A LINEAR MODE PHOTON-COUNTING (LMPC) DETECTOR ARRAY IN A CUBESAT TO ENABLE EARTH SCIENCE LIDAR MEASUREMENTS

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Effort funded under the NASA Earth Science Technology Office InVEST 12 open solicitation
**HgCdTe electron initiated avalanche photodiode (e-APD) array**

- Developed by DRS Technologies in Dallas TX
- 2x8 pixels with built-in read-out integrated circuit (ROIC), 20 µm diameter active area, 64 µm pitch, with µ-lens array F/7 optical path, 7 mm diameter entrance aperture
- 90% quantum efficiency
- >1000 APD gain, more than sufficient to override ROIC noise
- Linear mode photon counting (LMPC) detectors from visible to mid-wave infrared (VIS/MWIR) wavelength range.

**BUS**
- HgCdTe responds from 0.4 to 4 microns to single photons (1000 electrons per photon)
- AC9 will use narrowband filters to pass 1.06, 1.55 and 2.06 microns for daylight operation
- Launch Nov 2016 (delivery Aug 2016)

**Optical Path**
- 1. Dewar
- 2. Stirling cycle cooler
- 3. IDCA controller
- 4. FPA conditioning circuits
- 5. Radiator structure
- 6. Warm filter and objective lens

**LMPC CubeSat – Aerospace AeroCube-9 (AC-9)**

**Diode Side View**
- AR Coating
- 5-7 µm
- P-Type MCT
- N-Type MCT
- CdTe Passivation
- Pre-amp input pad
- Readout Integrated Circuit (ROIC)

**Top View**
- IFOV=0.1°
- Warm Filter
- Objective Lens
- Dewar Window
- Cold Filter (2)
- Cold Shield
- Microlens Array
- Focal Plane Array

**AC9**
- Filter wheel with 5 settings
- 3 Bandpass filters
- 1 blank (opaque)
- 1 open

**Launch Nov 2016 (delivery Aug 2016)**

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HgCdTe responds from 0.4 to 4 microns to single photons (1000 electrons per photon)

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Launch Nov 2016 (delivery Aug 2016)
Why Fly a Linear Mode Photon Counting Detector?

At least three Tier 1 missions are strongly driven in science capability by photon detection sensitivity
- LIST which is strongly related to ICESat & DESDynI will not reach threshold goals without single photon response matched to high power efficient transmitters that respond to 1 micron
- While threshold science can be achieved with photomultipliers for CO2 at 1.5 and 2 microns, single photon response will significantly extend the science
- The potential for high sensitivity passive arrays across the 0.4-4 micron HgCdTe response shows potential for many other missions as this technology and its support elements mature
Packing Density View

IDCA PAYLOAD
- Located centrally inside satellite
- Radiator/payload hard mount to body by solid brackets that are mechanically fixed but made from thermally isolating material.

RADIATION DETECTOR
- Commercially available Teledyne Dosimeter
- Uses AC8 Derived daughter PCB
- Co-Located with IDCA sensor

ACS COMPONENTS
- All ACS components hard mount to body around primary payload

SINGLE STAGE LASER
- Output of laser co-bore sighted with IDCA sensor

Sensor
Enabling Technology: Linear Mode HgCdTe e-APD

- High, near noiseless, uniform, avalanche gain
- Gain normalized dark current as low as 100 e/s
- Broad spectral range: UV – MWIR
- High quantum efficiency
- High intrinsic bandwidth (~ 10 GHz)
- Large dynamic range
- Demonstrated photon counting sensitivity
- Continuous operation with no dead time or after-pulsing
  - Minimum time between events MBE < ~ 10 ns (limited by current ROIC bandwidth)

**APD Gain vs. Bias**

- 53 Pixels
  - M = 1270 @13.1 V
  - s/mean = 4.5 %

**Excess Noise Factor vs. Gain**

- Theory for Ideal k = 0
  - (McIntyre History-Independent)
- Measured data

**Broad Spectral Response**

- 8 ns pulse separation (ROIC BW limited)

**High SNR Single Photon Sensitivity**
Blocking Noise from ROIC Glow

16-Pixel-Mean PDE vs. FER

- A8327-14-2 (No metal shield)
- A8327-14-1 (With metal shield)

Pixel-by-Pixel FER Comparison

- No mirror blocking metal
- With mirror blocking metal

All pixels:
- >50% PDE

"Tab" metal shield

FER ≤ 200 kHz for every pixel with blocking metal layer, a 1/5 reduction. Multiple metal layers are expected to decrease FER to diode limit (< 20 kHz).

ROIC Glow Photons

- No metal shield
- With Metal shield

Si ROIC

HgCdTe Array

10/27/14

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Sun et al., ESTF 2014, Paper B4P5
## LMPC HgCdTe e-APD Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GSFC ACT Program Specification</th>
<th>Oct. 2014 Status</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size and form factor</td>
<td>2x8 pixel array, 20 µm dia, 64 µm pitch</td>
<td>Demonstrated</td>
<td>Form factor can be changed if funds available for a new ROIC</td>
</tr>
<tr>
<td>Photon Detection Efficiency 0.9 to 4.2 µm</td>
<td>&gt; 40% (&gt; 50% goal)</td>
<td>&gt; 50% (&gt; 65% demonstrated)</td>
<td>From optical input to the analog outputs</td>
</tr>
<tr>
<td>Dark count rate</td>
<td>&lt; 500 kHz (&lt;100 kHz goal)</td>
<td>&lt; 200 kHz demonstrated</td>
<td>Including detector dark current, ROIC and system noise</td>
</tr>
<tr>
<td>Pulse pair separation</td>
<td>≤ 10 ns (&lt; 6 ns goal)</td>
<td>9 ns demonstrated</td>
<td>Stray capacitance limiting bandwidth</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>&lt; 1.0 ns rms (&lt; 0.5 ns rms goal)</td>
<td>~1.6 ns rms (&lt; 1 ns rms in 2011 FPA)</td>
<td>Improvement with smaller pitch APDs pixel designs expected.</td>
</tr>
<tr>
<td>Excess Noise Factor</td>
<td>&lt; 1.4</td>
<td>Demonstrated</td>
<td>1.2-1.25 Decreased diode junction width</td>
</tr>
<tr>
<td>Outputs</td>
<td>Analog and Digital (optional)</td>
<td>Demonstrated</td>
<td>Linear mode multi-photon resolution with analog outputs</td>
</tr>
<tr>
<td>Housing</td>
<td>LN2 Dewar (80K) with window, f/1.5 to f/4.9</td>
<td>Demonstrated</td>
<td>May be housed in an existing long lifetime space cryo-cooler</td>
</tr>
<tr>
<td>Simultaneity of Specifications</td>
<td>All specifications met at the same time</td>
<td>Demonstrated with exception of jitter</td>
<td>All spec’s met, except jitter, at the same time on the same device at the same threshold.</td>
</tr>
</tbody>
</table>
Physical Dimensions of the Cooler and Cold Filter Performance

Basic Dimensions of the Integrated Detector Cooler Assembly

The background count rate was calculated using:

- Materion’s measured cold filter transmission
- QE from previous LMPC APD array (analysis uses 300 K blackbody temperature, dual stacked cold filters, f/7, and a (64 µm)^2 detector.)

The total expected background count rate is 103 kHz

Stacked filter transmission is very good (>90%) at 1064 nm, 1572 nm, and 2060 nm
Overall System Block Diagram

Analog board

- analog Power Supplies
  - Pre-Filter
  - Linear Capture
  - High-speed Capture & MUX
  - Photon Counters

Digital board

- digital Power Supplies
  - Capacitive Isolators
  - Zynq 7020 SoC (ARM + FPGA)
  - FPGA LPDDR2
  - ARM LPDDR2
  - Flash (QSPI, μSD, Atmel)

Main Vehicle Bus (Power, GPS Time, Tx2/Rx2, Tx1/Rx1)

Control and Status

DRS Sensor Connector (Power, analog outputs, status)
Three Data-Capture Subsystems

16x Analog Signals from DRS HgCdTe detector

Low-pass Filter e.g. LFCN-105 ($F_{3db}=180$ MHz)

16

Photon Counters (16 Channel)

Thresholds 16

2×LTC2605 (16-bit DAC×16)

Comparators (ADCMP605)

16

Linear-mode (16 Channel)

Low-pass ($F_{3db}=7$ MHz)

AD9249 (65MSPS×16)

16

High-speed (Single Channel)

16

16:1 MUX (ADG782)

AD9286 (500MSPS×1)

Note: I²C/SPI control signals omitted for clarity

FPGA

ARM

Main Bus (Isolated)

8 GB µSD Card

8 MB Backup Flash

16+ MB Boot Flash

16+ MB Boot Flash

2 GB LPDDR2 (667 MT/s)

1 GB LPDDR2 (667 MT/s)
AC9 Launch Options

- NASA CSLI Option 1
  - 450 km x 820 km x 99 deg inclined
  - Aug 2016 delivery to Integrator
  - Nov 2016 launch

- NASA CSLI Option 2
  - 600 km SSO 10:30 LTDN
  - April 2016 delivery to Integrator
  - July 2016 launch
# L1 Requirements

<table>
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<tr>
<th>No.</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The LMPC shall measure near and short wave IR sources with the 2X8 Mercury Cadmium Telluride (MCT) electron Avalanche Photo Diode (e-APD) focal plane array (FPA) for 1 year to support the component needs for future NASA missions</td>
</tr>
<tr>
<td>2</td>
<td>The LMPC shall detect laser light from a ground source</td>
</tr>
<tr>
<td>3</td>
<td>The LMPC shall perform a radiometry assessment by scanning the Earth's moon for response calibration</td>
</tr>
<tr>
<td>4</td>
<td>The LMPC shall conduct a variable radiometric response experiment by imaging the sunlit Earth and clouds (i.e. no laser source)</td>
</tr>
<tr>
<td>5</td>
<td>The vehicle shall conform to CubeSat standards</td>
</tr>
<tr>
<td>6</td>
<td>The LMPC shall measure the effects of space radiation on the dark current, APD gain and quantum efficiency of a 2x8 HgCdTe electron Avalanche Photo Diode (e-APD) focal plane array (FPA) in a relevant space environment</td>
</tr>
</tbody>
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<td>1</td>
<td>The LMPC shall be compatible with an optical communications link</td>
</tr>
<tr>
<td>2</td>
<td>Measure an atmospheric gas absorption line</td>
</tr>
</tbody>
</table>
Summary

• Demonstrate single photon detection in space compatible with dark current

• Present status:
  – *Despite the relative early stage of the LMPC ACT-10 2 by 8 array, AC9 will have the ability to resolve a 13kcount or greater increase in dark current induced by the radiation exposure*
    • Developments under other programs have significantly reduced systematic background counts due to ROIC glow and pixel jitter to < 1 ns
  – *The ideal coating performance of the Materion cold filters insures relevant performance at the 3 principal earth science lines*
  – *Current performance of AC9 star trackers with potentially 0.01 degree open loop pointing opens relevant optical communication demonstrations*
  – *Impact of cryo-cooler vibration on spacecraft*
    • Linear acceleration RMS = [ 0.0133, 0.0141, 0.0096 ] g
    • Angle (jitter) RMS = [ 0.06, 0.36, 0.15 ] milli-deg (nominal R_gyro)
    • Angle (jitter) RMS = [ 0.06, 0.51, 0.77 ] milli-deg (bounding case R_gyro)

Even the tight 0.1 degree pointing will not be affected by cryo-cooler vibration