Detectors in Astronomy

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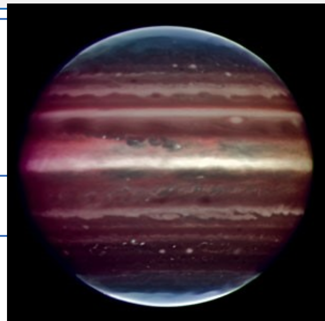
ESO

1. *Introduction*
2. Detectors based on photo-electric effect:
   A. CCD
   B. CMOS detectors
   C. MAMA & photo-multiplier tubes
3. Characteristics of CCD and CMOS detectors
4. Signal-to-noise ratio
5. FITS files
6. Summary

Optical, near- and mid-IR observation

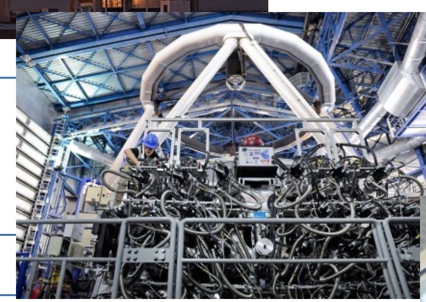
Science object



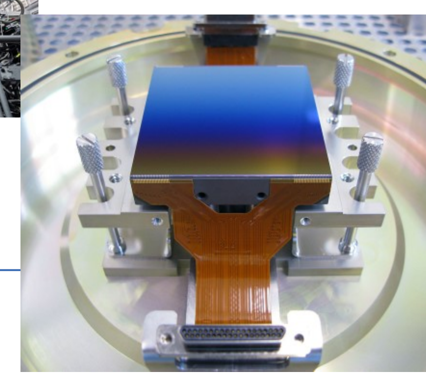
Atmosphere (optional)

Telescope

Instrument



Detector



Disclaimer

- This talk is only about UV, optical, IR photons detectors;
- It does not describe radio detectors…
- … neither neutrino, cosmic rays, nor gravitational wave detectors!

Ideal detector

- An ideal detector of light would record all information carried by each of the photons provided by the object/atmosphere/telescope/instrument system – and only them, with no loss, – within quantum uncertainty limits:
  - Energy (wavelength, frequency)
  - Polarization
  - Phase
  - Location of arrival on detector
  - Time of arrival

Different methods of detection. *Retina: isomerization*

- Eye retina: absorption of one photon changes the structure of a molecule, which triggers a number of chemical reactions before a neuron signalling (http://www.ncbi.nlm.nih.gov/books/NBK22541/)

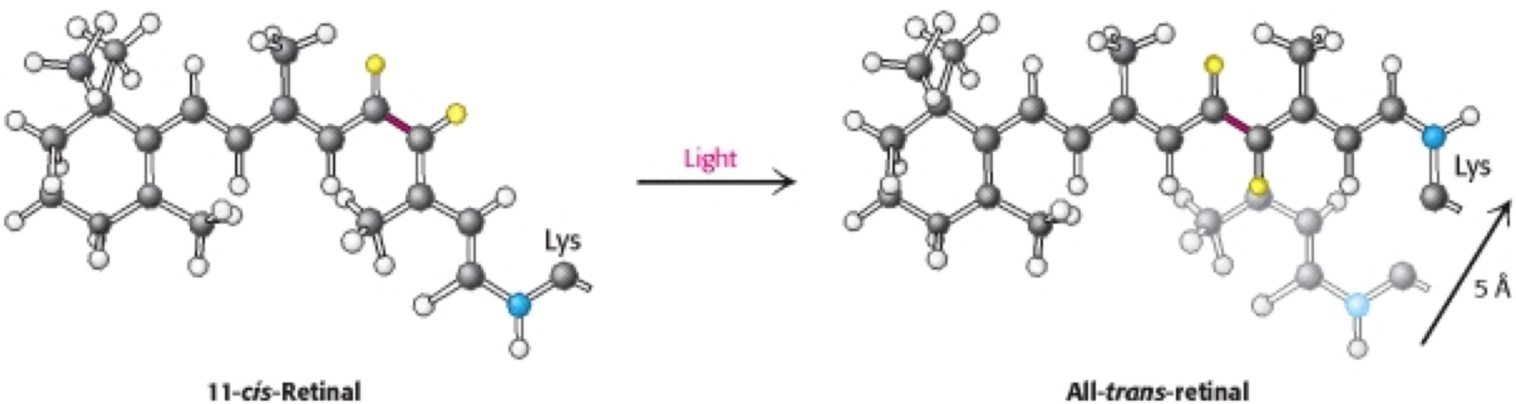


Figure 32.23 Atomic Motion in Retinal

Biochemistry. 5th edition.
Berg JM, Tymoczko JL, Stryer L.
New York: W H Freeman; 2002.

The Schiff-base nitrogen atom moves 5 Å as a consequence of the light-induced isomerization of 11-*cis*-retinal to all-*trans*-retinal by rotation about the bond shown in red.

Isomerization: process by which one molecule is transformed into another molecule which has exactly the same atoms, but the atoms have a different arrangement

Different methods of detection.
Photographic plate: chemical reaction

- Photographic plates:
  - Ag^+Br^- (crystal) + hν (radiation) → Ag^+ + Br + e^-
  - $Ag^+ + e^- \rightarrow Ag^0$
  - Chemical process to remove Br

- Hardly used anymore in modern observatories

Different methods of detection.
(Current) astronomical detectors: photo-electric effect

- Photo-electric based detectors
  - Charge Coupled Devices (CCD): optical
  - CMOS: infra-red, optical
  - Multi-Anode Microchannel Array (MAMA): STIS, ACS, COS (UV)

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   A. *CCD*
   B. *CMOS/IR detectors*
   C. *MAMA & photo-multiplier tubes*
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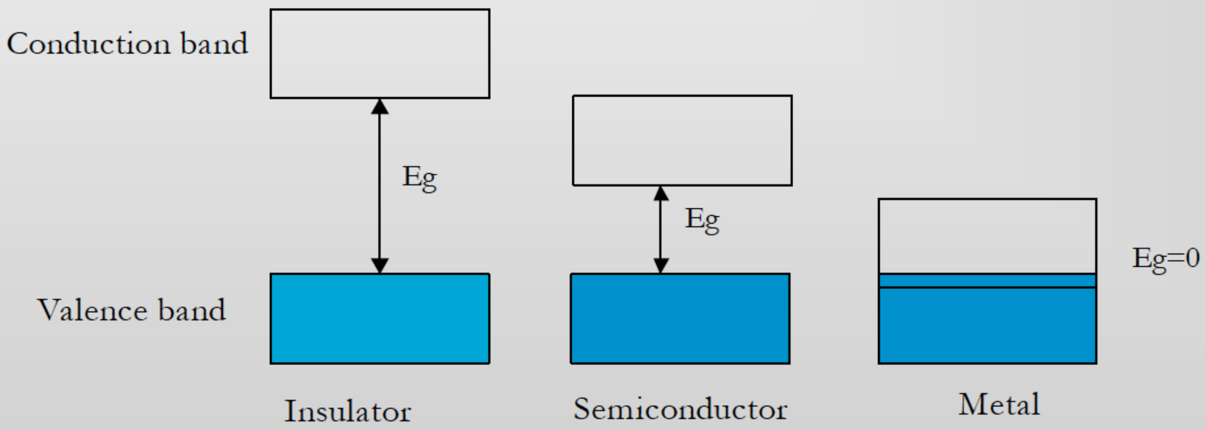
Absorption of photons in a semiconductor: Valence & Conduction Bands

- In a crystal lattice, the allowed bands of electrons can be described by valence and conduction bands (similar to quantum orbits of electrons in Hydrogen).
- valence band = "ground states" that are normally completely filled
- conduction band = "excited states" that are normally completely unfilled, electron in the conduction band can move if there is electric field
- electrons are either in a valence or in a conduction band



Eg is the bandgap energy between the valence and the conduction band.

Eg(Insulator) >> Eg(Semiconductor)>> Eg(Metal)

Dorn 2009

Photo-electric effect in a semi-conductor

There are **two** methods to move electrons from the valance band to the conduction band:

- **By thermal excitation of electrons in the valance band (intrinsic)**

$$n_e = N \exp\left[-\frac{E_g}{2kT}\right]$$

$n_e \rightarrow$ Number of electrons promoted across the gap *(= no. of holes in the valence band)*

N $\rightarrow$ Number of electrons available at the top of the valance band for excitation

This is the origin of dark current and why we have to cool detectors

$$T_{\max} = \frac{200K}{\lambda_{cutoff}}$$

- **Photoelectric effect by photons absorbed by the semiconductor**

Photon energy (hv) > band gap energy (Eg) => photo-electron can jump into conduction band

This is basically why semiconductors are used for astronomical observations.

The longest wavelength a detector is sensitive is the cutoff wavelength Λ_{cutoff}.

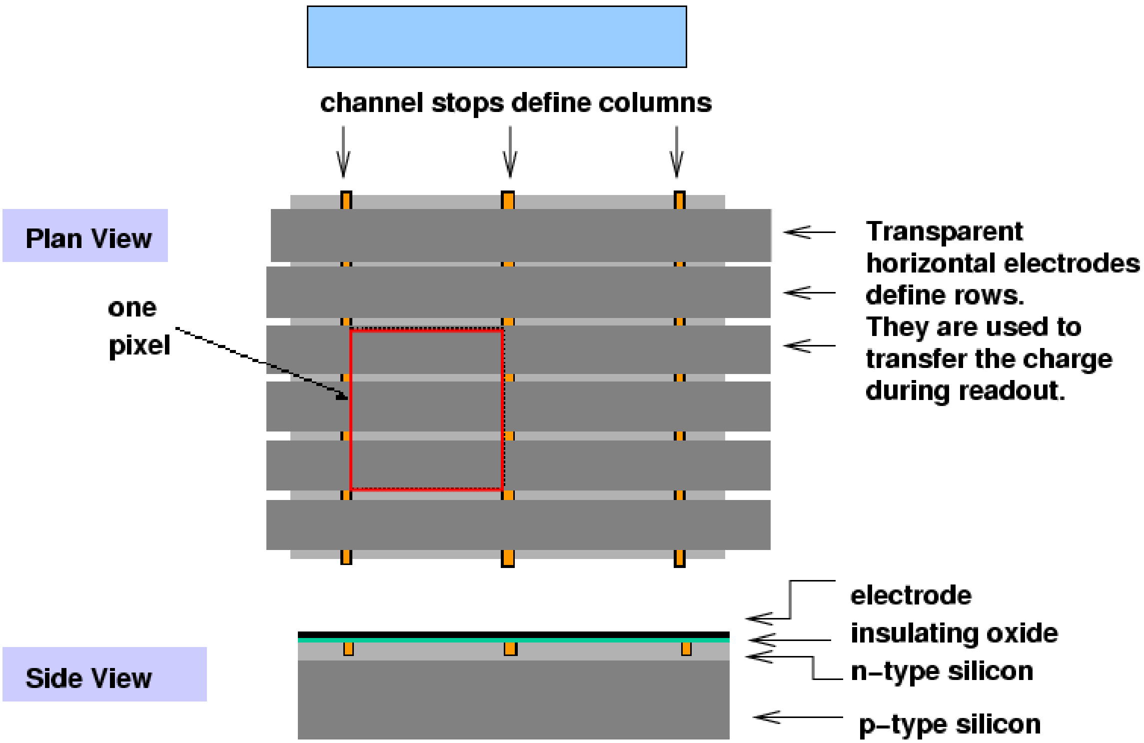
$$\lambda_{cutoff}(um) = \frac{hc}{E_{bandgap}} = \frac{1.24}{E_{bandgap(eV)}}$$

Parameters: Quantum Efficiency (QE) , Dark current

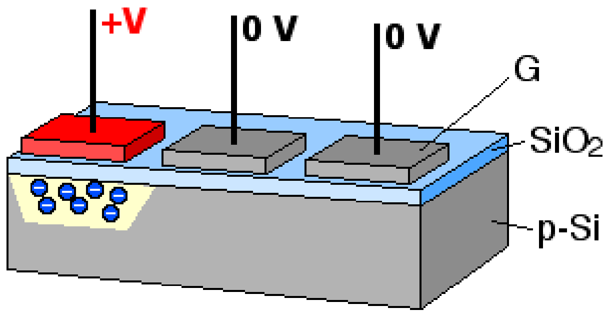
$$QE = \frac{\#\ of\ photo-electrons\ in\ the\ conduction\ band}{\#\ of\ photons\ which\ reached\ the\ detector}$$

Dark level: # of thermally excited electrons which reached the conduction band

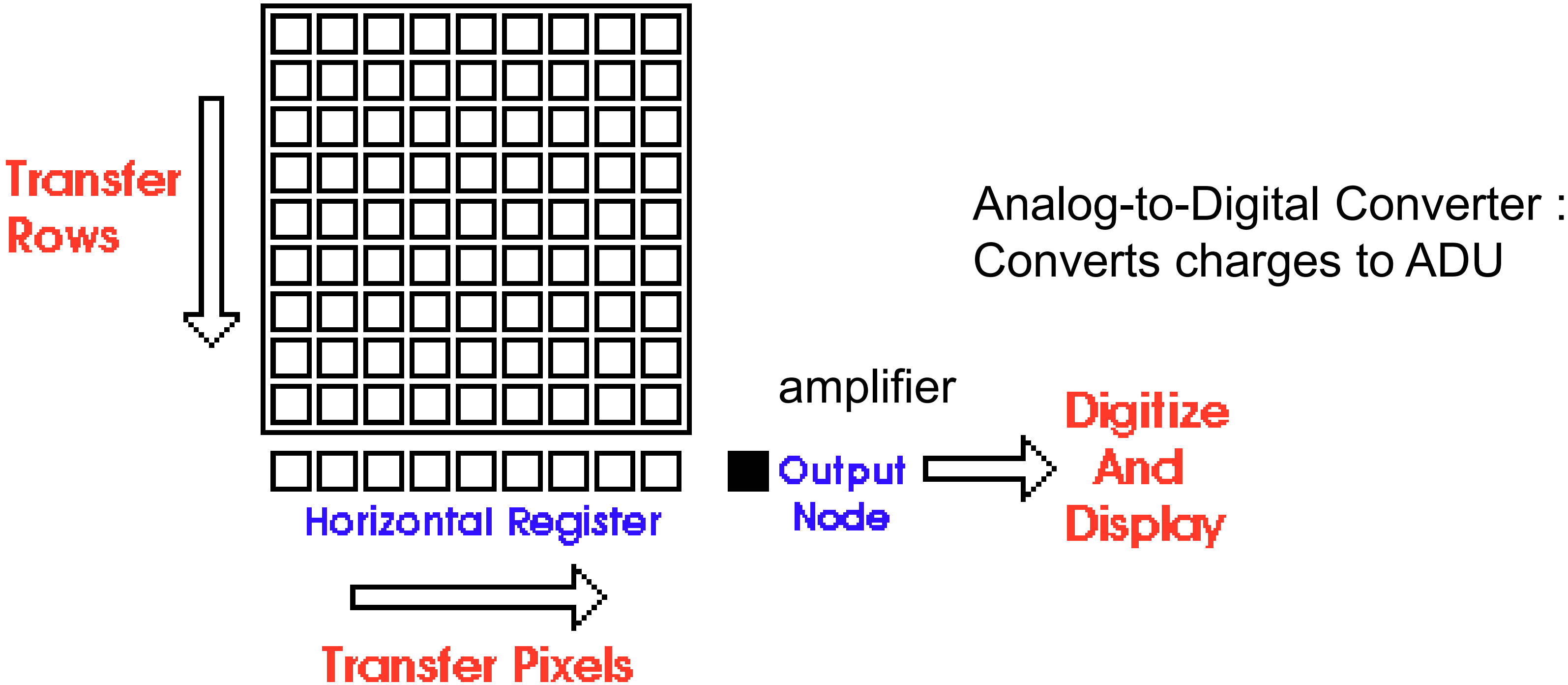
A. Charge Coupled Device (CCD) & variations



Animation by Michael Schmid

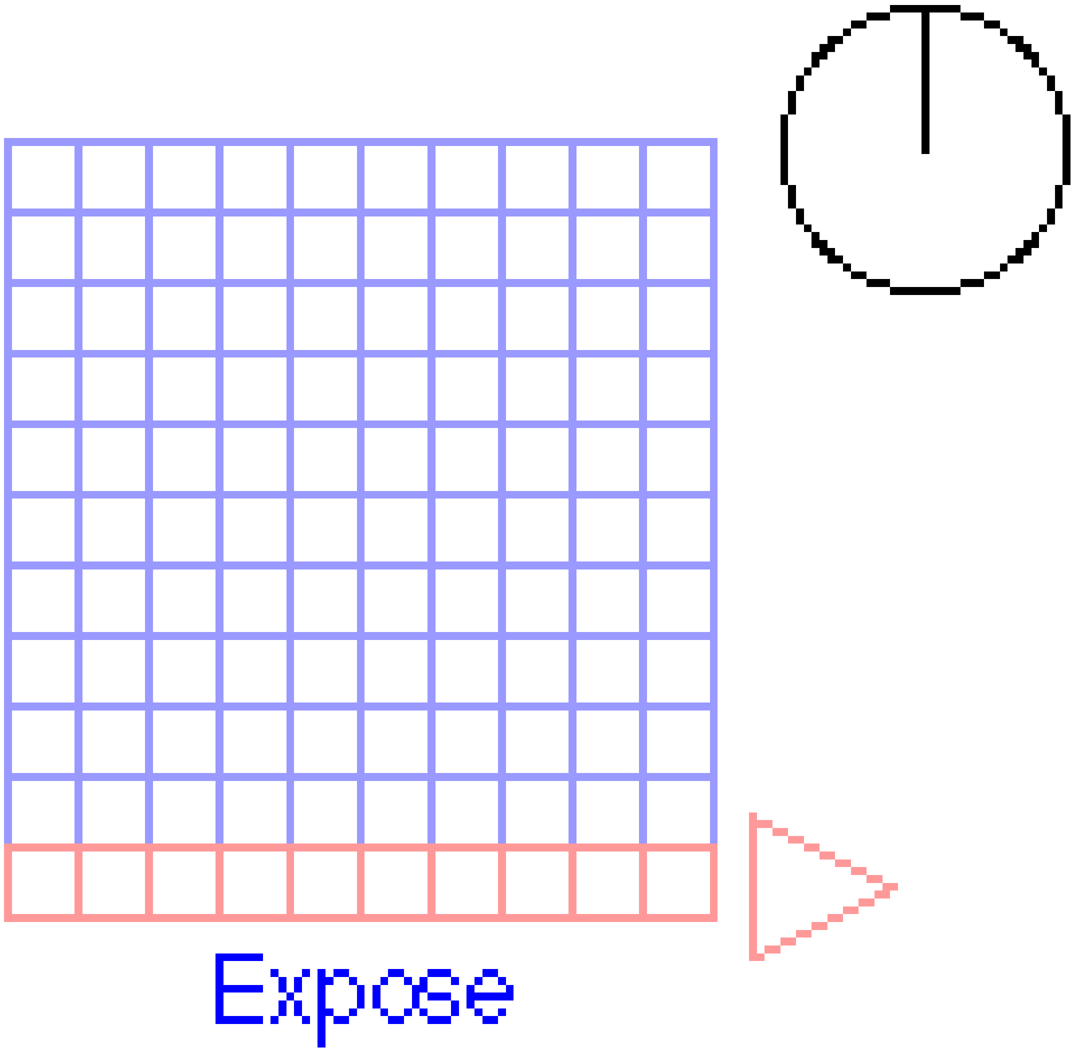


A. Charge Coupled Device (CCD) & variations



Parameters*: full-well capacity, bias level, gain, ADC saturation level*

- *Gain*: ⚠ g = number of ADUs/electron or number of electrons/ADU (g = 1/CONAD)
- *Full well capacity:* maximum # of photo-electrons in a pixel
- *Bias level:* artificial electronic offset which ensures that the ADC always receives a positive signal.
- *ADC saturation level*: # of bits used by the A/D converter is: 16 bits -> 65 535 ADUs


Expose

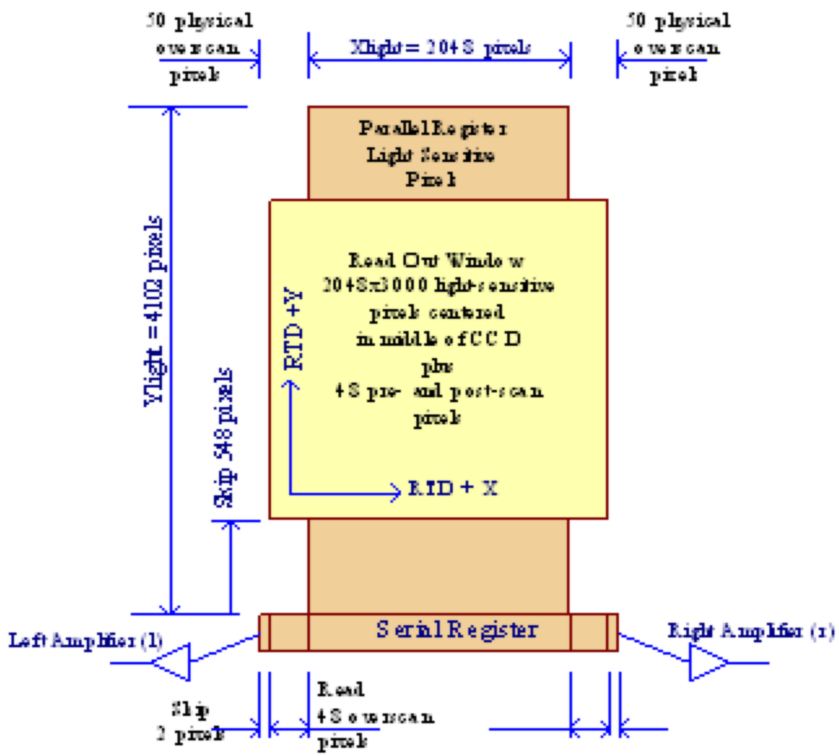
Pre-/post-/over-/under- scan regions

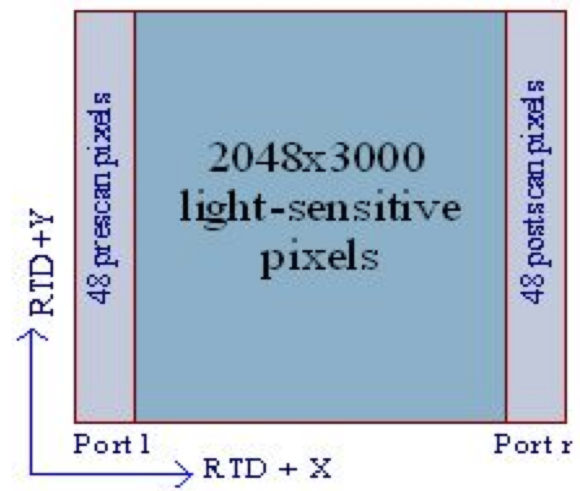
Regions not exposed to light: pseudo-pixels generated by sending additional clock cycles to the output electronics

UVB Arm CCD Data Format

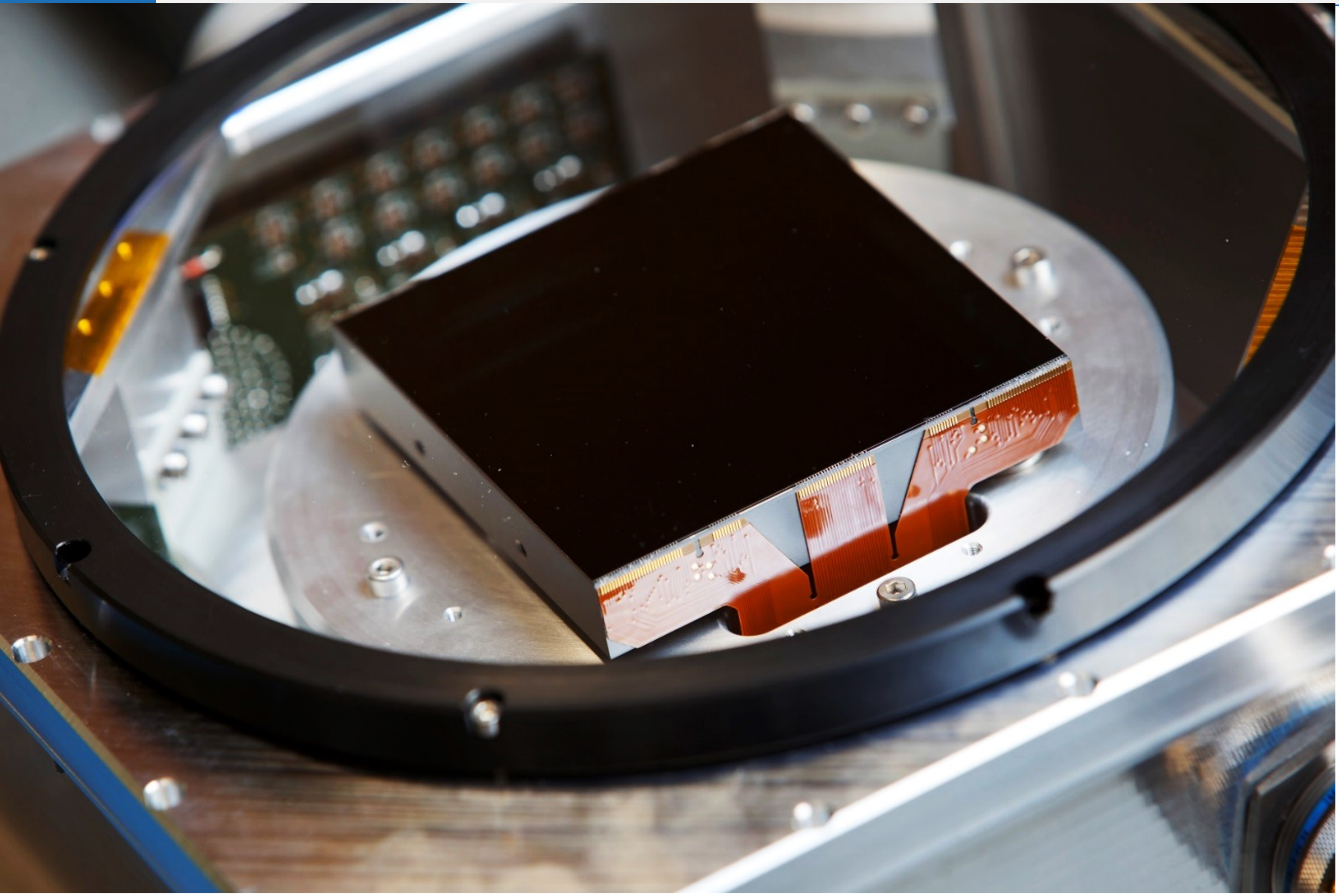
Normal Scientific Readout Modes (1 - 6)

There are 48 prescan and 48 overscan pixels visible on the image.

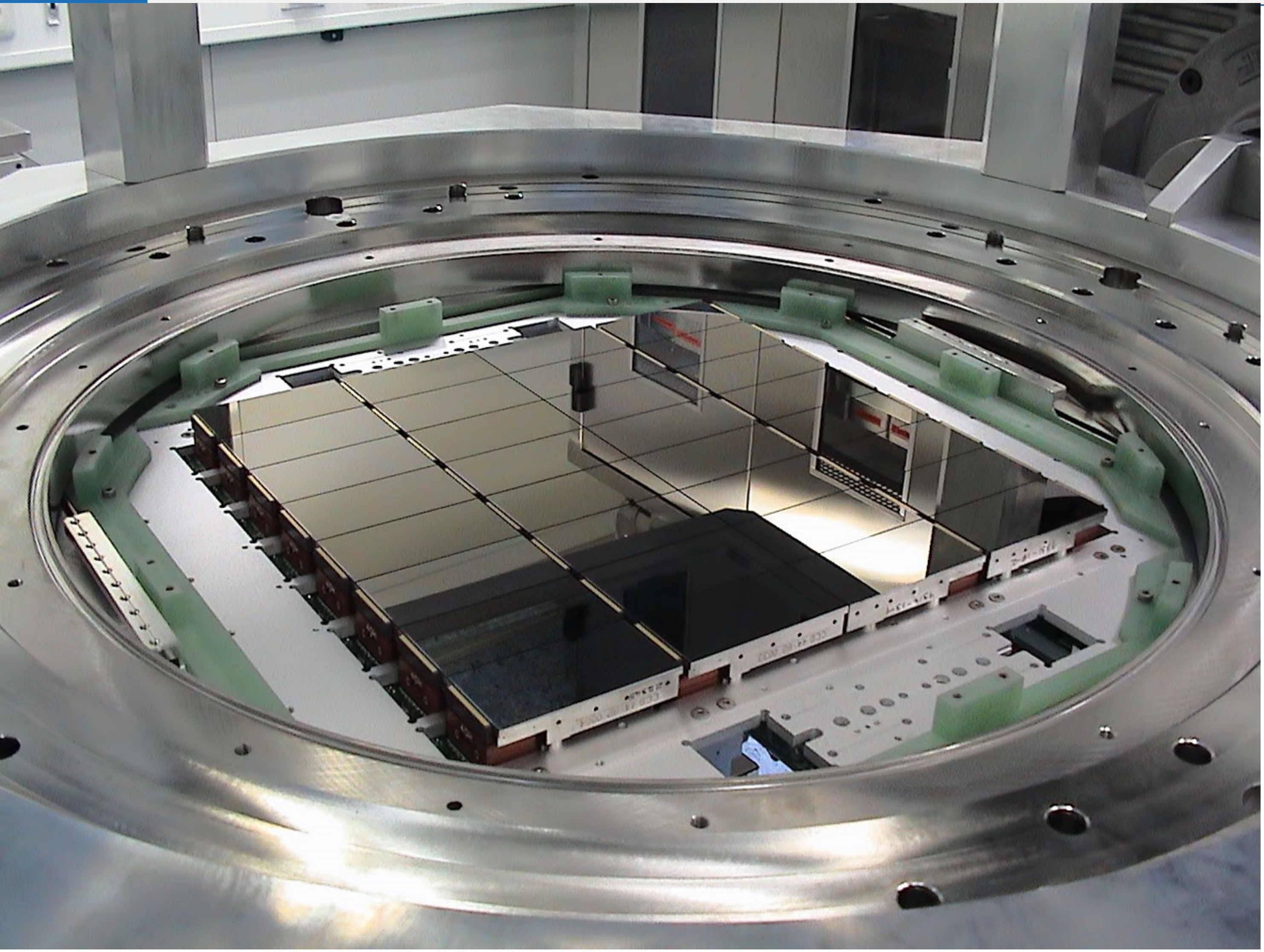




RTD display when CCD is read out through Left Amplifier

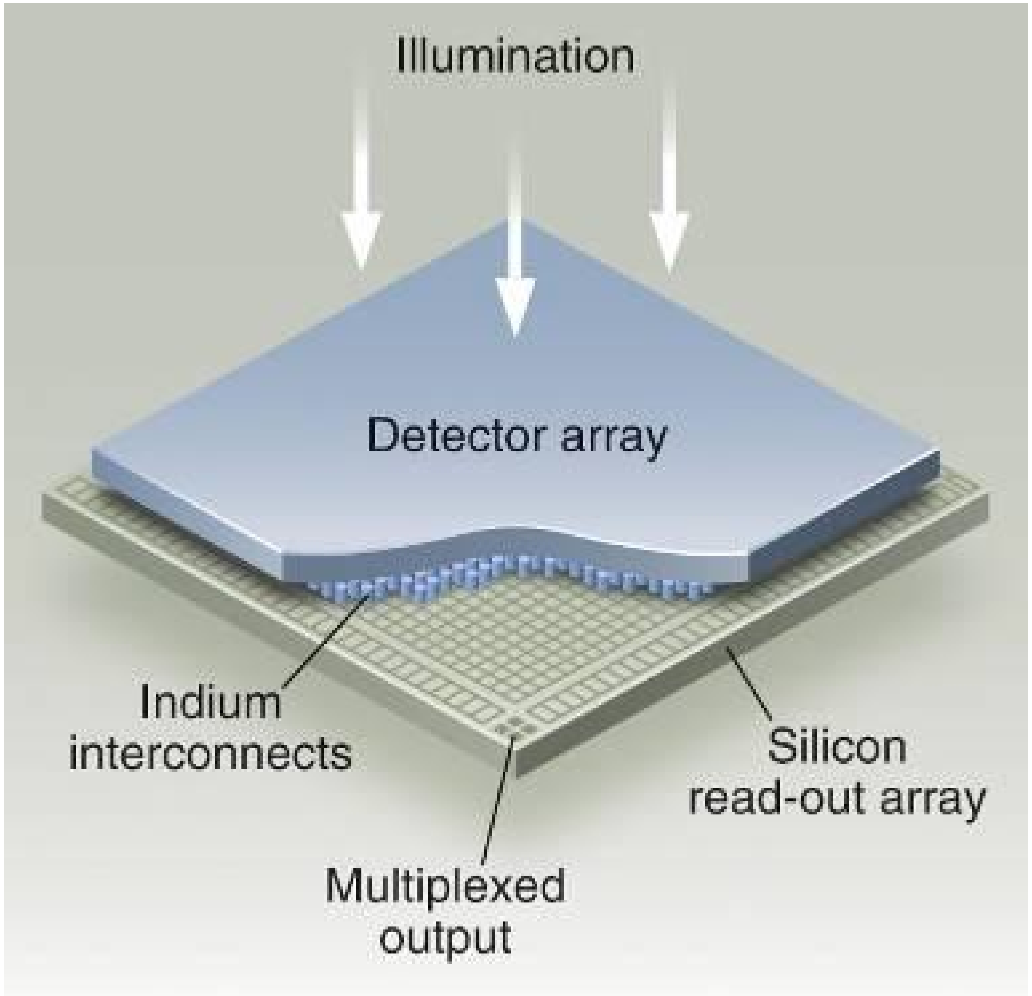


One of the 2 CCDs used in ESPRESSO:
81 millions pixels

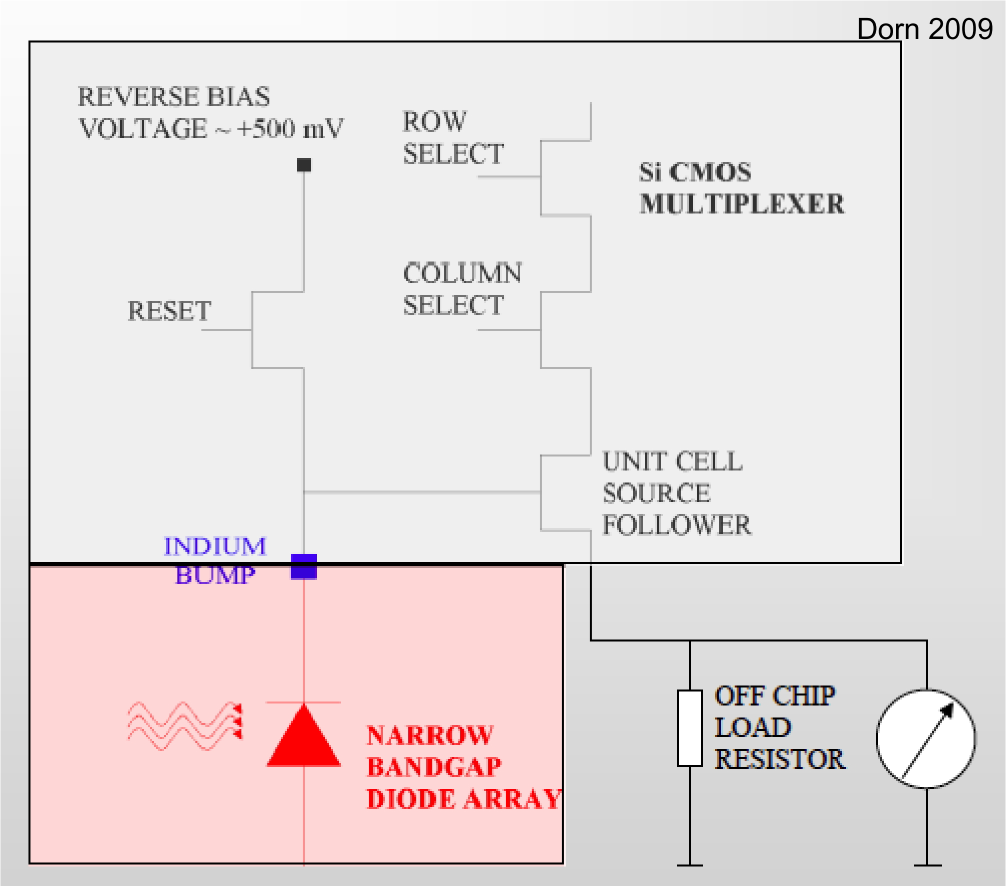


OmegaCAM detector array: 32 2048x2048 detectors; 268 millions pixels

B. Hybrid Complementary Metal Oxide Semiconductor (CMOS) detectors



B. Hybrid Complementary Metal Oxide Semiconductor (CMOS) detectors



1. Charge diode capacity by reverse bias voltage
2. Floating capacity is discharged by absorbed photons
3. Read voltage across diode capacity by addressing unit cell source follower

Each pixel is read individually.

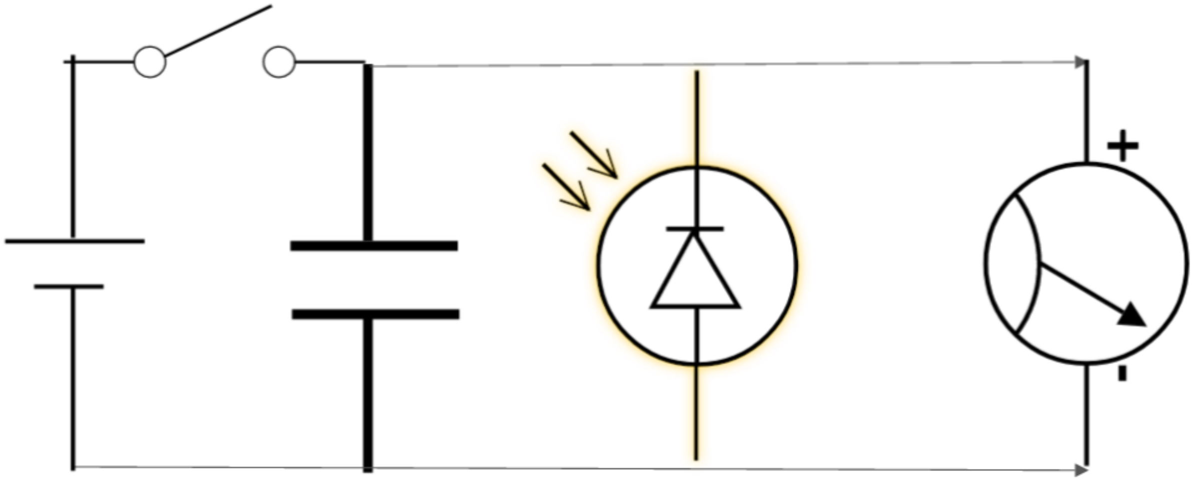
Each pixel can be read multiple times during an exposure.

Exposure time is reported as DIT. A file usually includes the average of NDIT individual exposures.

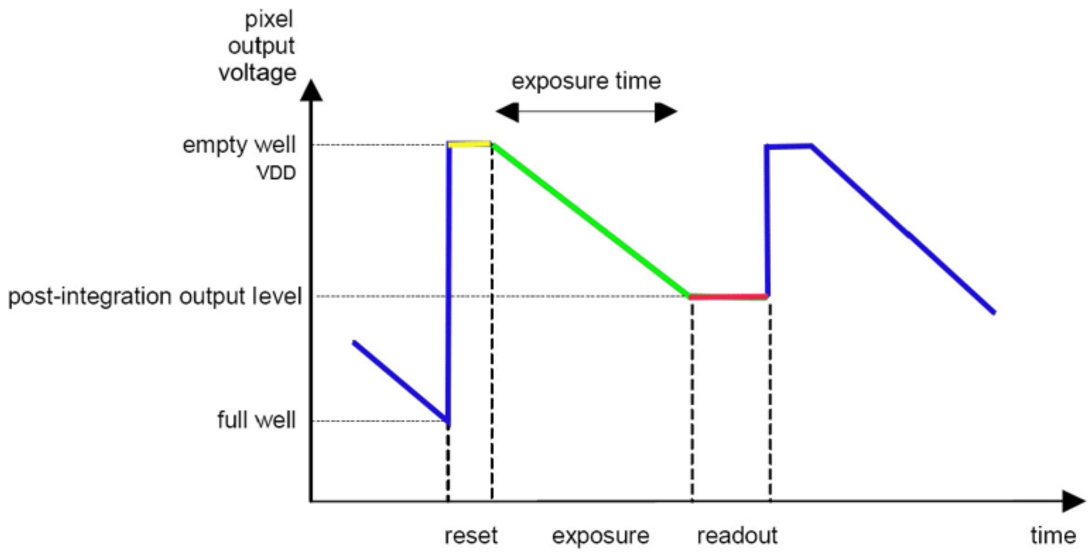
Parameters: full-well capacity, gain

- *Full well capacity: maximum # of photo-electrons in a pixel*
- Gain: *g = number of ADUs/electron*

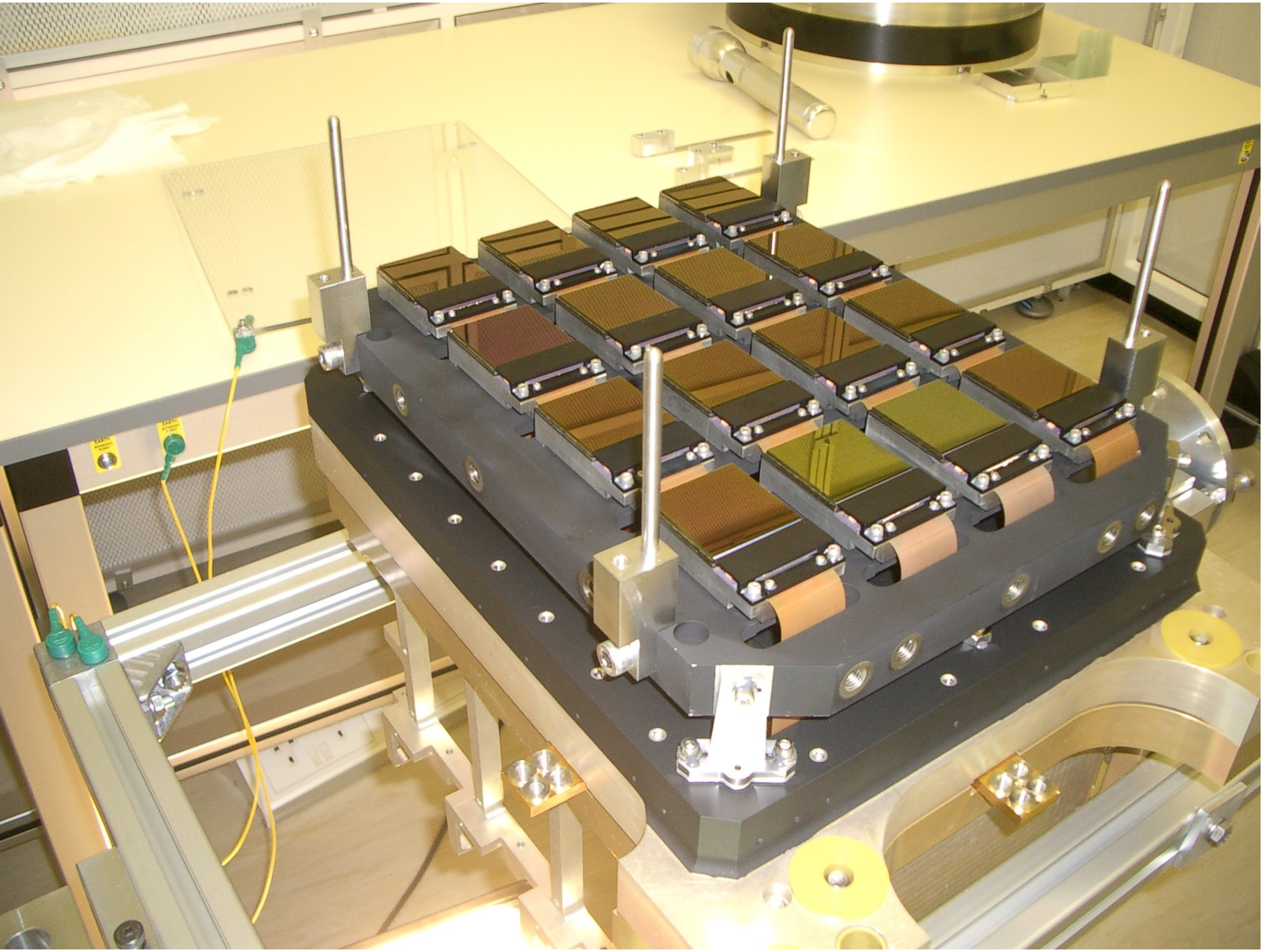
B. Hybrid Complementary Metal Oxide Semiconductor (CMOS) detectors



The signal lifetime in the pixel: reset to black level (high voltage V DD : yellow), photocharge integration (dropping voltage: green), and voltage readout (red).

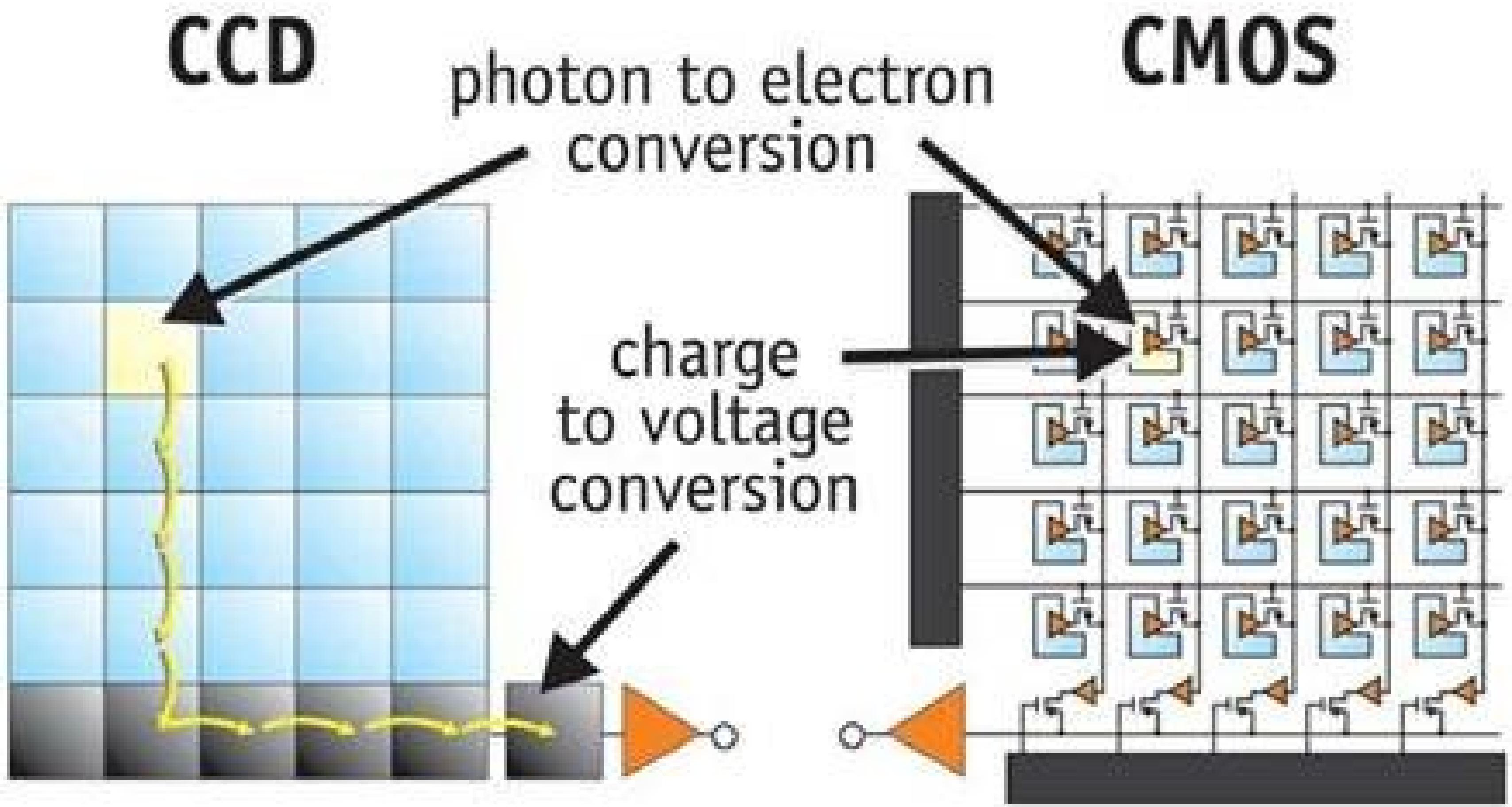


De Groof et al. 2008



Mosaic of 16 2048x2048 CMOS detectors used in VIRCAM

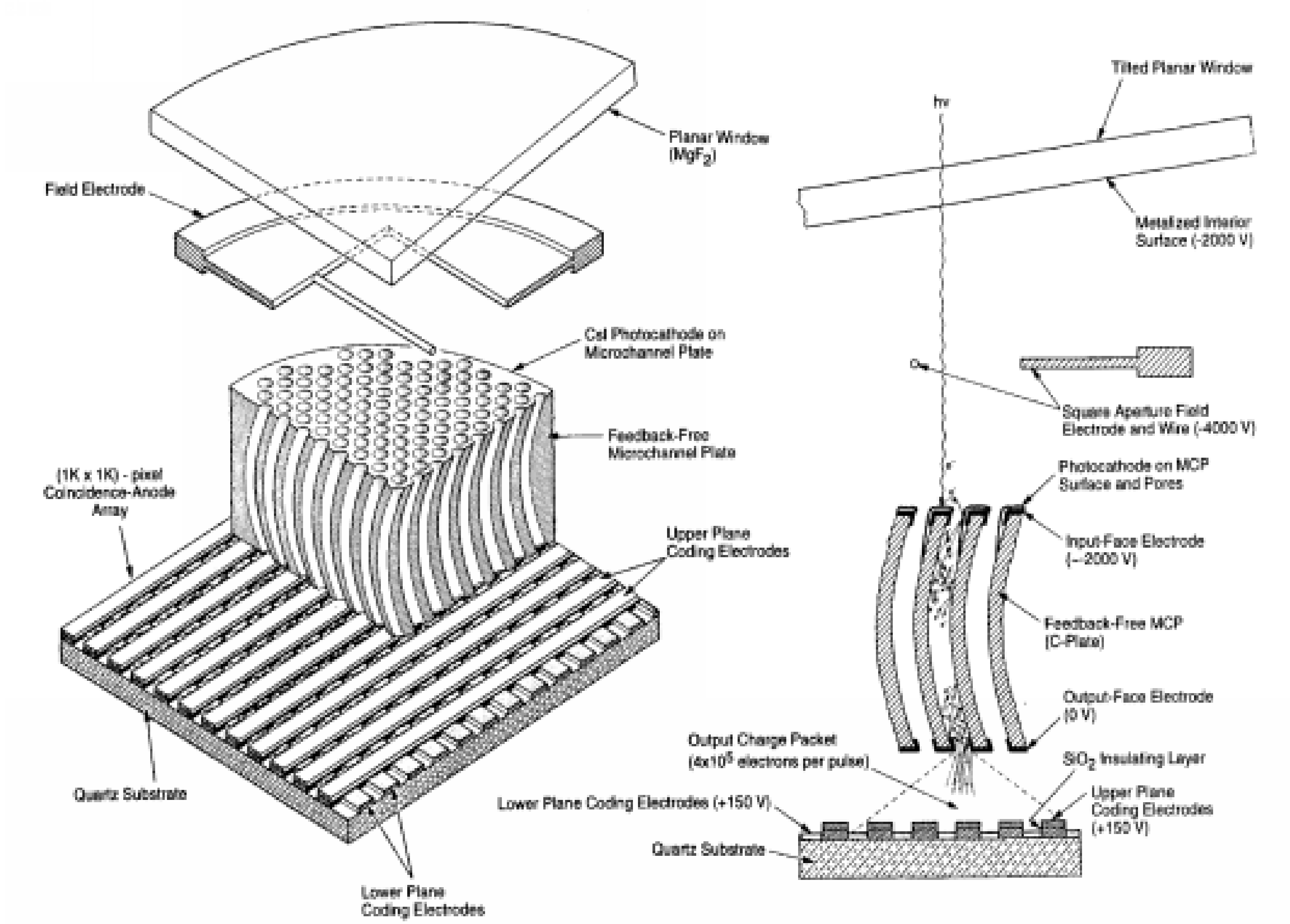
Comparison: CCD *vs* CMOS



Requires a shutter

Usually, no need for a shutter

C. Multi-Anode Microchannel Array (MAMA)



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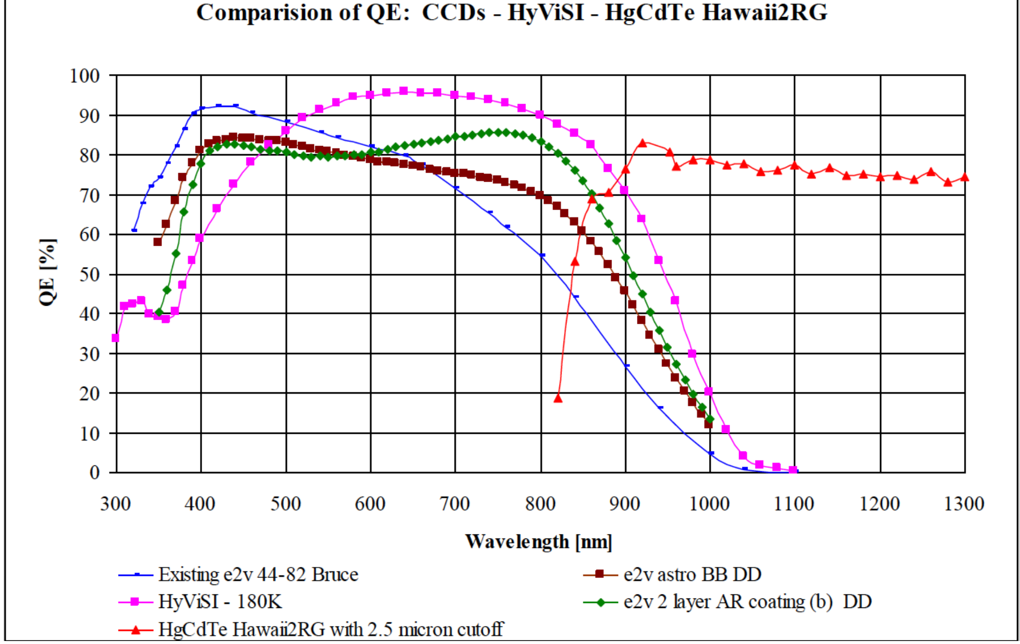
Behavior relative to ideal detector
(for optical, near- and mid-IR astronomy)

Dorn 2009



- Energy:
  - Broad band sensitivity
  - Need for filters or spectrograph
- Polarization: N/A: need for polarization optic
- Phase: N/A: specific optics; interferometry

Behavior relative to ideal detector
(for optical, near- and mid-IR astronomy)

- Time of arrival:
  - MAMA: Time-tag to each individual photon individually
    - But not too many photons can arrive at the same time!
  - CCDs: time associated with each exposure
    - Limited by the read-out time
    - Most CCDs tuned to faint target observations leading to long read-out time;
    - Can be windowed
    - Trick: move charges in a direction while integrating
      - HIT mode on FORS
      - Time delay and integration to match sidereal rate for fixed telescopes
  - CMOS detectors: time associated with each exposure
    - limited by the read-out time, but faster then CCD
    - ‘burst’ mode can allow to save each frame
    - pixels are often read one after the other

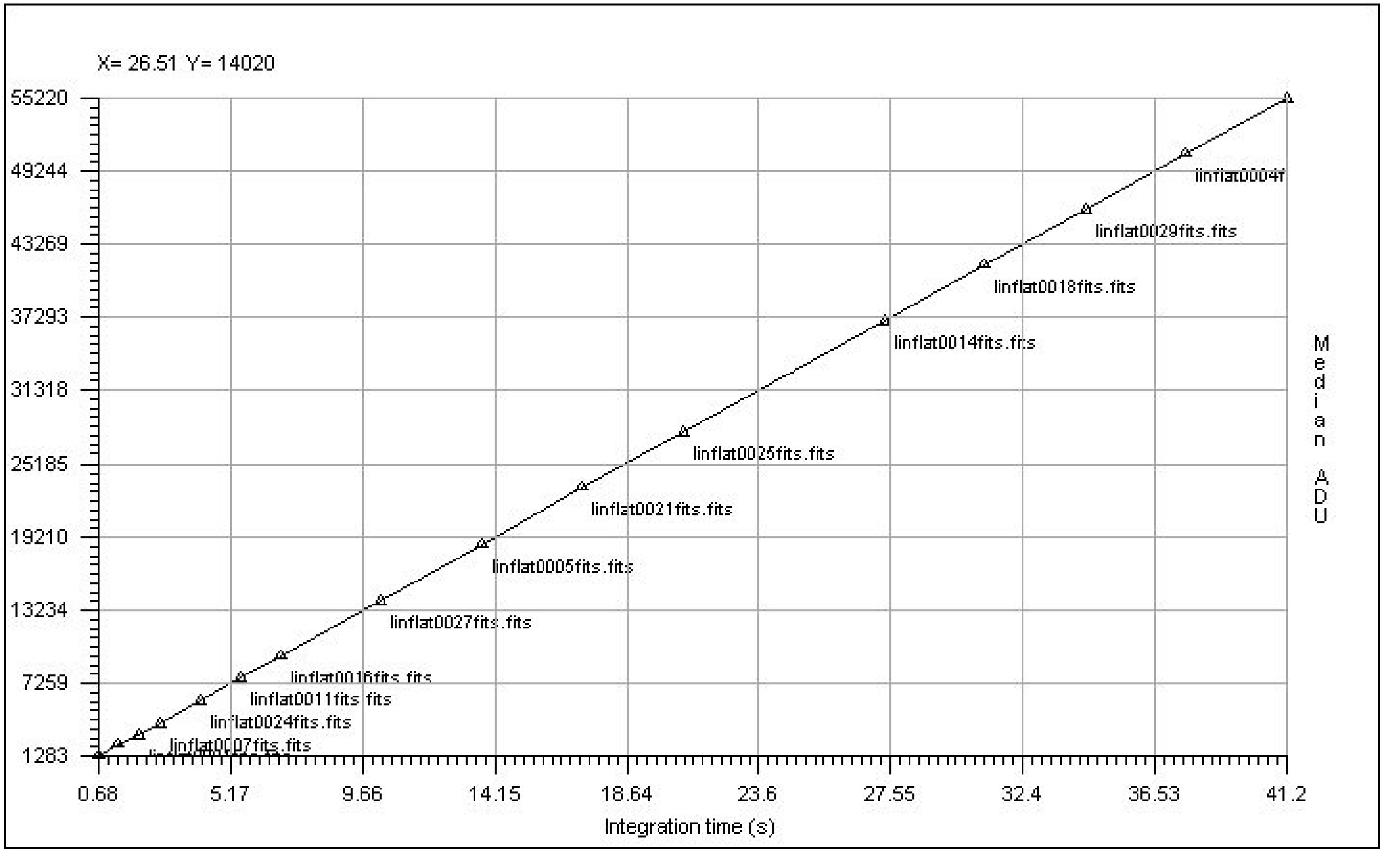
Behavior relative to ideal detector
(for optical, near- and mid-IR astronomy)

- One electron for each photon?
  - Linearity
    - Behavior at low/high flux: see next slides
    - Pixel-to-pixel variation (also called fixed pattern noise)
    - Fringing
    - Charge transfer efficiency
  - Are there electrons not associated with incoming photons?
    - Bias level
    - Hot columns/rows, hot pixels, traps…
    - Dark current
    - Radiation events (‘cosmic rays’)
    - Read-out noise
    - Quantization noise

Behavior relative to ideal detector
(for optical, near- and mid-IR astronomy)

- Linearity
  - MAMA: good behavior at low flux only, otherwise pile-up
  - CCD:
    - old CCDs (1980's…) were not linear at low flux: they needed to be 'flashed'. Solved in current CCDs.
    - good behavior in general
    - saturation when approaching the full well capacity
    - pixel-to-pixel variation caused by small differences between pixels
  - CMOS detectors: intrinsically non-linear, as accumulation of charges changes bias on detector for simple readout
    - more complex readout electronics (up to 70 transistors per pixel!)
    - pixel-to-pixel variation (fixed-pattern noise): mostly caused by small difference between electronics assigned to each pixel

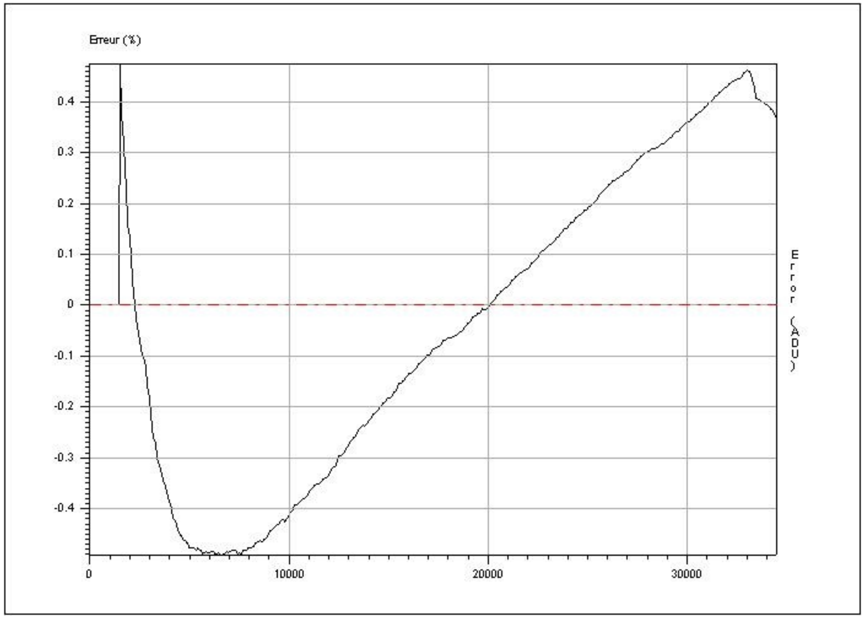
CCD Linearity

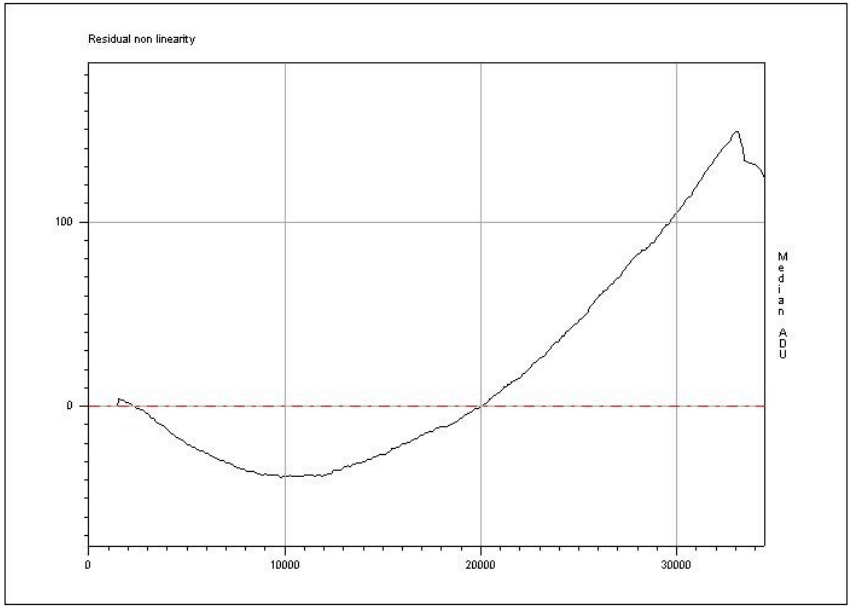


This graph and following: from http://www.eso.org/sci/facilities/develop/detectors/optdet/instruments.html

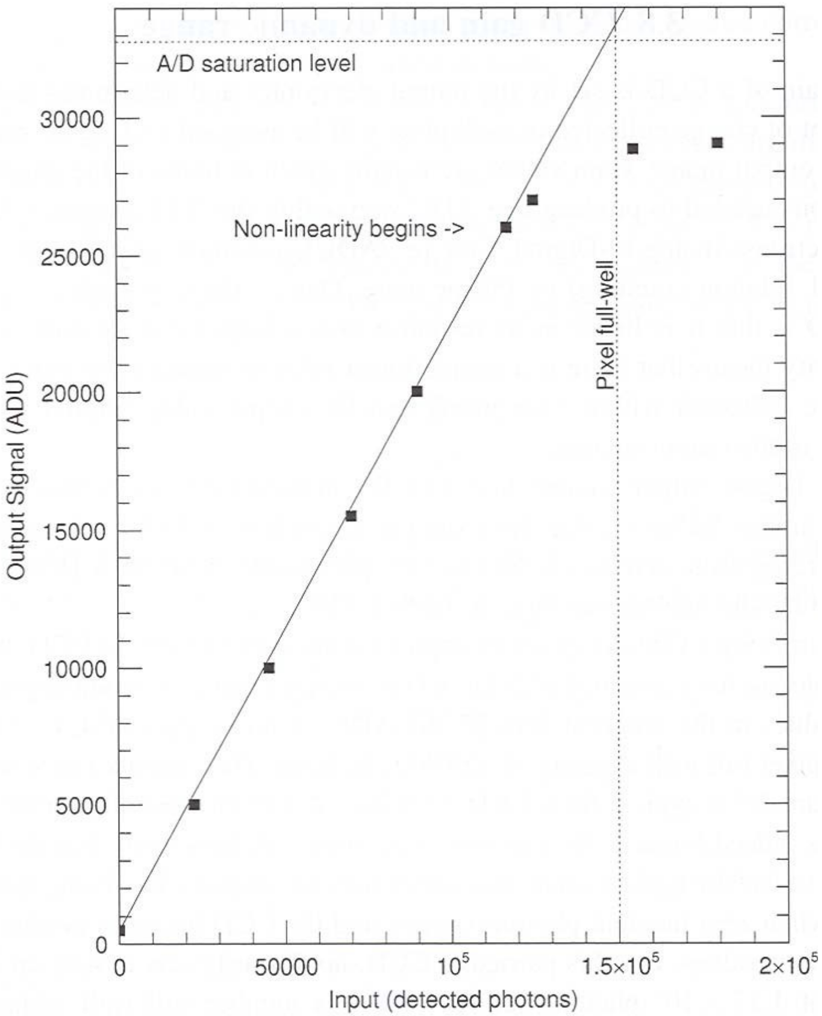
CCD Linearity

- OmegaCAM, detector #84 ‘Centaurus’





CCD linearity



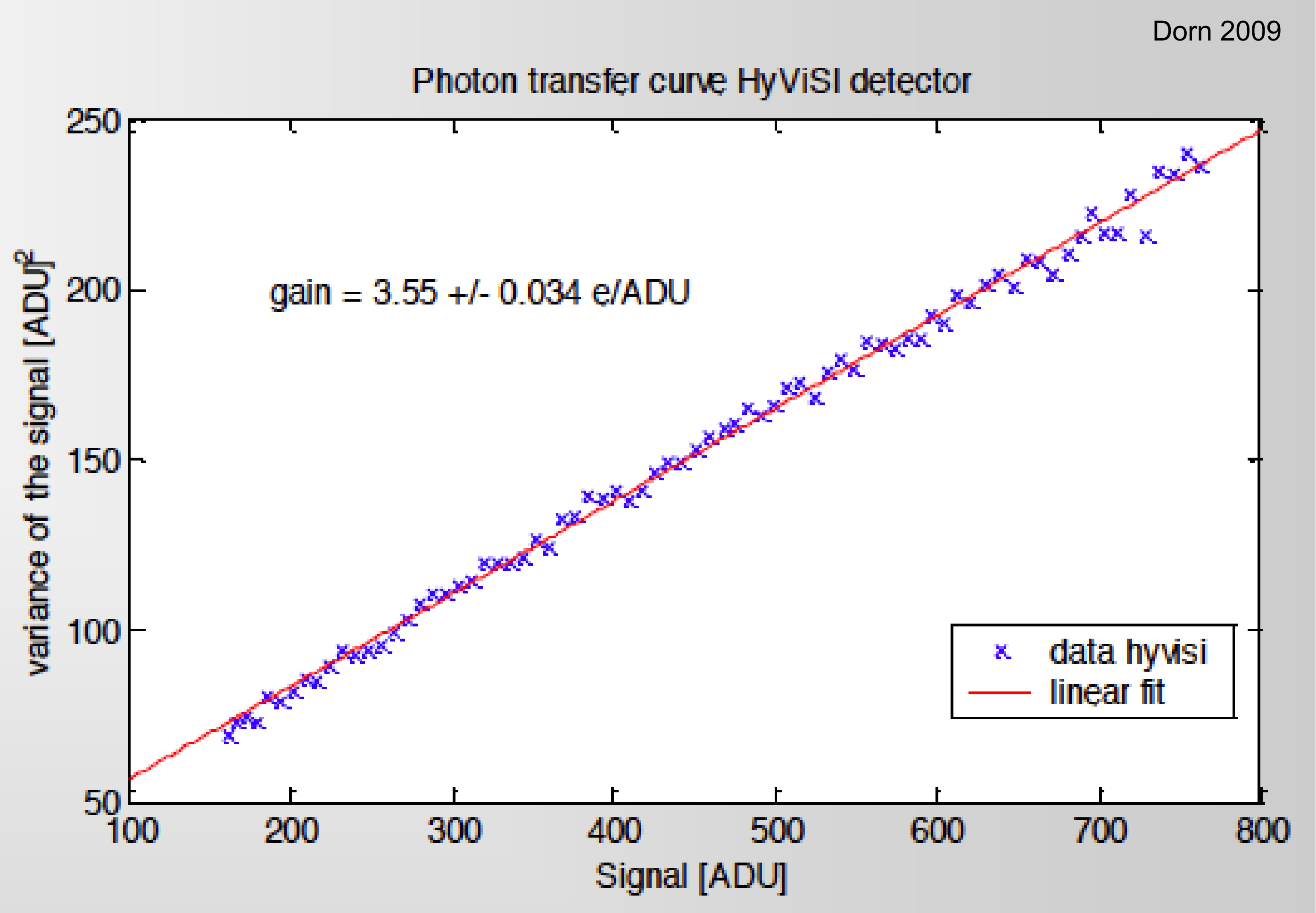
Different quantities:

ADC saturation level: set by the Analog/Ditigal Converter. (here: 15 bits: 2^15 = 32767)

Full-well capacity: physical limit set by the characteristics of the pixel; usually higher than ADC saturation level

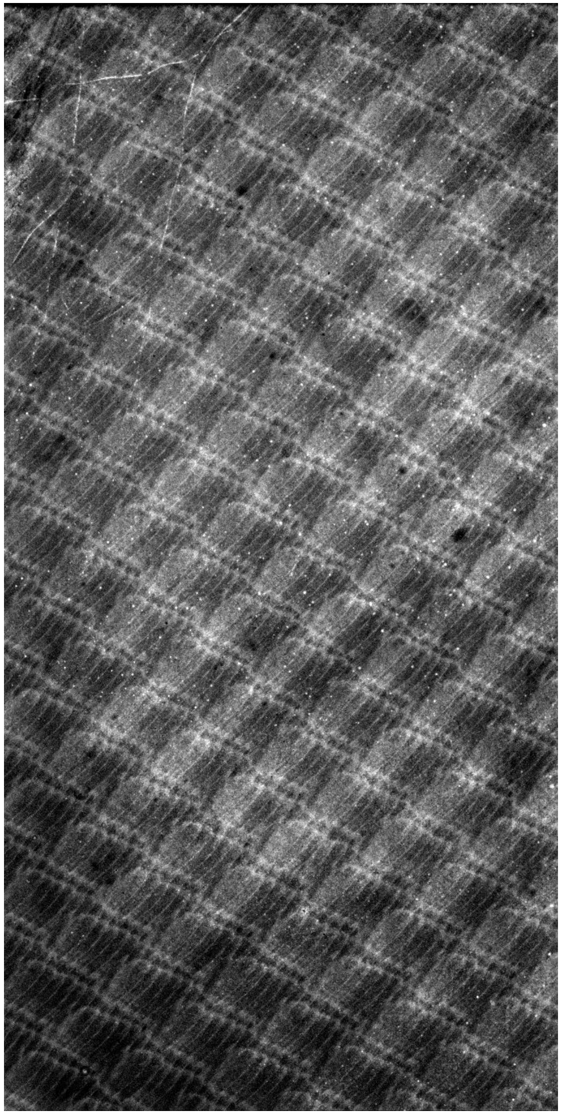
Linear range: range within which the CCD responds linearly within a given level (say 1%)

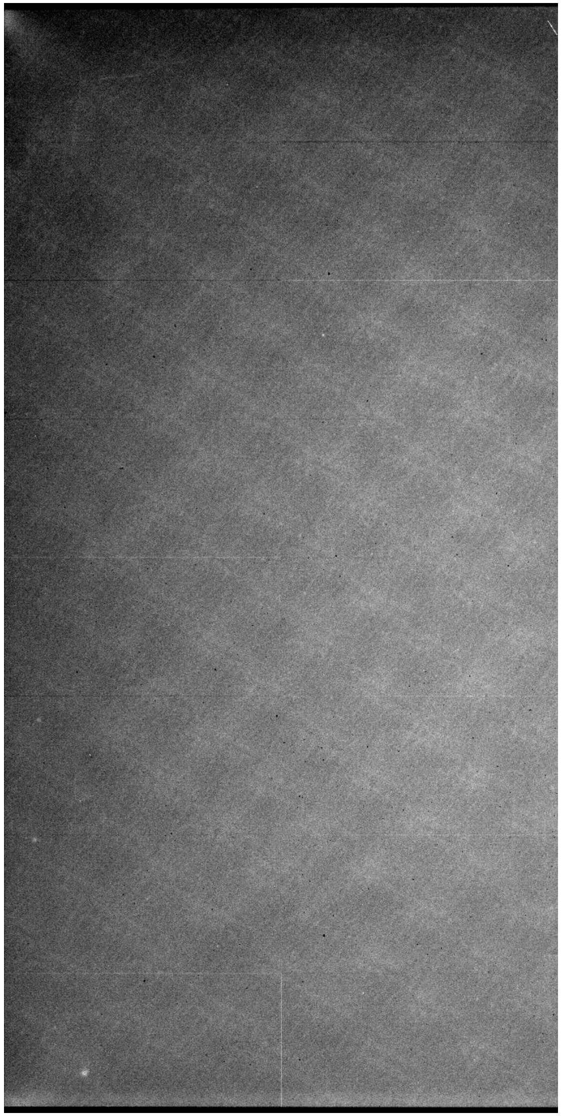
Photon transfer curve

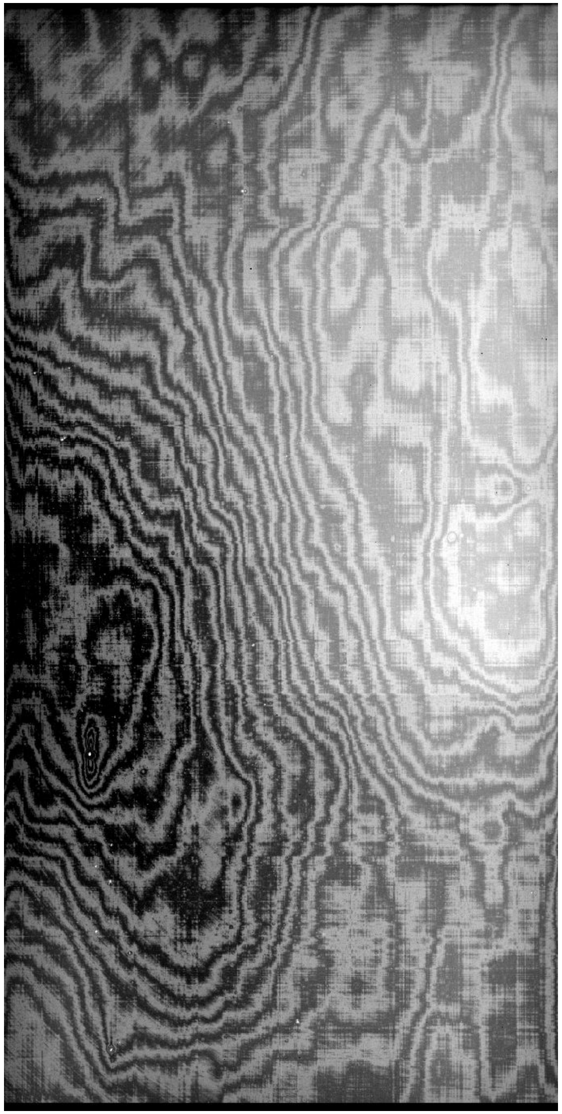


- Take 2 images with same illumination levels
- Change illumination level
- Make difference
- Measure variance
- Report vs signal
- Slope is gain of the ADC converter

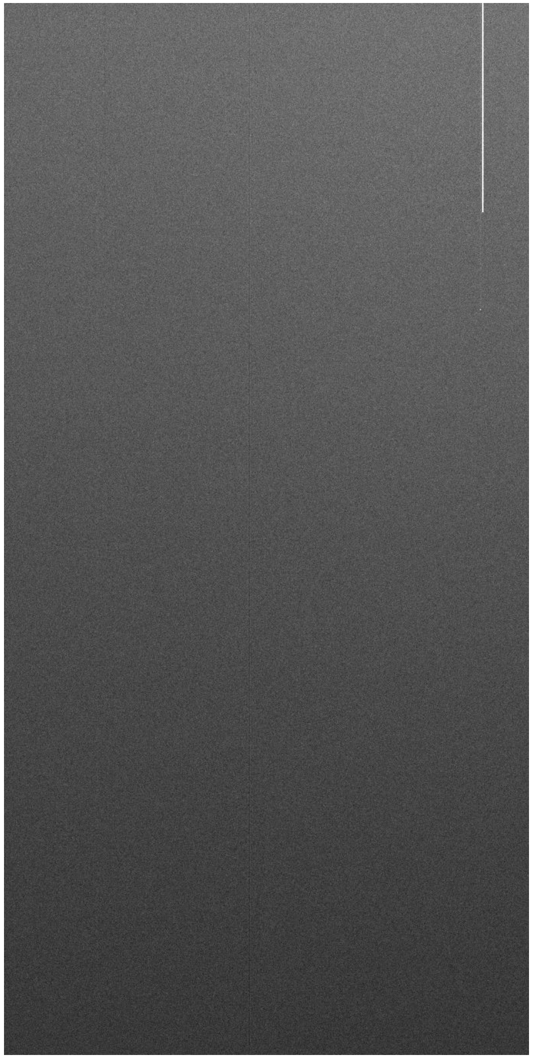
Pixel-to-pixel variation; fringing



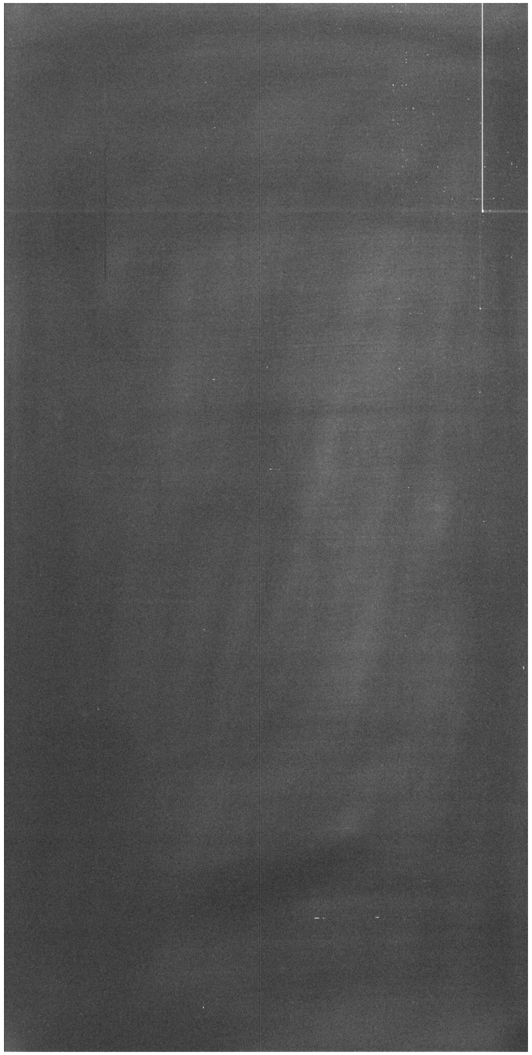




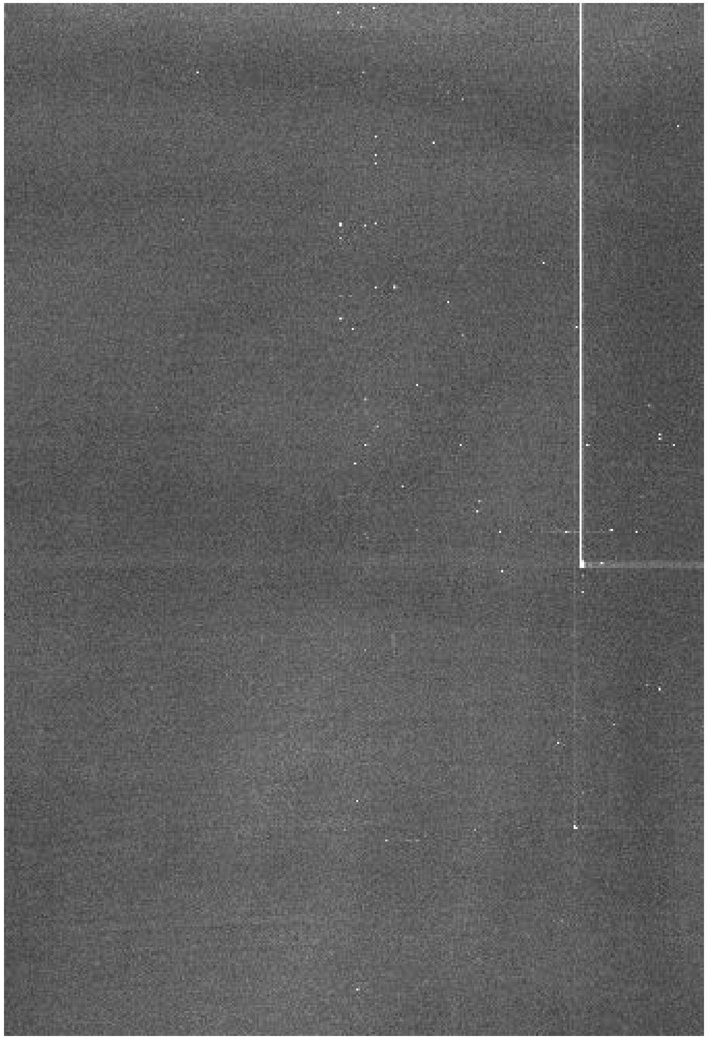
Bias level, hot columns, pixels



bias

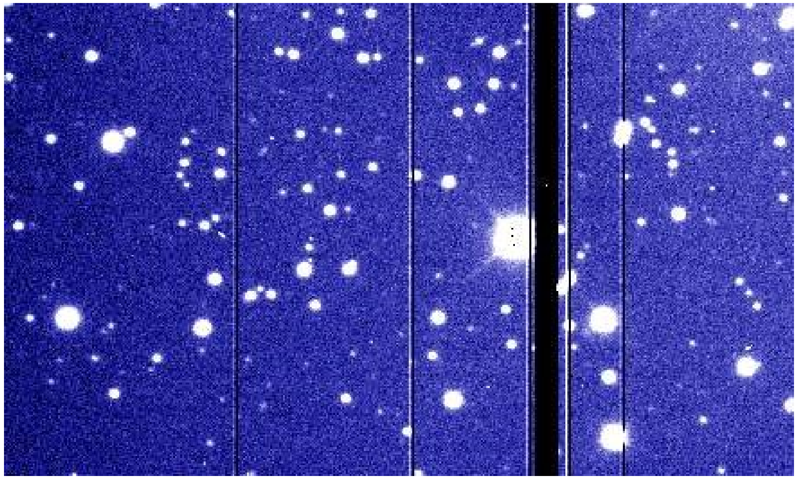


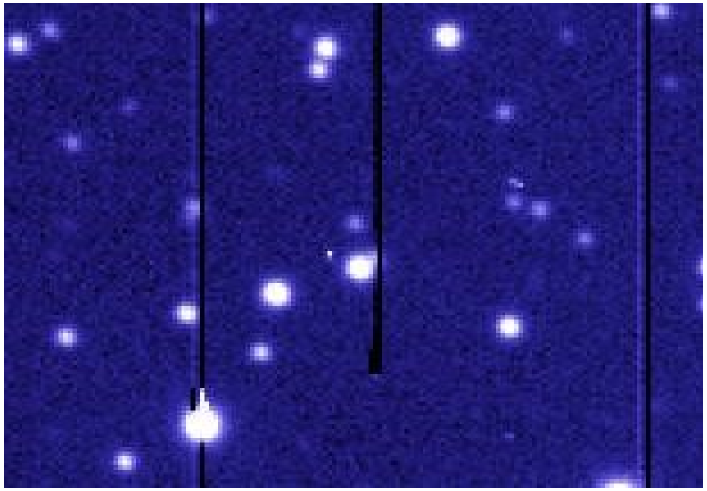
3600s dark

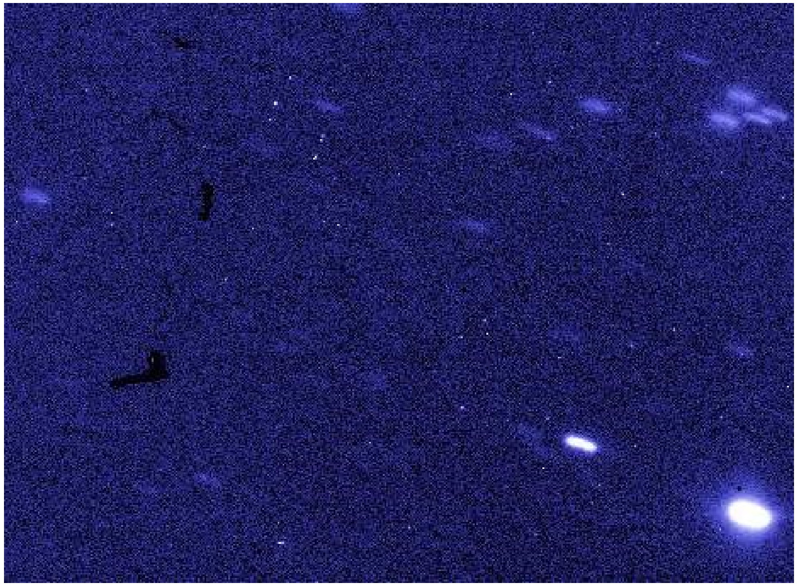


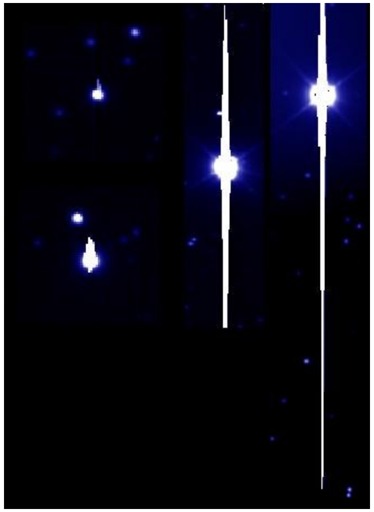
Zoom on dark

Defects:
bad columns, traps, ‘stuff’, saturation, blooming









https://www.eso.org/~ohainaut/ccd/CCD_artifacts.html

Radiation events ('cosmic rays')

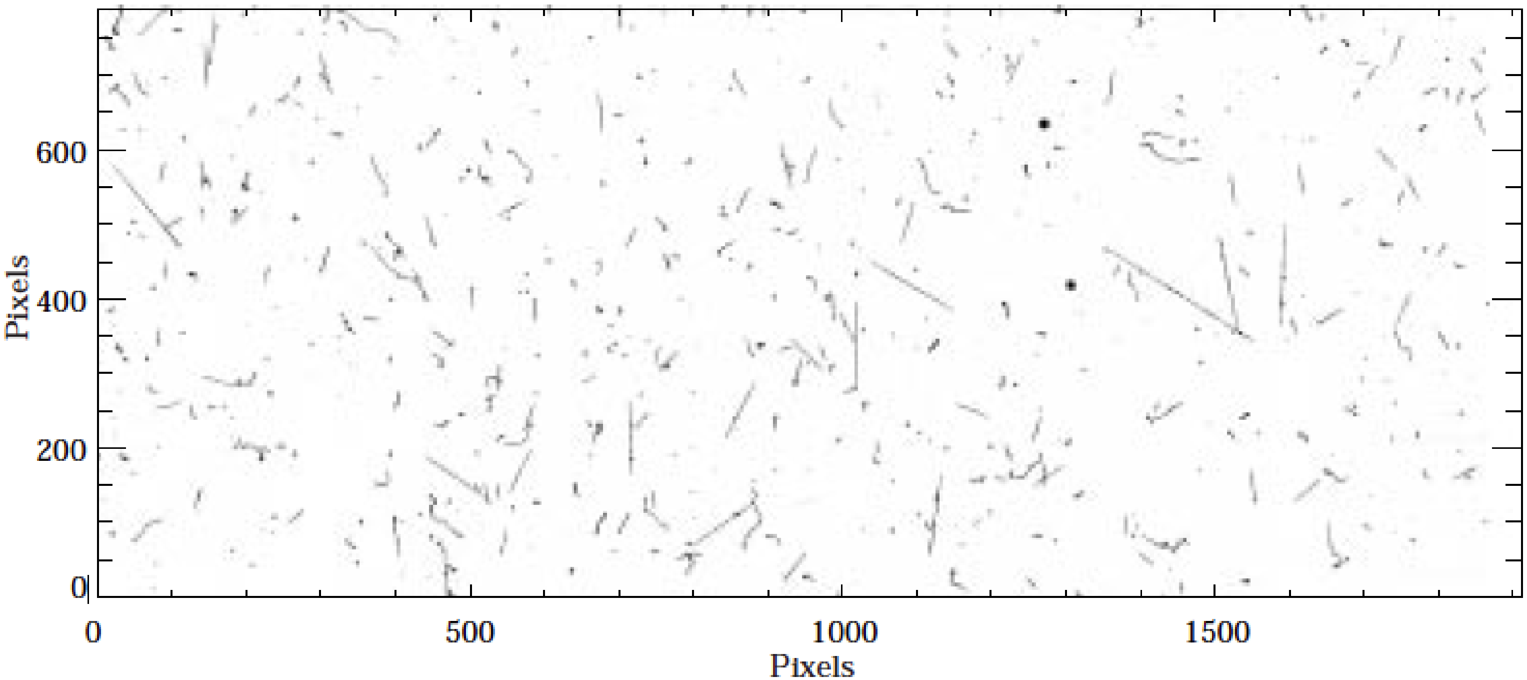


Figure 1. A 1980 pixel × 800 pixel subfield of a 3600 s dark exposure (totally depleted 270-μm thick LBNL CCD, NOAO CCD laboratory in Tucson), showing cosmic-ray muons (straight tracks), worms (low-energy electrons),and spots. While the spots look insignificant, they are about as abundant as the worms and can indicate considerable deposited energy.

Smith et al. 2002, SPIE 4669, 172

Radiation events

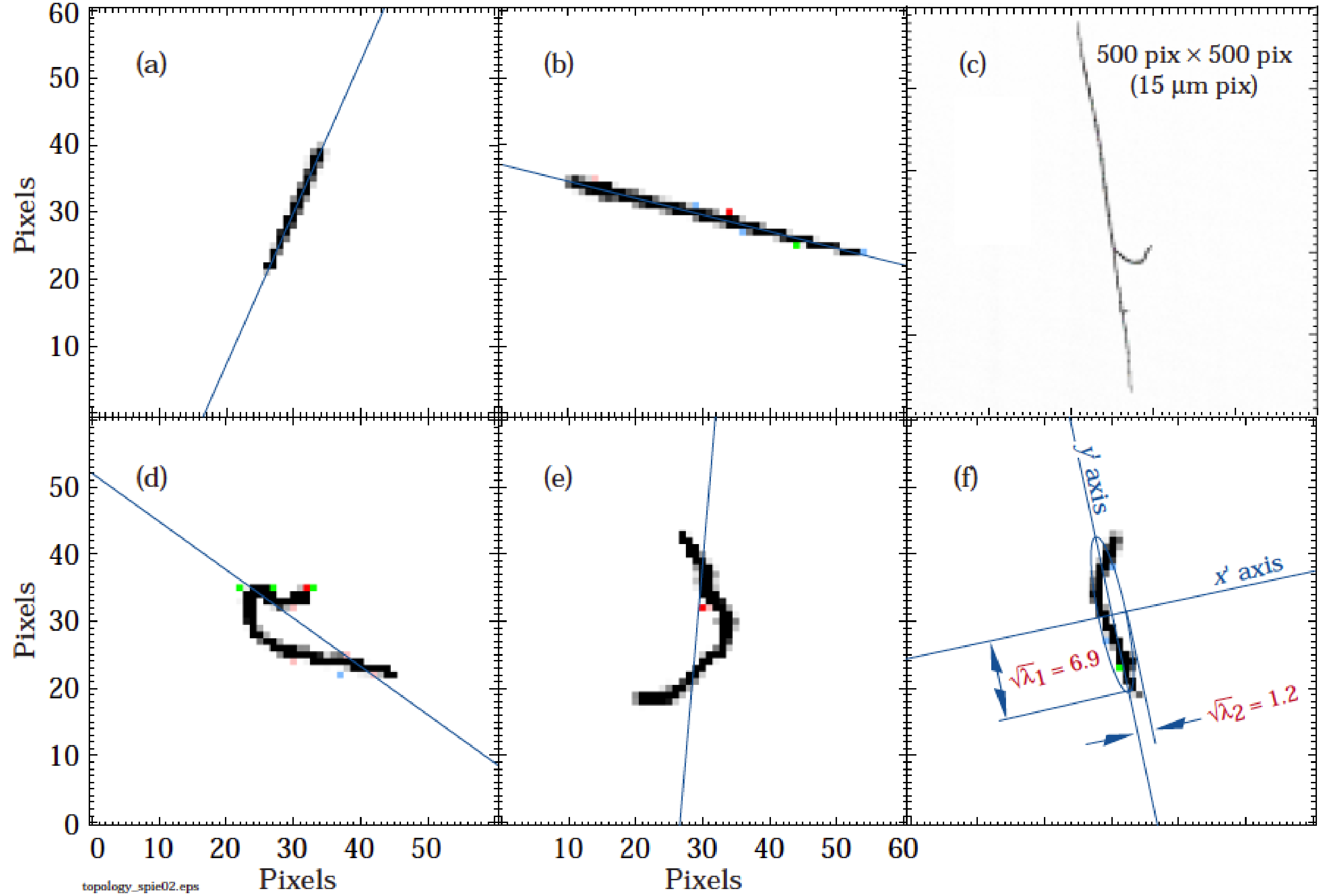


Figure 2. Examples of cosmic-ray muons (a–c) and worms (d–f) in a totally depleted 200-μ thick LBNL CCD. (c) shows one of the longest tracks found, and two δ rays (knock-on electrons) can be seen. (f) also indicates the the definition of λ_1 and λ_2, the principal moments of the distribution.

Charge Transfer Efficiency (CTE)

- Fraction of electrons that are successfully moved from one pixel to another during read-out
  - Charge Transfer Inefficiency: CTI = 1 - CTE
- Values can differ between parallel and serial readout: E.g.: OmegaCAM CENTAURUS:
  - Serial: 1
  - Parallel: 0.9999995 (1 charge loss every 1000 for a pixel at row 2048)
- Degrades due to radiation:
  - in particular, affects space instruments
  - depends on signal level

CTI evolution for *HST*/STIS CCD

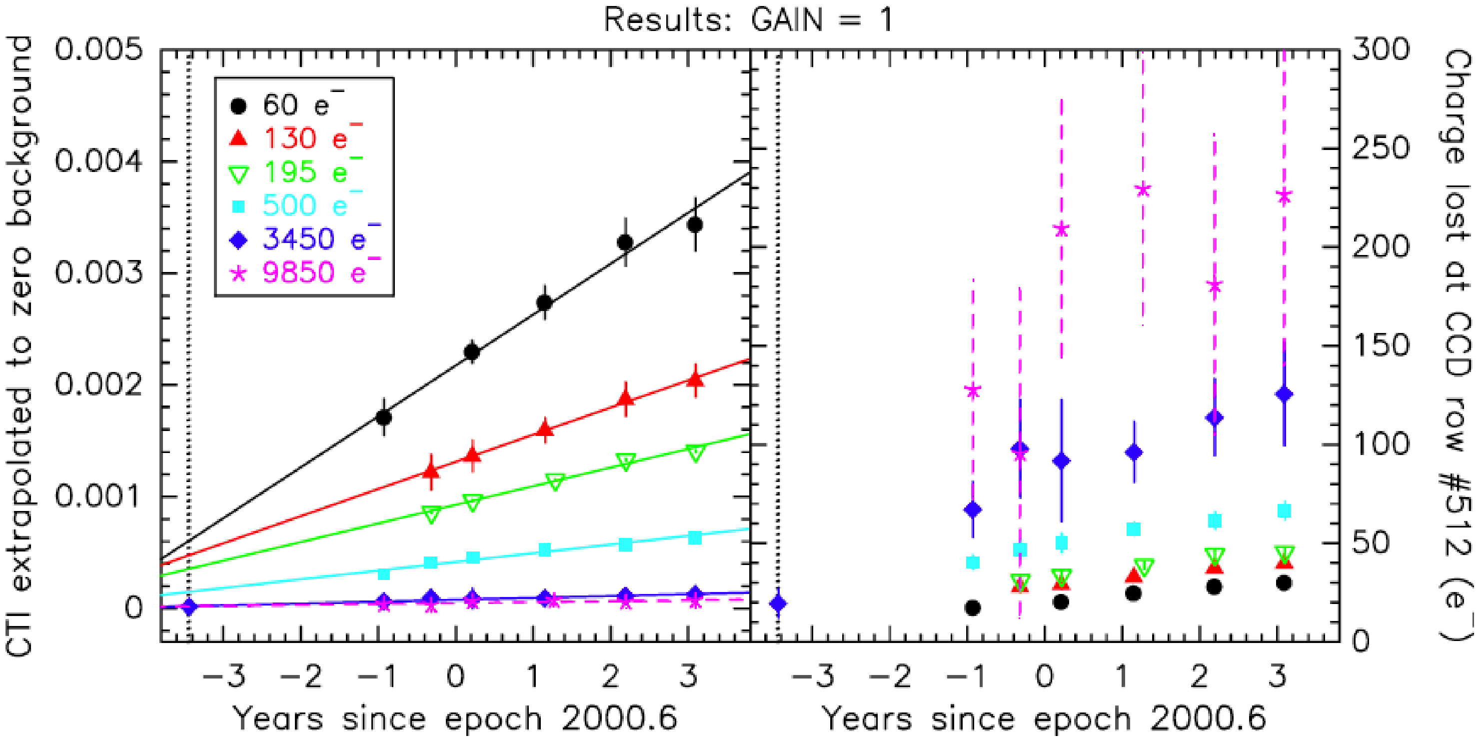


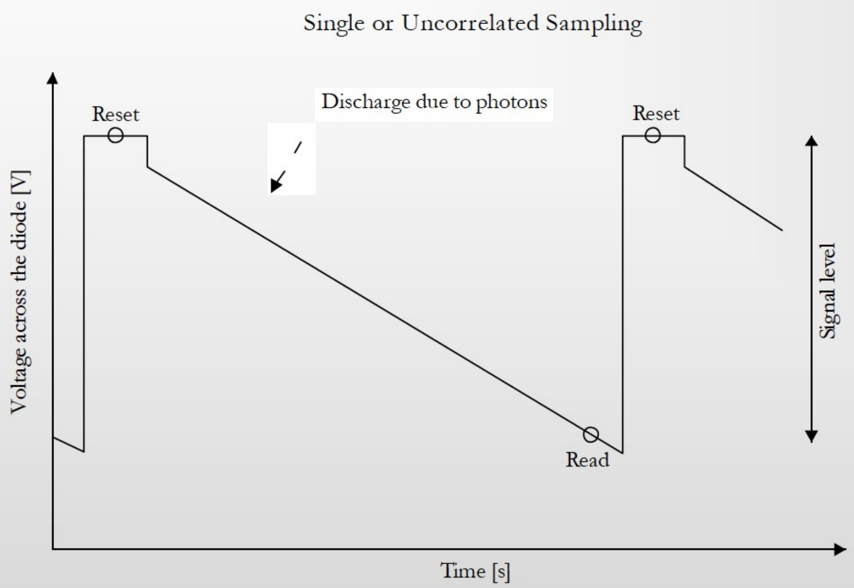
Figure 3: *Left panel:* CTI extrapolated to zero background for gain = 1 as a function of time and signal level, derived from the internal sparse field test. Both the data and the corresponding linear fits are plotted. Symbols associated with individual signal levels (corrected for CTI) are indicated in the legend. *Right panel:* Absolute charge lost due to CTI for an object at the central row of the STIS CCD as a function of time and signal level. Symbol types are the same as in the left panel. The epoch of HST Servicing Mission 2 (during which STIS was installed on HST) is depicted as a black dotted line.

Goudfrooij, P., Wolfe, M. A., Bohlin, R. C., Proffitt, C. R., and Lennon, D. J., 2009, "STIS CCD Performance after SM4," Instrument Science Report STIS 2009-02.

Sources of noise

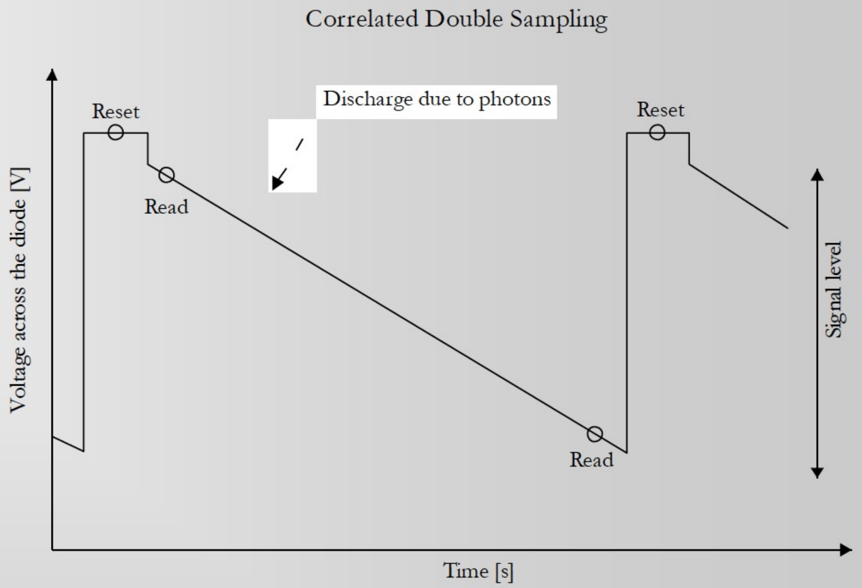
- Read-out noise (RON):
  - Noise produced by the electronics of the amplifier
  - Follows a gaussian distribution
- Thermal noise: thermal excitation of electrons in valence band
  - origin of dark current, reason to cool detectors
  - Poisson distribution
- kTC noise in CMOS/IR detectors: reset voltage is not always constant
  - Usually dealt with by readout mode
- Quantization noise (QN):
  - Analog-to-digital converter (ADC) converts electrons to ADUs
  - 16-bits ADCs produced a max of 2^16 = 65 535 ADUs
  - ADC only outputs discrete levels: range of analog inputs can produce same output: round-off error is quantization noise
  - QN = 1/sqrt(12) ADU

CMOS (IR) detectors read-out mode



Single (reset read) or uncorrelated Sampling

Cannot remove KTC noise or drifts in the detector but can measure saturation or full well capacity of the detector pixels (use also for dark current measurements by not resetting the device). Provides high dynamic range.
KTC noise = drifts in voltage due to Temp effects.

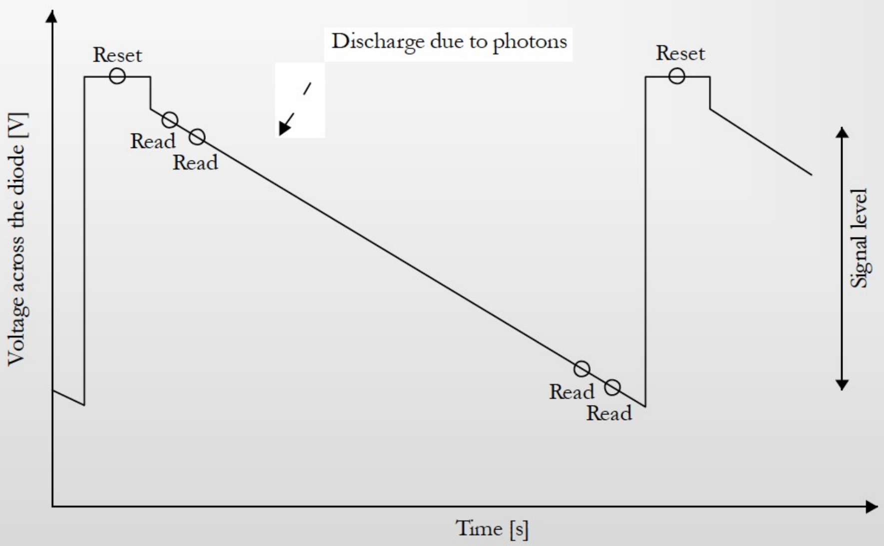


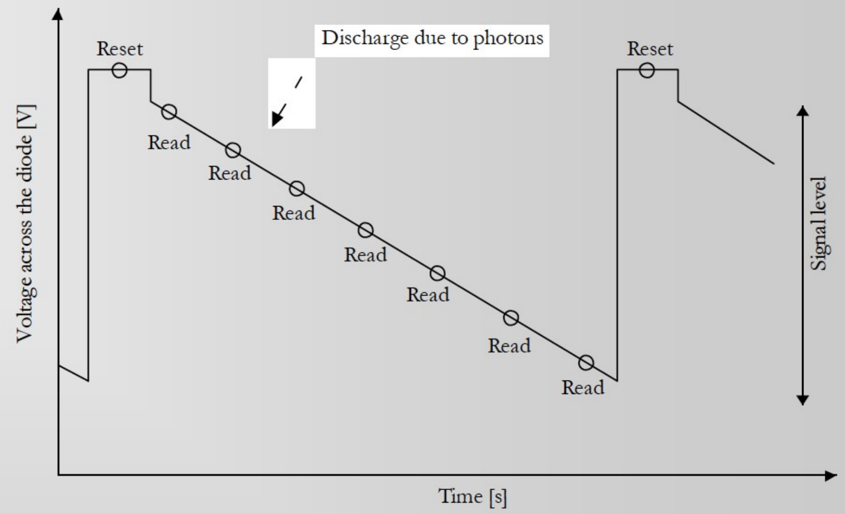
Correlated Double Sampling (CDS)

This mode removes KTC noise but cannot detect saturation of the pixels. It is the standard readout mode.

Dorn 2009

CMOS (IR) detectors read-out mode





Fowler (reset-read-read) Sampling

Readnoise decreases as $$\frac{1}{\sqrt{n}}$$

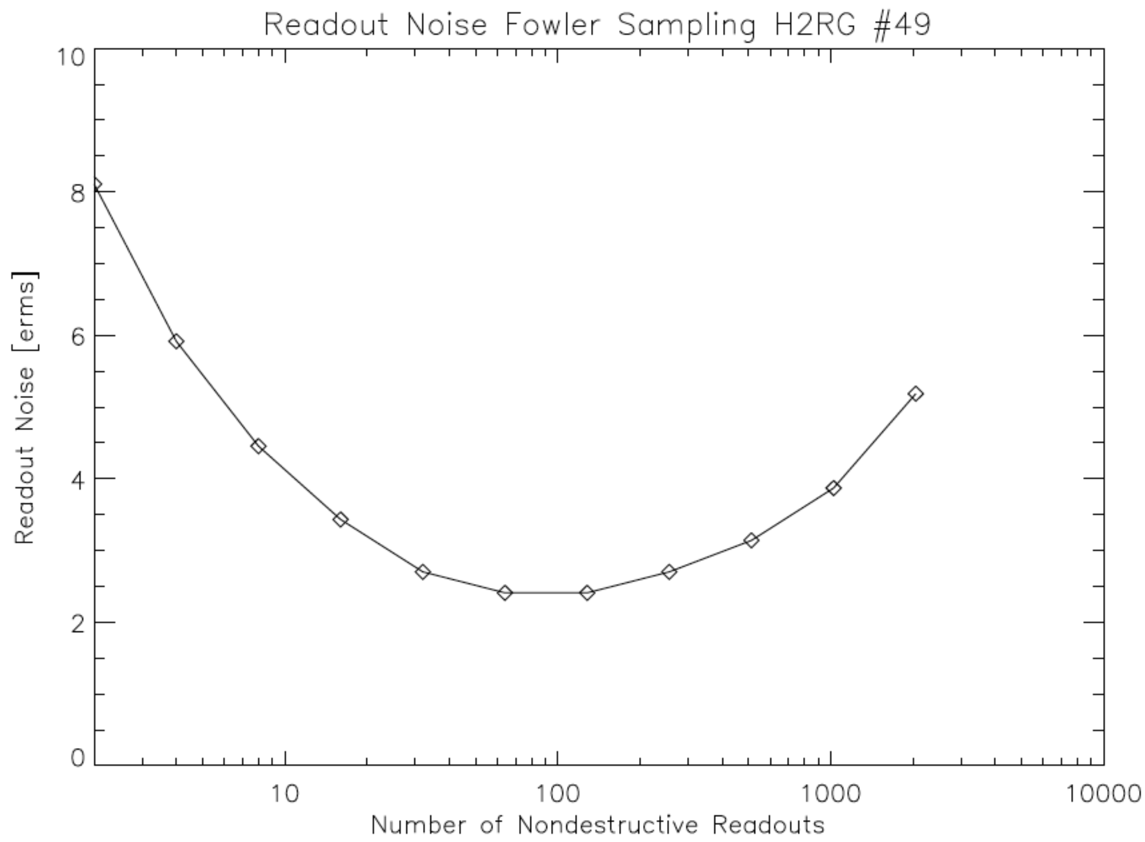
with n being the numbers of samples.
Is better in readnoise limited conditions than DC.
Saturation not known.

Up-the-Ramp Sampling

Fit line to get the mean flux rate = slope.
This mode is good if some pixels saturate before the end of the exposure time.

Dorn 2009

RON decrease using Fowler-sampling



Source of noise

- 1/f, pink noise, flicker noise: affects a number of electronics, origin not well understood
  - Noise behaving as $1/f^{\alpha}$, (f = read-out frequency)
    - $\alpha \sim 0 - 2$, often close to 1
  - Consequence: SNR does not increase with # of integrations
  - Usually not relevant in modern detectors
  - Unfortunately affects AQUARIUS arrays: VISIR, MATISSE, *JWST*/MIRI
    - For VISIR, requires high chopping frequency

Behavior relative to ideal detector

(for optical, near- and mid-IR astronomy)

- Location of arrival of photons on detector
  - Pixel size is often chosen as to satisfy the Nyquist sampling criterion (2 pixels/resolution element)
  - However, different problems can occur:
  - CCD:
    - Coating can increase the FWHM of the PSF
    - Bad clocking pattern
    - Lateral charge diffusion
    - Thickness combined with a fast camera
    - For space instrument:

    Significant CTE leads to shift of PSF centroid.

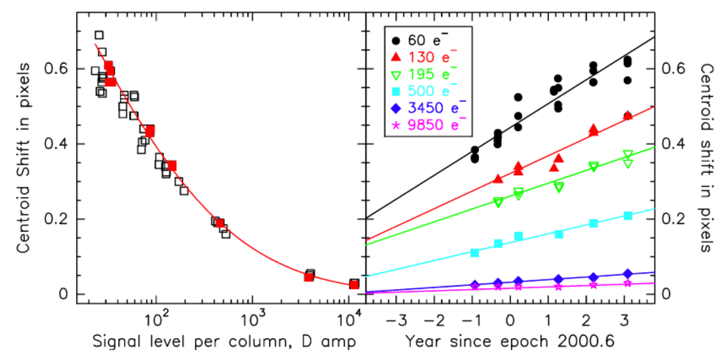
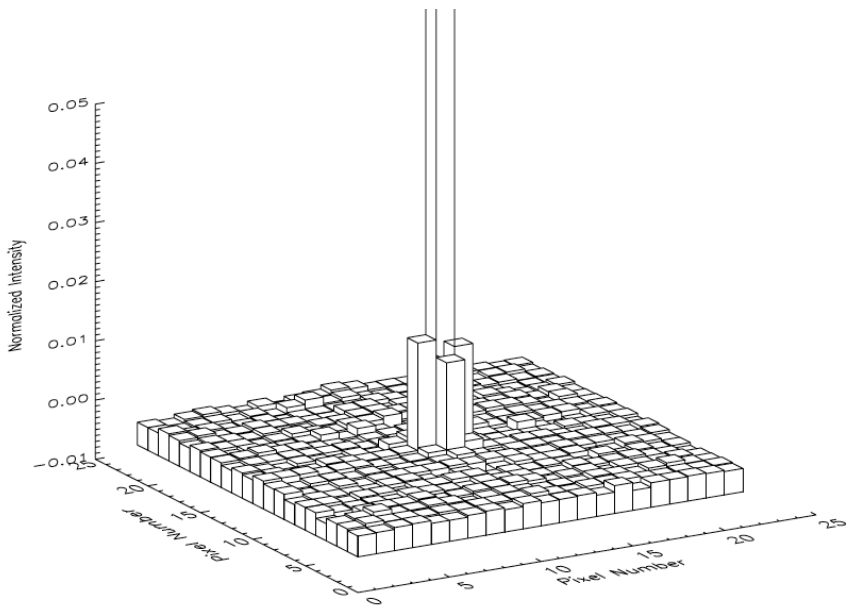


Figure 5: *Left panel*: The centroid shift (in unbinned CCD pixels) as a function of signal level as read out by the D amplifier for the gain = 1 observing block in October 2002, ~ 5.5 years after STIS installation. Centroid shifts for the central location on the CCD are shown in filled squares, and a least-squares fit to the latter is shown by the solid line. *Right panel*: The centroid shift for the central location on the CCD as functions of time and signal level as read out by the D amplifier. Both the data and the corresponding linear fits are plotted. Symbols associated with individual signal levels (corrected for CTI) are indicated in the legend.

Behavior relative to ideal detector
(for optical, near- and mid-IR astronomy)

- CMOS (IR) detectors:
  - Interpixel capacitance
    - affects the point-spread function
    - affects the determination of the gain



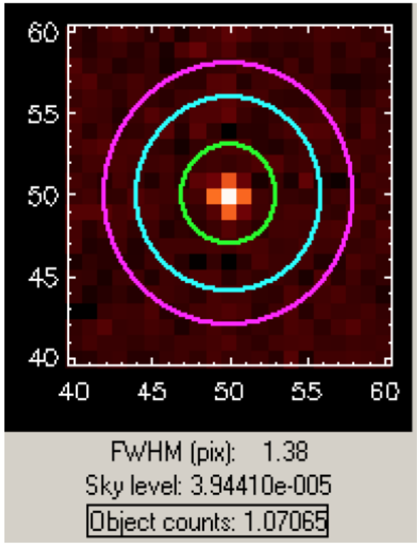


Figure 8 Normalized point spread function of interpixel capacitance of HgCdTe Hawaii-2RG array measured by single pixel reset using the guide window mode. Intensity of closest neighbors: upper 1.4%, lower 1.5%, left 1.8%, right 1.7%. Total integrated intensity 1.07.

Finger et al 2006, SPIE 6267

1. Introduction
2. Detectors based on photo-electric effect:
   1. CCD
   2. CMOS/IR detectors
   3. MAMA & photo-multiplier tubes
3. Characteristics of CCD and CMOS detectors
4. *Signal-to-noise ratio*
5. FITS files
6. Summary

Signal-to-noise ratio

- $\text{SNR} = \frac{Signal}{Noise}$
- Signal = object detected photons $= O_e(\text{t})$
- Noise $= \sigma = \sqrt{variance}$
  - Variance from
    - Photon noise: (in electrons)
      - object: object detected photons $= O_e(\text{t})$
      - sky: sky detected photons $= S_e(t)$
      - thermal background: background detected photons $= B_e(t)$
      - detector dark current: dark current rate $= D_e(t)$
    - Read-out noise: in electrons RON_e^2
    - Quantization noise:$\left({}^{1}/_{\sqrt{12}} \times \text{g}\right)^2$
    - Other noise: can often be corrected (if enough care taken during calibrations)

Signal-to-noise ratio

- SNR = $$\frac{O_e(t)}{\sqrt{(O_e(t)+S_e(t)+B_e(t)+D_e(t)+RON_e^2+\frac{g^2}{12})}}$$
- Different regimes:
  - Read-out noise limited:
    - faint target, little sky
    - RON contribution larger all other contributions
    - Exposure should be as long as possible: limited by radiation events, observing constraints
  - Photon noise limited:
    - bright target, bright sky (extreme case: mid-infrared imaging from ground), large thermal background, dark current (UV in space)
    - little affected by number of exposures:
      - trade-off with overheads associated with individual exposures

Signal-to-noise ratio

- Object photon noise limited: SNR = $\sqrt{O_e(t)} \propto \sqrt{t}$
- RON limited: SNR = $\frac{O_e(t)}{RON_e} \propto t$
- Background limited
  - SNR = $\frac{O_e(t)}{\sqrt{X_e(t)}}$ (X is either S, B, D) $\propto \sqrt{t}$
  - Often limited by systematics affecting the determination of the background or the determination of O_e

Special case of mid-infrared wavelengths

Number of photons from sky and telescope is larger than number of photons from the object ($S_e >> O_e$) !

- Very short exposure times (~ 10 ms)
- Synchronization of detector reading with chopping (~ Hz motion of a mirror in the light path – such as M2)

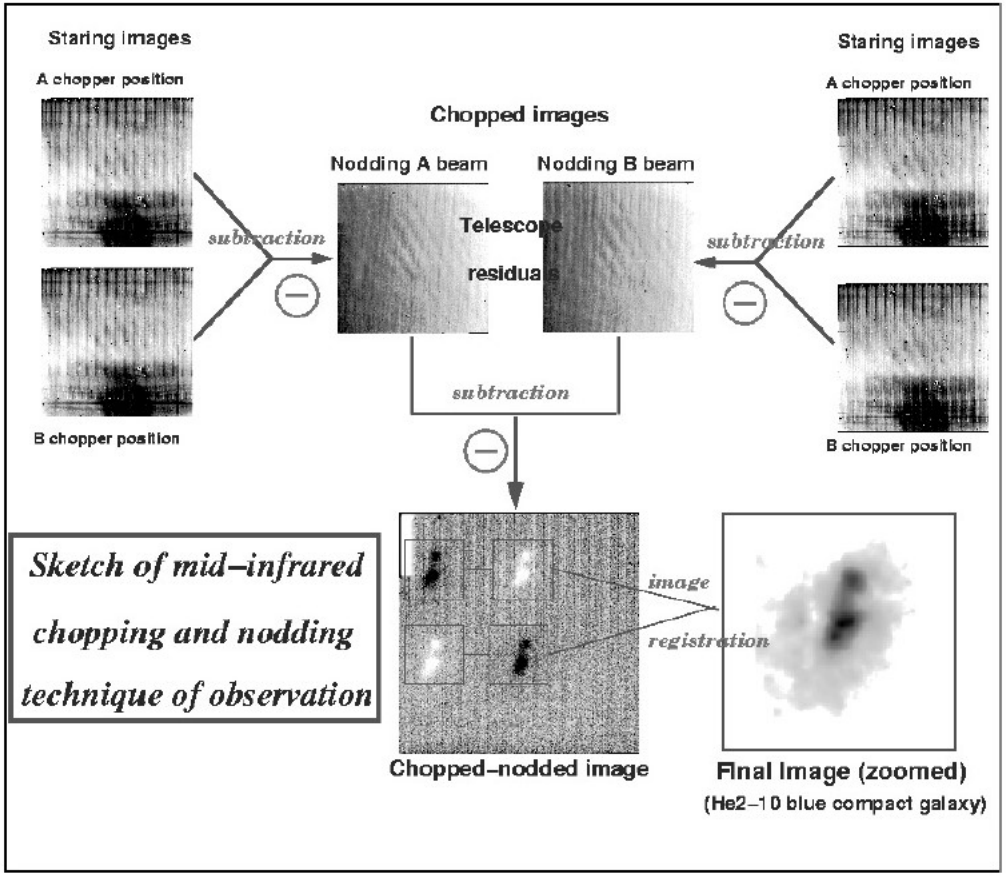


Figure 5: Illustration of the chopping and nodding technique on observations of the blue compact galaxy He2-10. The galaxy only appears after chopping and nodding (courtesy VISIR commissioning team, June 2004).

VISIR User Manual

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Flexible Image Transport System (FITS) files

- Widely used format for transporting, analyzing and archiving astronomical images. *Much more than just a format.*
  - Primarily designed to store scientific data sets of multidimensional arrays (images) and 2-dimensional tables organized into rows and columns of information
- Endorsed by ESO, NASA and the International Astronomical Union (*Vatican Library, …)*
- Header keywords provide descriptive information about the data:
  - Site, Telescope, Instrument and Detector information
  - World Coordinate System parameters
- Header keywords and data format follow a (strict) standard

FITS file

- A FITS file is comprised of segments called Header/Data Units (HDUs),
  - First HDU is called the `Primary HDU', or `Primary Array’:
    - can contain a 1-999 dimensional array of 1, 2 or 4 byte integers or 4 or 8 byte floating point numbers using IEEE representations.
    - typically a 1-D spectrum, a 2-D image, or a 3-D data cube.
  - Any number of additional HDUs may follow the primary array: FITS `extensions'. Types of standard extensions are currently defined:
    1. *Image Extensions* contain a 0-999 dimensional array of pixels, similar to a primary array (header begins with XTENSION = 'IMAGE ')
    2. *ASCII Table Extensions* store tabular information with all numeric information stored in ASCII formats (header begins with XTENSION = 'TABLE ')
    3. *Binary Table Extensions* store tabular information in a binary representation. Each cell in the table can be an array but the dimensionality of the array must be constant within a column. (header begins with XTENSION = 'BINTABLE')

First entries in a FITS Primary HDU header:

```
SIMPLE  =                    T          / Standard FITS
BITPIX  =                    8          / # of bits per pix value
NAXIS   =                    0          / # of axes in data array
EXTEND  =                    T          / FITS Extension may be present
ORIGIN  = 'ESO-Paranal'                 / Source of the file
DATE    = '2007-10-28T04:39:41.9020'    / Date the file was written
TELESCOP= 'ESO-VLT-U1'                  / ESO Telescope Name
INSTRUME= 'CRIRES  '                    / Instrument name
OBJECT  = 'Hip012377'                   / Content description
RA      =            39.869764          / 02:39:28.7 RA (J2000) pointing (deg)
DEC     =              0.32674          / 00:19:36.2 DEC (J2000) pointing (deg)
EQUINOX =                2000.          / Standard FK5 (years)
RADECSYS= 'FK5     '                    / Coordinate reference frame
EXPTIME =           30.0000000          / Integration time
MJD-OBS =       54401.19303370          / Obs start 2007-10-28T04:37:58.111
DATE-OBS= '2007-10-28T04:37:58.1114'    / Observing date
UTC     =            16676.000          / 04:37:56.000 UTC at start (sec)
LST     =             8455.544          / 02:20:55.544 LST at start (sec)
```

Data types in an image array:

- 8-bit (unsigned) integer bytes
- 16-bit (signed) integers
- 32-bit (signed) integers
- 32-bit single precision floating point real numbers
- 64-bit double precision floating point real numbers

Summary

- Bias
- Read-out noise (RON)
- Dark level
- Quantum efficiency (QE)
- Full-well capacity
- Gain (g); pixel-to-pixel variation, fixed-pattern noise
- ADC saturation level
- Linearity
- Exposure time; DIT/NDIT
- Fringing
- Charge Transfer Efficiency (CTE)
- Detector defects: bad/hot columns; hot pixels.
- Radiation events 'cosmic rays'