Detectors that cover a dynamic range of more than 1 million …in several dimensions

Detectors for Astronomy Workshop
Garching, Germany
10 October 2009

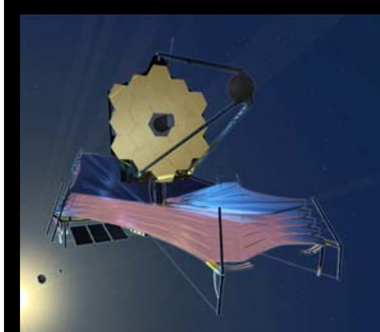
James W. Beletic

TELEDYNE
IMAGING SENSORS
A Teledyne Technologies Company

Teledyne

Providing the best images of the Universe




The Ideal Imaging Sensor

The ideal sensor:

- detects every photon (100% QE)
- provides photon noise limited performance

No single sensor is ideal for every application.

Incident signal

- Wavelength (λ)
- Flux
- Background

Environment

- Temperature
- Vibration
- Radiation

Operating mode

- Integration time
- Frame readout time
- Shutter (rolling, snapshot)
- Multiple storage cells per pixel
- Windows
- Reset (pixel, line, global)
- Event driven

Interface

- Input (analog, digital)
- Output (analog, digital)
- # of readout ports
- Mechanical
  - e.g. order sorting filter

Other Requirements

- Linearity
- Anti-blooming
- Minimal persistence

Huge Dynamic Range to be Covered (1 of 3)

HgCdTe

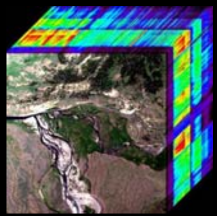
Silicon

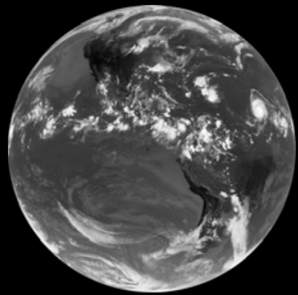
Photon Wavelength (µm) **& Energy** (keV)

Wavelength (µm): 0.01 | 0.1 | 1 | 10 | 100 µm

Energy: 100 | 10 | 1 | 0.1 keV | 1 eV

Range: 10^6





Astronomy

Planetary & Earth Science Visible - SWIR

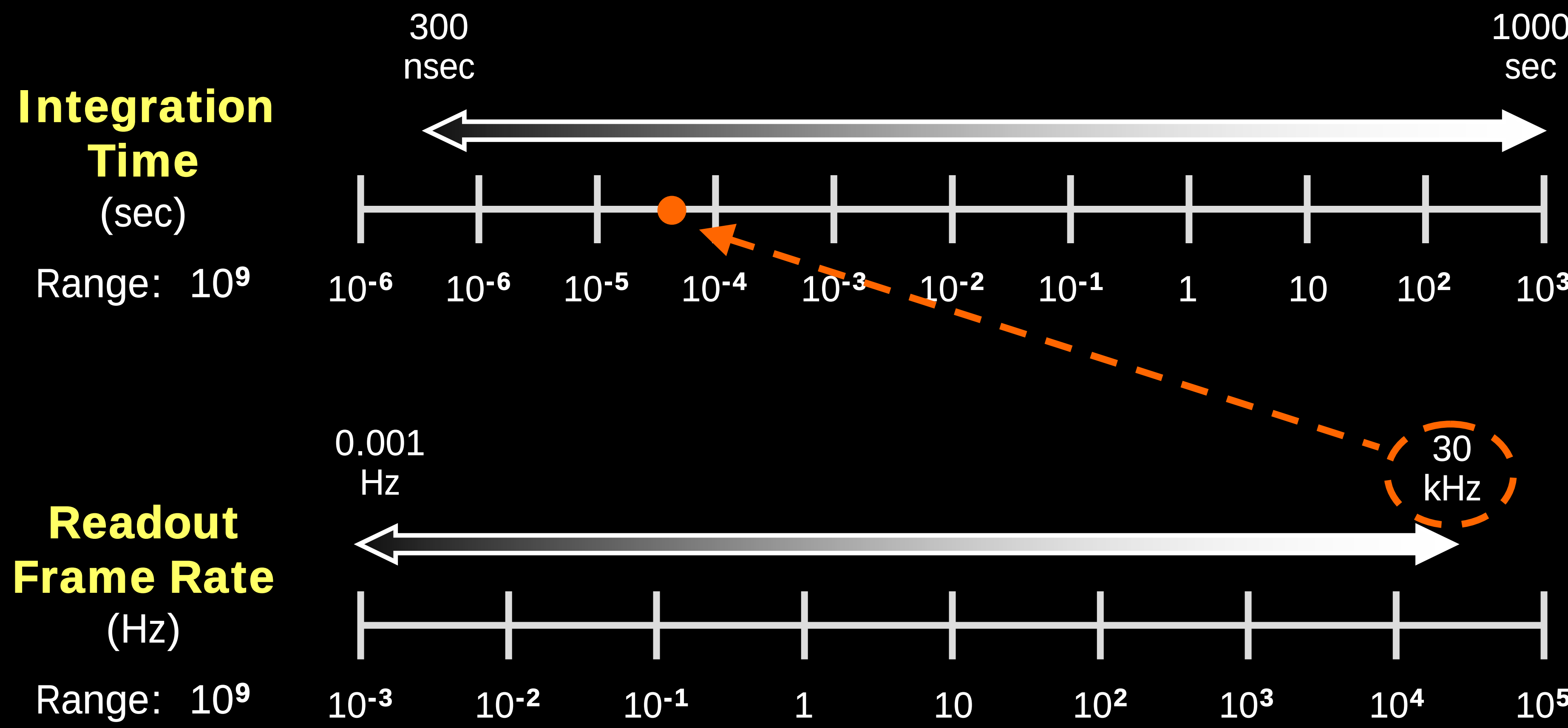
Earth Science Thermal IR

Flux (photons/pixel/sec)

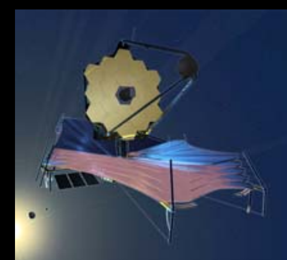
Range: 10^{13}

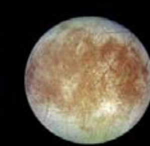
10^{-2} | 10^{-1} | 1 | 10 | 10^2 | 10^3 | 10^4 | 10^5 | 10^6 | 10^7 | 10^8 | 10^9 | 10^{10} | 10^{11} | 10^{12}

Huge Dynamic Range to be Covered (2 of 3)



Huge Dynamic Range to be Covered (3 of 3)





JWST
50 krad

Ganymede
300 krad

Europa
> 1 Mrad

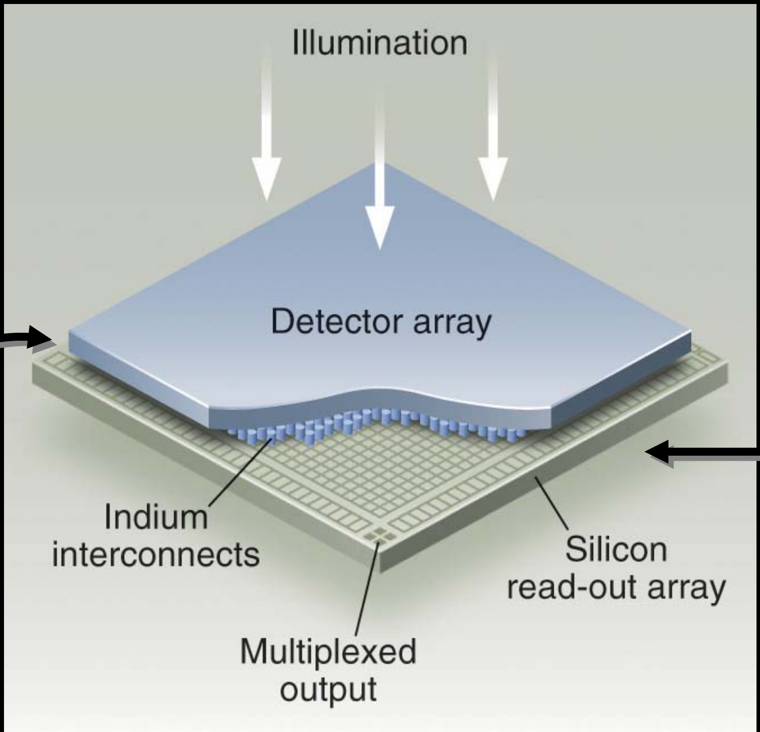
Radiation Environment

(Rad)

Range: 10^6

1 | 10 | 10^2 | 10^3 | 10^4 | 10^5 | 10^6 | 10^7

Hybrid CMOS Imaging Sensors



Detector

- Wavelength (λ)
- Quantum Efficiency
- Dark current & Noise
- Radiation environment
- Persistence

The functionality ("the brains") of a CMOS-based sensor is provided by the readout circuit

Readout Circuit

Input signal
- Flux – object and background

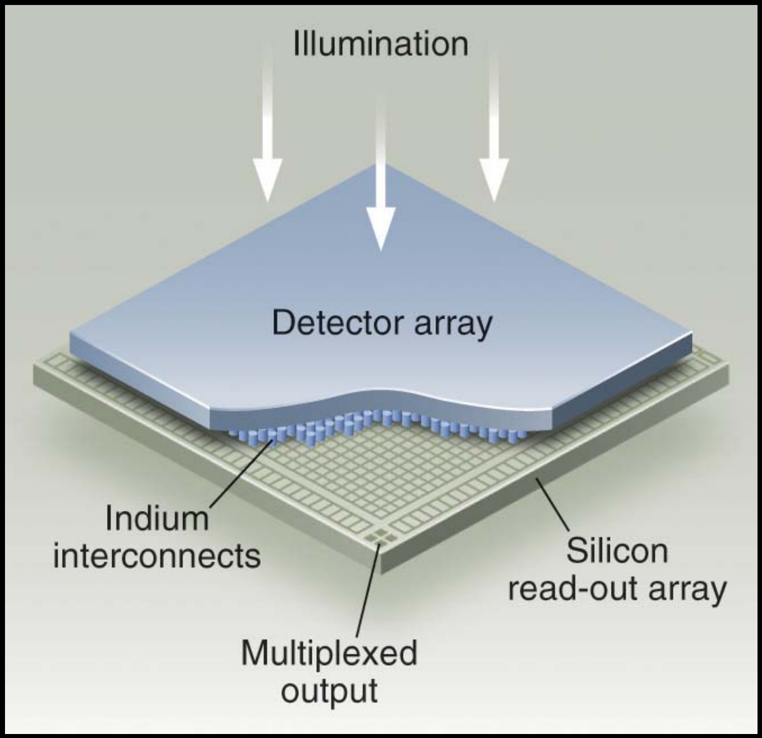
Operating Mode
- Integration time
- Frame readout time
- Shutter (rolling, snapshot)
- Multiple storage cells per pixel
- Windows
- Reset (pixel, line, global)
- Event driven

Interface
- Input (analog, digital)
- Output (analog, digital)
- # of readout ports

Environment
- Temperature
- Radiation

Other Requirements
- Linearity
- Anti-blooming

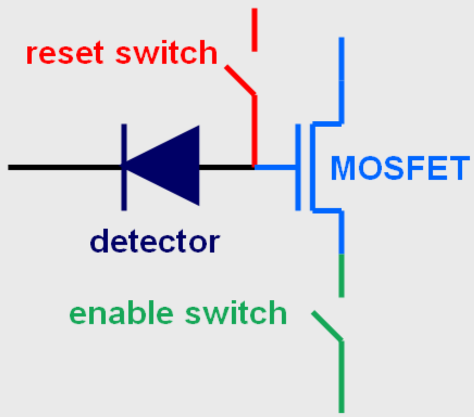
Hybrid CMOS Imaging Sensors



The functionality of a Readout Integrated Circuit (ROIC) is only limited by:

- **the design rule of the CMOS process**
- **the size of the pixel**
- **your imagination**

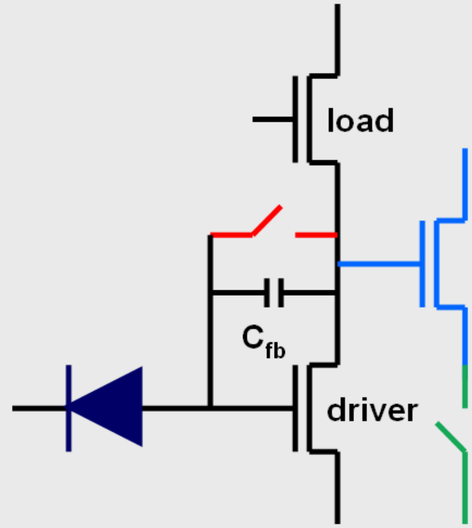
CMOS Pixel Amplifier Types



Source follower
(SF)

- Integration on detector node
- Low power & compact
  (3 FETs / pixel)
- Ideal for small pixels & low flux
- Poor performance for high flux

- Full Well: ~100,000 electrons
- Readout Noise: <15 e-



Capactive TransImpedance Amplifier (CTIA)

- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SF for low flux
- Worse performance than DI for high flux
- Full Well: ~1 to 10 million e-
- Readout Noise: <50 e-

Classes of Sensors for Astronomy & Civil Space

Low light level, long exposure astronomy

- H1, H2, H1R
- HxRG: H1RG, H2RG, H4RG-10, H4RG-15

Planetary Missions, Earth Science

- 6604a
- Next generation hyperspectral
- Thermal IR pushbroom sensor

Solar Astronomy

- High speed, low noise, large format polarization sensors

High Speed, low noise & photon counting

- Speedster128, Speedster256D
- Event driven x-ray detectors
- Avalanche photodiodes

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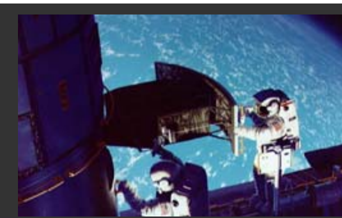
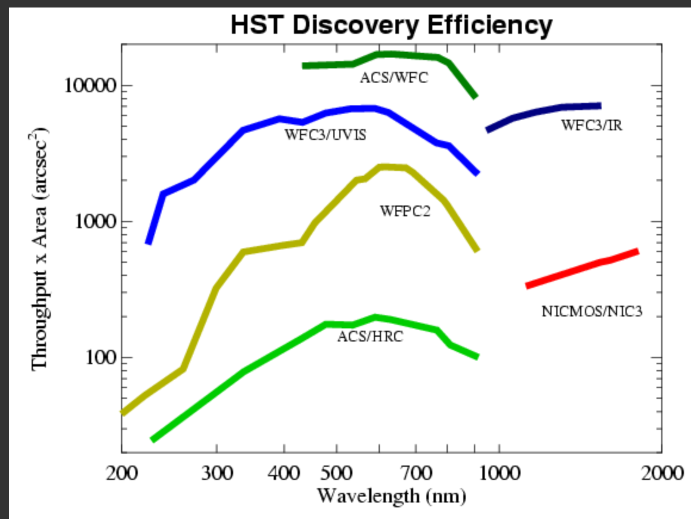
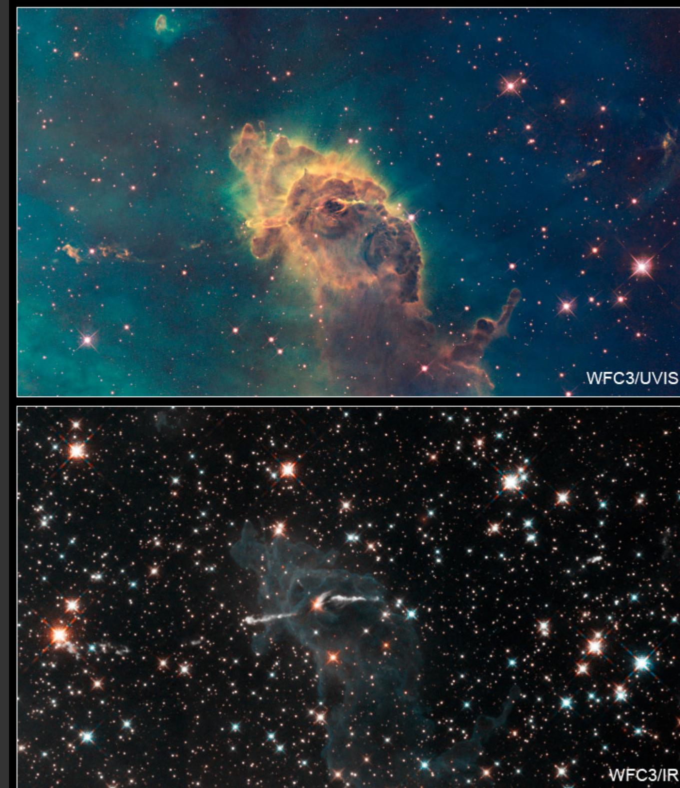
Low light level, long exposure astronomy

- H1, H2, H1R
- HxRG: H1RG, H2RG, H4RG-10, H4RG-15

Hubble Space Telescope
Wide Field Camera 3

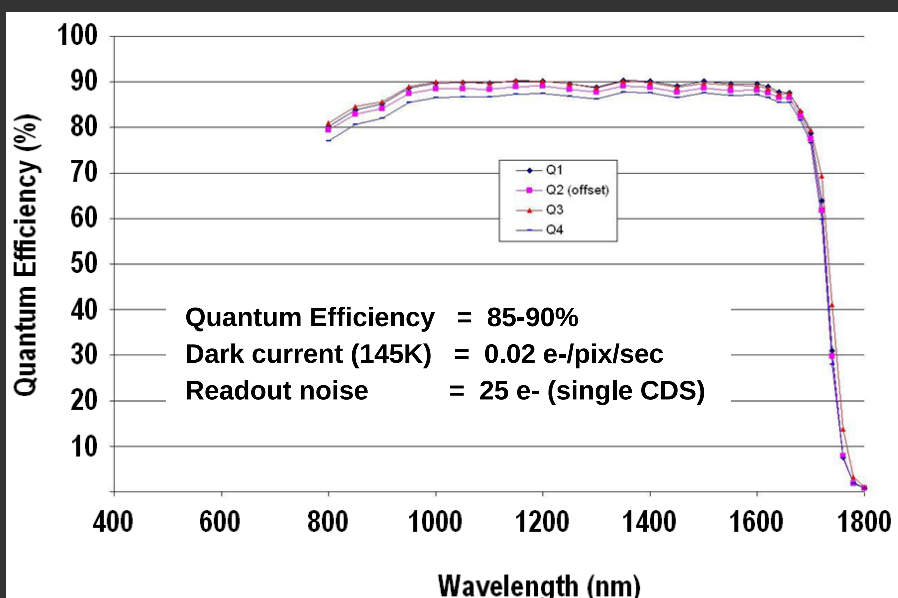






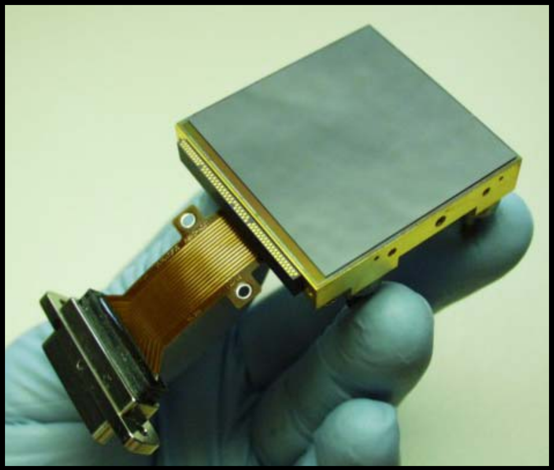
Stellar Jet in the Carina Nebula
Hubble Space Telescope • WFC3/UVIS/IR

NASA, ESA, and the Hubble SM4 ERO Team STScI-PRC09-25b



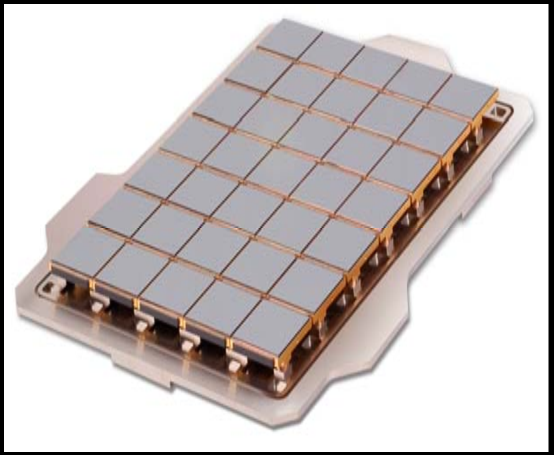
- **1024×1024 pixels, 18.5 micron pitch**
- **Substrate-removed 1.7 µm HgCdTe arrays**
- **Nearly 30x increase in HST discovery efficiency**

HAWAII-2RG 2048×2048 pixels



HAWAII-2RG (H2RG)

- 2048×2048 pixels, 18 micron pitch
- 1, 4, 32 ports
- "R" = reference pixels (4 rows/cols at edge)
- "G" = guide window
- Low power: <1 mW (4 port, 100 kHz rate)
- Detector material: HgCdTe or Si
- Interfaces directly to the SIDECAR ASIC
- **Qualified to NASA TRL-6**
  - Vibration, radiation, thermal cycling
  - Radiation hard to ~100 krad



Teledyne Imaging Sensors
HAWAII-2RG™
Visible & Infrared Focal Plane Array

The 2048×2048 pixel HAWAII-2RG™ (H2RG) is the state-of-the-art readout integrated circuit for visible and infrared astronomy in ground-based and space telescope applications.

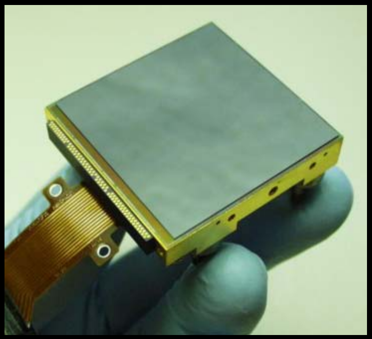
- Large (2048×2048 pixel) array with 18 µm pixel pitch.
- Compatible with Teledyne Imaging Sensors (TIS) HgCdTe infrared (IR) and silicon PIN HyViSI™ visible detectors, providing sensing of any spectral band from soft X-ray to 5.5 µm.
- Substrate-removed HgCdTe enhances the J-band QE, enables response into the visible spectrum (70% QE down to 400nm) and eliminates fluorescence from cosmic radiation absorbed in the substrate.
- Reference rows and columns for common-mode noise rejection.
- Guide window output – windowing with simultaneous science date acquisition of full array. Programmable window which may be read out at up to 5 MHz pixel rate for guiding. Readout is designed to allow interleaved readout of the guide window and the full frame science data.
- Selectable number of outputs (1, 4, or 32) and user-selectable scan directions provide complete flexibility in data acquisition.
- Built with modularity in mind – the array is 4-side-buttable to allow assembly of large mosaics of 2048×2048 H2RG modules, such as TIS' 4096×4096 mosaic FPA and larger mosaics.
- Fully compatible with the TIS SIDECAR™ ASIC Focal Plane Electronics.

For more information, please email **Richard Blank** at **rblank@teledyne.com** or call +1 **805 373-4083**.

IMAGING SENSORS

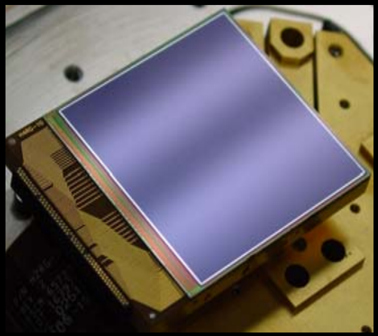
www.teledyne-si.com

Large Format Hybrid Arrays



H2RG
2048×2048 pixels
18 µm pitch
37×37 mm

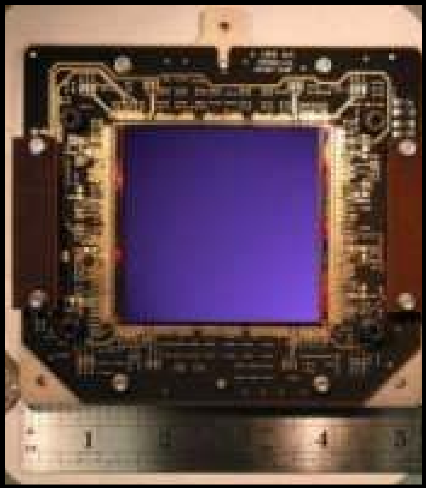
Since 2002



H4RG-10
4096×4096 pixels
10 µm pitch
41×41 mm

16 Mpixel

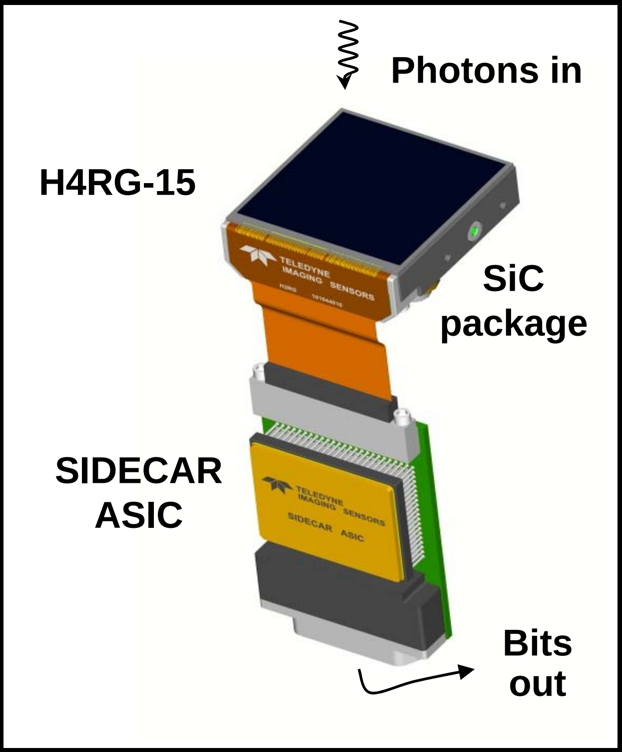
Since 2006



...
2048×2048 pixels
30 µm pitch
61×61 mm

6×6 cm

Since 2009



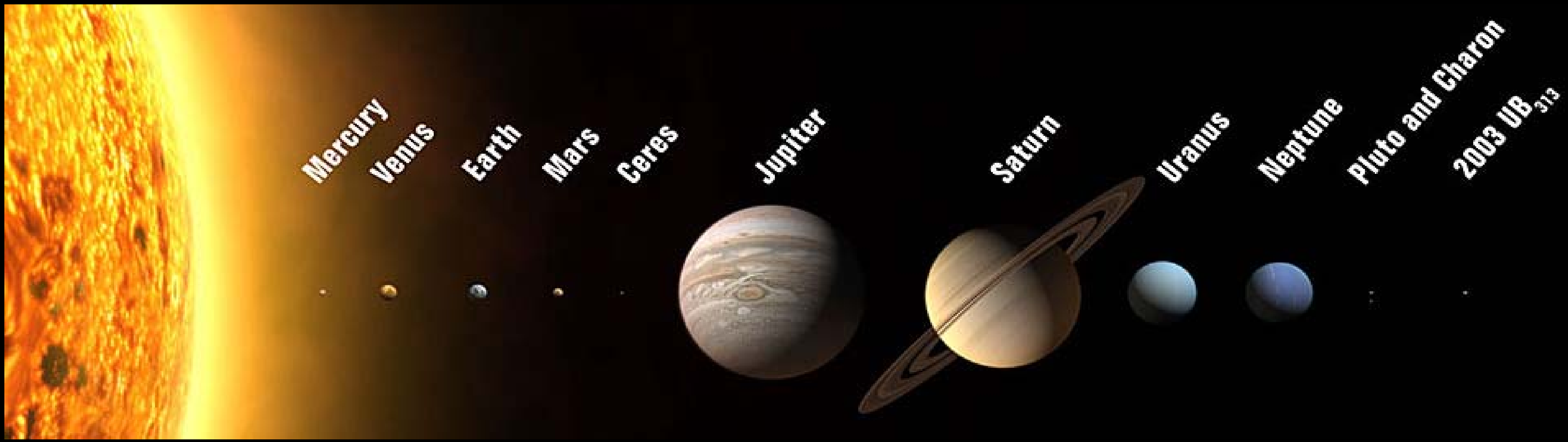
H4RG-15
4096×4096 pixels
15 µm pitch
61×61 mm

Development starting Nov 2009
First arrays early 2011

Classes of Sensors for Astronomy & Civil Space

Planetary Missions, Earth Science

- 6604a
- Next generation hyperspectral
- Thermal IR pushbroom sensor



Moon Mineralogy Mapper Discovers Water on the Moon

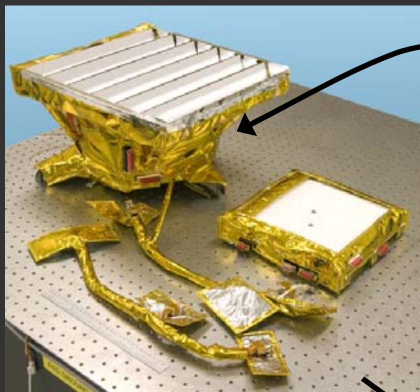
Moon water findings are a game-changer

Discovery calls into question 40 years of assumptions about lunar surface

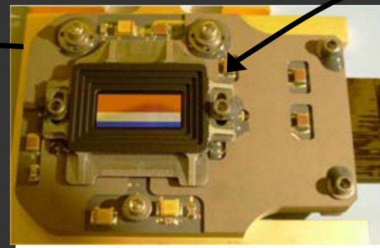
By Andrea Thompson
SPACE

updated 12:38 p.m. PT, Thurs., Sept . 24, 2009

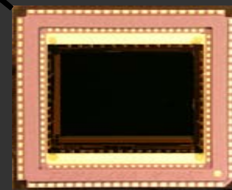
The discovery of widespread but small amounts water on the surface of the moon, announced Wednesday, stands as one of the most surprising findings in planetary science.



Instrument at JPL before shipment to India



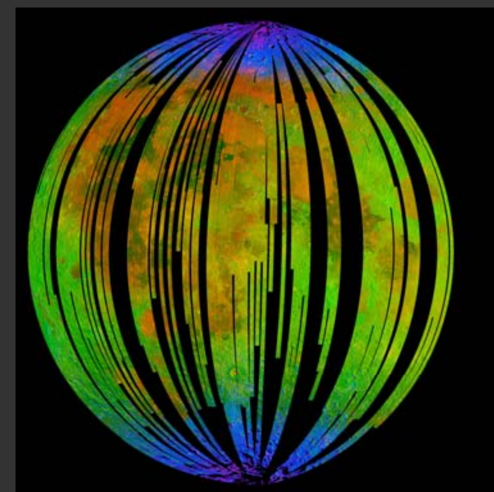
Focal Plane Assembly



Sensor Chip Assembly

Teledyne Infrared FPA

- 640 x 480 pixels (27 μm pitch)
- Substrate-removed HgCdTe (0.4 to 3.0 μm)
- 650,000 e- full well, <100 e- noise
- 100 Hz frame rate (integrate while read)
- < 70 mW power dissipation
- Package includes order sorting filter
- Total FPA mass: 58 grams

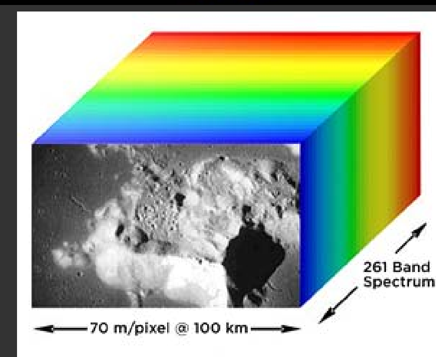


Completion of Chandrayaan-1 spacecraft integration
Moon Mineralogy Mapper is white square at end of arrow

6604A

Chandrayaan-1 in the Polar Satellite Launch Vehicle

Launch from Satish Dhawan Space Centre



Moon Mineralogy Mapper resolves visible and infrared to 10 nm spectral resolution, 70 m spatial resolution
100 km altitude lunar orbit

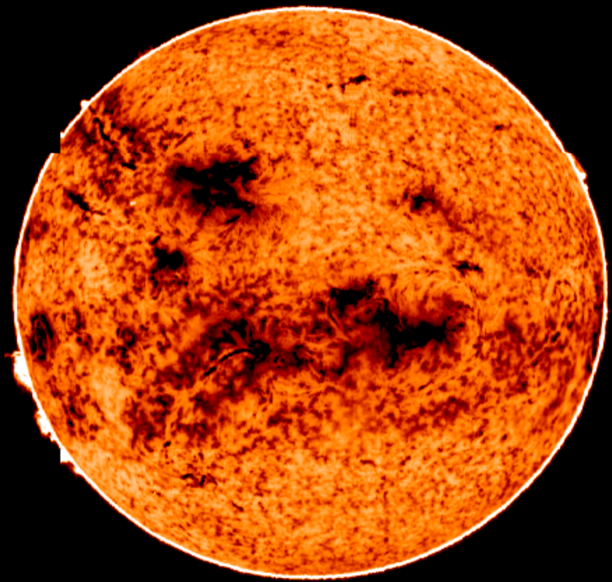
Next Generation Hyperspectral array

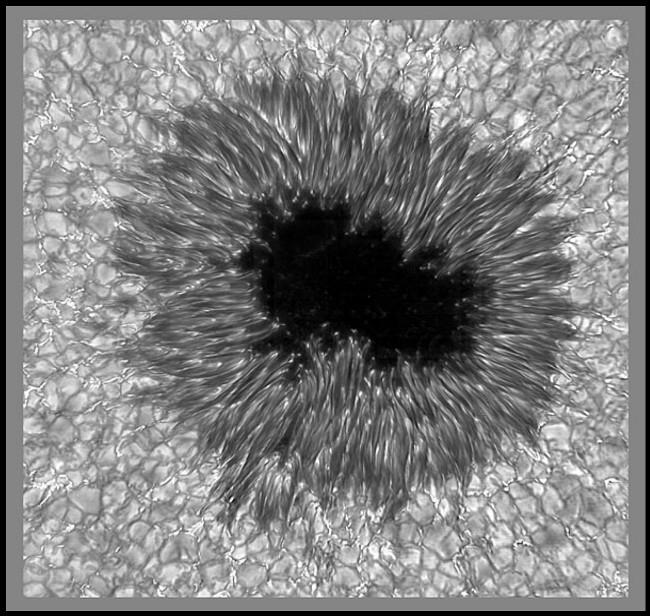
Parameter	Unit	6604A	Next Gen Hyperspectral
Pixel pitch	microns	27	30
Spatial pixels	columns	640	640, 1280 or 1500
Spectral pixels	rows	480	480
Well capacity	electrons	650,000	1,000,000
Readout noise	electrons	120	100
Integration time	msec	10	4
Readout mode		Integrate while read	Integrate while read
Windowing		Yes	Yes
Power dissipation	mW		< 150
Frame rate			250
Input		Analog	Digital
Output		Analog – 4 ports	Analog – 1 port per 160 columns

Classes of Sensors for Astronomy & Civil Space

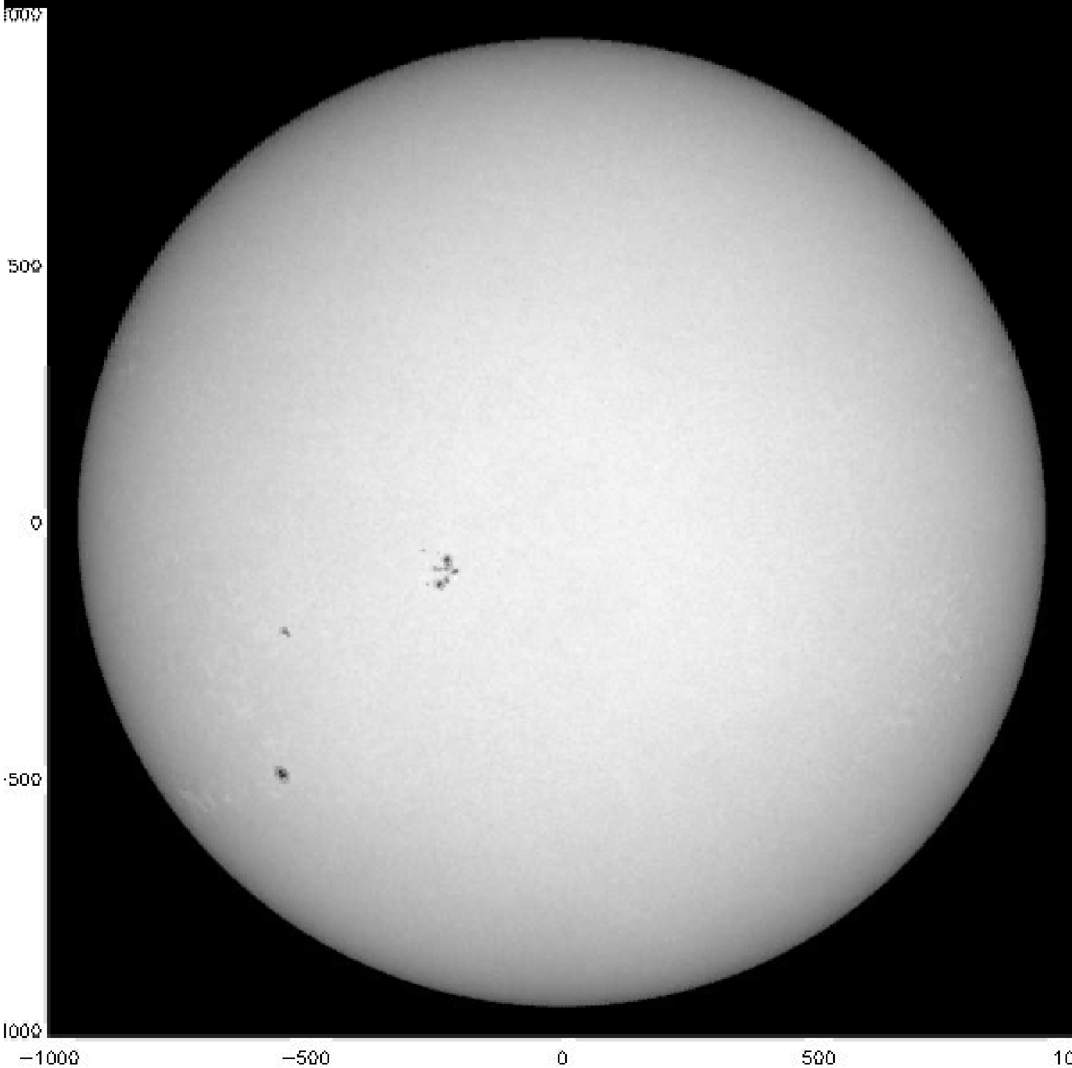
Solar Astronomy

- High speed, low noise, large format polarization sensors





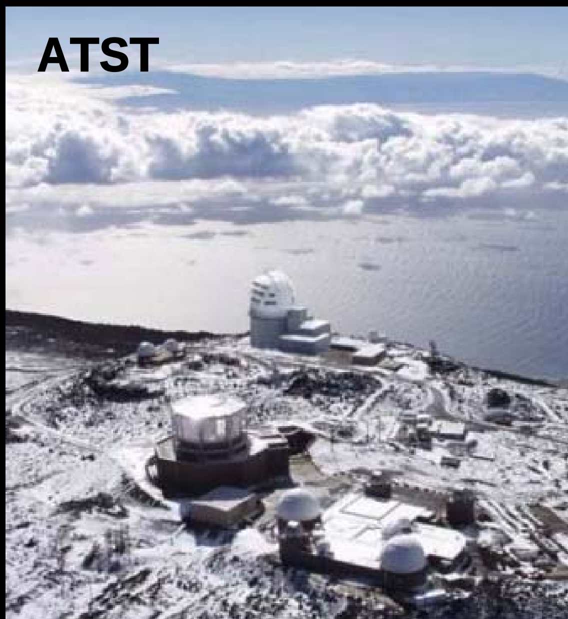
Ground-based Solar Astronomy

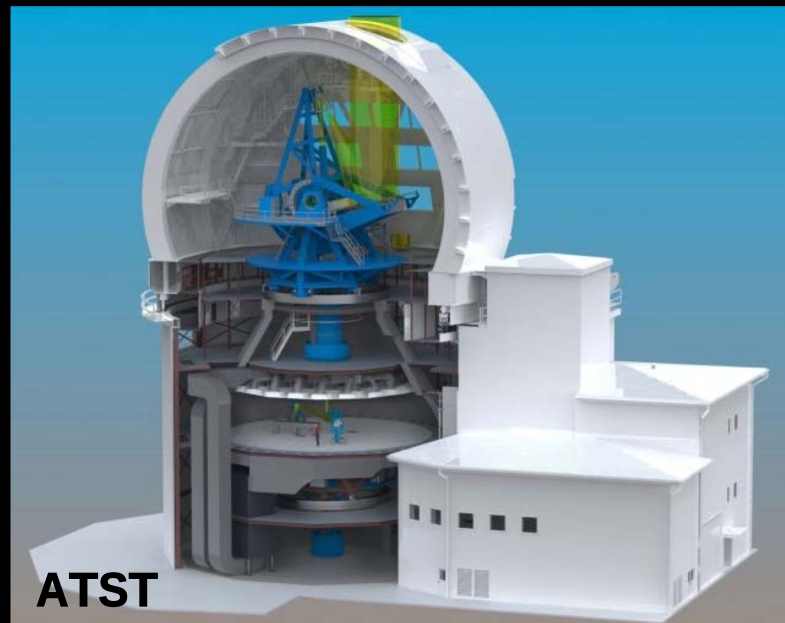


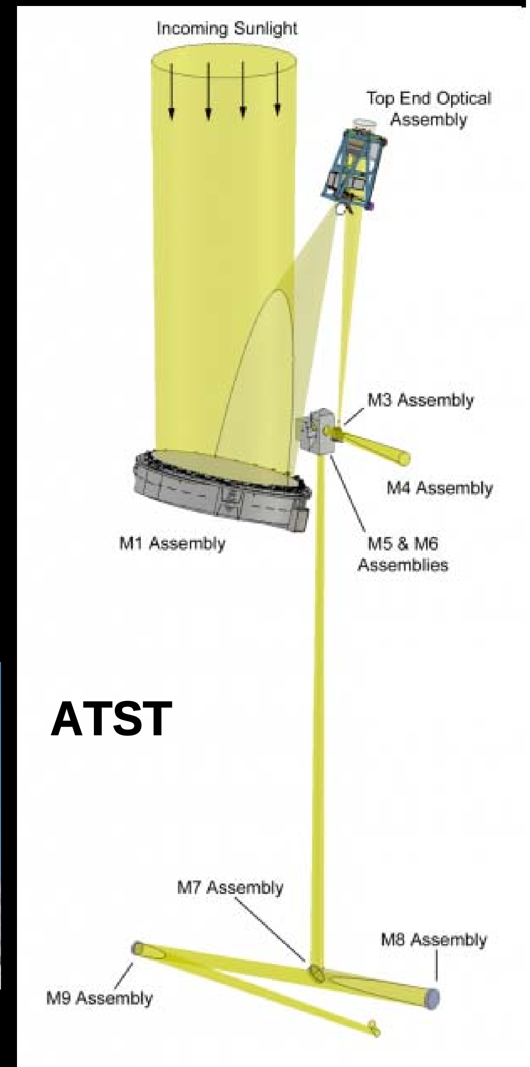
1. To understand the Sun, need to understand magnetic field
2. Measure magnetic field by measuring polarization
3. Measure 4 or 8 polarization states at ~2 kHz rate
   - Individual measurements at ~10 kHz

…and of course, want large arrays of pixels

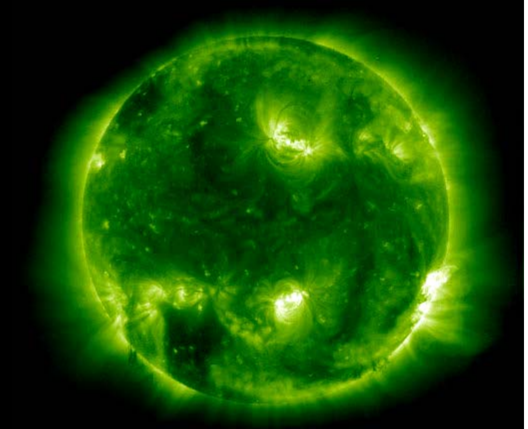
Advanced Technology Solar Telescope (ATST)
European Solar Telescope (EST)







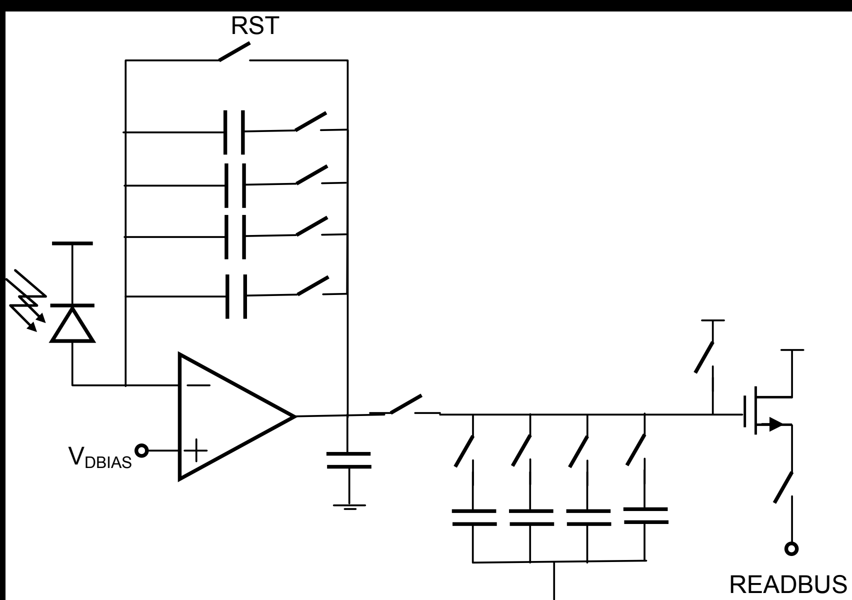
Ground-based Solar Astronomy



3 types of sensors required.

The new type of polarization sensor is:

- 2048×2048 pixels
- 20 to 24 µm pixel pitch
- Record 4 (8) polarization states at 2.5 kHz, switching between charge caching sites at 10 (20) kHz
- Read out the summed charge at 100 Hz frame rate



Teledyne has made a sensor that takes three successive 280 nsec exposures, using charge caching approach similar to what is shown in schematic at left.

Welding machine

Won R&D 100 award

Classes of Sensors for Astronomy & Civil Space

High Speed, low noise & photon counting

- Speedster128, Speedster256D
- Event driven x-ray detectors
- Avalanche photodiodes

Speedster

Speedster128 designed in 2005 to be next generation high speed, low noise IR array

- 128 x 128 pixels
- 40 μm pixel pitch
- Digital input – clocks and biases generated on-chip
- Analog output
- Two gain settings – high gain for lowest noise
- Chip functionality and performance (in low gain) proven
- High gain mode (which should be lowest noise) does not work as designed

Speedster256-D (2008 design) took Speedster128 design

- Improved CTIA pixel
- 256 x 256 pixels
- 12 bit analog-to-digital converters on-board
- Up to 10 kHz frame rate

Event Driven X-ray sensor

Large format x-ray sensors detect a small number of x-rays per frame

X-rays produce hundreds to thousands of electron-hole pairs per absorbed x-ray

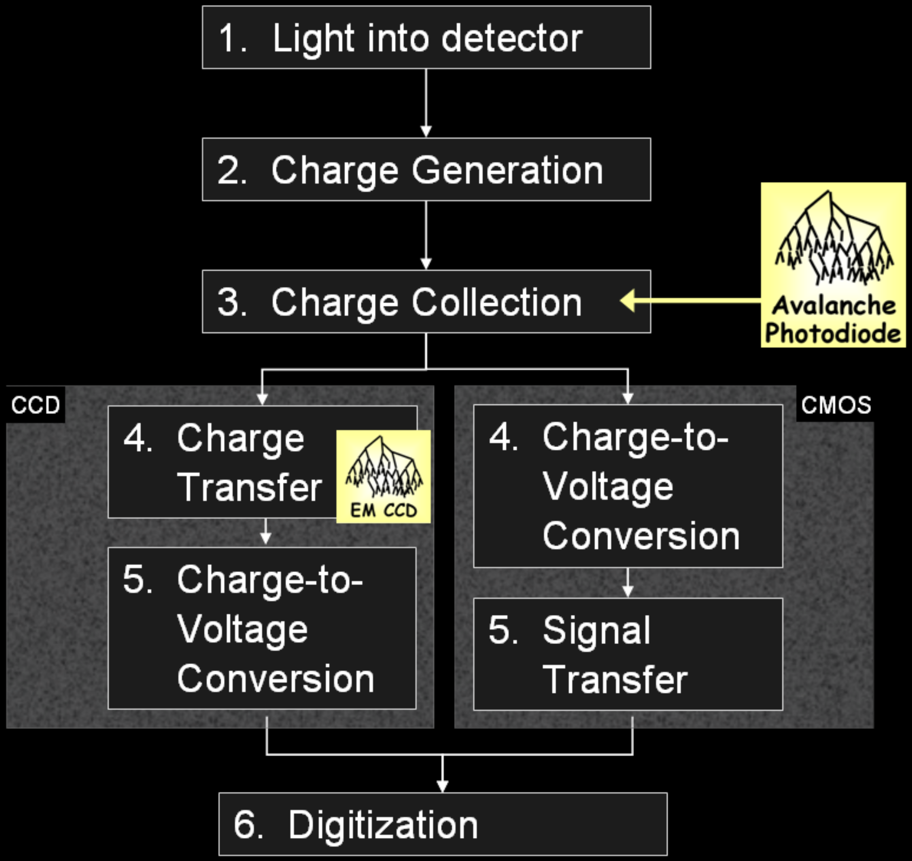
Event driven readout being developed to:

- Only read out pixels where x-rays detected
- Single event readout provides x-ray energy measurement
- High time resolution

HgCdTe Avalanche Photodiodes (APDs)

Teledyne has commenced development of HgCdTe APDs

- Electron avalanche 5 µm λ_{co}
- Hole avalanche 1.7 µm λ_{co}



- Proven high quality HgCdTe molecular beam epitaxy (MBE) may be crucial to successful development.
- Readout circuits to be optimized from existing intellectual property (IP).