ADVANCED PHOTODETECTORS FOR SPACE LIDAR

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Abstract for IGARSS 2014

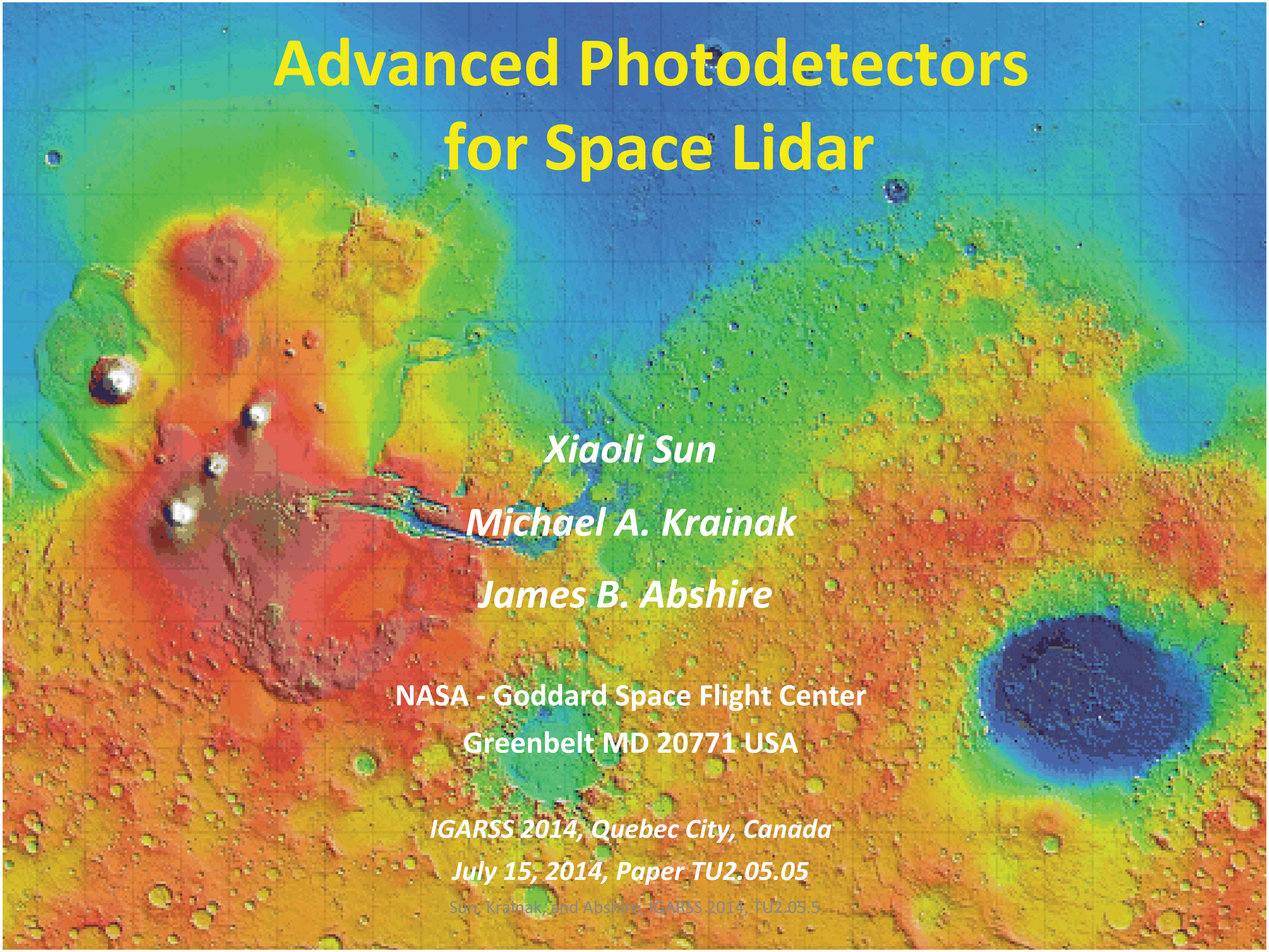
The detector in a space lidar plays a key role in the instrument characteristics and performance, especially in direct detection lidar. The sensitivity of the detector is usually the limiting factor when determining the laser power and the receiver aperture size, which in turn determines the instrument complexity and cost. The availability of a suitable detector is often a deciding factor in the choice of lidar wavelengths. A direct detection lidar can achieve the highest receiver performance, or the quantum limit, when its detector can detect signals at the single photon level.

Most space lidar developed to date operate at visible or near-IR wavelengths because of the availability of rugged high sensitivity photodetectors. Recently lidar wavelengths are extending further into the infrared due to need for scientific observations at those wavelengths, the increased availability of lasers, and the low solar background light during daytime measurements. Ideally the detector should be operated in linear photon counting mode where the output is linear to the incident optical signal power and at single photon resolution. They have to have high photoelectron multiplication gain to override electronics noise from the preamplifier or the read-out integrated circuit (ROIC). They have to operate continuously without prior knowledge of the signal arrival time. There should be no dead-time and afterpulsing upon each photon detection to preserve the temporal profile of the signal.

Conventional silicon avalanche photodiodes (APD) can have relatively high quantum efficiency and high gains to 1064 nm wavelength. InGaAs APDs have high quantum efficiencies from 0.9 to 1.7 μm but the APD gain is still too low to overcome the preamplifier noise or the excess noise from randomness of the APD gain becomes overwhelming. InGaAs photomultiplier tubes (PMT) can count single photons up to 1.6-μm wavelength, but with a few percent quantum efficiency and limited dynamic range. Geiger mode InGaAs APDs can count single photons with relatively high quantum efficiency up to 1.6-μm wavelength, but suffer from non-linear effects, such as afterpulsing, and can only be operated in a gated mode, which makes them difficult to use in lidar.

NASA Goddard Space Flight Center (GSFC) has been working with industry to develop photodetectors for future space lidar. We have successfully space-qualified silicon APDs, both linear mode and single photon Geiger mode devices. We have been working with several industrial partners to develop both linear and Geiger mode InGaAs APDs for operating to 1.7 um. We have also studied the potential use of InGaAs PMT and hybrid PMTs for space lidar.

Recently, we have collaborated with DRS Technologies and successfully developed HgCdTe electron-initiated avalanche photodiode (e-APD) with a near 90% quantum efficiency and single photon sensitivity for the CO_2 lidar at 1.57-μm wavelength in the NASA's planned Active Sensing of CO_2 Emission of Days, Nights, and Seasons (ASCENDS) mission. We are also developing a linear mode photon counting HgCdTe e-APD focal plane array (FPA) for use in future space lidar for swath-mapping of surface topography and trace gas measurements from 0.4 to 4.3-μm wavelength. These new detectors can also be used in future passive spectrometers in space to achieve quantum limited performance. In this paper, we will first give a brief overview and comparison of photodetectors used in the past and current space lidar. We will describe various activities at NASA GSFC in the development of advanced photodetectors. Finally we will describe our recent results of the linear mode single photon counting HgCdTe e-APD array detector.



Advanced Photodetectors for Space Lidar

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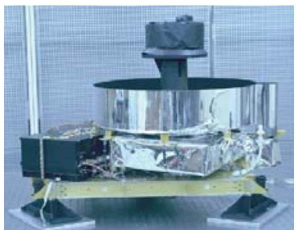
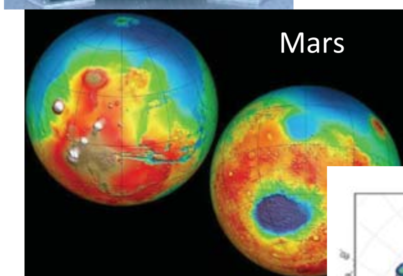
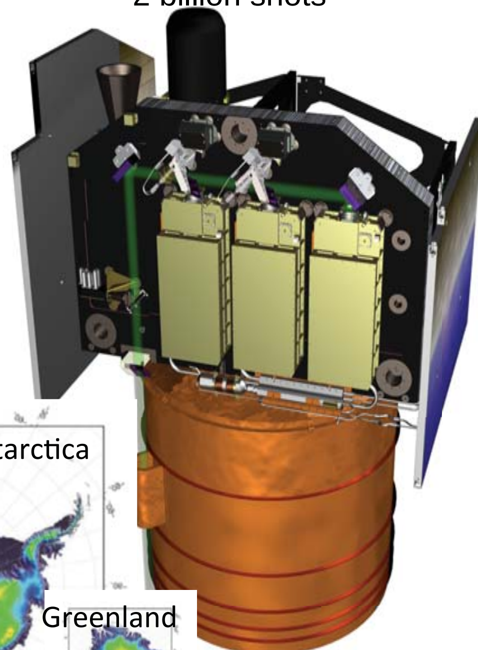
Space Lidar Developed at NASA GSFC

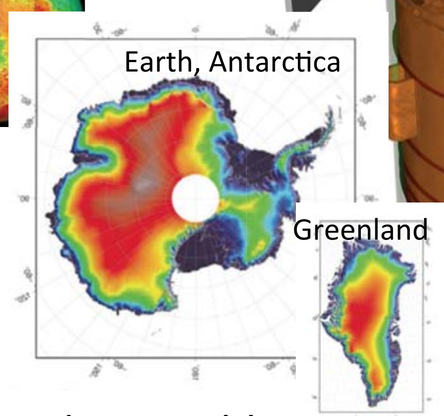
MGS/MOLA – Mars
(1996 -2000)
Nd:YAG laser, 670 Mshots



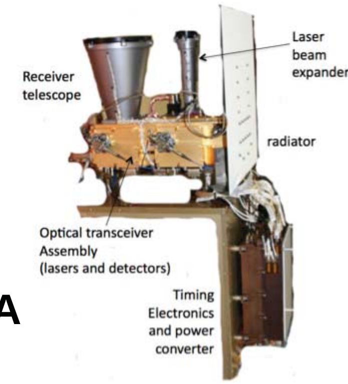


ICESat/GLAS – Earth
(2003-2009)
Nd:YAG laser
~2 billion shots

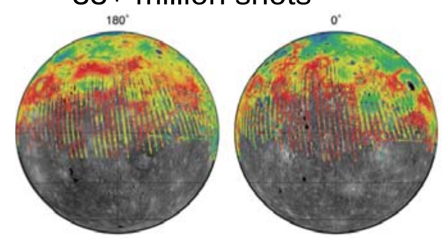




LRO/LOLA – Moon
(2009-present)
Nd;YAG laser, 2.7+ billion shots

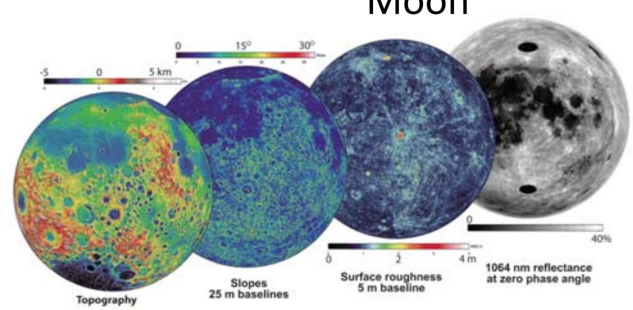


MESSENGER/MLA
Mercury
(2004-present) Nd;YAG laser,
33+ million shots



Mercury

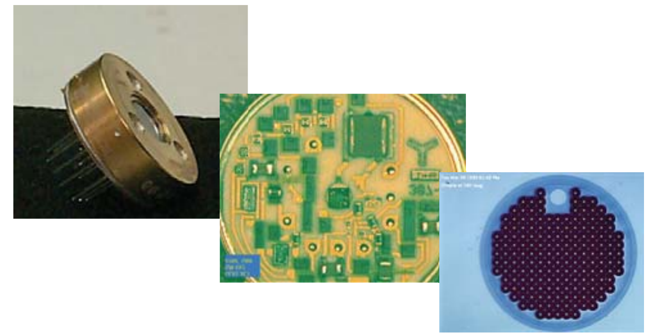
Moon

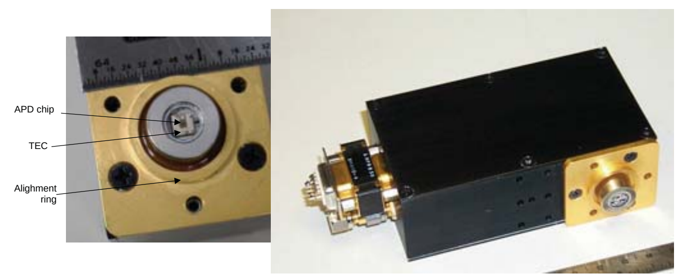


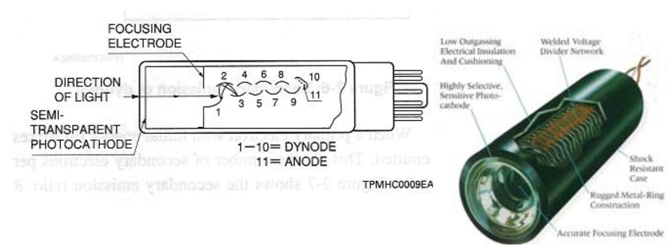
- Space lidar are indispensable remote sensing instruments.
- New laser & **detector** technologies are needed to further improve measurements, improve efficiency, & lower costs.

Detectors used in NASA's Space Lidar to Date

- **Si APD, linear mode, IR-enhanced**
  - for all surface topography lidar at 1064 nm. MOLA, GLAS/ICESat-1, MLA, LOLA.
- **Geiger mode Si APD photon counters**
  - for atmosphere backscattering measurement at 532 nm in GLAS/ ICESat-1.
- **PMT Multialkali photocathodes**
  - 532 nm: CALIPSO, ATLAS/ICESat-2



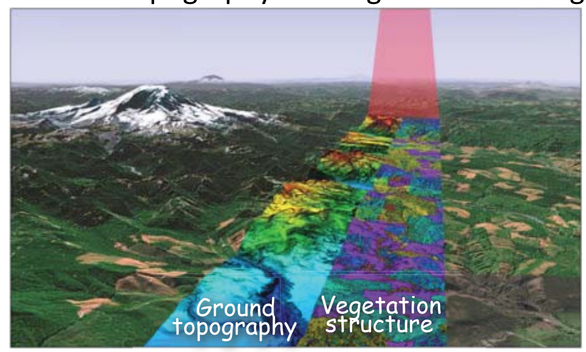




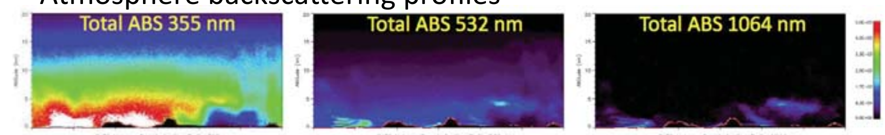
Some Space Lidar under Development at NASA

- Multi-beam swath-mapping surface and vegetation lidar.
- Atmosphere backscattering profile lidar at different wavelengths and polarizations.
- IPDA lidar for gas column (CO_2 CH_4, etc.) concentrations
- Laser surface reflectance spectrometer for surface elemental (e.g., ice) measurements on moons & planets

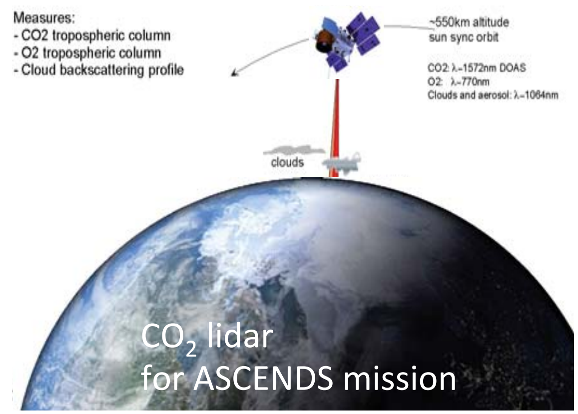
Surface topography and vegetation coverage



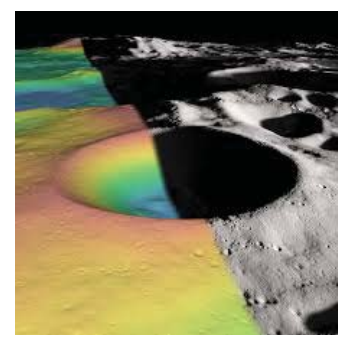
Atmosphere backscattering profiles



Column gas absorption across the spectral line



Surface reflection/ absorption at the laser wavelength

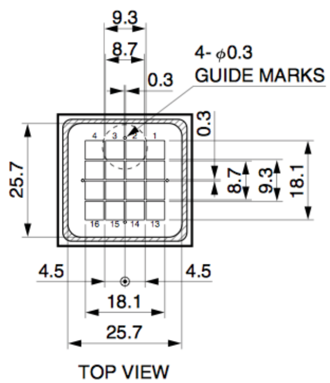


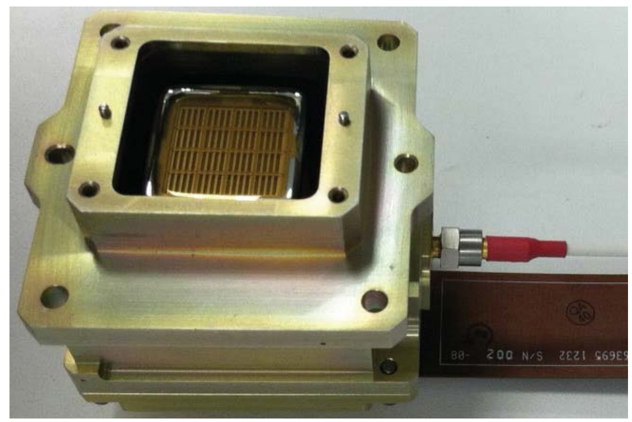
Technical Challenges for Detectors in Future Space Lidar

- **Single photon sensitivity and high quantum efficiency**
  - to achieve near quantum limited receiver performance.
- **Spectral response from visible to infrared wavelength**
  - to extend lidar capabilities & reduce solar background
- **Single to multiple photon laser signal detection**
  - Needed for unbiased target distance & surface reflectance measurements under complex and highly variable terrain and atmosphere conditions.
  - Typical conditions for lidar measurements to Earth's surface from space
- **Multi-pixel arrays**
  - More parallel lidar measurements & design flexibility for lidar receivers

Advanced Detectors for Space Lidar
16-channel PMT for ATLAS/ICESat-2

- Hamamatsu R7600-300-M16 with Extended Bialkali Cathode
- 15% QE at 532 nm, large active area, high speed
- 16-channel segmented anode to allow limited linear mode photon counting
- High optical damage threshold
- Radiation tolerant to 30krad





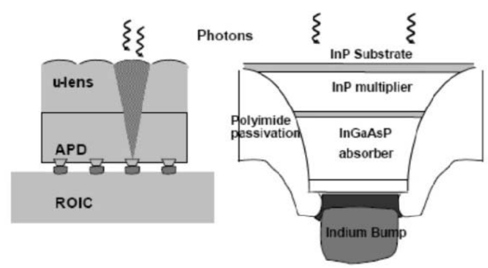
- Timing jitter < 250 ps, Dead time: < 3.3 ns
- Lifetime validated: >3.5 years continuous
- Burst mode pulsed laser damage threshold
  (> 2 uJ per pulse with 30 consecutive pulses of a 10 kHz laser)

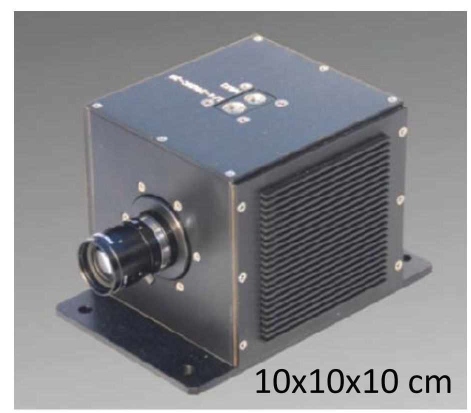
Advanced Detectors for Space Lidar - InGaAs APD and SPAD

- High quantum efficiency from 0.9 to 1.7 um
- Maximum APD gain ~50 under <10 excess noise factor in linear mode operation (Bai *et al*., SPIE 8704, 2013)
- Mostly used in Geiger mode operation for single photon counting
  - Single photon detection, but can combine pixels to achieve multi-photon detection
  - TEC cooled to maintain a low dark count rate and a reasonable range gate width (signal photon may be preempted by proceeding noise photons)
  - Have to operated in gated mode to maintain a sufficiently low afterpulsing rate
- Susceptible to proton radiation damage

Spectrolab LG3D SPAD array

- 32x32 pixels, 100 µ pitch
- Microlens array for high fill factor
  Built-in ROIC with 0.5 ns timing
- 20 KHz frame rate
- 2-8 µs range gate
- Used in ground based observations



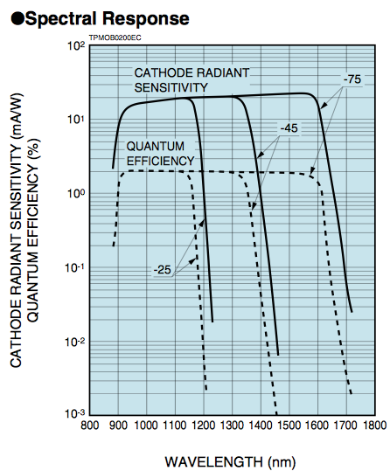


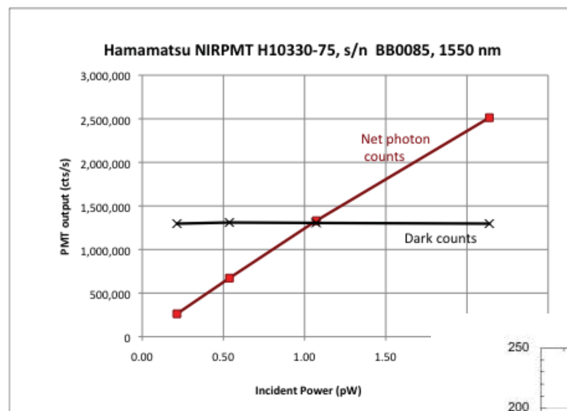
Advanced Detectors for Space Lidar - PMT with InGaAs Photocathode

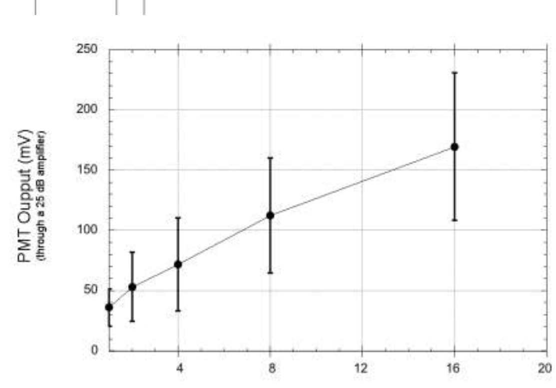
- Field-assisted InP/InGaAsP photocathode
- 2% quantum efficiency typical 0.95 to 1.65 um at 100's KHz dark counts
- Up to 17% QE at higher dark count rates with hand selected units
- Single photon sensitivity with a PMT gain $>10^6$ at 800V
- Limited dynamic range in analog multi-photon signal detection.
- Need to determine lifetime and space radiation damage

Hamamatsu H10330B-25/-45/-75

HV supply and PMT housing

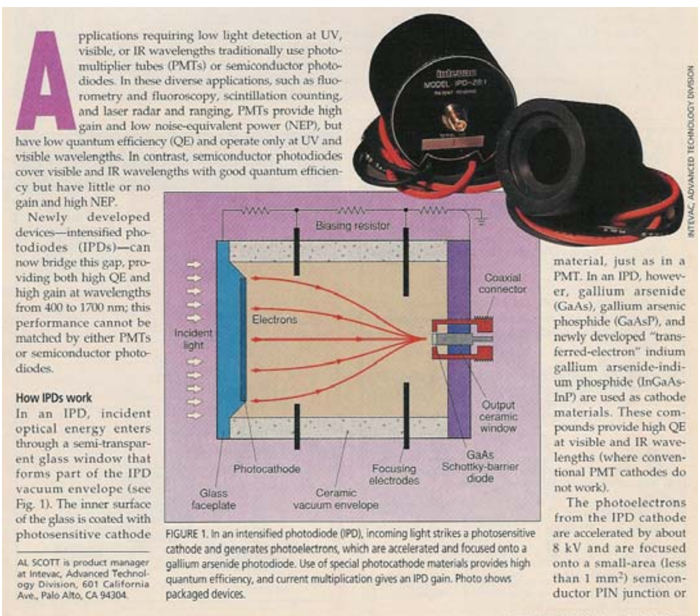






Advanced Detectors for Space Lidar - InGaAsP Intensified Photodiode

- Transfer-electron InGaAsP photocathode and GaAs APD hybrid (aka IPD, HPMT, VAPD)
- Overall gain of ~20,000 at 8KV
- 20-25% quantum efficiency, 1.0-1.6 um, single and multi-photon linear output
- Dark count rate <1 MHz at room temperature and < 100 KHz at -20°C
- Large active area, 3 mm diameter, and 1GHz electrical bandwidth
- Need improvement in yield, reliability, and packaging.



Applications requiring low light detection at UV, visible, or IR wavelengths traditionally use photomultiplier tubes (PMTs) or semiconductor photodiodes. In these diverse applications, such as fluorometry and fluoroscopy, scintillation counting, and laser radar and ranging, PMTs provide high gain and low noise-equivalent power (NEP), but have low quantum efficiency (QE) and operate only at UV and visible wavelengths. In contrast, semiconductor photodiodes cover visible and IR wavelengths with good quantum efficiency but have little or no gain and high NEP.

Newly developed devices—intensified photodiodes (IPDs)—can now bridge this gap, providing both high QE and high gain at wavelengths from 400 to 1700 nm; this performance cannot be matched by either PMTs or semiconductor photodiodes.

How IPDs work

In an IPD, incident optical energy enters through a semi-transparent glass window that forms part of the IPD vacuum envelope (see Fig. 1). The inner surface of the glass is coated with photosensitive cathode material, just as in a PMT. In an IPD, however, gallium arsenide (GaAs), gallium arsenic phosphide (GaAsP), and newly developed "transferred-electron" indium gallium arsenide-indium phosphide (InGaAs-InP) are used as cathode materials. These compounds provide high QE at visible and IR wavelengths (where conventional PMT cathodes do not work).

The photoelectrons from the IPD cathode are accelerated by about 8 kV and are focused onto a small-area (less than 1 mm²) semiconductor PIN junction or

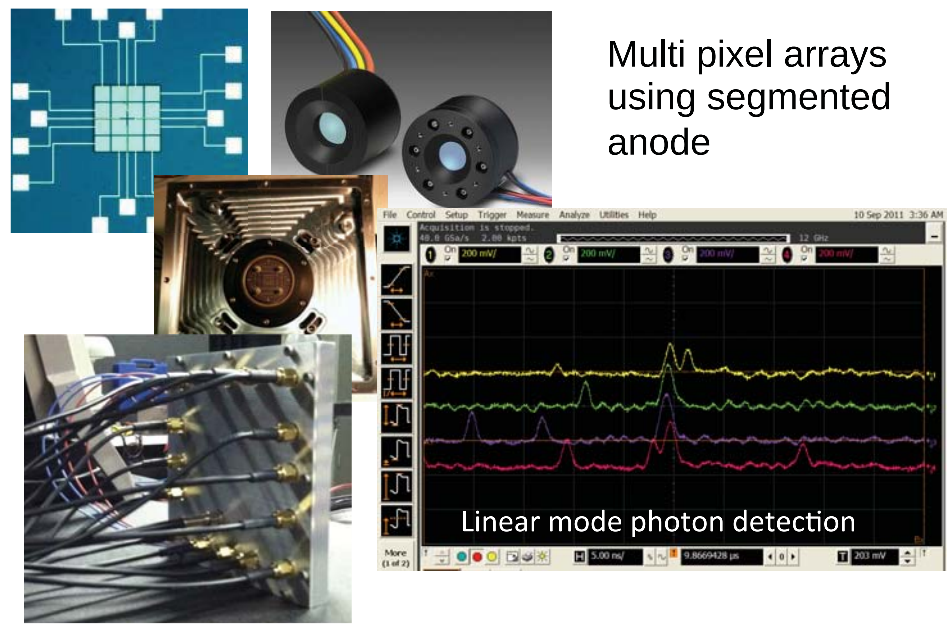
FIGURE 1. In an intensified photodiode (IPD), incoming light strikes a photosensitive cathode and generates photoelectrons, which are accelerated and focused onto a gallium arsenide photodiode. Use of special photocathode materials provides high quantum efficiency, and current multiplication gives an IPD gain. Photo shows packaged devices.

AL SCOTT is product manager at Intevac, Advanced Technology Division, 601 California Ave., Palo Alto, CA 94304.

Laser Focus World November 1995 115

16-channel InGaAsP IPDs from Intevac

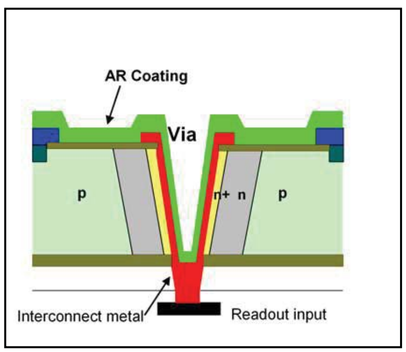
Multi pixel arrays using segmented anode

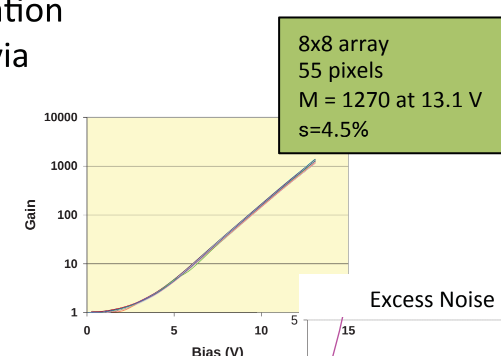


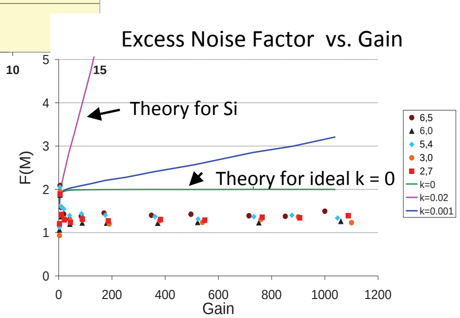
Advanced Detectors for Space Lidar - HgCdTe e-APD Arrays

- High quantum efficiency from visible to midwave infrared (MWIR)
- High and nearly noiseless gain
- Available from DRS (Beck, 2006), Raytheon (Jack, 2010) , and CEA (Rothman 2007)
- 77K operation, required a small cryo-cooler

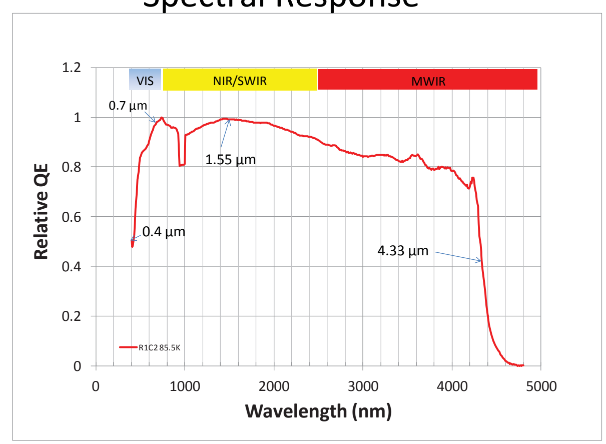
DRS HDVIP e-APD, a cylindrical diode with the n⁻ multiplication region around the central via interconnect



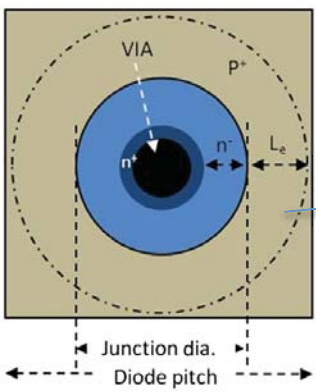




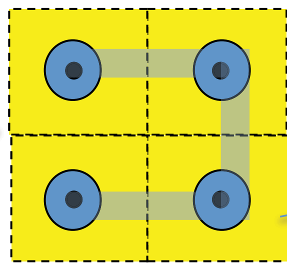
Spectral Response



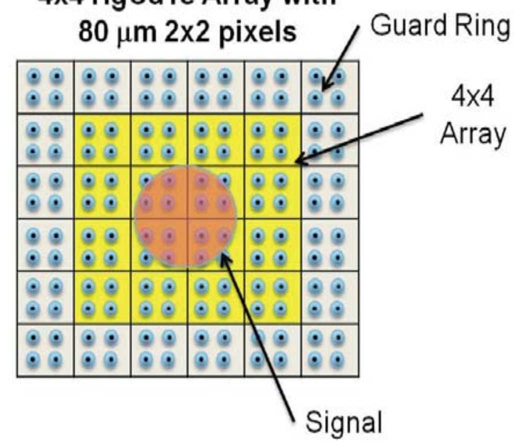
DRS 4x4 HgCdTe e-APD Arrays Developed for CO_2 IPDA Lidar*

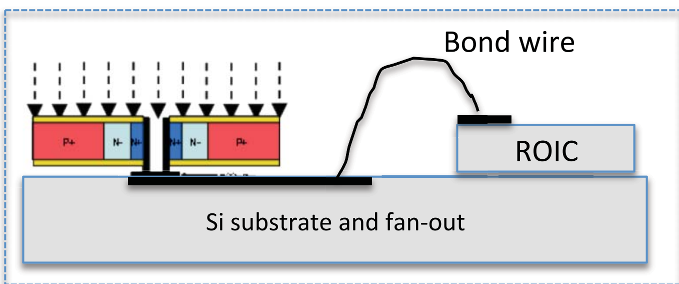


4 HgCdTe e-APD
in parallel to form a pixel



4x4 HgCdTe Array with
80 µm 2x2 pixels

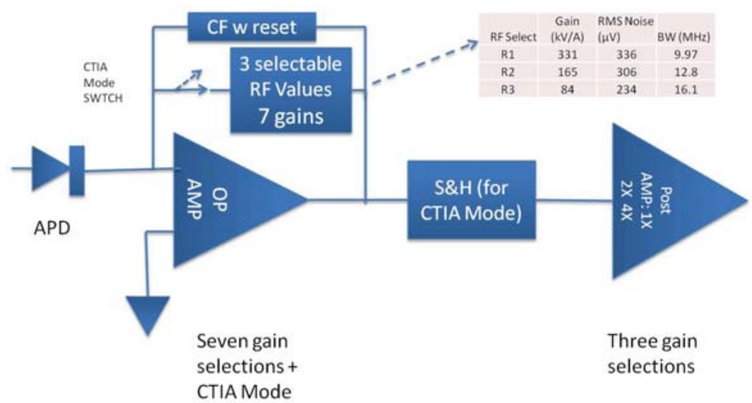




~7 MHz bandwidth to match the laser pulse shape (0.5 to 1 µs wide)

*\- *ESTO IIP-10 program, J. Abshire, PI*

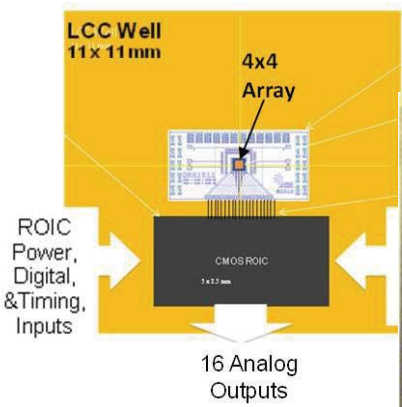
Custom CMOS ROIC, RTIA or CTIA mode of operation

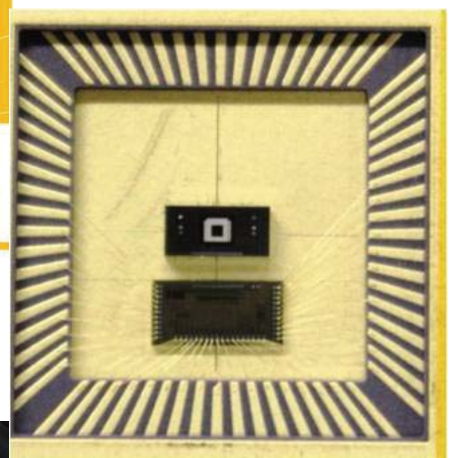


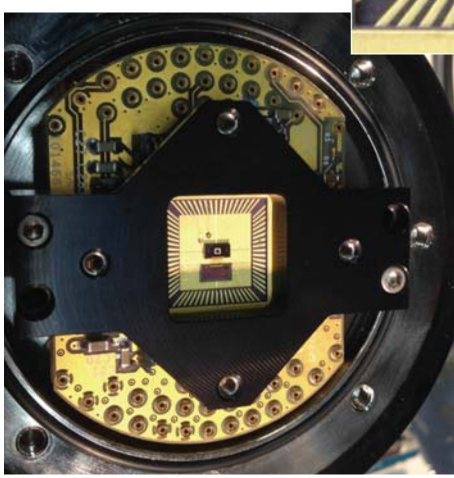
RF Select	Gain (kV/A)	RMS Noise (µV)	BW (MHz)
R1	331	336	9.97
R2	165	306	12.8
R3	84	234	16.1

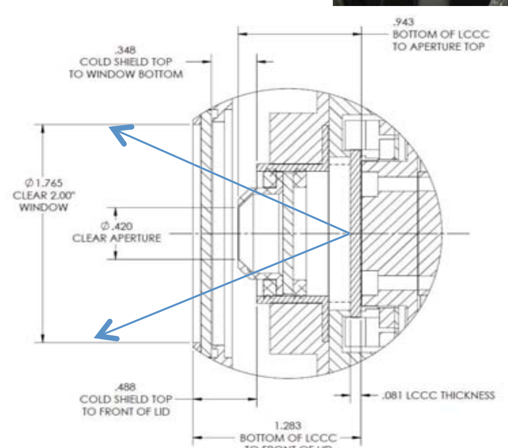
Beck *et al.*, *J. Elect. Materials*, V43, 2014

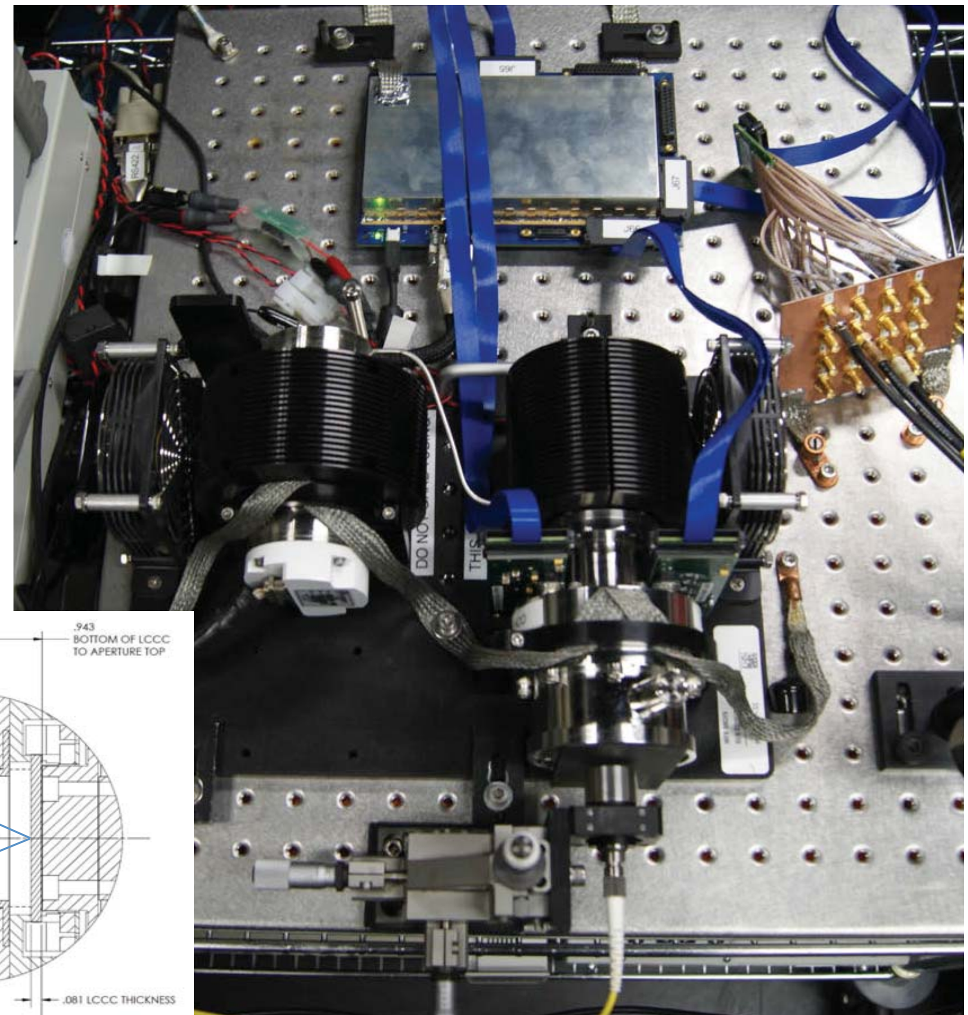
DRS 4x4 HgCdTe e-APD Arrays Developed for IPDA Lidar (cont'ed)







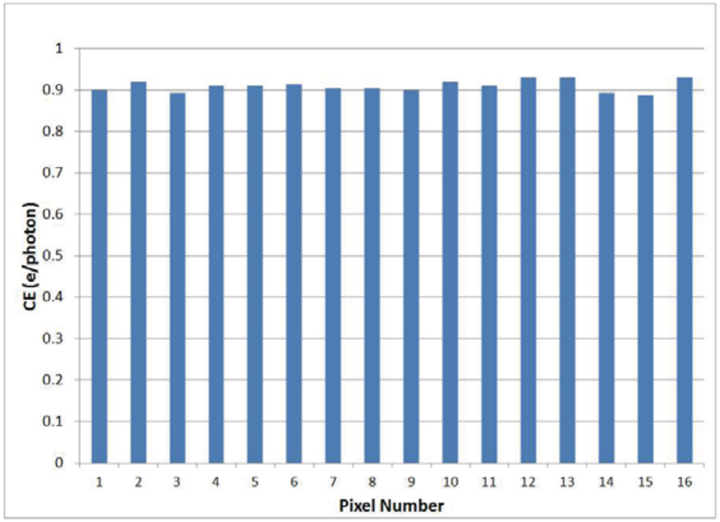




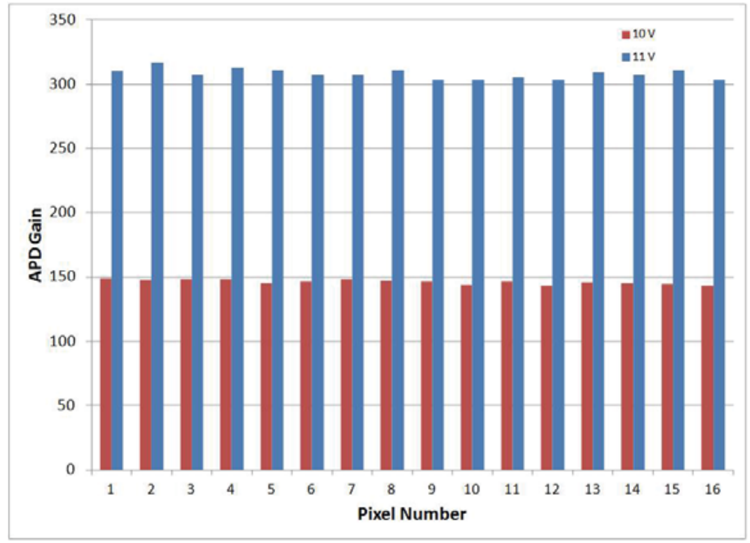
DRS 4x4 HgCdTe e-APD Array for IPDA lidar

Test Results – Pixel Uniformity

Quantum Efficiency vs. Pixel #

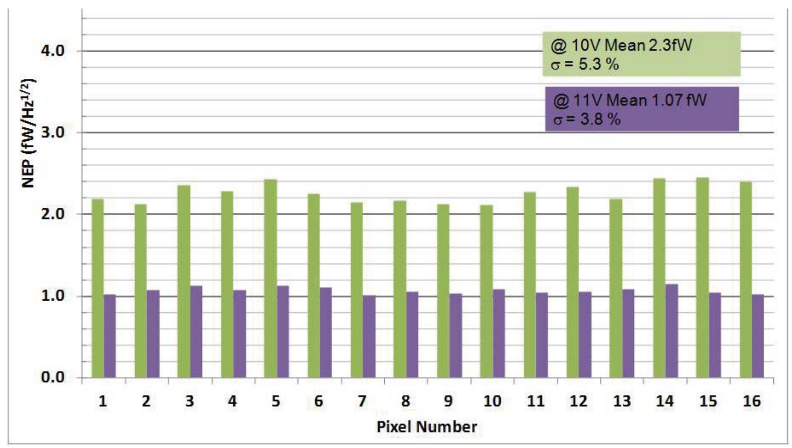


APD Gain at 10 and 11 V vs. Pixel #

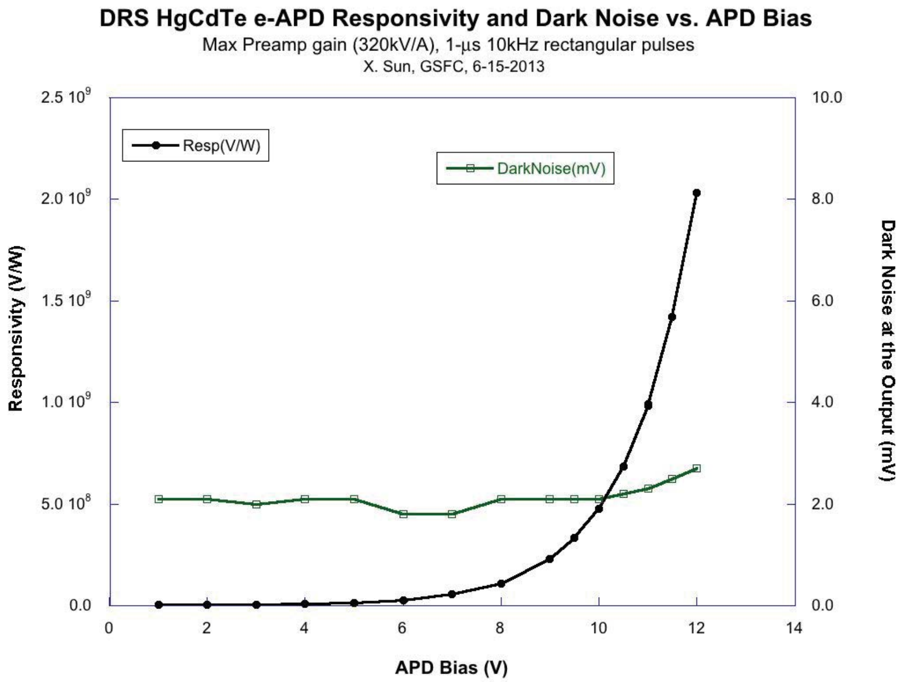


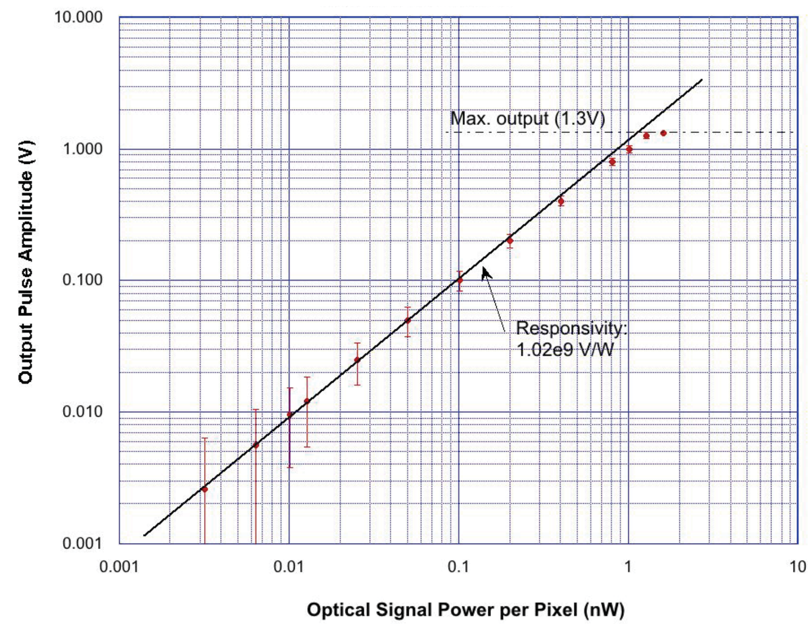
- Uniform and high QE and APD gain
- Extremely low dark current
- Low ROIC noise
- NEP < 1 $fW/Hz^{1/2}$
  (compare to ~200 $fW/Hz^{1/2}$ for InGaAs APD)
- Two units delivered to NASA

* Test results shown were from SN A8052-4E



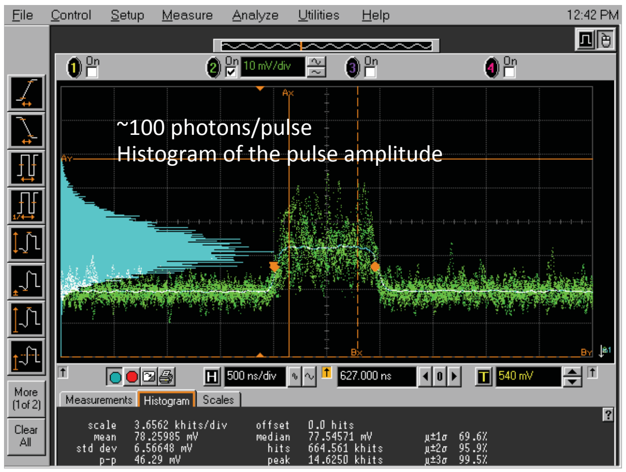
DRS 4x4 HgCdTe e-APD Array for IPDA lidar
- Responsivity, Gain, and Linearity

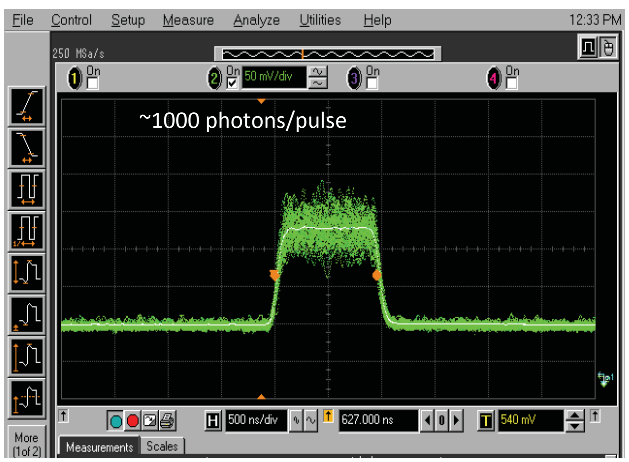


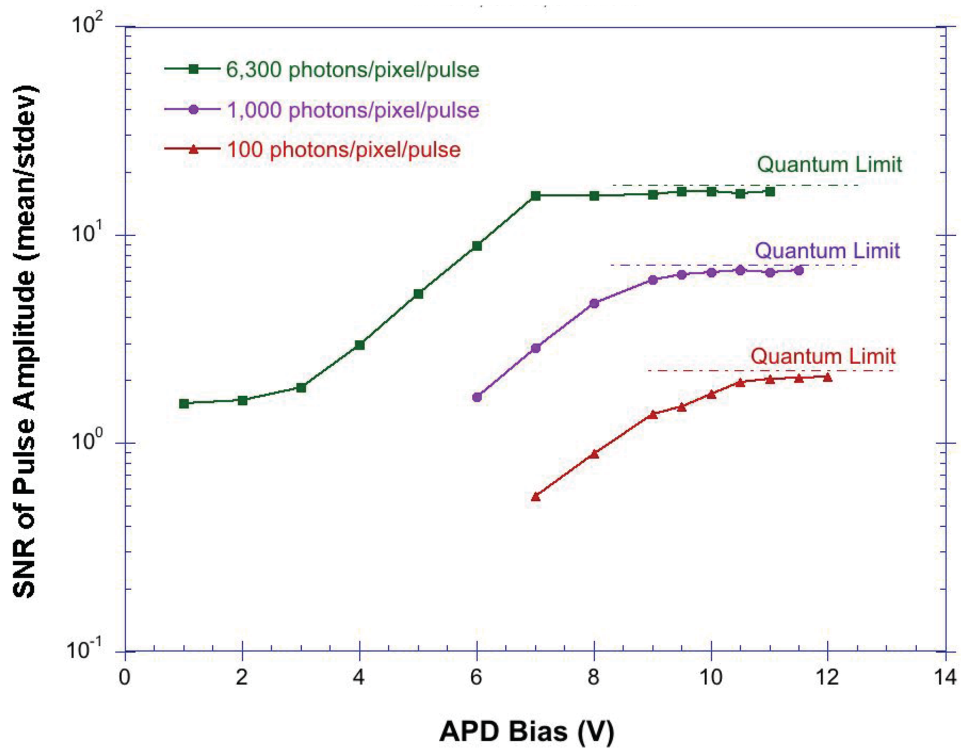


- Detector dark noise rises above preamp noise at APD bias >10V
- NEP = 0.7fW/Hz$^{1/2}$ at APD bias = 11 and **0.4 fW/Hz$^{1/2}$ at 12 V**
- Linear response over 4 orders of magnitude
- More dynamic range available by lowering APD gain and preamplifier gain.

DRS 4x4 HgCdTe e-APD Array for IPDA lidar - Signal to Noise Ratio



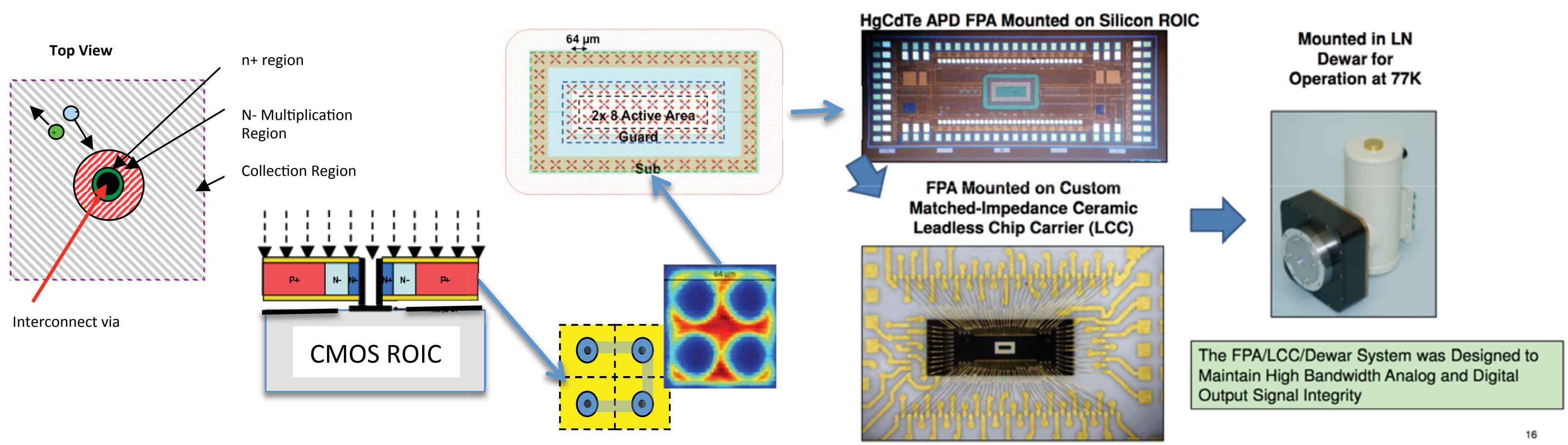




- SNR became independent of the APD gain above ~10V APD bias –> **noiseless gain**
- SNR -> 90% quantum limit, or QE~80% **-> High QE and sufficient APD gain**

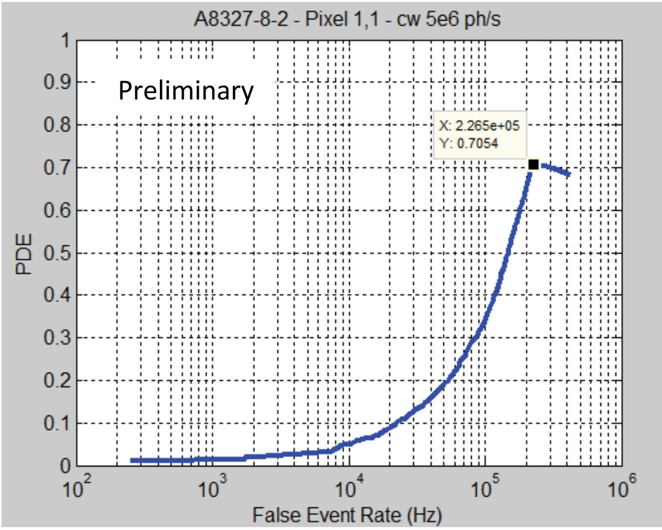
DRS 2x8 Linear Mode Photon Counting HgCdTe e-APD Detector

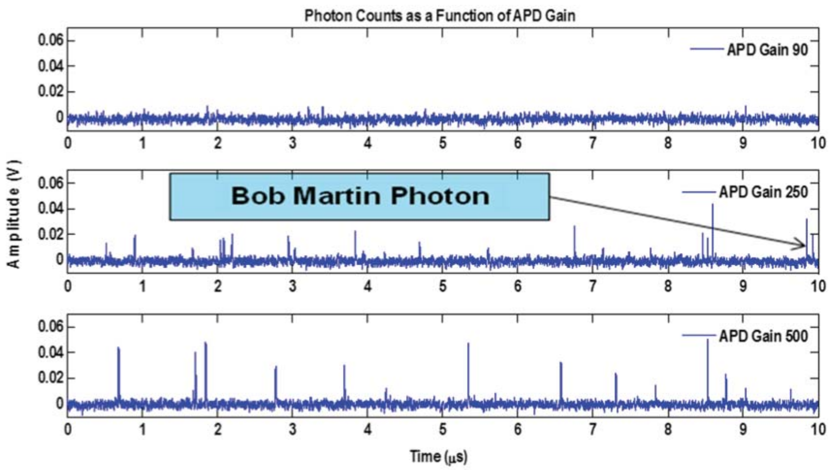
- First discovered in 2010 (Beck *et al.*, SPIE 8033, 2011, *Optical Engineering*, 2014)
- Improved in 2012-2014 under NASA ESTO ACT program
- ROIC *directly beneath* the HgCdTe e-APD array
  - Much lower stray capacitance => **fast ROIC response time & lower preamplifier noise**
  - ~8 ns impulse response pulse width.
- Incident light spot on the center of the 4 surrounding HgCdTe e-APDs
  - High and uniform APD gain
- Light barrier under e-APD array blocks ROIC glow.

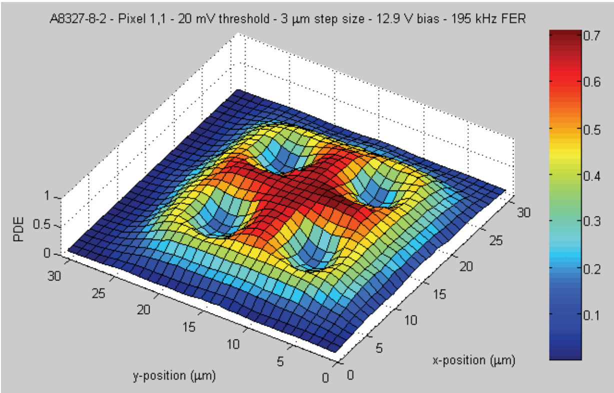


DRS 2x8 HgCdTe e-APD Detector Array
- Test Results

- DRS successfully reproduced 2x8 LMPC HgCdTe e-APD arrays with high yield.
- >50% photon counting efficiency at <150 KHz dark count rate
- The light barrier between e-APD and the ROIC reduced the dark count rate by ~5x
- A new ROIC design is expected to completely block ROIC glow

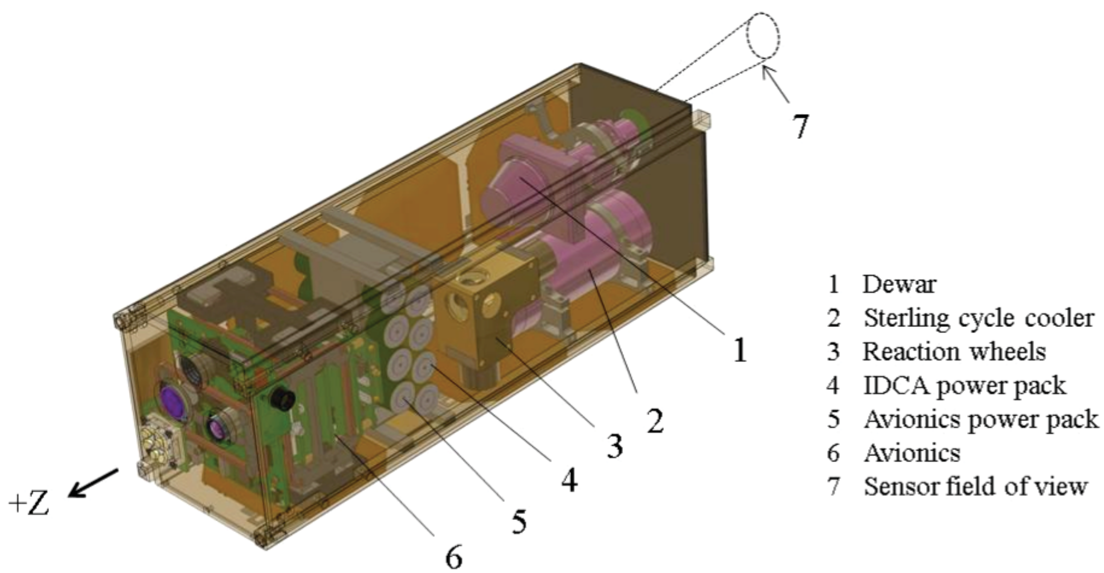






In-space test of an HgCdTe e-APD LMPC detector array in a Cubesat

- Supported by NASA ESTO InVEST program, (R. Fields, Aerospace Corp., PI)
- Plan for launch in late 2015.
- Integrate an HgCdTe e-APD FPA with a tactical cooler
- Fly the assembly in an Aerospace 3U Cubesat for >6 months in space
- Periodically power on cooler & detector. Check dark count rate & responsivity



- Use on board LEDs to verify detector time responses.
- Scan detector assembly across Moon for calibration
- Point to Earth to detect laser light from ground stations.

Summary

GSFC

- Advanced photodetectors will greatly benefit future space lidar.
- Capabilities needed:
  - Higher quantum efficiency from visible to MWIR
  - Linear mode photon counting
  - Continuous operation with no dead-time, after pulsing, and other nonlinear effects
- Considerable improvements are still needed in present NIR photodetectors: InGaAs APDs, SPADS, PMTs, and IPDs.
- New HgCdTe e-APD arrays (by DRS) have been developed as nearly ideal photodetectors for space lidar from 0.4 to 4.0 um.