High Dynamic Range UV to SWIR Photon Counting Sensor for PEM-Based Imaging Polarimeters

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Remote sensing of aerosols

Why: Global climate and environmental impacts

- Aerosols are a major source of uncertainty in the magnitude of climate forcing, both direct (radiative) and indirect (impact on clouds)
- Near-surface airborne particulate matter is a major health hazard

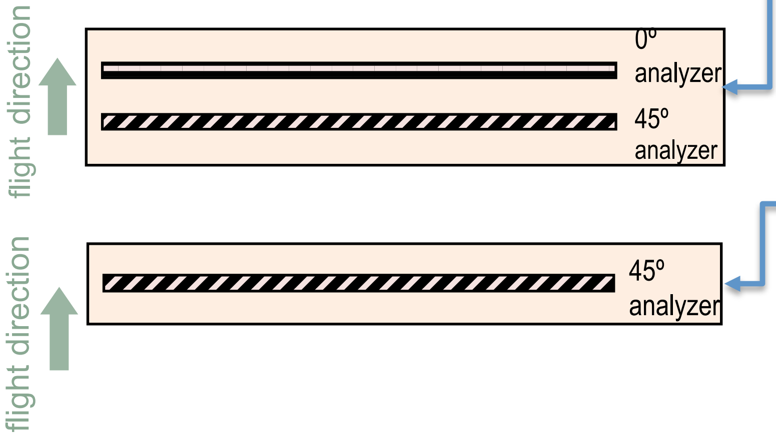
UV to SWIR sensitivity is desired

- **VNIR and shortwave infrared (SWIR) bands** discriminate particle size
- **UV bands** are sensitive to absorption by iron and aluminum oxides in dust particles, aromatic hydrocarbons in organic aerosols, and soot

Multiangle radiance and polarization helps discriminate particle size and shape, and provides compositional proxies such as refractive index

Advanced Component Technology: Demodulation with a single PEM

AirMSPI



Motivation

- Photoelastic modulators (PEMs) enable accurate polarimetry by rapidly varying retardance between the x- and y-components of electromagnetic waves at ~42 kHz
- A two PEM approach is currently used by JPL's MSPI and MAIA instruments
  - Uses a slow beat frequency 25 Hz due to detector speed and sensitivity limitations
  - Requires 2 detector lines per spectral band
- Single PEM approach:
  - Makes more efficient use of available light
  - Enables measurement of radiance (*I*) and Stokes *Q* and *U* in the same pixel
  - Requires only 1 detector line per spectral band

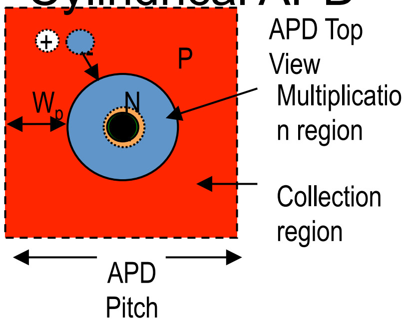
Detector and ROIC requirements

- Sufficient sensitivity and speed to allow a 1 PEM design
- UV to SWIR sensitivity with high QE in single detector
- High dynamic range, dual mode, from single photon counting to charge integrating

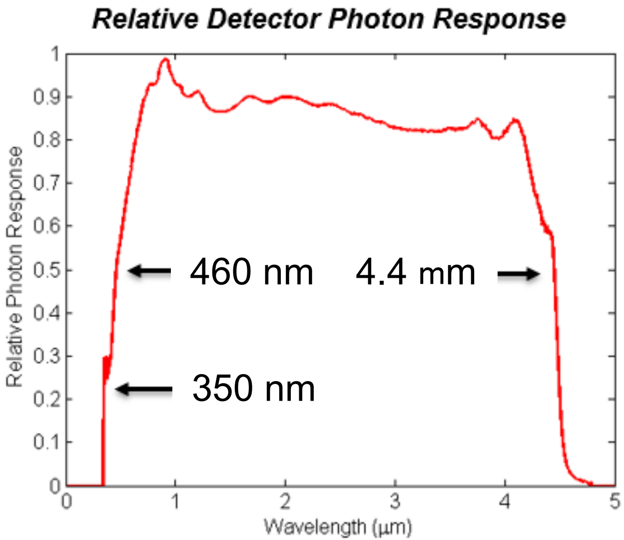
1-PEM design enabled by the HgCdTe APD

- **Unique detector solution: The HgCdTe linear mode avalanche photodiode (APD)**
- **HgCdTe APD Detector**
  - UV to SWIR photon counting sensitivity with high QE and SNR
  - Very uniform, linear mode APD gains > 1000
  - High dynamic range from single photon to large signal

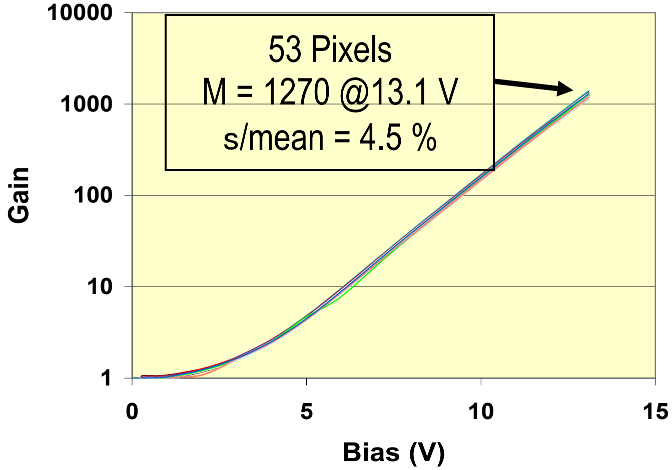
Cylindrical APD



Broad UV to MWIR response

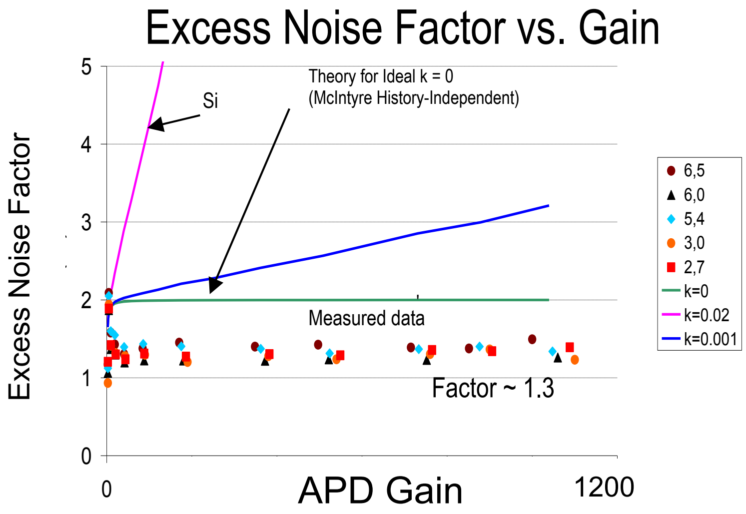


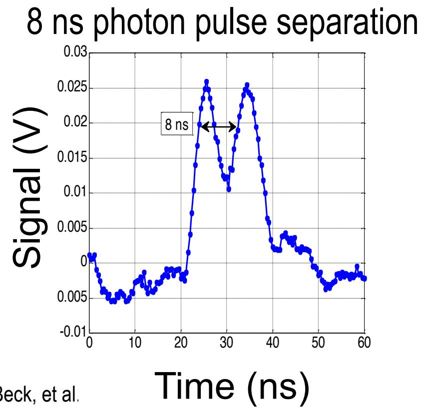
APD Gain vs. Bias



HgCdTe linear mode APD

- Single photon detection efficiency (PDE) > 50%
- High, near noiseless, uniform, gain with excess noise factor ~ 1.3
- Continuous operation with no dead time
- Minimum pulse separation ~ 10 ns - 20 ns, (preamp bandwidth limited)
- Dark current as low as 100 e/s (input referred)





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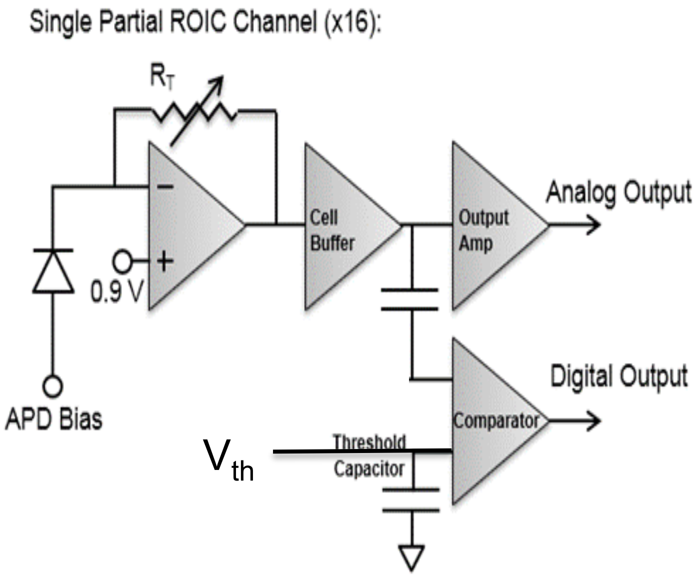
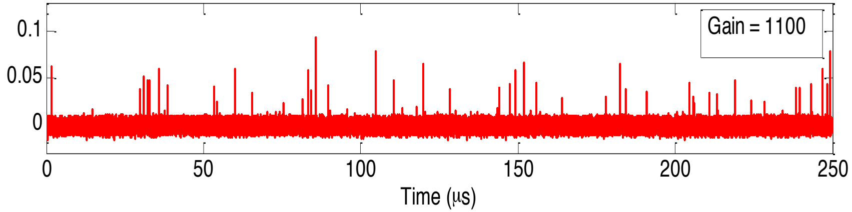
2x8 Linear Mode Photon Counting (LMPC) APD preamp



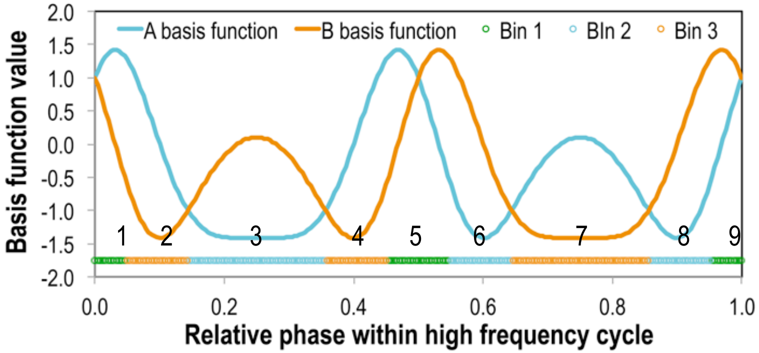
Output stream showing high SNR single photon sensitivity



- 2x8 format with 16 analog and 16 digital outputs
- RTIA ROIC in 0.18 μm CMOS
- ROIC gain = 300 V/A

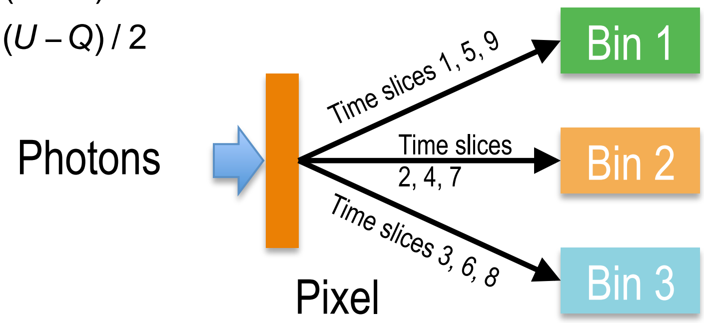
The APD approach enables the use of charge binning

- Uneven partitioning of signals into 3 bins is required to recover the Stokes parameters: *I, Q, U*
- kTC noise would normally introduce too much noise into the charge binning process
- With APDs the kTC noise contribution is greatly reduced because of the APD gain



$$A = (Q + U)/2$$

$$B = (U - Q)/2$$

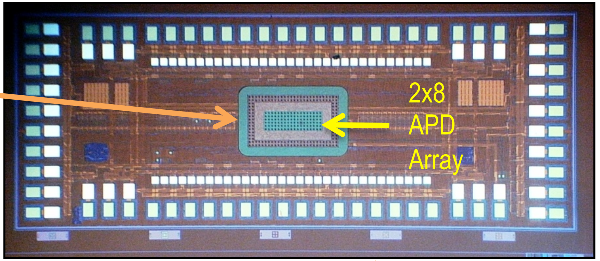


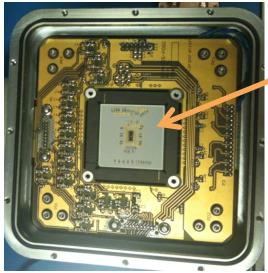
2x8 APD array photon counting system delivered to JPL

2x8 LMPC System: FPA, Custom LCC, Internal Electronics Interface Board, LN2 Dewar, External Electronics

Focal Plane Array (FPA)

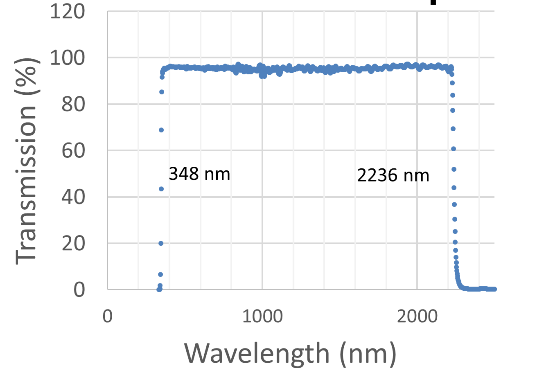
- 2x8 APD array
- 64 µm pixels
- 64 µm pitch
- Vertically integrated to readout integrated circuit with RTIA preamp





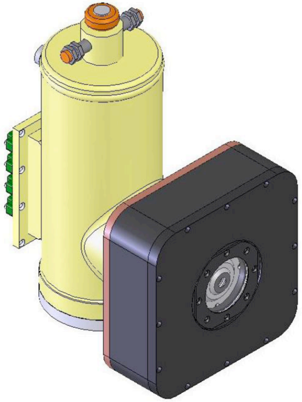
Leadless chip carrier (LCC)

348 nm to 2267 nm bandpass filter



ROIC

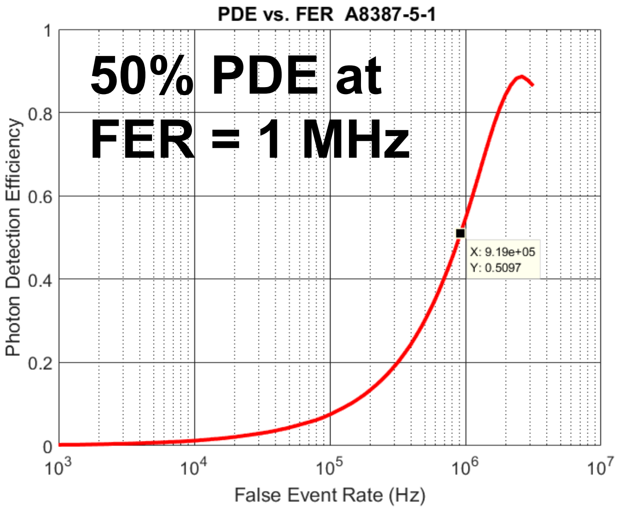
Electronics



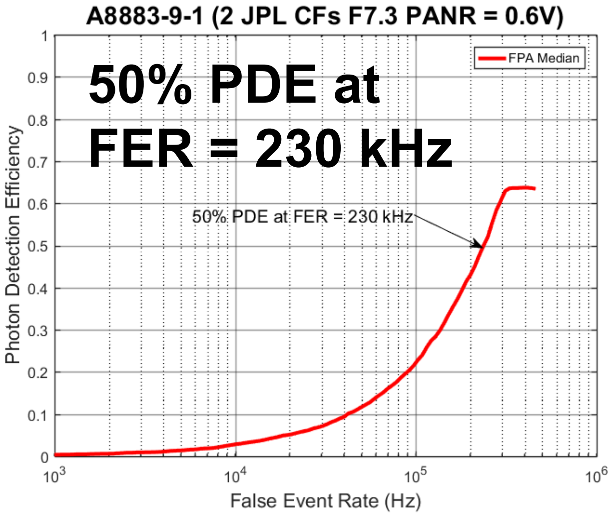
LN2 Dewar

Photon Detection Efficiency (PDE) vs. False Event Rate (FER) Data

1st FPA: Mean PDE vs. FER

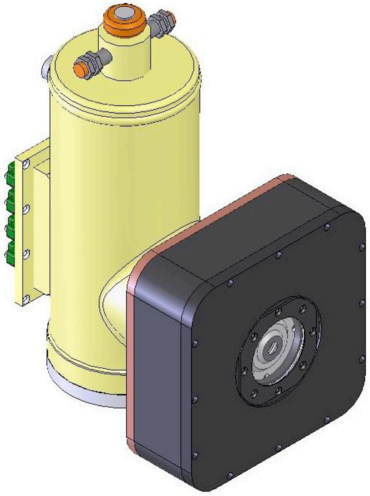


Improved 2nd FPA: Mean PDE vs. FER



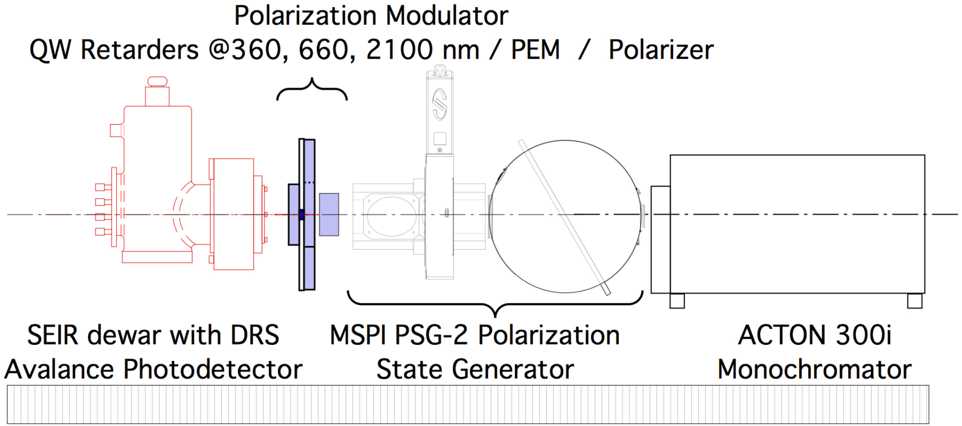
- 1st FPA: 1 MHz false event rate (FER) attributed to out of band flux through the cold filter.
- 2nd FPA: 230 kHz FER after improvement to reduce out of band flux

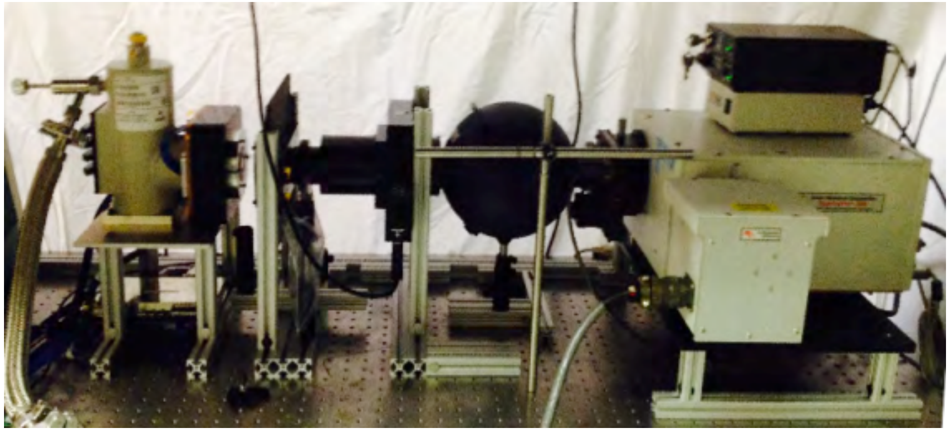
Laboratory demonstration setup at JPL



Detector and LN2
Dewar from DRS

1st 2x8 FPA used

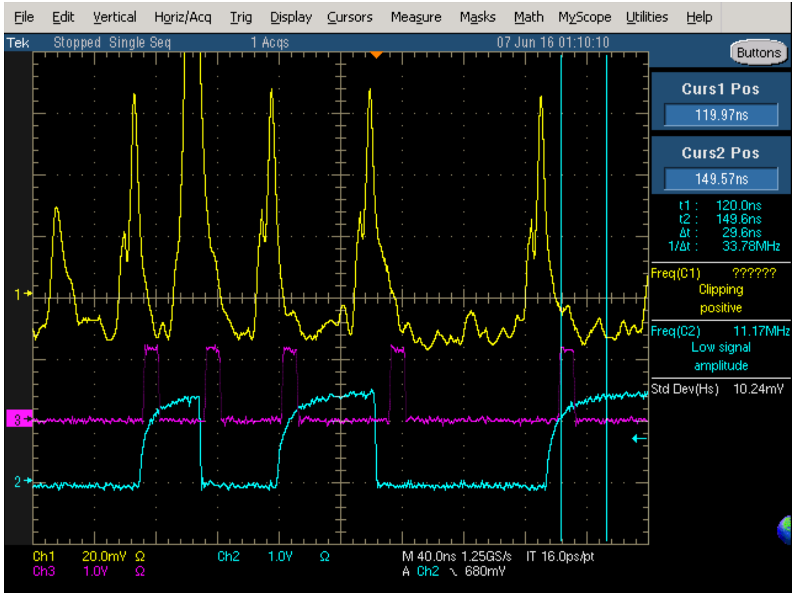




Counting pulses and processing in FPGA

Digital pulses from the DRS system trigger a flip-flop in the FPGA

Edge detection synchronizes the flip-flop to the system clock for counting

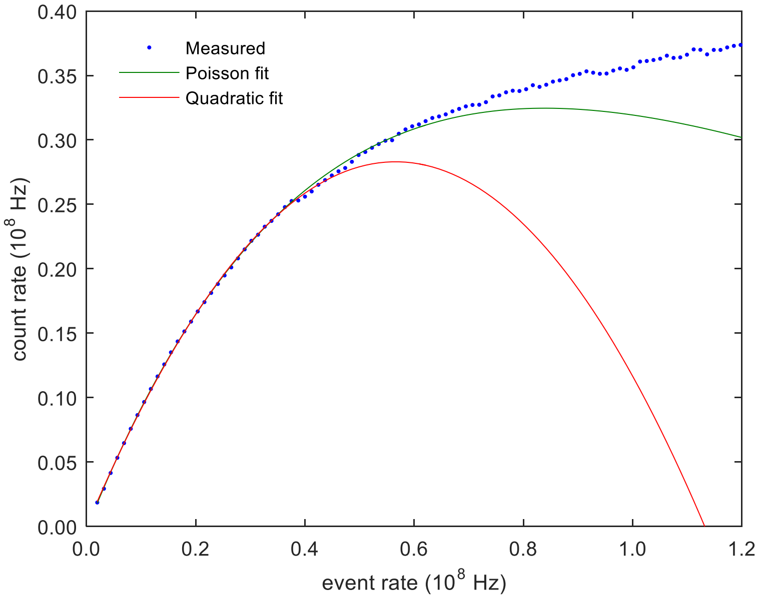


analog pulse:	yellow
digital pulse:	not shown
flip-flop:	cyan
synchronized:	magenta

Modeling of detector nonlinearity

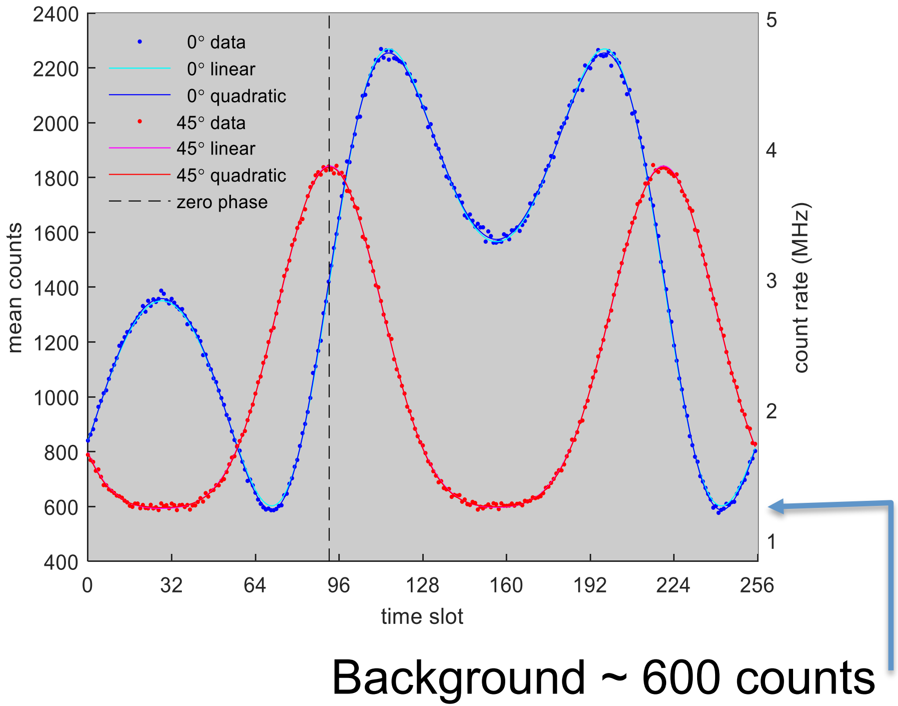
- Linearity of count rate vs. illumination characterized up to 1.4x10^9 ph/s
  - Fairly linear up to 15 x 10^6 ph/s
  - Non linearity inevitable due to Poisson statistics and photon collision at higher fluxes
  - Good fit of non-linearity with Poisson model for overlapping events below 60 x 10^6 ph/s with simple quadratic
  - Correction for non-linearity can be applied, if necessary, after collection

Counts vs. Input Event Rate



Success: Expected waveforms fitted to measured data

- For the demonstration, counts were binned in 256 time slots* over 122 ms
  - 650 nm illumination, wire grid polarizer rotated in 5°steps
  - 3-bin data synthesized from this by summing sets of time slots
- At these count rates, nonlinearity does not have a large effect
- Fits are quite good, yielding I, Q, U, retardance and phase offset
- Fits such as these can be performed assuming linear response, or including a quadratic term

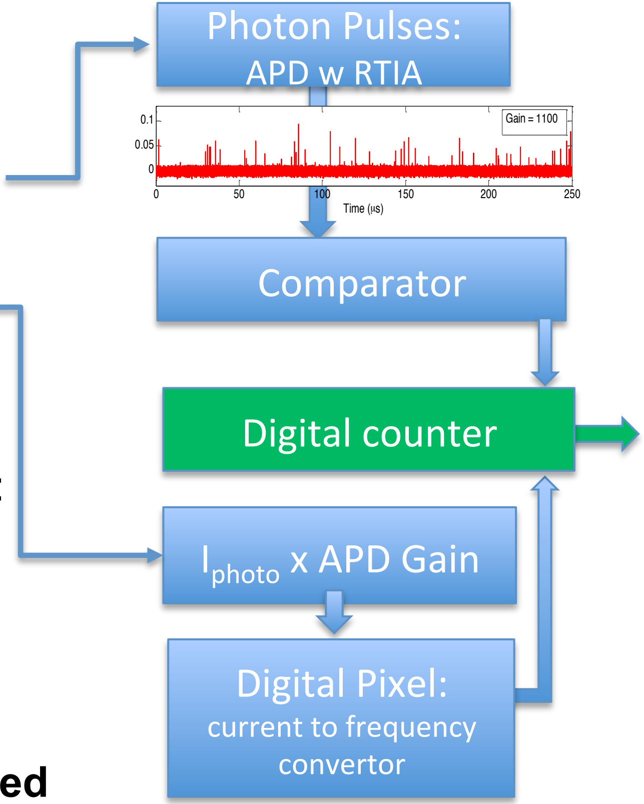


* 1/42 kHz = 23.8 μs per PEM cycle, 23.8 μs /256 = 93 ns wide time slot, 5120 PEM cycles gives 122 ms
Using 256 bins produces too much data for practical use

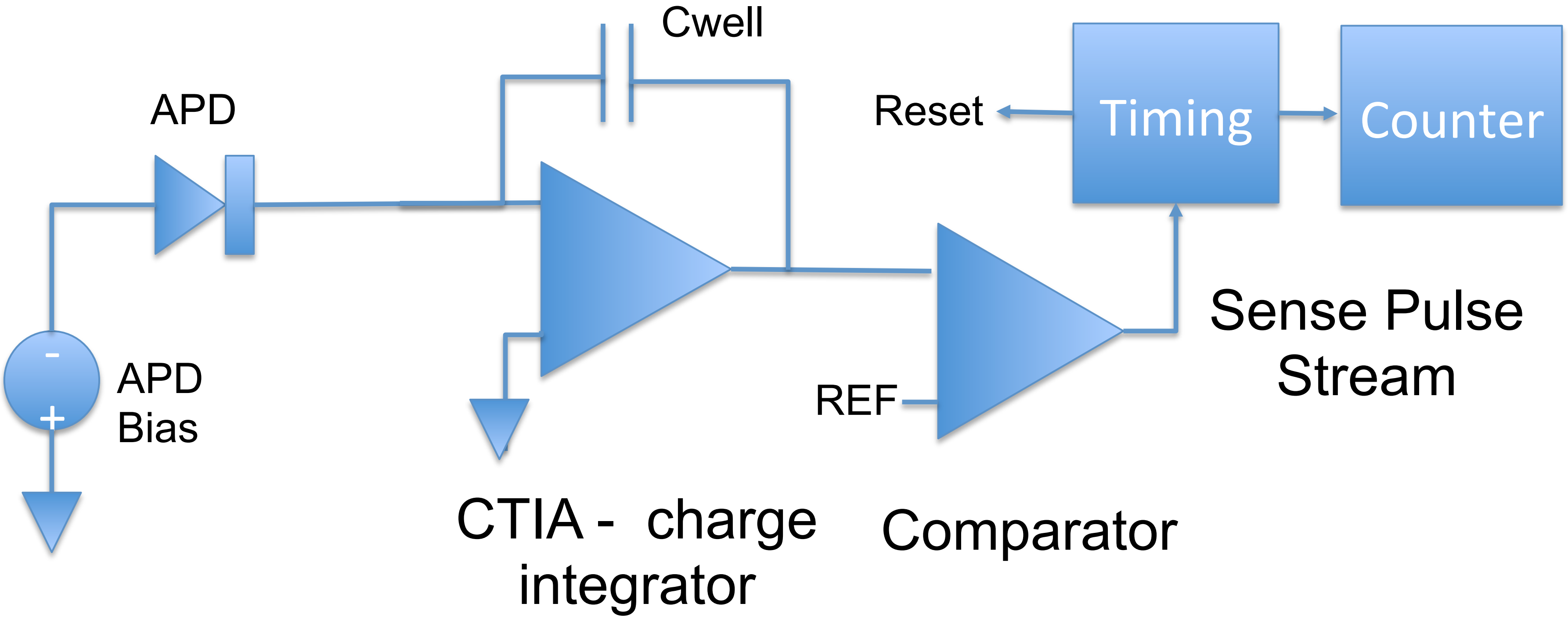
ROIC approach for higher signals

ROIC will have two modes: Photon Counting and Current integration

- Photon Counting mode in single-photon signal regime
  - **This has been demonstrated**
- Current integration mode in higher signal regime
  - At higher signals, single photon pulses coalesce
  - Current integration required
  - Digital pixel method chosen over analog integration:
    - Current is integrated and digitized into charge increments that are counted
  - APD gain can be used to improve SNR
  - Both modes share the same digital back end
  - **Test chips designed and currently being evaluated**



Digital Pixel ROIC: current to frequency converter



Summary

- Successfully demonstrated HgCdTe photon counting mode APD/ROIC and binning in a single PEM polarization modulated system

- Chose the digital pixel (current to frequency) approach to handle the large signal regime:

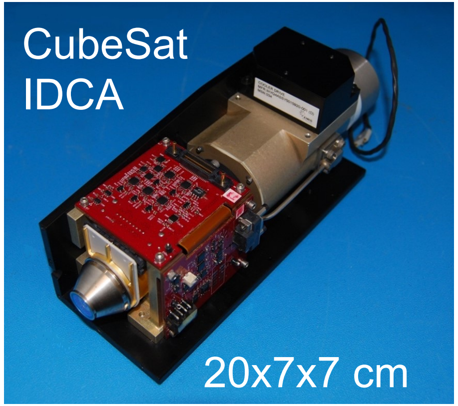
- Designed a 2x15 digital pixel test chip that will
  - Verify the digital pixel approach for the high flux operation condition
  - Explore parasitics of the critical capacitive elements
  - Add a digital back end that is common to both modes of operation, enabling high dynamic range

Conclusions: The HgCdTe linear mode APD

- Is a unique, near noiseless gain, high dynamic range, APD with high SNR single photon sensitivity from the UV to the Infrared
- Can provide laser pulse return amplitude and range information
- Has a very high fundamental communications data rate
- Has demonstrated workable proton radiation tolerance
- Enables many new NASA applications
  - High sensitivity polarimetry
  - CO_2 and methane monitoring
  - LIDAR surface topology
  - LASERCOM
  - Lunar and planetary remote sensing

2x8 LMPC APD demonstrated in a tactical Dewar configuration for the AC9 CubeSat mission

2x8 LMPC APD in tactical Dewar



Thank you for your attention