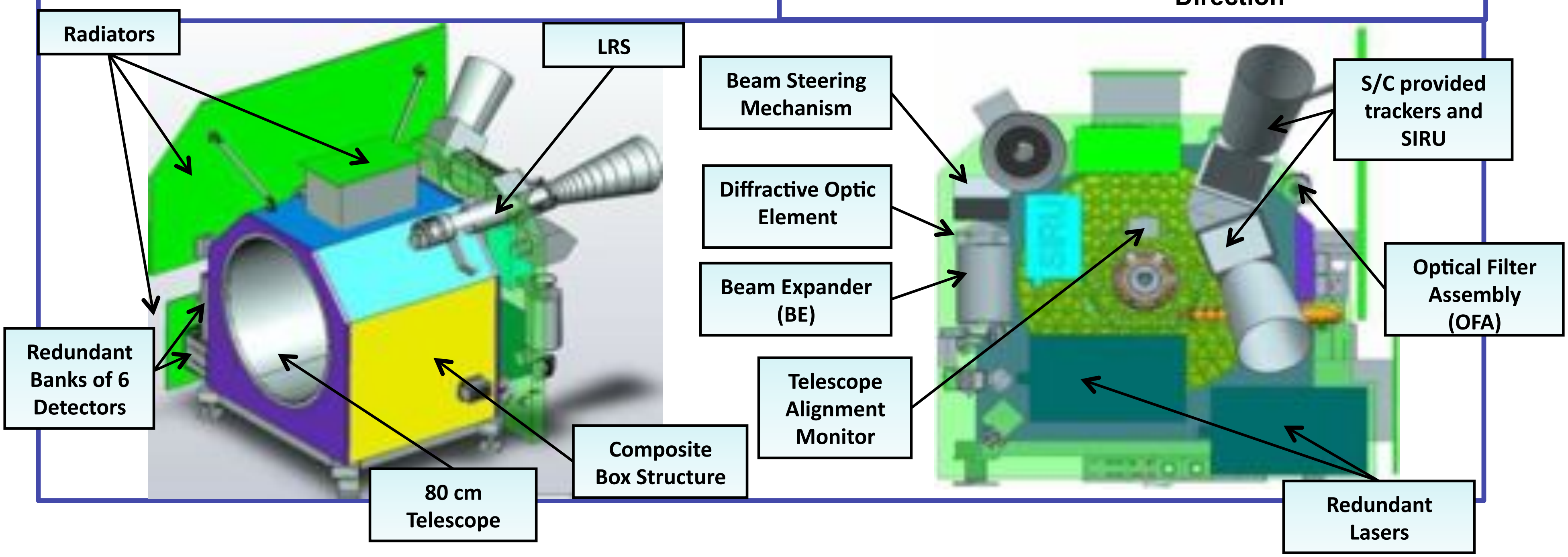
ICESat2/ATLAS
Instrument Overview

Multi-beam Micropulse Laser Altimeter

- Single laser beam split into 6 beams
- 10 m ground footprints
- 10 kHz rep. rate laser (~1mJ)
- Multiple detector pixels per spot
- On-board boresight alignment system
- Laser Reference System gives absolute laser pointing knowledge

Ground Track and Footprint

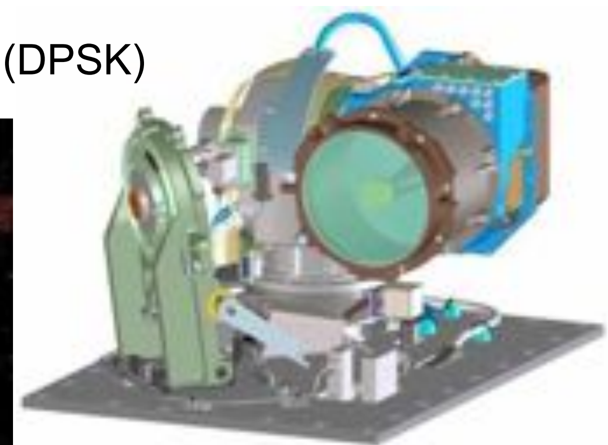




Laser Communication Relay Demonstration (LCRD)

NASA-Goddard, JPL and MIT-LL team. Dave Israel (NASA-GSFC) - PI

- GEO-Ground downlinks at 622 Mbps using Pulse Position Modulation (PPM) and 1.25 Gbps using Differential Phase Shift Keying (DPSK)
- Ground-GEO uplinks at 10 Mbps (PPM) and 1.25 Gbps (DPSK)

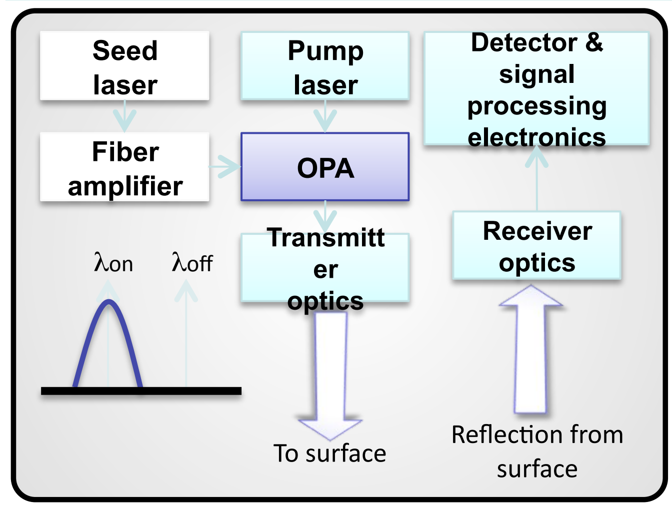


Space Flight Terminal

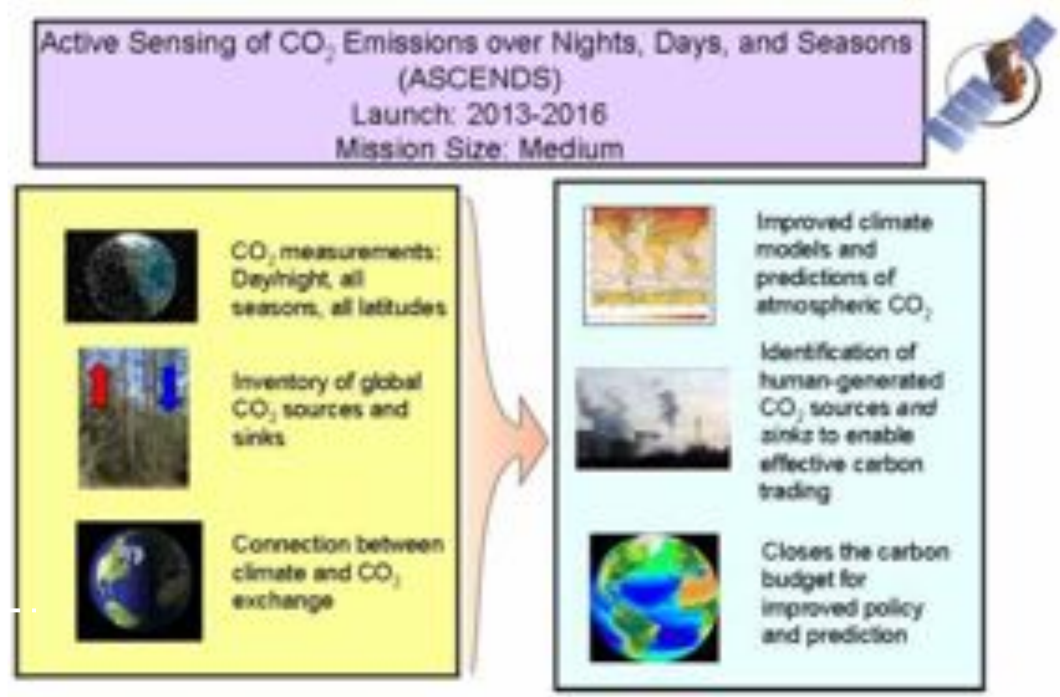
Ground Terminal (Concept)

Trace Gas Measurement for Earth & Planetary Sciences

- Generation of high spatial resolution maps of trace gas
  - Mars & earth applications
    - Laser-based measurement from orbits
    - Replacing low-resolution passive spectrometers
- Target trace gases
  - Earth
    - CO_2, CH_4, etc. as greenhouse gases
    - Absorptions at NIR wavelengths
  - Mars
    - CH_4, H_2O, etc. as life indicators
    - Absorptions at MIR wavelengths
- Differential Absorption Lidar (DIAL)
  - Receiver measures energy of the laser echoes from surface
    - On-line and off-line measurements
  - Continuous global coverage
    - No need for sunlight
- OPA-based transmitter
  - 1064nm pulsed pump
  - Tunable seed
  - NIR/MIR outputs
    - Simpler than OPO
    - Alternative to NIR fiber amp



NASA's ASCENDS Mission
Scheduled Launch - late 2019



Why lasers ?

- Measures at night & all times of day
- Constant nadir/zenith path
  - Illumination = observation path
  - Continuous "glint" measurements over oceans
- Measurements at high latitudes
- Small measurement footprint
- Measure through broken clouds
- Measure to cloud tops
- Very high spectral resolution & accuracy

Ascends Science Definition Working Group is now conducting OSSE studies to refine measurement requirements

There are several lidar approaches for CO2 column:

Broadband laser - 1570 nm band - λ tuned receiver

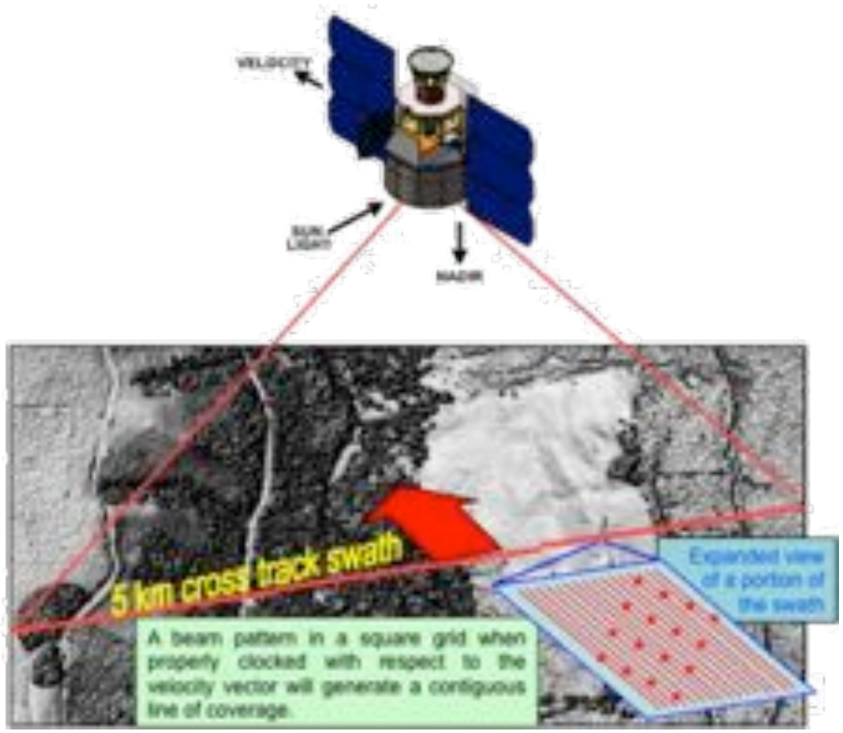
1 line - 2 um band - pulsed - direct detection

1 line - 2 um band - CW heterodyne detection

1 line - 1570 nm band - synchronous direct detection

This approach → 1 line - 1570 nm band - pulsed direct detection

LIST Instrument



Parameters	Specifications
Pulse Energy (IR)	~ 50 µJ/Channel
Repetition Rate	10 kHz
Average Power	~ 500 mW/Channel
Number of Channels	1000
Pulse Width	< 1 nS
Center Wavelength	1 µm
Wavelength Stability/Linewidth	<20 pm
Spatial Mode	$M^2 < 1.4$
Footprint from 400 km	5 m
Wall-Plug Efficiency	>20% (Prime power ~ 2.5 kW)
……	……..

- Complete mapping of the entire Earth in 3 years with 5-m spatial resolution
  - 5 km Swath with 1000 parallel profiling lines (or channels)
- Detecting ground echoes through tree canopies (2% opening) under clear sky conditions (~70% one way transmission)
- Resource Goals: < 10 kW peak electrical power (or 10 W per channel) and <700 kg mass

AGENDA

I. NASA LASER INSTRUMENTS

II. DETECTOR REQUIREMENTS

III. CANDIDATE DETECTORS

IV. SUMMARY

Need detector with high sensitivity
Key issue is achieving low-noise gain

Received Signal photons (1, 10’s, 100’s) →

Absorber
at λ (1 micron)

- InGaAs
- InAlAs
- InGaAsP
- InAlAsP
- “Thick” Silicon
- Multipass Silicon

Signal electrons (1, 10’s, 100’s) →

Electron Gain mechanism

- Transistor amplifier (too noisy)
- Electron multiplier plate (dynode) in vacuum - PMT (low noise)
- Electron bombardment in vacuum - IPD (~noiseless)
- Electron multiplication in semiconductor “impact ionization” – APD (low noise to noiseless!)

Signal electrons (~1k’s to 1 M) →

NASA-GSFC Single-Photon Counting Detectors

NASA Goals

Photon counting wavelength range	(Separate detectors) 0.3 - 4.0 μm
Detection efficiency:	> 10%
Detector size:	> 200 μm diameter (n/a to array)
1-D and 2-D arrays	.
Dark counts:	< 100 kcps
Maximum Count Rate:	> 100 Mcps
Electrical bandwidth:	> 500 MHz
Linearity:	> 98% fit
Timing jitter:	< 200 ps
Afterpulsing	< 1% in 1 μs
Resolves photon number:	Highly desirable
Operating temperature:	prefer thermo-electric cooler range
Space-qualifiable:	rugged, reliable, overlight protection

AGENDA

I. NASA LASER INSTRUMENTS

II. DETECTOR REQUIREMENTS

III. CANDIDATE DETECTORS

IV. SUMMARY

AGENDA

III. CANDIDATE DETECTORS

1. Photomultipliers
2. Avalanche Photodiodes
3. Superconducting Nanowires (not discussed)

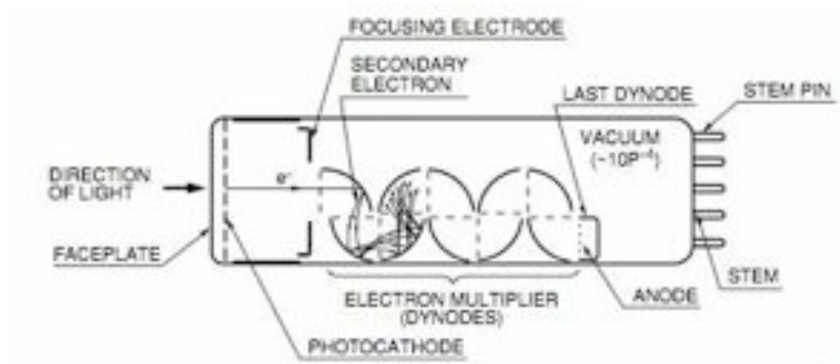
AGENDA

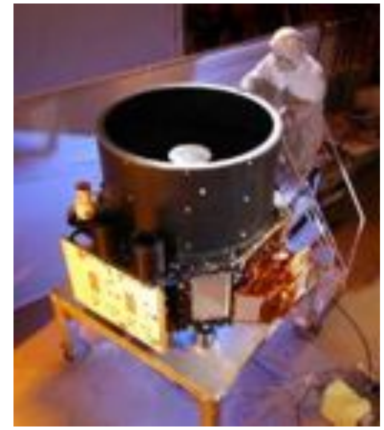
III. CANDIDATE DETECTORS

1. Photomultipliers
2. Avalanche Photodiodes
3. Superconducting Nanowires (not discussed)

Photon-counting Detector Technology

Photomultipliers – Dynode: CALIOP PMT





On-orbit on CALIOP/CALIPSO lidar (2006 launch) for use at 532 nm
Had been used on the Space Shuttle LITE lidar (1994).

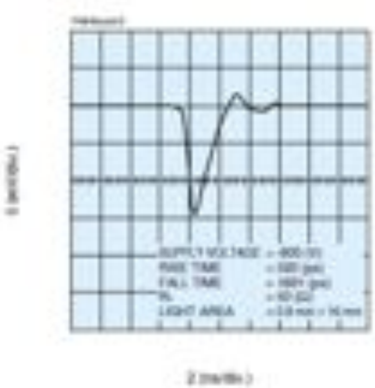
EMR Photoelectric (Princeton, NJ). Acquired by Schlumberger
(no longer selling PMTs)

Model EMR 541E-01-13
Trialakali Photocathode
15% quantum efficiency at 532 nm
50 MHz bandwidth
Used in analog mode (full waveform capture)
Excess noise factor = 1.2
NEP = 0.11 fW/rt-Hz (equivalent to 2 x 10^6 dark counts per second for Least Significant Bit)
Receiver uses 14-bit digitizer

Photomultipliers – Dynode: PAMELA PMT

1 GHz bandwidth, 15% QE @532 nm

Figure 6: Typical Time Response



Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

The time-of-flight system of the PAMELA experiment: In-flight performances

R. Carbone[a,b,*], G. Barbarino[a,b], D. Campana[b], G. De Rosa[a,b], W. Menn[c], G. Osteria[b], S. Russo[a,b], M. Simon[c]

Photo-multiplier tubes

The light produced by the scintillators is viewed by mod. R5900 [3] PMTs, manufactured by Hamamatsu Photonics. The R5900 is a metal package head-on PMT, with a square section of 30×30 mm². This PMT suits very well our needs, for its limited size, weight (25.5 g) and power consumption. Although not specifically designed for space-borne applications, it has undergone several environmental tests by NASA and it has been already successfully employed in a space-borne experiment. The R5900 PMTs for the PAMELA ToF are selected with a Quantum Efficiency QE > 21%.

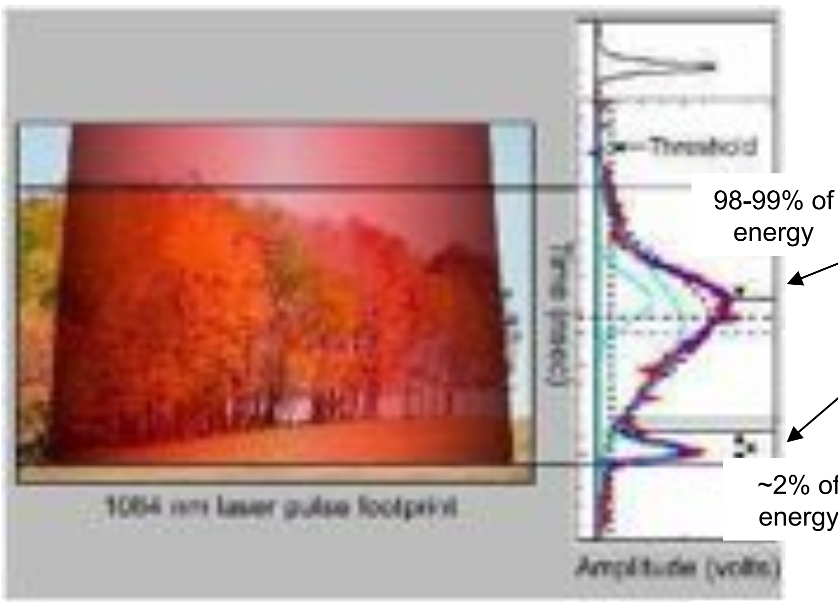
The R5900 is relatively tolerant of magnetic fields and although the core of the PAMELA apparatus is a permanent magnet, the PMTs need only a 1 mm thick μ-metal screen.

Redundant 900 V HV supplies are connected to each PMT through a regulator circuit capable of 800 V swing. This is used to trim the individual PMT gains and to compensate for differential aging of the PMTs and scintillators. Voltage is distributed within each PMT by a resistive voltage divider designed to accommodate the largest particle rates to be measured.

Scintillator application: Flux rate is very low compared to lidar

Requirement to detect the weakest signal drives the lidar design
(courtesy of J.Abshire)

A sample ICESat/GLAS Echo Waveform from tree(s)



Echo pulse waveform
(backscattered laser power vs time)

Echo pulse from Tree canopy

Echo pulse from ground under trees
Energy proportional to canopy opening faction
For LIST, the opening fraction is ~2%

- *GLAS acquires waveforms from vegetated terrain in a ~ 70 m diameter laser footprint*
- *Waveforms show height distribution of backscattered light reflected from canopy surfaces and underlying ground*

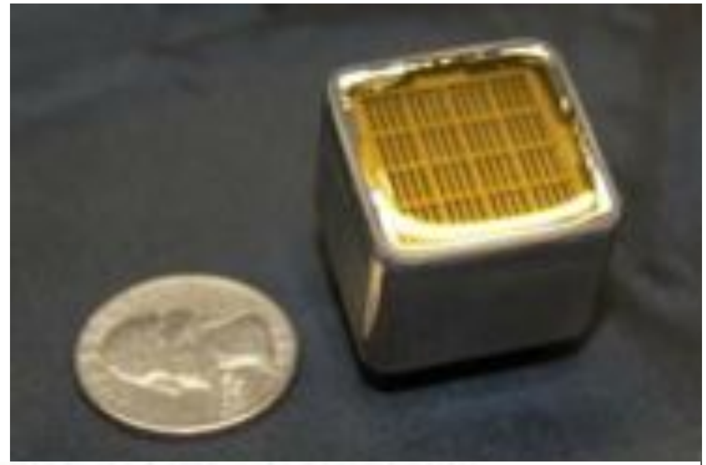
⇒ Energy in ground echo is ~2% of that from tree tops

- Is weakest signal the altimeter receiver has to detect
  - Energy scales with sub-canopy surface reflectivity
    - Must reliably detect signal in presence of noise
      - (detected solar background rate)
    - Need at least several detected photons/pixel

ICESat2/ATLAS detector

Hamamatsu R-7900-16M

- Successfully used on PAMELA ESA space mission
- Qty: 680 will fly on Alpha Magnetic Spectrometer ESA space mission.
- Quantum Efficiency >15%
- 350 ps timing jitter
- 1 GHz BW
- High reliability
- Negligible radiation damage



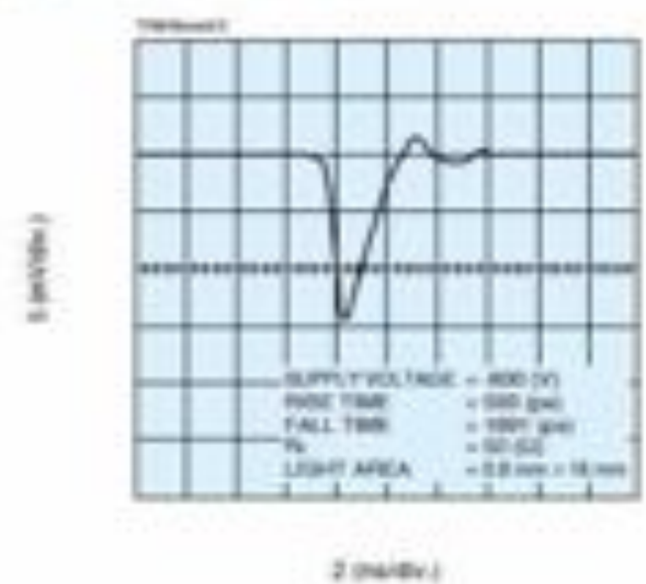
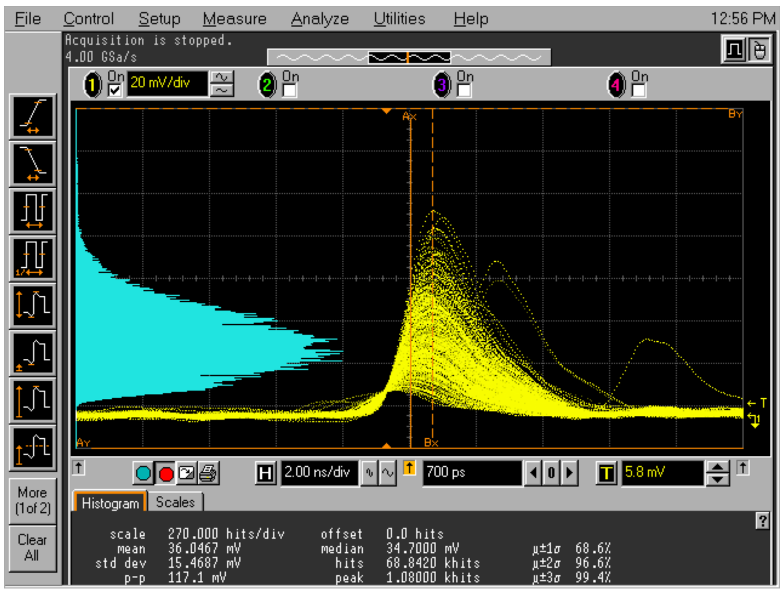


Figure 6: Typical Time Response

Dynode Near-Infrared PMT
Excess Noise Factor

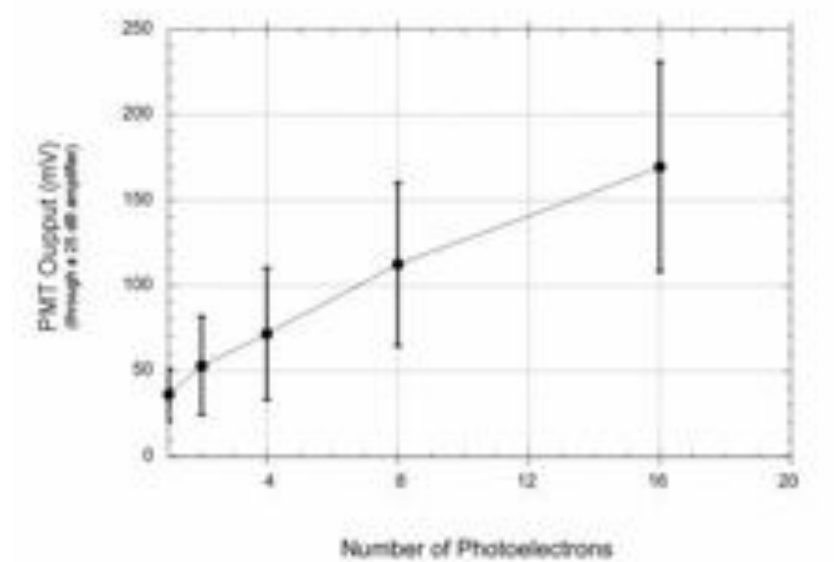
PMT output pulse waveform
of single detected photon, 600V (gain ~3e5)



The excess noise factor may be obtained from pulse amplitude fluctuation under single photon detection, as,

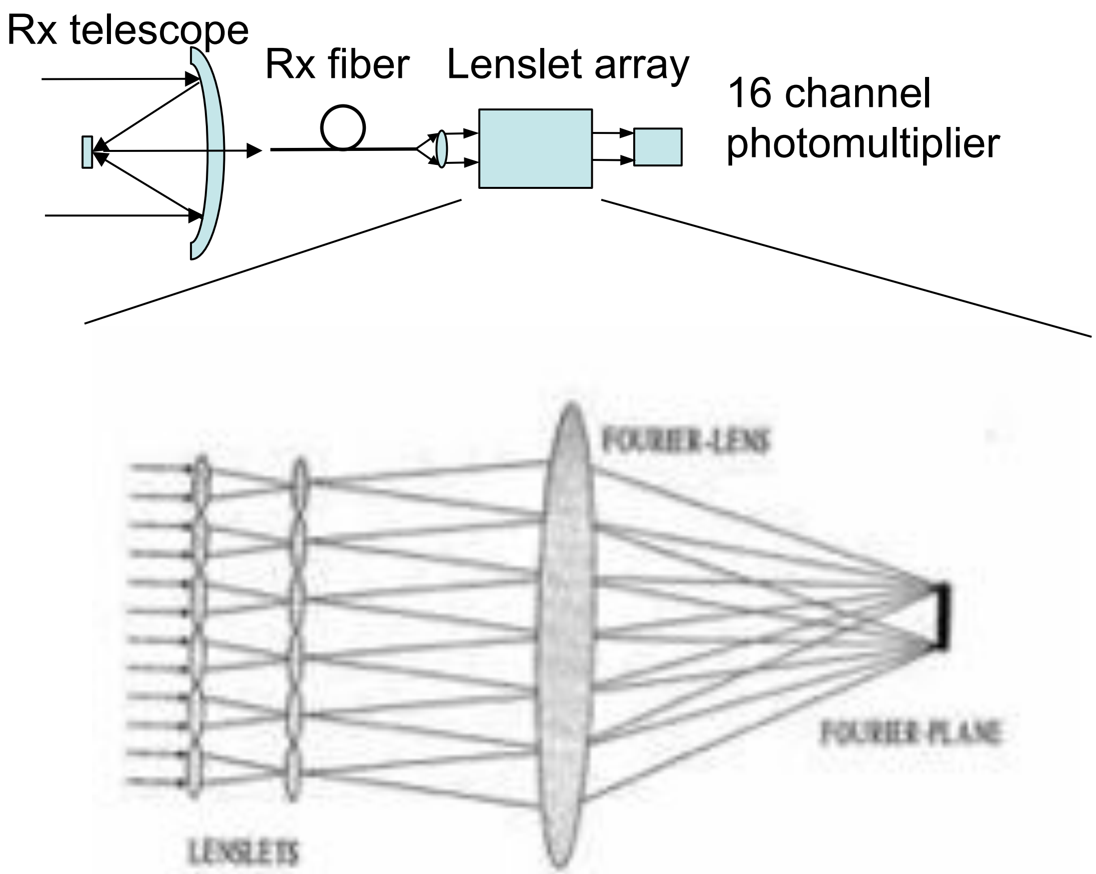
$$F \equiv \frac{\langle g^2 \rangle}{\langle g \rangle^2} = 1 + \frac{\sigma_g^2}{\langle g \rangle^2} = 1 + \frac{\sigma_{ampl}^2}{\mu_{ampl}^2} \approx 1.2$$

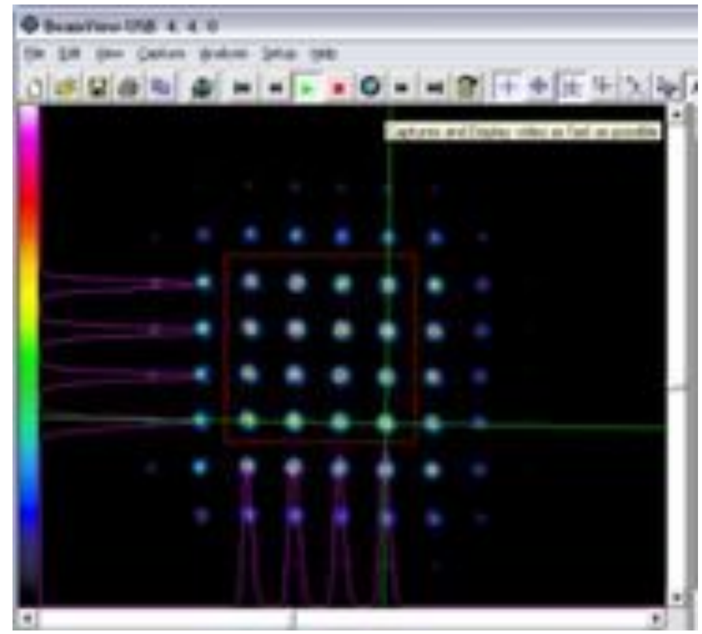
PMT output vs input, 600V (gain ~3e5)
under 80 ps FWHM1060 nm laser pulses



The excess noise factor is still too large to resolve the number of photons in the pulse (the error bars too large and overlaps for up to 16 detected photons, or 94 incident photons)

Uniform array of spots for spatial photon number resolution

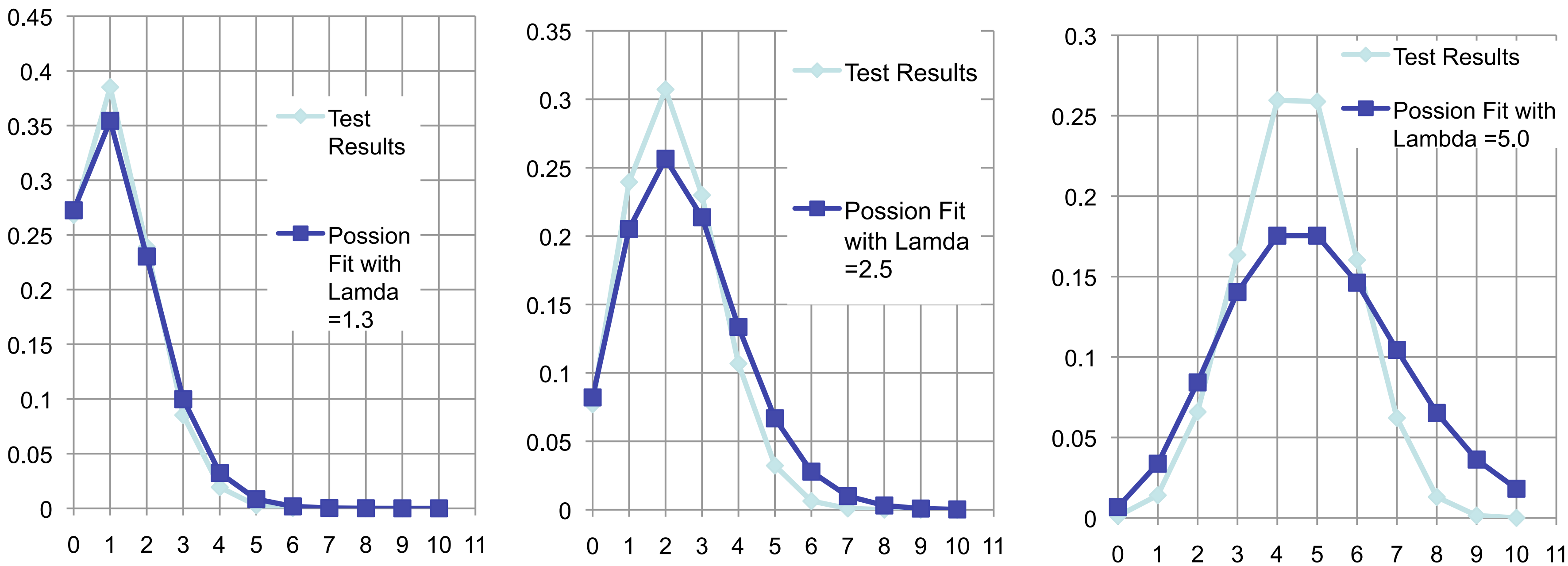




Uniform intensity spots
Generated with two
5 x 5 microlens arrays

From: “Array generation with lenslet arrays”
N. Streibl et al. Applied Optics Vol 30. No. 19 July 1, 1991

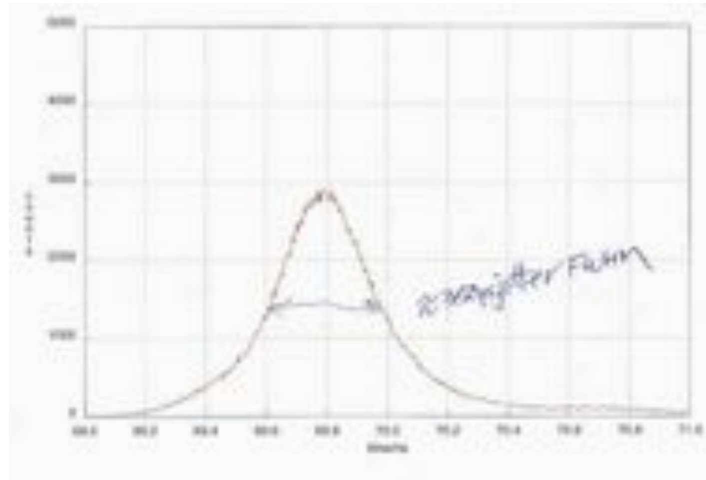
Spatial photon number PMT Test Results



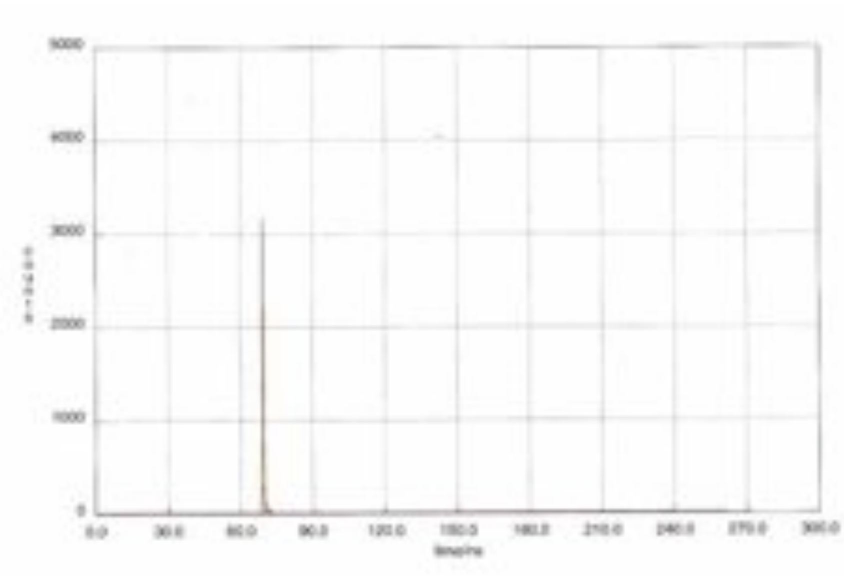
$$f(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Measured scaled histogram of the pulse height distribution and Poisson theory for (a) $\lambda=1.3$ b) $\lambda=2.5$ c) $\lambda=5.0$

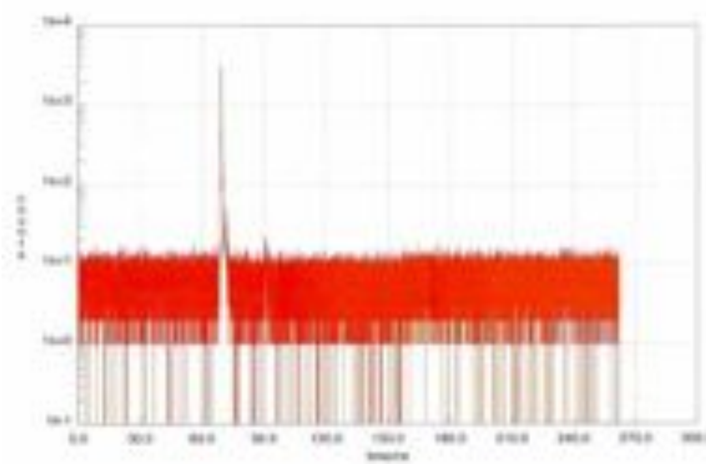
Dynode Near-Infrared PMT
Jitter and Afterpulsing



Histogram of PMT output pulse time in response to 80 ps FWHM 100kHz laser pulses At gain ~1e6



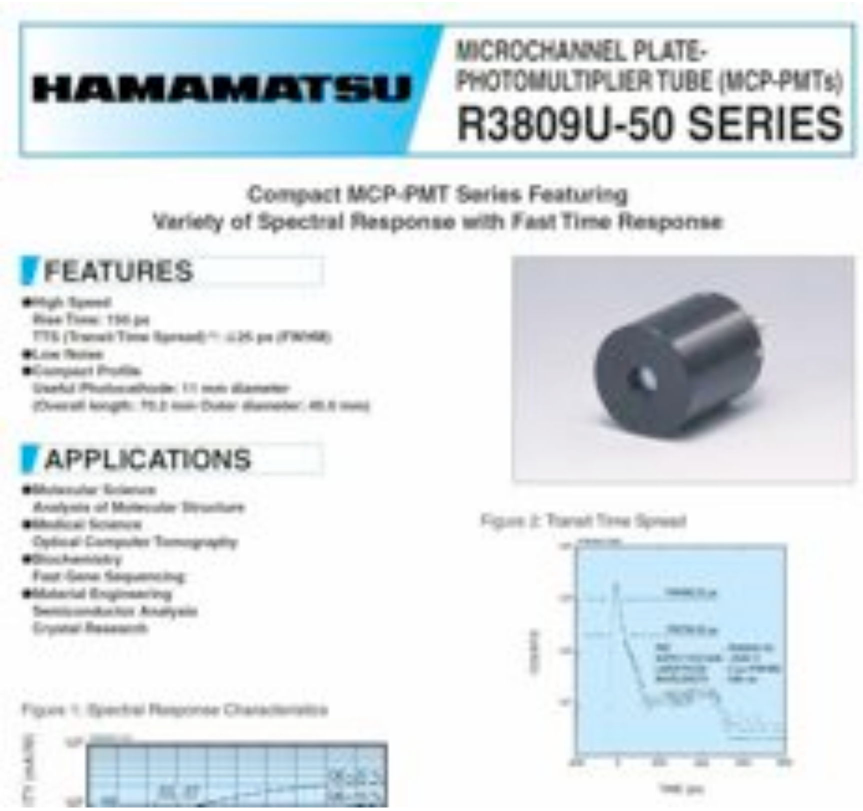
No measurable afterpulsing !



350 ps FWHM timing jitter

Photon-counting Detector Technology

Photomultipliers – Micro Channel Plate



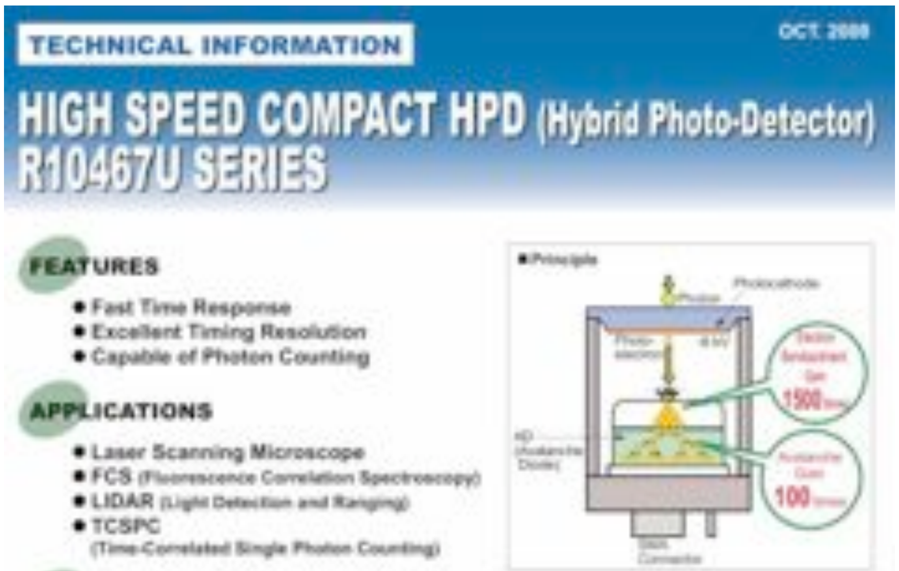
Very low timing jitter (<100 ps)

> 1 GHz bandwidth

35% QE @532 nm

Multi-anode (100 pixels) version available Model **R4110U**

Photomultipliers – Hybrid - Visible


TECHNICAL INFORMATION

OCT. 2008

HIGH SPEED COMPACT HPD (Hybrid Photo-Detector) R10467U SERIES

FEATURES

- Fast Time Response
- Excellent Timing Resolution
- Capable of Photon Counting

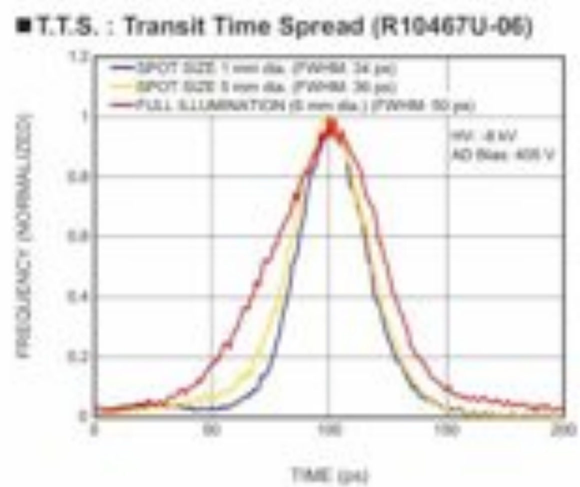
APPLICATIONS

- Laser Scanning Microscope
- FCS (Fluorescence Correlation Spectroscopy)
- LIDAR (Light Detection and Ranging)
- TCSPC (Time-Correlated Single Photon Counting)

Very low timing jitter (<100 ps)

> 1 GHz bandwidth

45% QE @532 nm



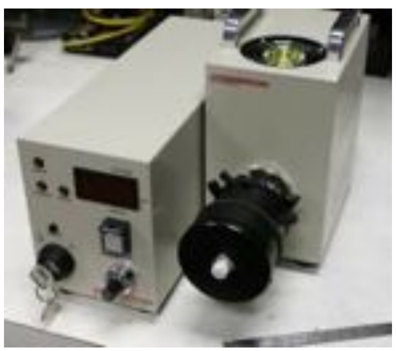
Photomultipliers – Dynode: Near infrared PMT

- Hamamatsu NIR-PMT 10330-75, s/n BB0085 near infrared photomultiplier tube. "Champion" device.

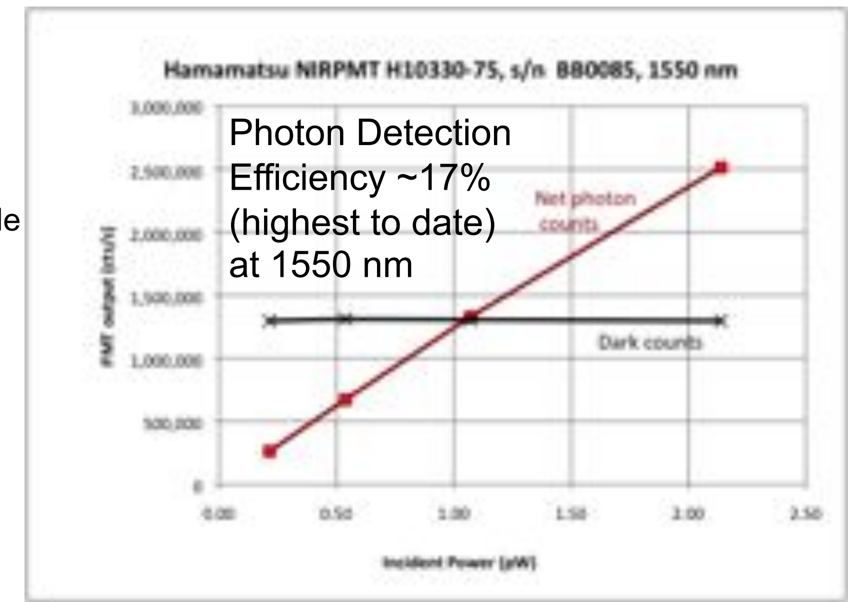
- 18% quantum efficiency: 0.9 to 1.55 um wavelength.

H10330-75   TEC cooled with no vacuum pump

HV supply and PMT housing



TO-8 PMT package with transmissive photocathode



Photon-counting Detector Technology

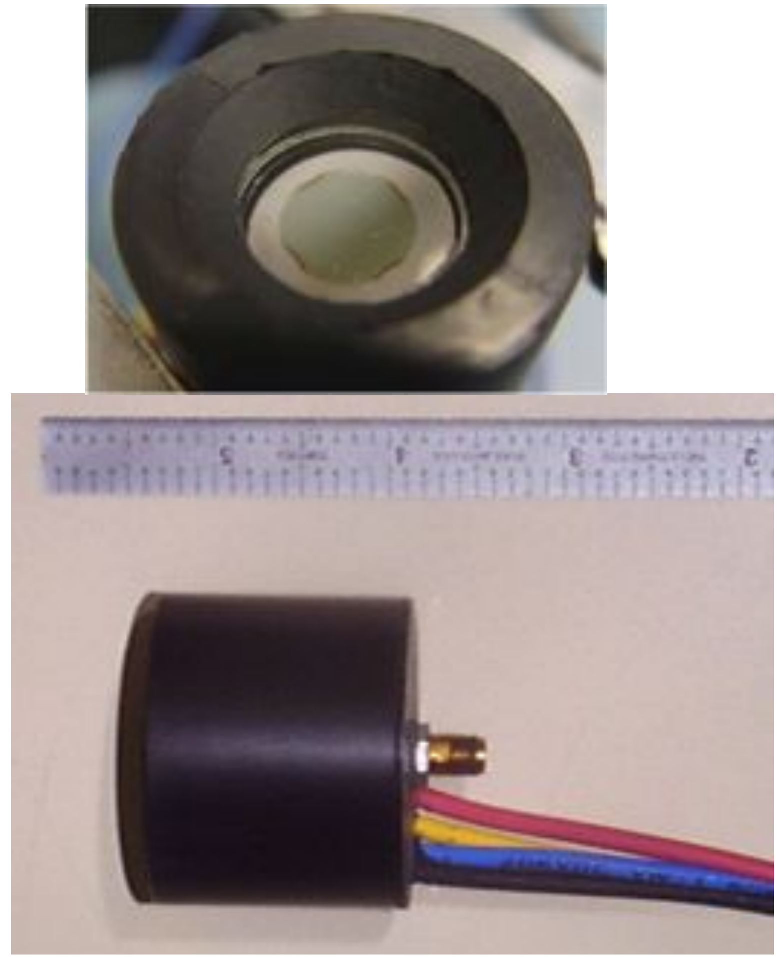
Photomultipliers – Hybrid - Infrared

- Transfer electron (TE) photocathode
  - InGaAsP for 1000-1300 nm
  - InGaAs for 1000-1600 nm (higher dark count rates)
  - PMTs with similar photocathode have been commercially available and the performance has been improving.

- GaAs Schottky APD anode for low timing jitter and wide electrical bandwidth (~1GHz).

- HPMTs with TE photocathodes
  >25% QE at 1064 nm

  >15% QE at 1550 nm

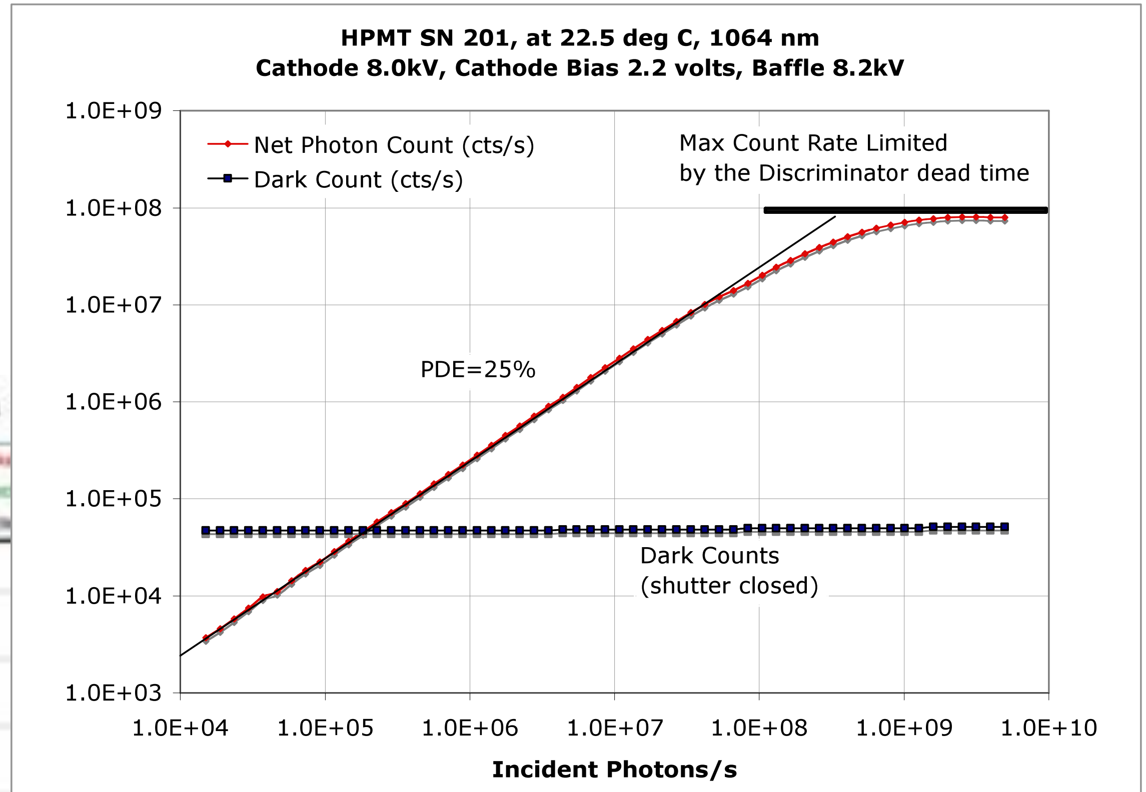


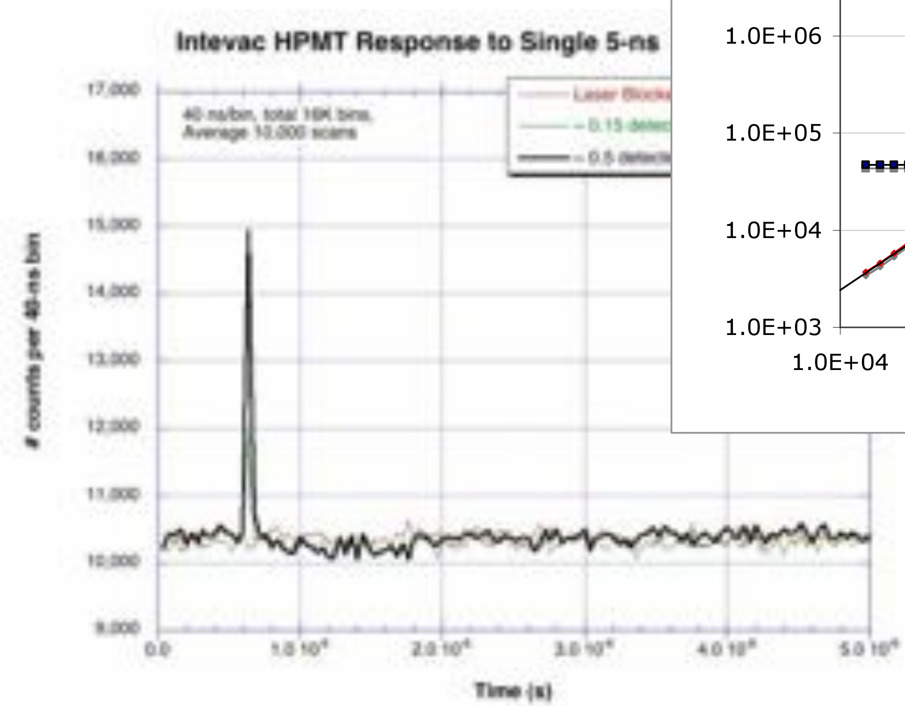
InGaAsP HPMT from Intevac Inc.

Photon-counting Detector Technology

Photomultipliers – Hybrid - Infrared

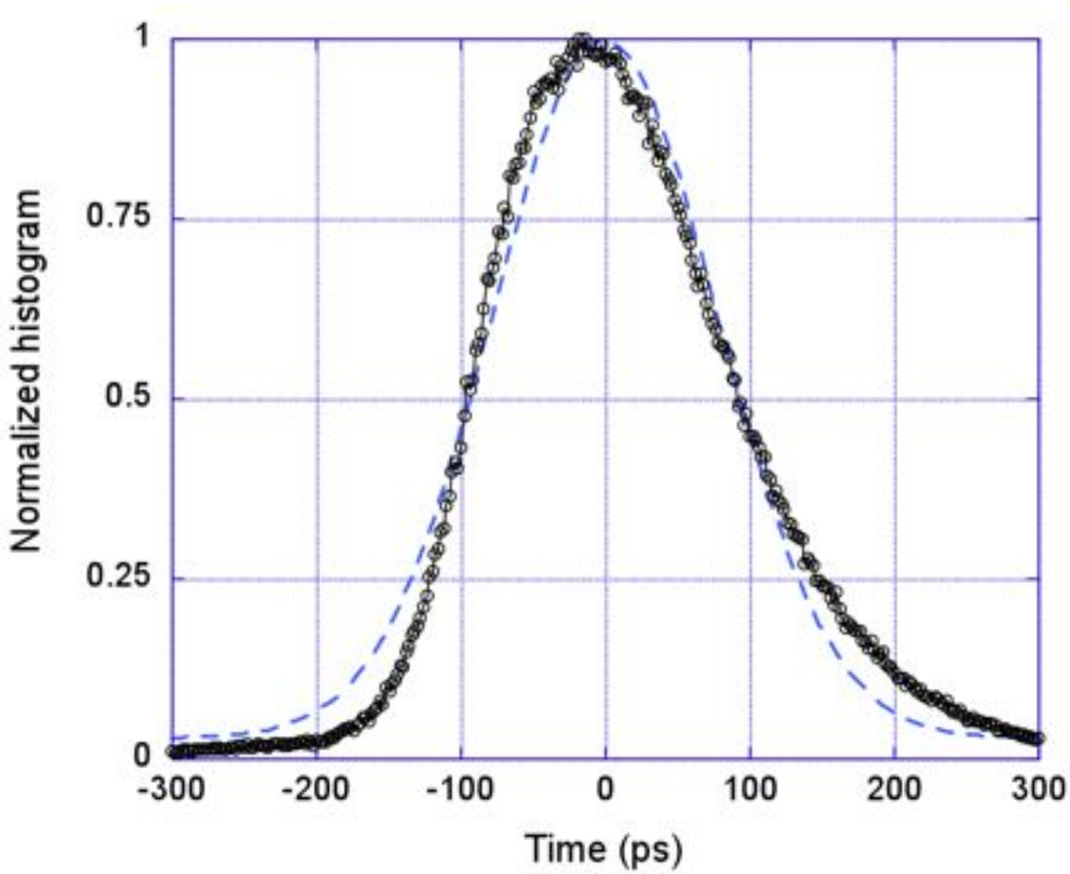
Incident laser pulse width <100 ps (PicoHarp 300, with a 1060 nm laser head)





No afterpulsing detected

Single-photon timing jitter per pixel measurement

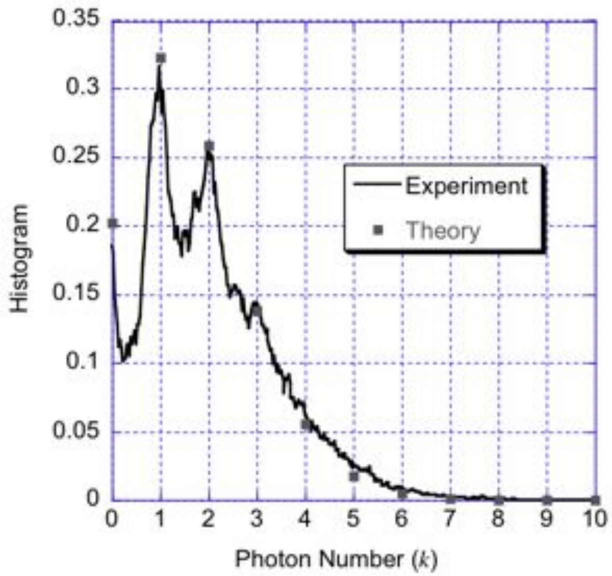


Results for IPD with thinner (0.8 μm) InGaAsP layer thickness.

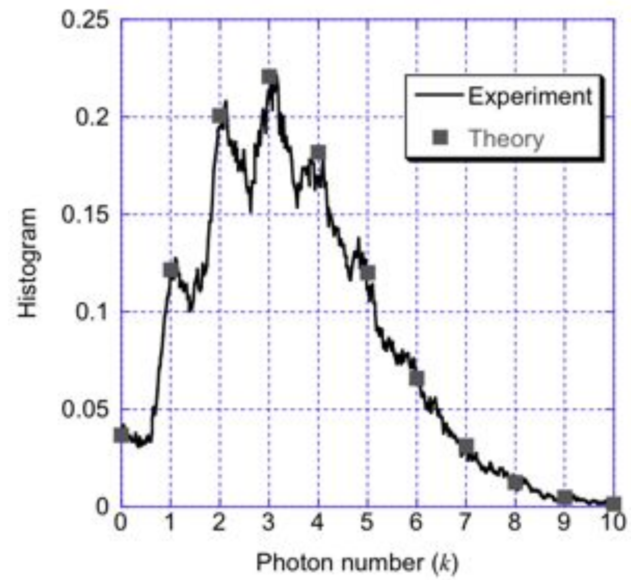
FWHM = 188 ps.

Dashed line is Gaussian fit with $\sigma = 78$ ps.

Photon number (pulse height distribution) per pixel measurement vs. theory



λ=1.6



λ=3.3

$$f(k,\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Measured scaled histogram of the pulse height distribution and Poisson theory for (a) λ=1.6 and b) λ=3.3

1550 nm HPMT

- Quantum efficiency > 20% (vendor data) at 1550 nm.
- Dark counts reduced by reducing area to 167 mm x 167 mm AND cooling to -30 C. (predict < 100 kcps)
- Single photocathode device with 16 (4x4) element anode will be used at the Jet Propulsion Laboratory Optical Communication Telescope Laboratory (OCTL) ground station for the Lunar Laser Communication Demonstration (LLCD)

NASA-GSFC Single-Photon Counting Detectors

NASA Goals

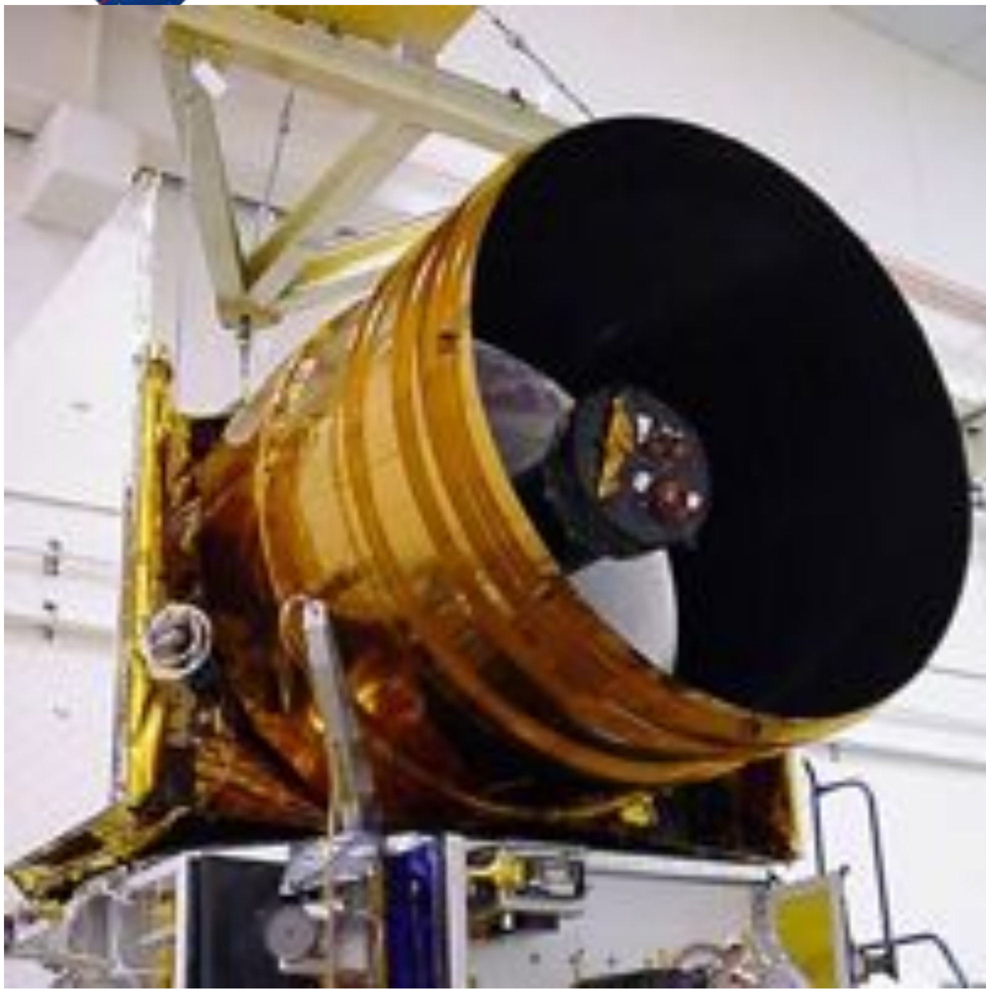
		HPMT/PMT
Photon counting wavelength range	(Separate detectors) 0.3 - 4.0 µm	Visible, Near-IR1 (0.9-1.3), Near IR2 (1.3-1.7)
Detection efficiency:	> 10%	20%
Detector size:	> 200 µm diameter	Vis,N1: 1 mm, N2: 167 µm
1-D and 2-D arrays		Vis 10 x10, N1: quad
Dark counts:	< 100 kcps	< 100 kcps or even lower
Maximum Count Rate:	> 10 Mcps	> 200 Mcps
Electrical bandwidth:	> 500 MHz	~ 1 GHz
Linearity:	> 98% fit	> 98%
Timing jitter:	< 200 ps	500 ps, less than 200 ps thin
Afterpulsing	none	~ none
Resolves photon number:	desirable	Yes
Operating temperature:	prefer TE cooler range	TEC
Space-qualifiable:	rugged, reliable, ÒoverlightÓ protection	??????

AGENDA

III. CANDIDATE DETECTORS

1. Photomultipliers
2. Avalanche Photodiodes
3. Superconducting Nanowires (not discussed)

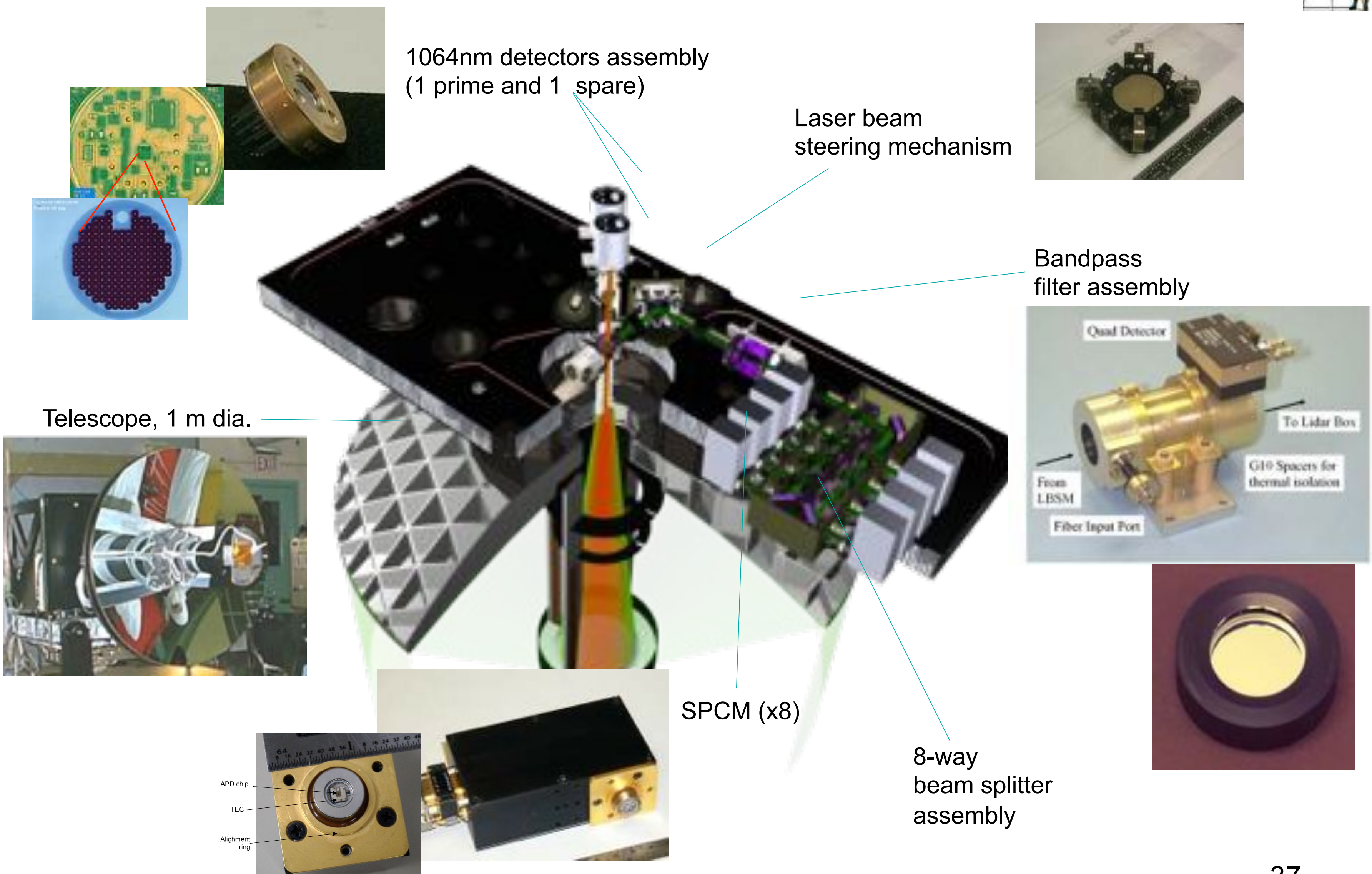
ICESat1-GLAS Integration



GLAS immediately following integration with ICESat in June 2002 at Ball Aerospace In Boulder, Colorado

Pictures courtesy of Ball Aerospace

GLAS Receivers and Key Components



Perkin Elmer SPCM

Table 2. Nominal performance characteristics of the SPCMs for ICESat/GLAS.

Photon detection efficiency @ 532 nm	65%
Dark count rate	< 300 cps
Electrical power from the spacecraft 30 V bus supply, at 35°C case temperature and 4.6 Mcps s^{-1} (including powered consumed by the DC–DC converter)	5 W
Output pulses	20 ns, TTL level
Dead time	45 ns
Maximum count rate	11 Mcps at correction factor of 2, 17 Mcps at saturation (clamping)
Active area diameter	180 µm
Size (not including DC–DC converter)	10.2 cm × 5.7 cm × 4.4 cm
Mass (not including DC–DC converter)	0.280 kg
Operating temperature range	−5 to 45°C
Operating duty cycle (with gating)	7% (40 Hz rep. rate)
Gating response time	150 ns
Hermiticity (leak rate, detector header)	$< 5 \times 10^{-9}$ cc s^{-1}
Recovery time upon over exposure to intense and short laser pulses	< 100 µs
Vibration (random, all three axes)	10 g
Thermal cycling (not powered),	−20 to 60°C 10 cycles, per MIL-STD-1010

Detection efficiency > 6% at 1064 nm, > 8% at 1030 nm

Photon-counting Detector Technology
APD –Silicon –Space-qualified (ICESat/GLAS)

JOURNAL OF MODERN OPTICS, 15 JUNE–10 JULY 2004
VOL. 51, NO. 9–10, 1333–1350

Taylor & Francis

Space-qualified silicon avalanche-photodiode single-photon-counting modules

XIAOLI SUN, MICHAEL A. KRAINAK, JAMES B. ABSHIRE, JAMES D. SPINHIRNE
NASA Goddard Space Flight Center, Code 924,
Greenbelt, Maryland, 20771, USA

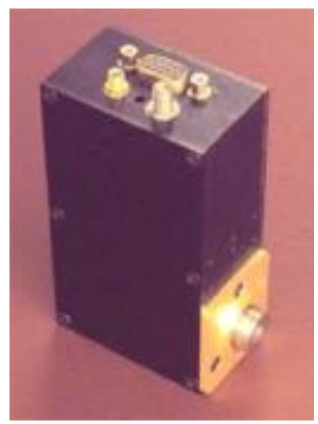
CLAUDE TROTTIER, MURRAY DAVIES, HENRI DAUTET
PerkinElmer Optoelectronics, 22001 Dumberry,
Vaudreil, J7V 8P7, Canada

GRAHAM R. ALLAN
Sigma Research and Engineering Corp., 9801 Greenbelt Rd, Suite 103,
Lanham, MD 20706, USA

ALAN T. LUKEMIRE and JAMES C. VANDIVER
Space Power Electronics, Inc., 108 Audrey Way, Kathleen,
GA 31047, USA

(Received 27 June 2003)

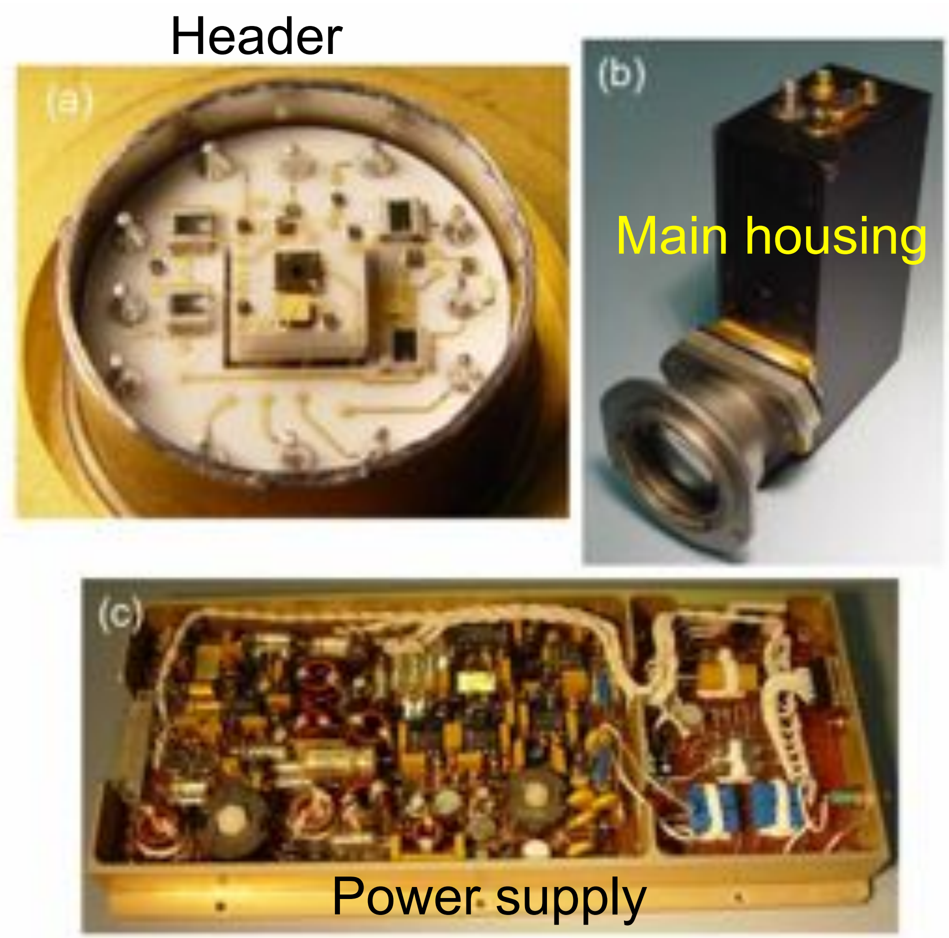
Abstract. A space-qualified silicon avalanche-photodiode (APD) based single-photon-counting-module (SPCM) was developed for the Geoscience Laser Altimeter System (GLAS) on board NASA's Ice, Cloud, and Land Elevation Satellite (ICESat). Numerous improvements were made over the commercially available SPCMs in both performance and reliability. The measured optoelectronic parameters include, 65% photon detection efficiency at the 532 nm wavelength, 15–17 mega-counts per second (Mcps) maximum count rate and less than $200\,s^{-1}$ dark counts before exposure to space radiation.



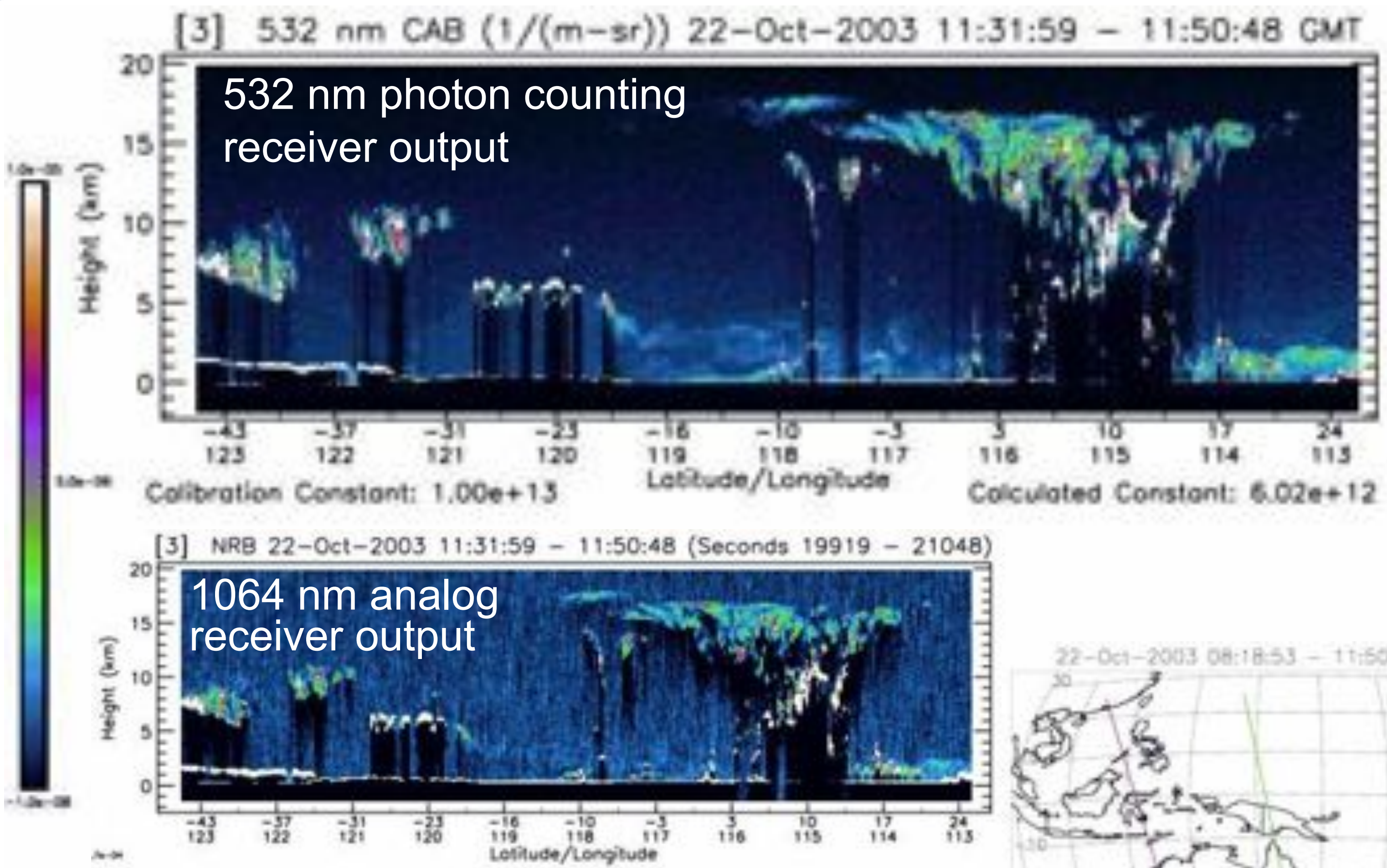
SPCM-AQ4C Single-Photon Counting Array

Photon-counting Detector Technology
APD –Silicon –Space-qualified (ICESat/GLAS)

- 0.17 mm diameter active area
- >65% QE @ 532 nm
  8% @ 1030 nm
  4 % @1064 nm
- >13e6/s max. count rate
- 30 - 50 ns dead time
- <500/s dark counts
- 280g (electronics with header)
- 2.1 W (module only)
- 4.8 W (with power supply)

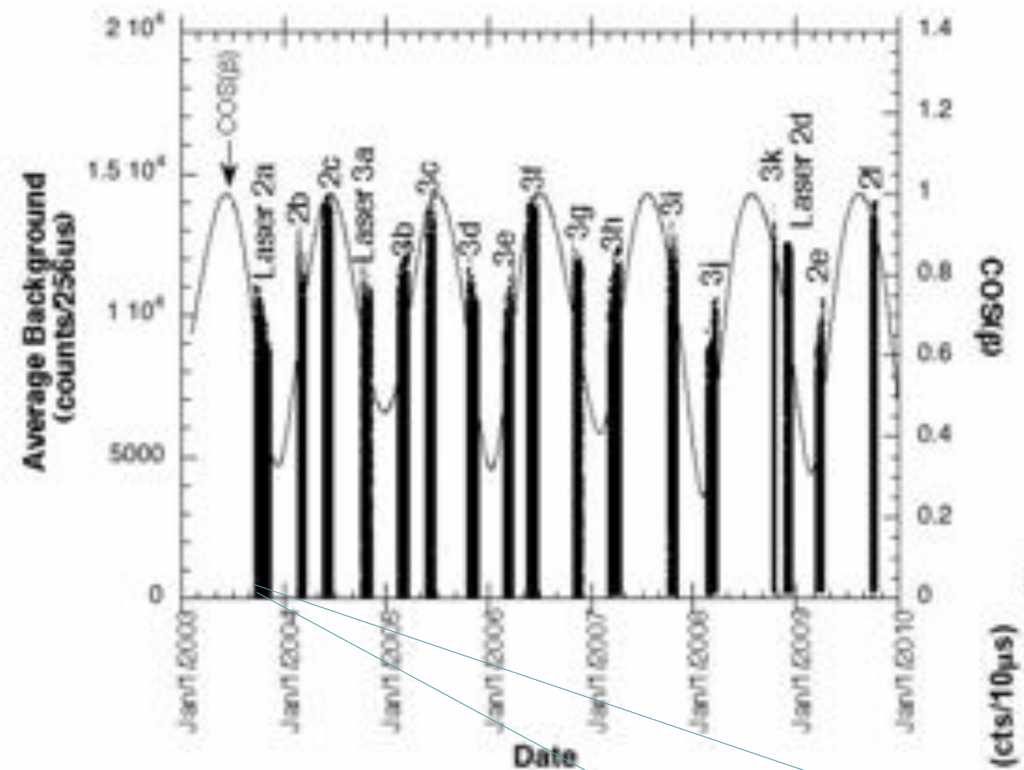


Sample In Orbit GLAS SPCM Output Data

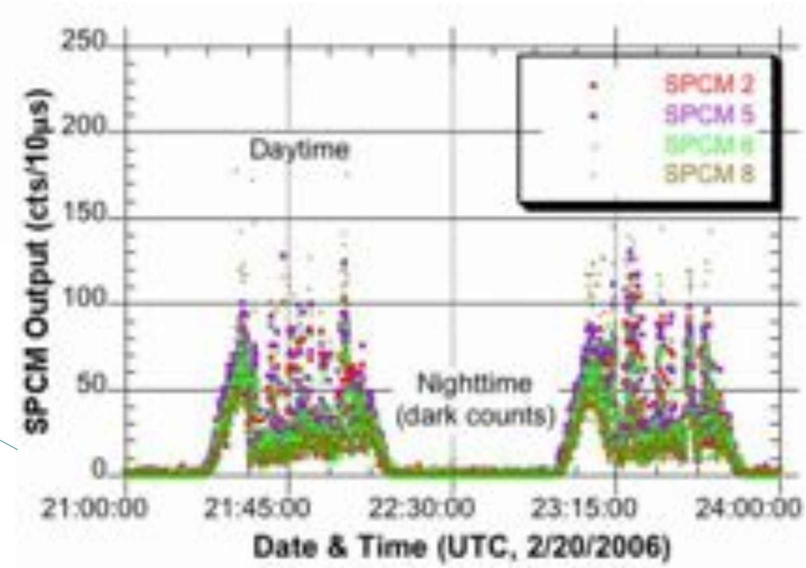


The photon counting receiver channel is
~20x more sensitive than the analog receiver channel

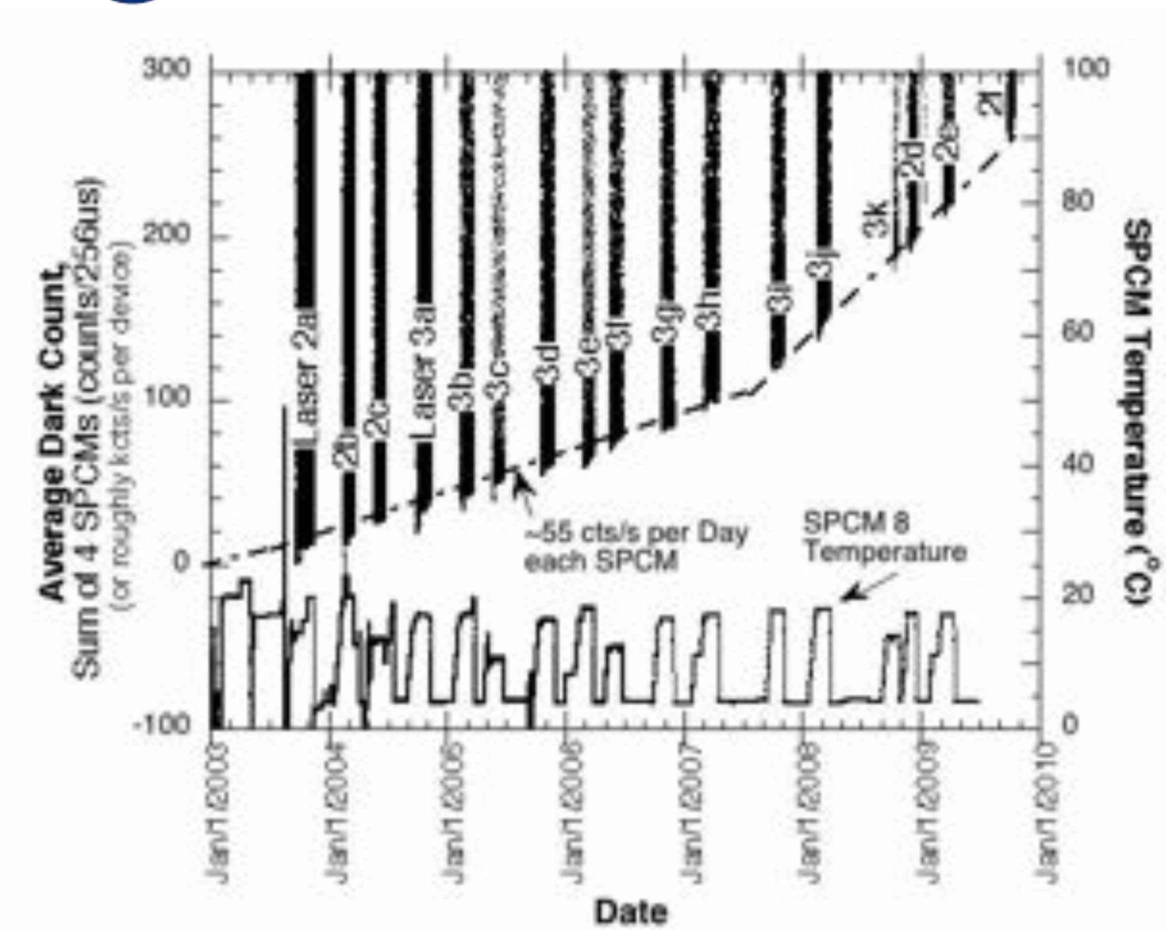
Sample SPCM Outputs in Response to the Sunlit Earth over Seven Years



Daytime maximum count rate corresponded to the solar energy intensity within the field of view

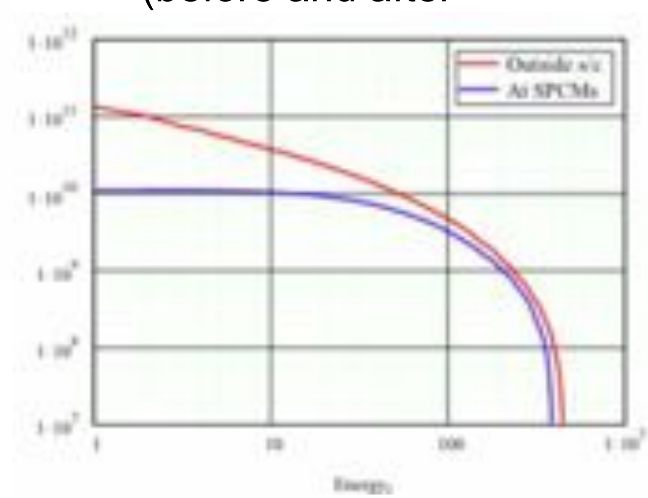


SPCM Dark Count Rate and Detector Radiation Damage Seven Years in Space

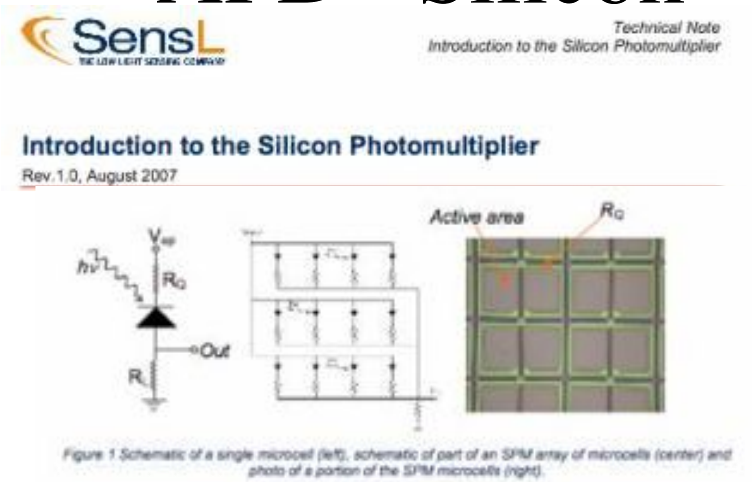


- The dark count rate increased at ~55 cts/s per day, or 20 kcts/s per year per device for the first five years, then ~80 kcts/s per year after the average temperature became lower.

Estimated Power Spectrum (before and after



Photon-counting Detector Technology
APD –Silicon –Micro/Macro Arrays

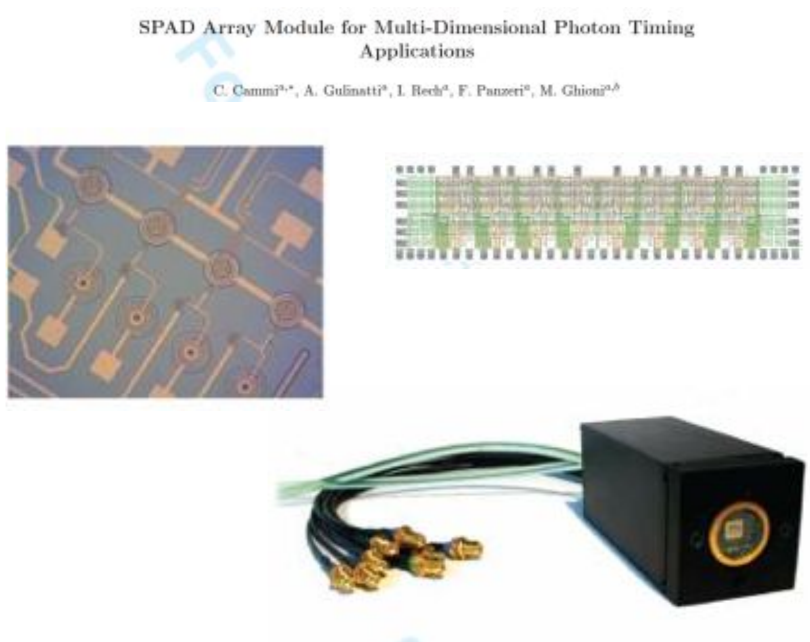

SensL

Technical Note
Introduction to the Silicon Photomultiplier

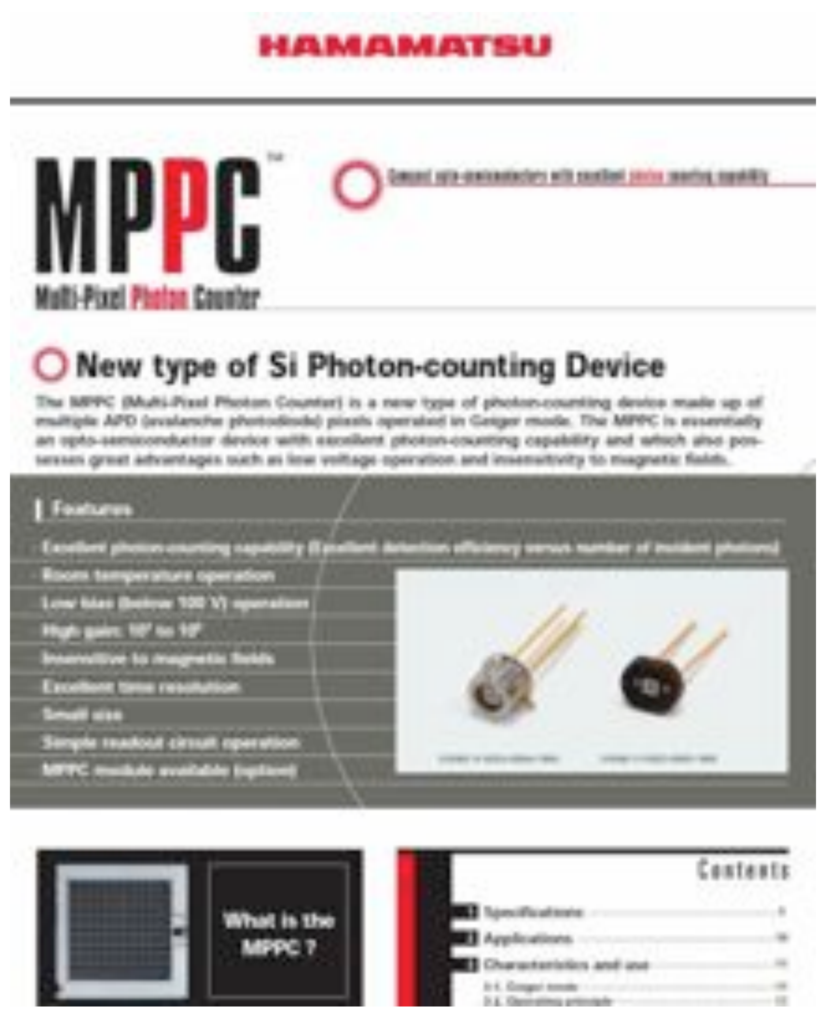
Introduction to the Silicon Photomultiplier

Rev.1.0, August 2007

Figure 1 Schematic of a single microcell (left), schematic of part of an SPM array of microcells (center) and photo of a portion of the SPM microcells (right).


SPAD Array Module for Multi-Dimensional Photon Timing Applications

C. Cammi, A. Gulinatti, I. Rech, F. Panzeri, M. Ghioni


HAMAMATSU

MPPC

Multi-Pixel Photon Counter

New type of Si Photon-counting Device

The MPPC (Multi-Pixel Photon Counter) is a new type of photon-counting device made up of multiple APD (avalanche photodiode) pixels operated in Geiger mode. The MPPC is essentially an opto-semiconductor device with excellent photon-counting capability and which also possesses great advantages such as low voltage operation and insensitivity to magnetic fields.

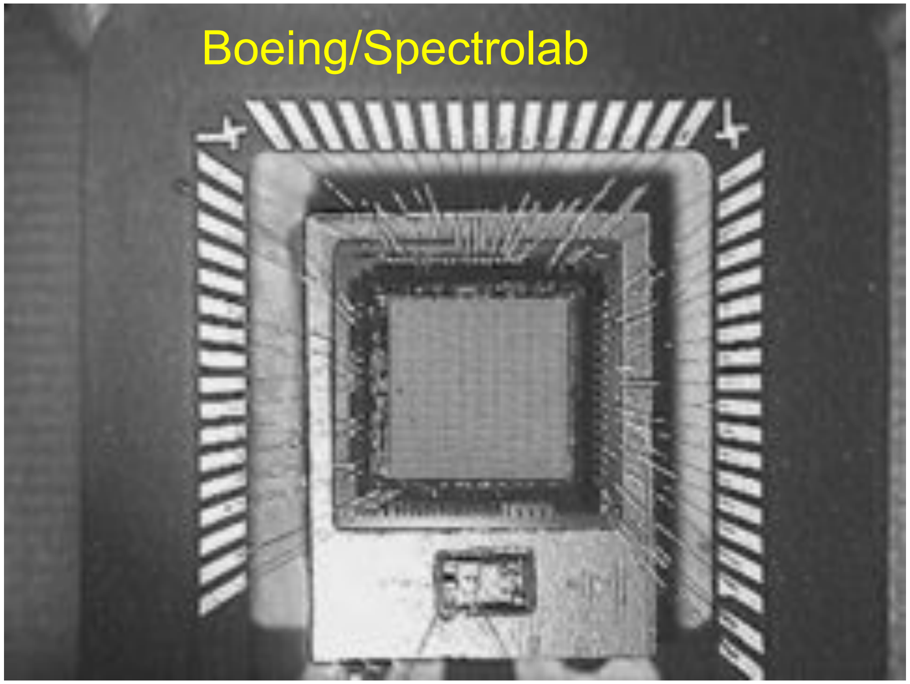
Features

- Excellent photon-counting capability (Excellent detection efficiency versus number of incident photons)
- Room temperature operation
- Low bias (below 100 V) operation
- High gain: 10^5 to 10^6
- Insensitive to magnetic fields
- Excellent time resolution
- Small size
- Simple readout circuit operation
- MPPC module available (option)

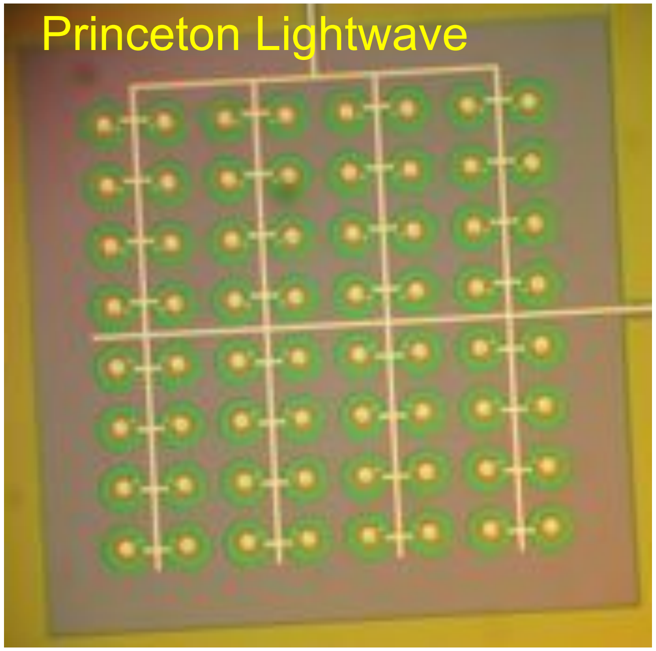
What is the MPPC ?

Contents

Photon-counting Detector Technology
APD –InGaAs(P)/InP –Arrays



Packaged 32x32 InGaAs APD array on readout IC, with microlens array, on TE cooler inside package



8 x 8 InGaAs NFAD matrix

InGaAs APD Radiation Effects

"Degradation of InP-Based Geiger-Mode Avalanche Photodiodes Due to Proton Irradiation"

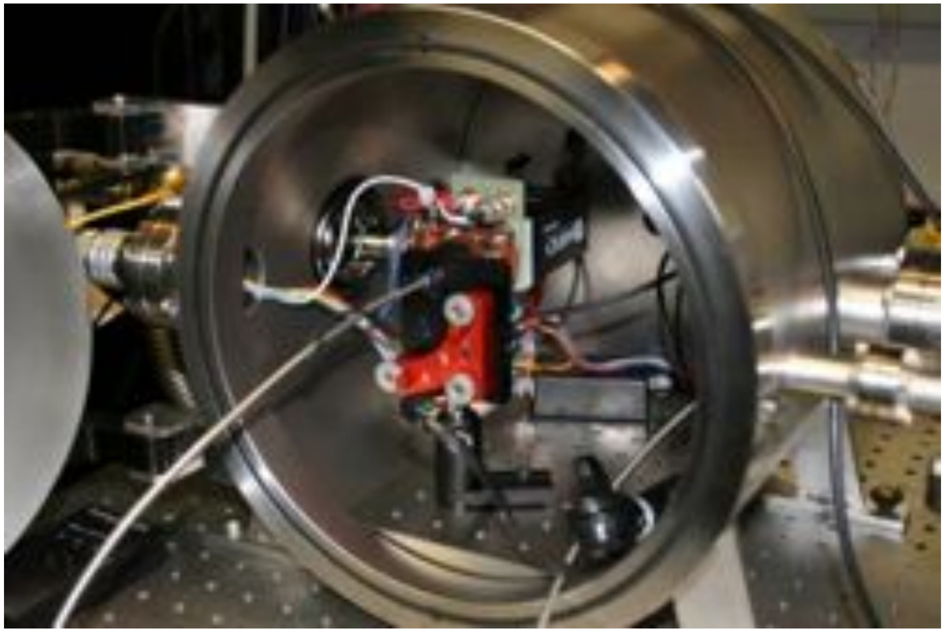
D. Harris, William H. Farr, and Heidi N. Becker   Jet Propulsion Laboratory **Single Photon Workshop 2009**

Conclusions

- Irradiation causes changes in dark I-V, DCR, and APCR
  - Changes in DCR are most problematic
- DE unaffected by irradiation
- Devices not usable after a fluence in mid 10^9 p/cm^2 range (50 MeV p)
- This is very low fluence – devices are very susceptible to damage
- Next Steps
  - Can damage be reduced by device design?
  - How stable is the damage?
    Can damage be induced to recover?

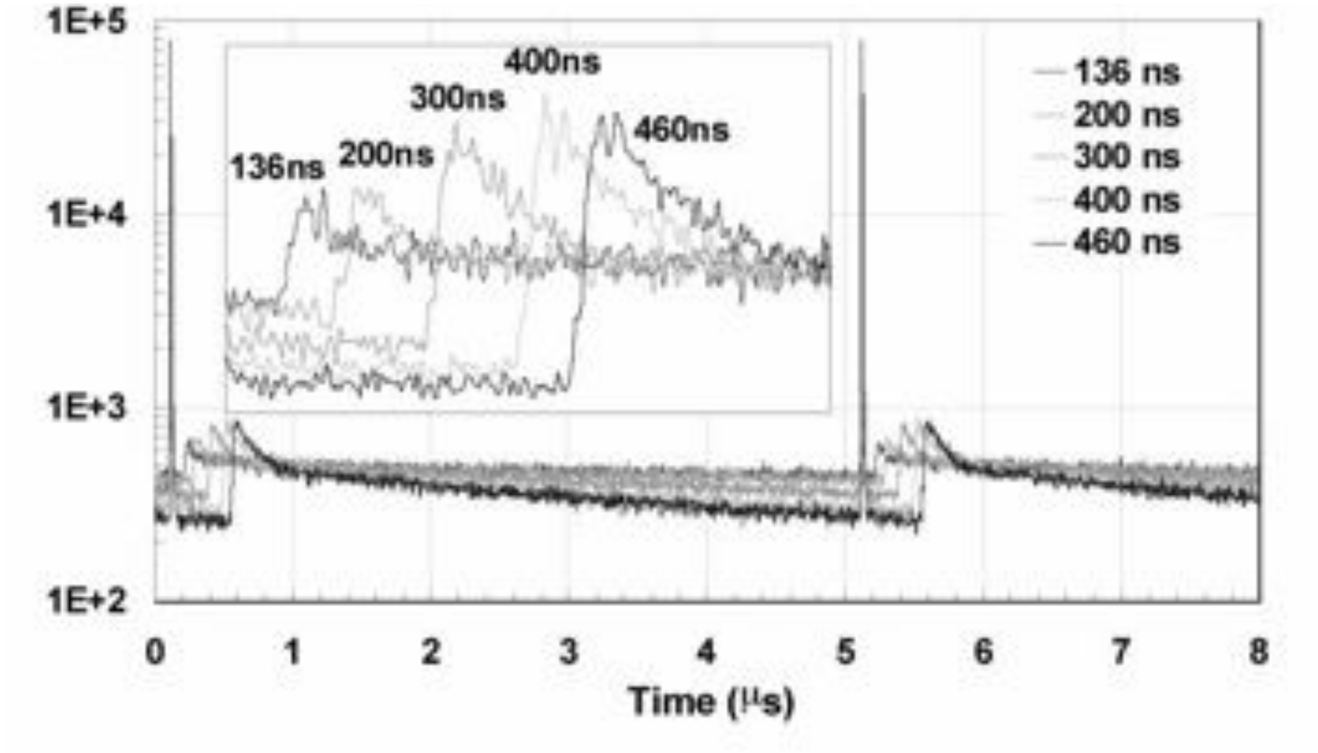
InGaAsP (1064 nm) & InGaAs (1550 nm) APD Photon-counting detector

InGaAs or InGaAsP APD active quench circuit and cold finger mount



InGaAs or InGaAsP APD low temperature test chamber

Afterpulsing in InGaAs and InGaAsP APDs



- MIT-LL avoids this issue with arrays and custom ROIC.
- Technology transfer in progress
- Rapid change in optical signal may be an issue
- Looking for alternatives - ??

HgCdTe APD arrays from DRS Technologies

Device description

- Made by DRS Technologies, Dallas TX.
- 8x8 array, with 64x64um pixels, 70um pitch, and 78% overall fill factor.
- Spectral response to 5 μm. Optimized can be >90% QE at 1550 nm.
- Reported to have high and nearly noiseless gain, up to 1400, potentially outperform Si APD at 1um and all other photodiodes in SWIR and MWIR wavelength region.
- Electrical bandwidth about 100 MHz, limited by the electron diffusion time across the device.

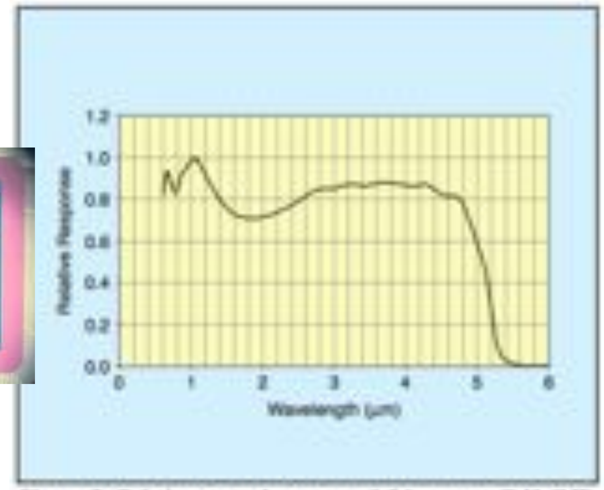


Figure 2: Relative spectral response of 5.1 μm cutoff HgCdTe HDVIP at 80 K

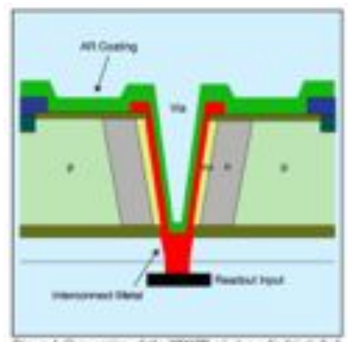


Figure 1 Cross section of the HDVIP pin-hv cylindrical diode architecture

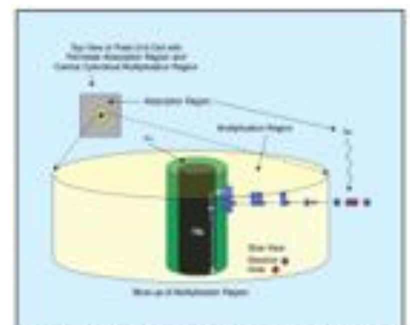


Figure 3 Electron avalanche photodiode diode pixel element in a 2D array configuration

Advanced Photon Counting Techniques V, edited by Mark A. Itzler, Joe C. Campbell, Proc. of SPIE Vol. 8033, 80330N · © 2011 SPIE · CCC code: 0277-786X/11/$18
doi: 10.1117/12.886161

Proc. of SPIE Vol. 8033 80330N-1

HgCdTe APD

Invited Paper

Linear Mode Photon Counting with the Noiseless Gain HgCdTe e-APD

Jeffrey D. Beck, Richard Scritchfield, Pradip Mitra, William Sullivan III,
Anthony D. Gleckler*, Robert Strittmatter*
Robert J. Martin**

1. INTRODUCTION

The idea of a solid state photon counter based the noiseless gain HgCdTe electron initiated avalanche photo diode (e-APD) began after APD linear gains of well over 1000 were achieved with very low dark currents and measured excess noises factors around 1.25 as shown in
Figure 1.[1] A deterministic ballistic ionization model was developed that qualitatively explained the near unity excess noise factor.[2] It became clear that such a device would offer several distinct advantages over the existing linear mode and Geiger mode APD in use, or being contemplated, at that time. The advantages of the linear mode HgCdTe e-APD are summarized below:

1) No after-pulsing associated with Geiger mode
2) Ability to resolve photons that are closely spaced in time
3) Ability to measure the number of photons in a multi-photon pulse
4) Ultra high dynamic range: ability to run in photon counting mode at low flux levels, and transition seamlessly to ordinary linear mode at higher flux levels
5) Broad and tunable spectral range offered by HgCdTe
6) The ability to obtain close to ideal probability of detect and probably of false alarm functions consistent with a deterministic gain mechanism
7) No need for active quenching circuitry

Advanced Photon Counting Techniques V, edited by Mark A. Itzler, Joe C. Campbell,
Proc. of SPIE Vol. 8033, 80330N · © 2011 SPIE · CCC code: 0277-786X/11/$18
doi: 10.1117/12.886161

AGENDA

I. NASA LASER INSTRUMENTS

II. DETECTOR REQUIREMENTS

III. CANDIDATE DETECTORS

IV. SUMMARY

Future prospects questions

1. What are the most interesting developments that you would like to see for your topic over the next ten years?

   - space-qualified time-resolved (ns) near-infrared single-photon-sensitive detector

   Best present candidate is HgCdTe APD

   - space-qualified visible (silicon) Geiger-mode APD array with 50 ps timing resolution

   Best present candidate is Cova group silicon APD array.

Future prospects questions

2. What are the biggest challenges for developing relevant technology over the next ten years?

- consistent funding
- material engineering

3. What science breakthroughs could be enabled by this technology over the next ten years?

- global earth-atmosphere trace-gas (CO_2, CH_4, etc.) measurements
- global Mars atmosphere trace-gas (H_2O, CH_4, etc.) measurements
- diffuse optical tomography of the human brain for perfusion etc.

SUMMARY

- NASA requires space-qualified time-resolved photon-counting detectors to enable future science and exploration missions
  - Past: ICESat/GLAS - Silicon APD
  - Present: ICESat-2/ATLAS – Dynode-gain photomultiplier
  - Future: ASCENDS, LIST, 3DWINDS, Lasercom - ?

- To date, photomultipliers and silicon APDs are viable.

- HgCdTe APDs have promising characteristics.

Acknowledgement

The authors would like to thank

NASA ESTO;

NASA ASTID program;

GSFC IRAD program;

GSFC SBIR program

and the

Instrument and Science Teams of:

MOLA, ICESat/GLAS, Calipso, MLA, LOLA, ICESat-2, LIST SDT, ASCENDS, GRACE-FO, GRACE-II, LADEE, LLCD & LCRD