CCDs
Focal plane commissioning
(AuxTel)

February 2020 (LSST/Yvette)

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(nombreux emprunts à
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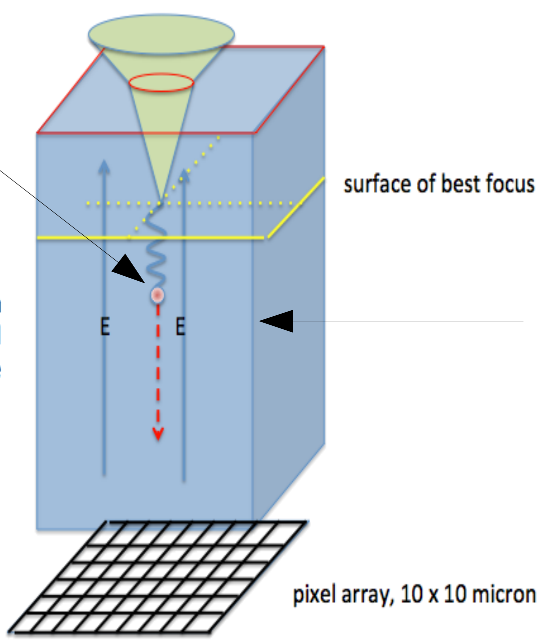
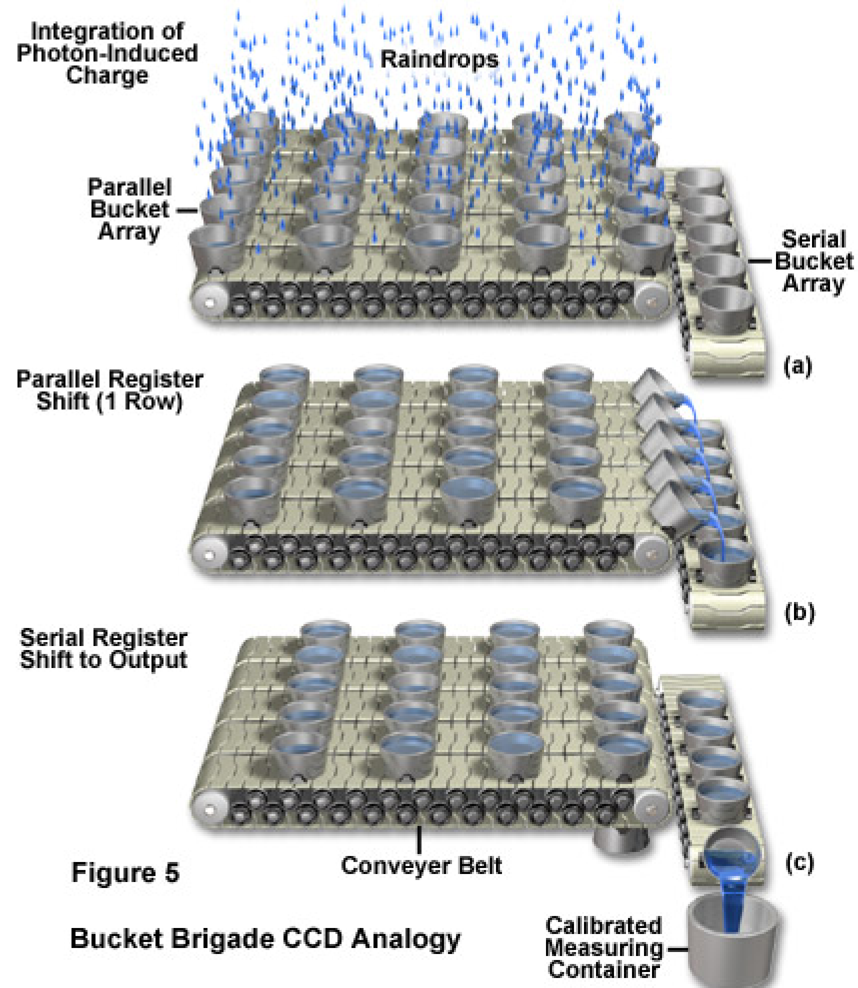
CCD

Photoelectric effect



Silicium Band-gap
= 1.2 eV
~ 1.1 μm

(diagramme : C. Stubbs)



yscteh.com

Dark current

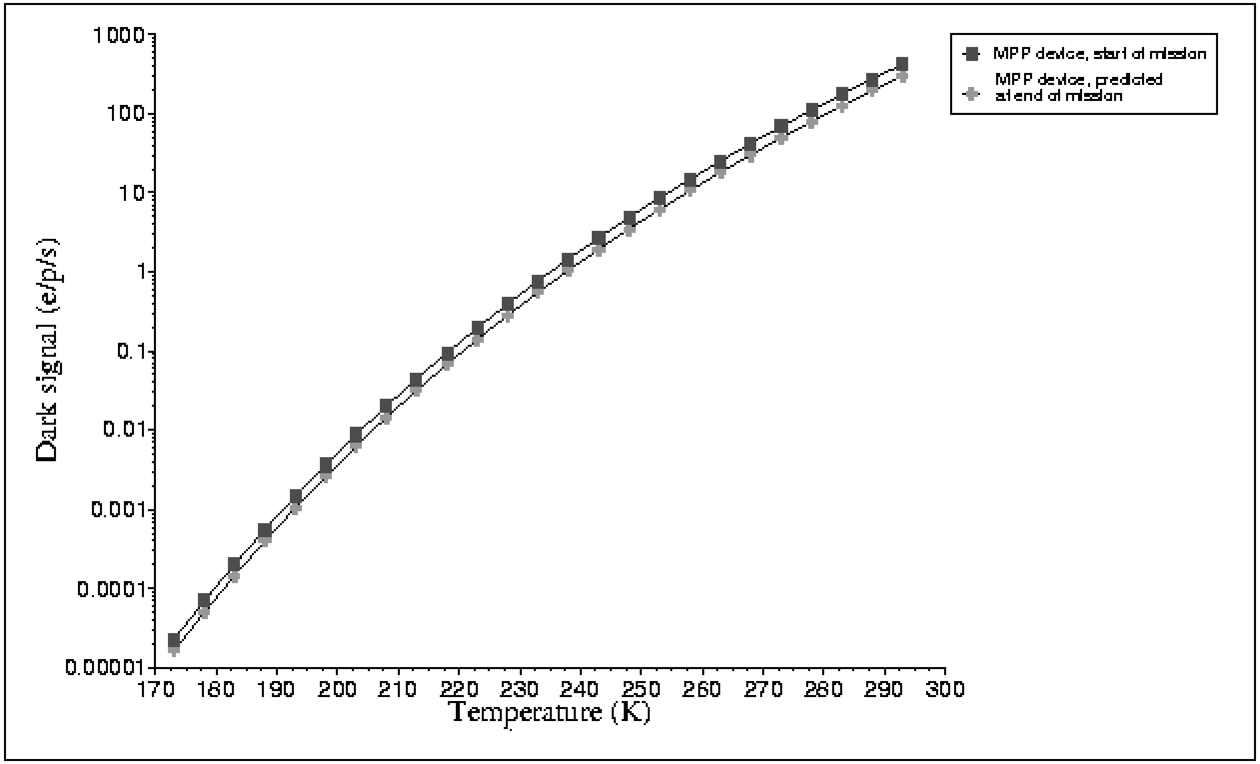


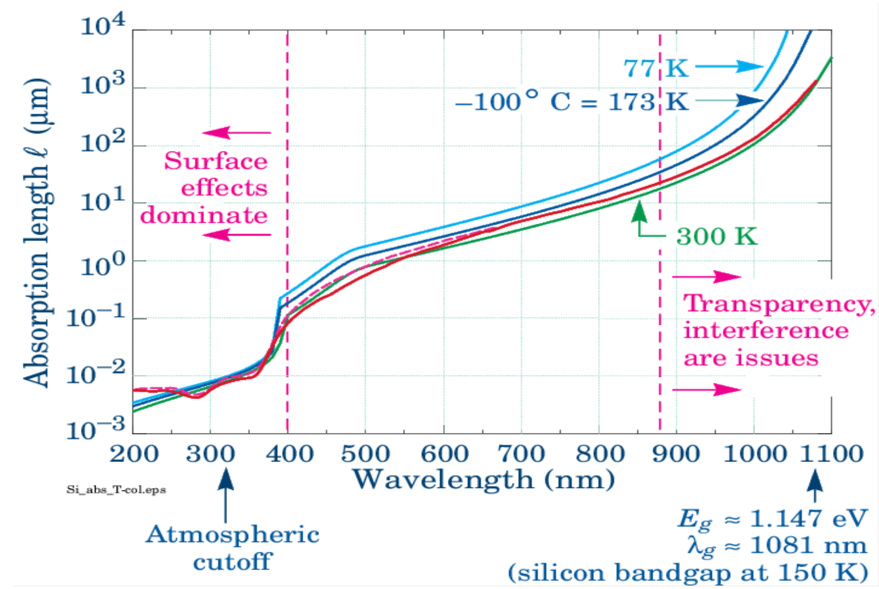
Figure one, dark signal for an MPP device at beginning and end of mission

T ~ -100 °C
is common.

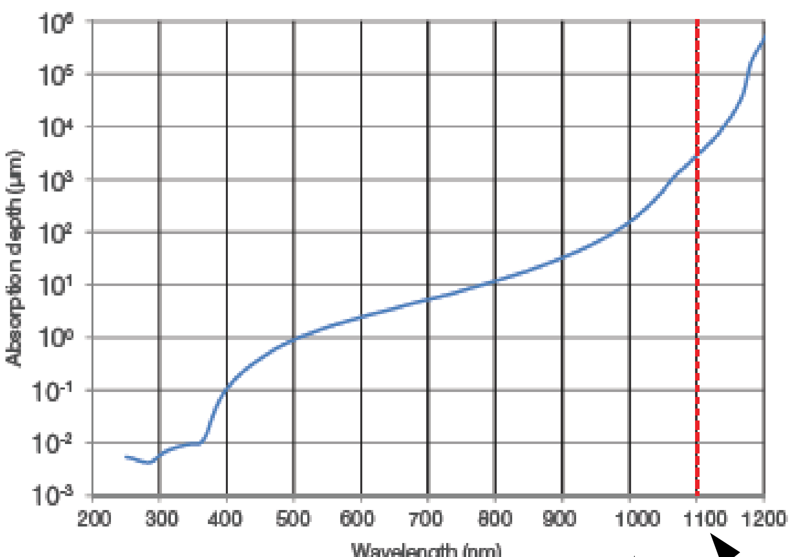
~ O(1-10) e/pix/h

(Chris Mc Fee, MSSL, 2000)

Interaction of photons in silicon



absorption length
vs wavelength
(T ~ 300 K)



100 μm

absorption length dependence on temperature
(snap.lbl.gov)

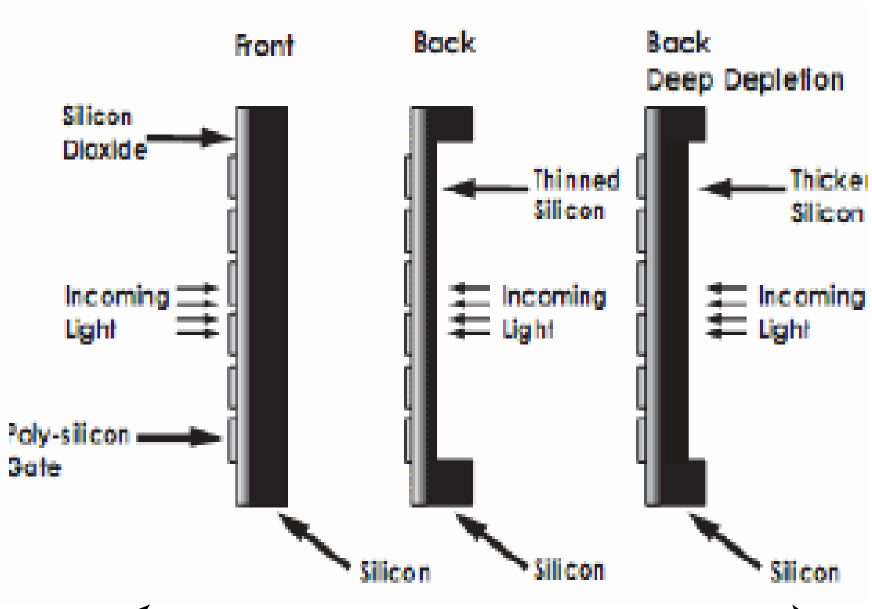
imposes a stable temperature for operations

(andor.com)

1 μm

bandgap

Classification botanique des CCD



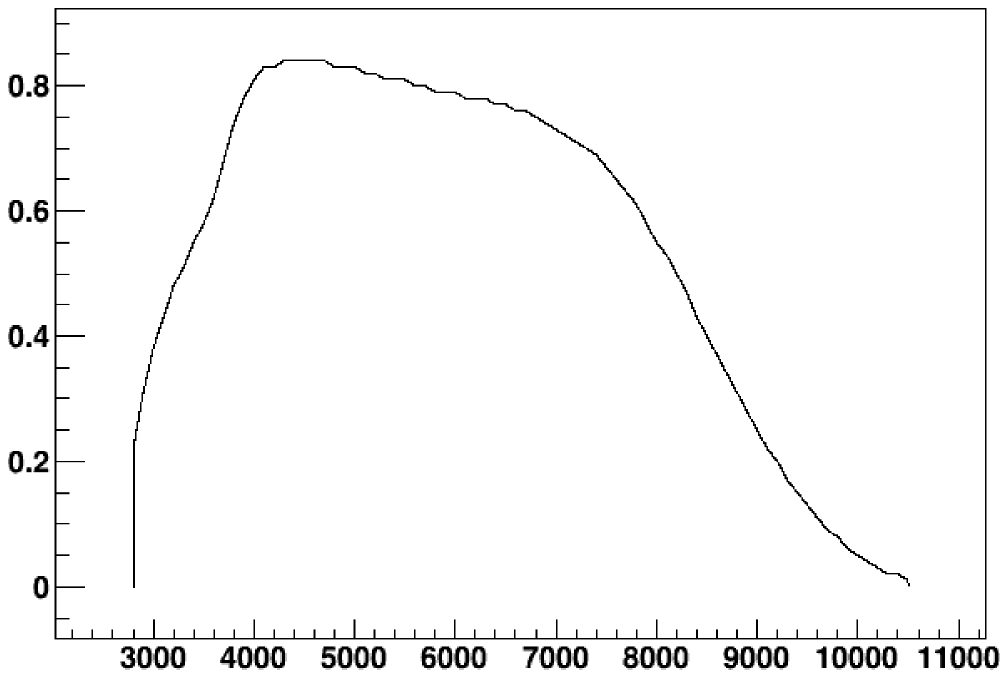
(roperscientific.de)

« Front-illuminated »
Sensibilité faible,
et quasi-nulle dans
le bleu.

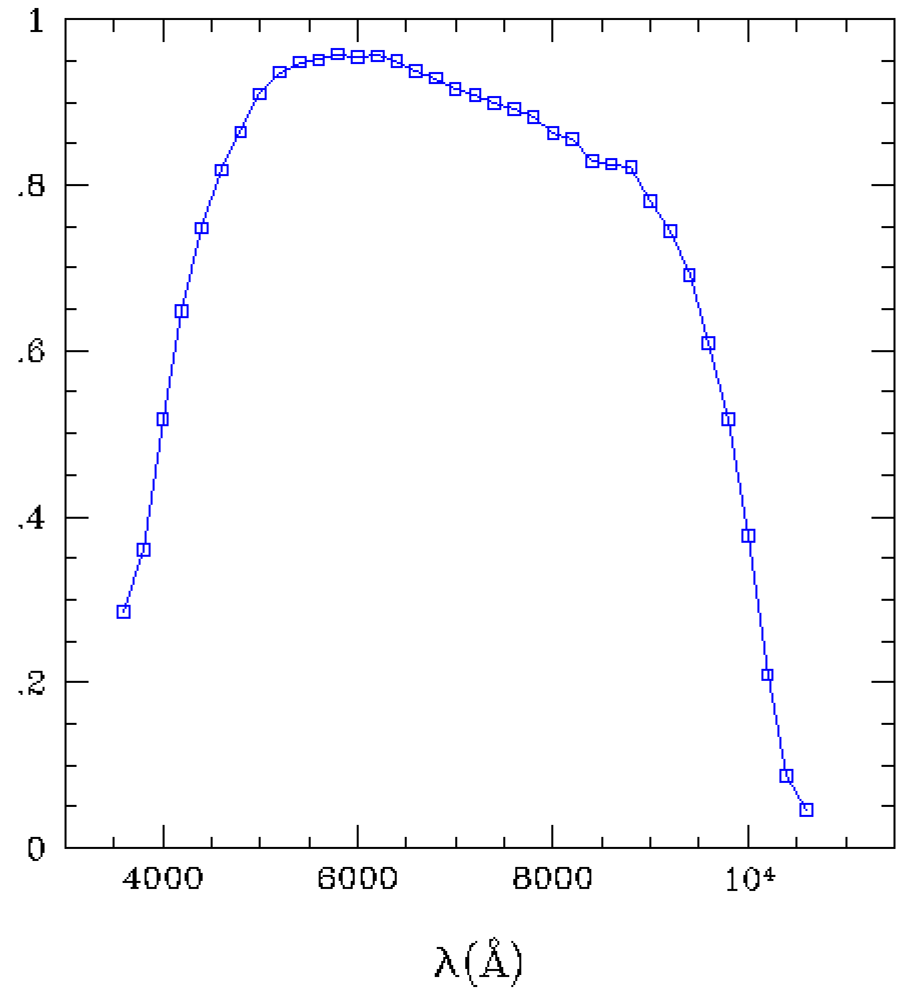
« Back-illuminated »
et aminci.
Sensibilité très bonne
dans le bleu,
plus modeste dans
le rouge

Deep-depletion
« Back-illuminated »
Sensibilité très bonne
dans le bleu et le rouge.

Quantum efficiency (el/photon)



CCD E2V 4290
Megacam Camera
(aminci, back-illuminated)
~1998



CCD S10892-02 (Hamamatsu)
Deep-depleted, Camera HSC (~2012)

LSST CCDs

- Thickness 100 μm
  - Most of the photons convert near the entrance, except in y band.
  - Deep-depleted (voltage > 50V, called back bias)
- 10 μm pixels: full well around 120 000 el, depends on voltage settings.

Read out jargon

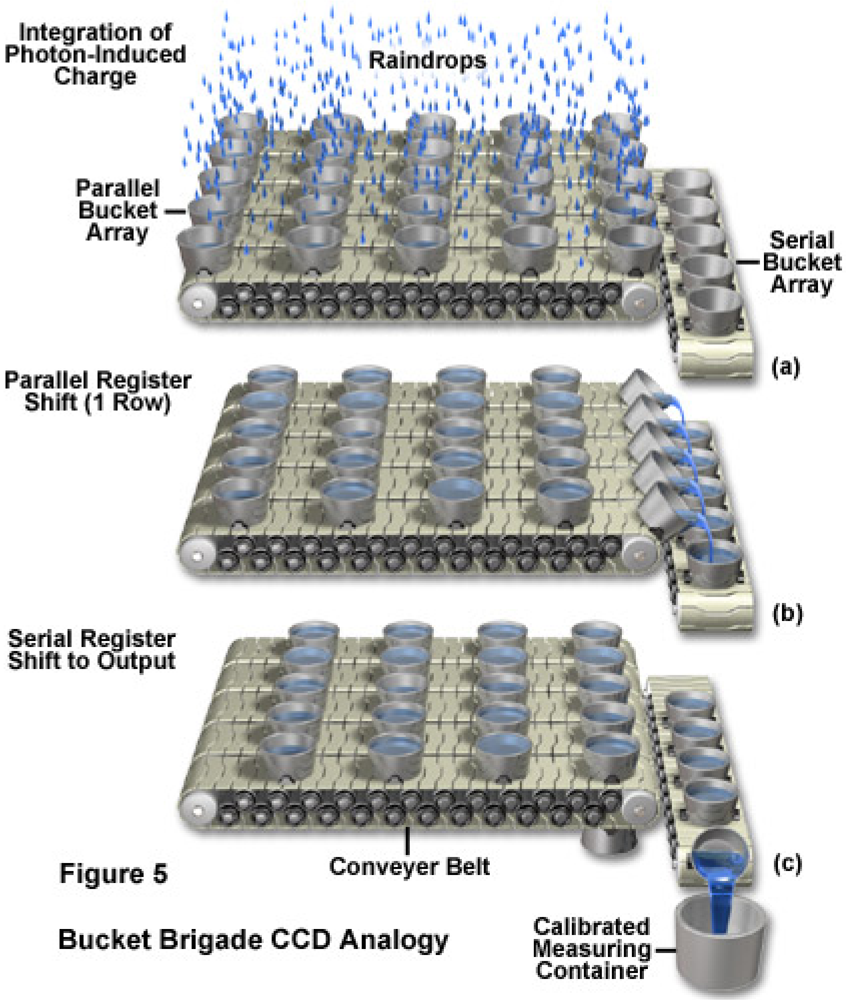


Figure 5

Bucket Brigade CCD Analogy

parallel

Serial

Convention:
serial direction = x
parallel direction : y

Ordres of magntude:

Parallel cycles: 1/ms
Series/pixel cycles : 1/us

"Phases"

Implementation of parallel transfer with 4 phases:

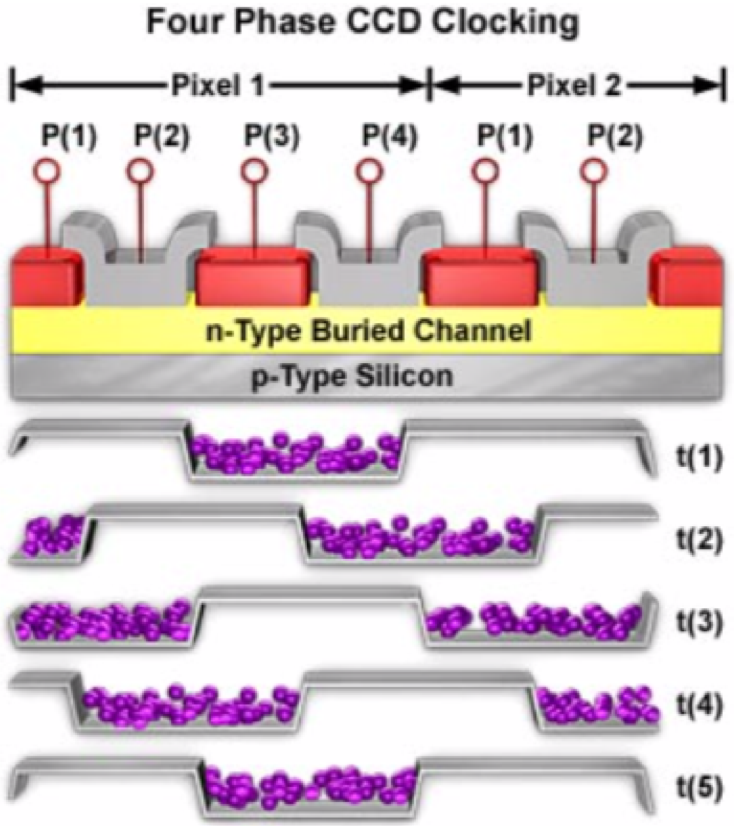


Figure 1

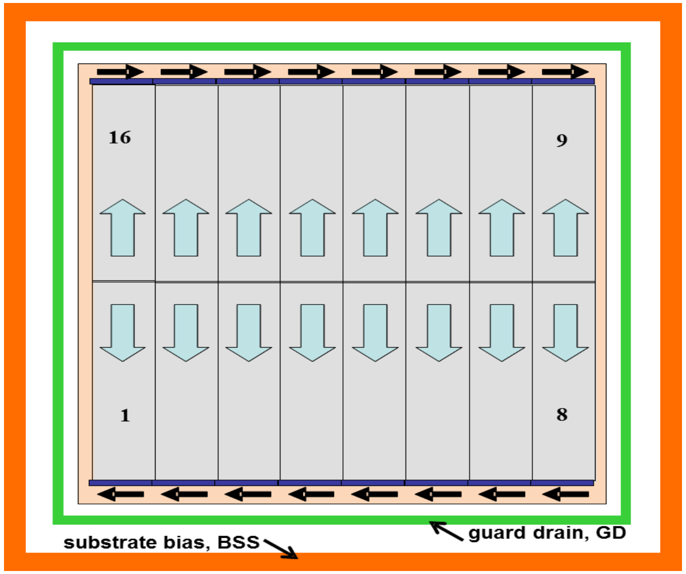
In general CCDs have 3 phases per pixel, occasionally 4 (e2v //).

The command of phases are called clocks.
The parallel clocks face big capacitances
→ big currents, strong induction on the output channel.

Les Détecteurs de LSST

• **Epaisseur 100µm (= sensibilité à l'IR)**
• **Si haute résistivité (nécessaire pour avoir un champ de dérive dans les 100mm) , fully-depleted**
• **une fenêtre d'entrée conductrice (pour imposer le champ de substrat / dérive) + un coating UV- IR + back-illuminated**
➔ *Sensible dans un grand domaine optique + faible distorsion par diffusion*
•Format : 4K x 4K + 4 die sites/6"wafer + 16-sorties en //
• **température de fonctionnement -100C**
• **suppression du courant d'obscurité**
➔ *Lecture faible bruit (<~ 9 e-) en 2s*
• **Taille de puits importante (<120 ke-)**
➔ *Grande dynamique*

CCD e2v : sens de lecture inversé ;
ITL : sens de lecture identique haut - bas)

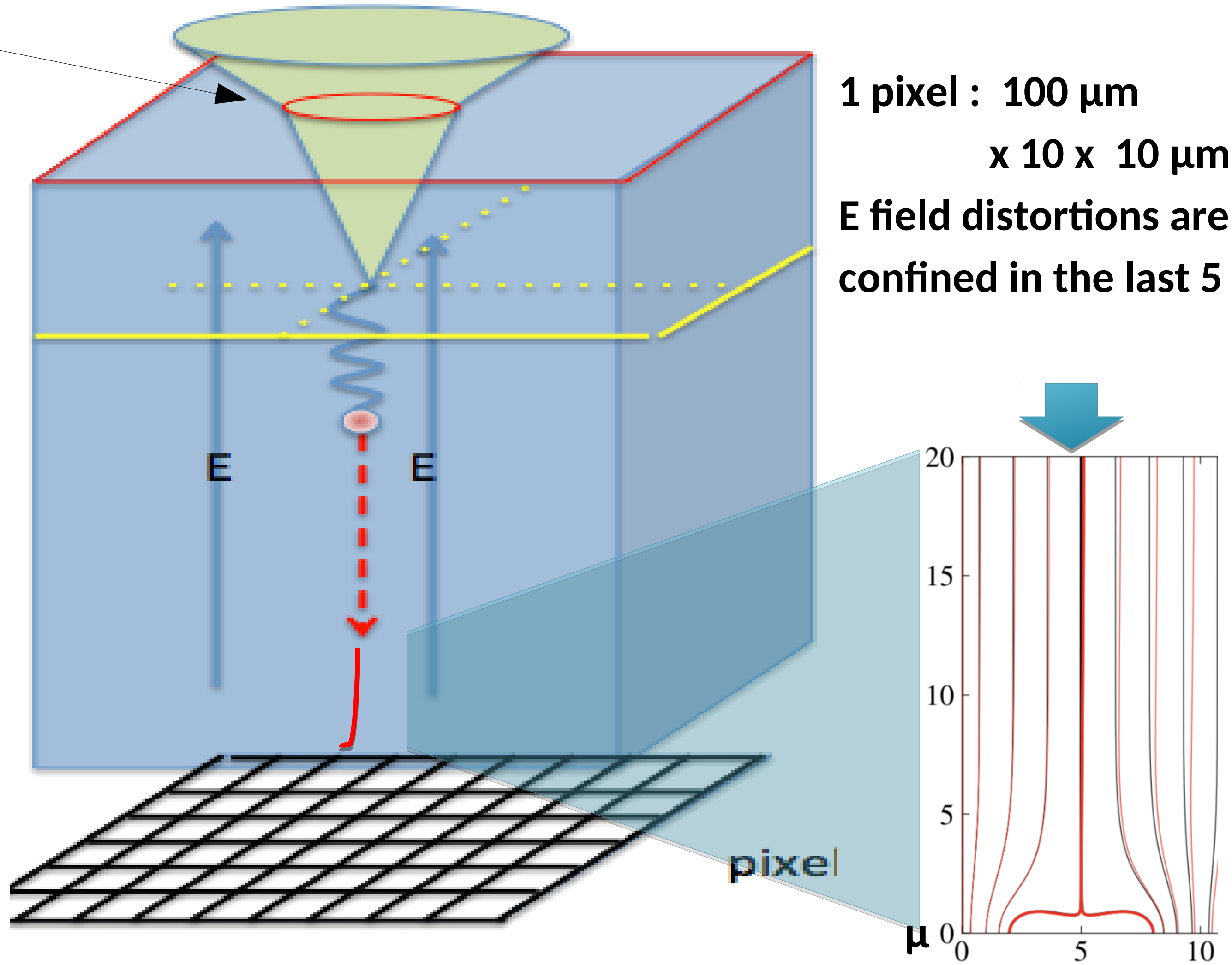


1 segment = 512x2000 pixels, soit 2 s pour lire à 500 kpix/s

Drift electric field

refraction
(n ~ 3.5)

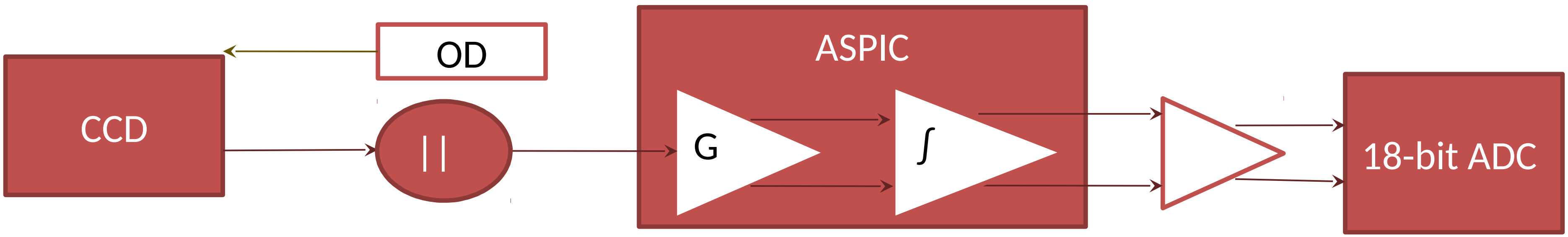
Pixels are not implemented in the Si bulk, drift lines only split at the end of the drift path.



1 pixel : 100 µm x 10 x 10 µm

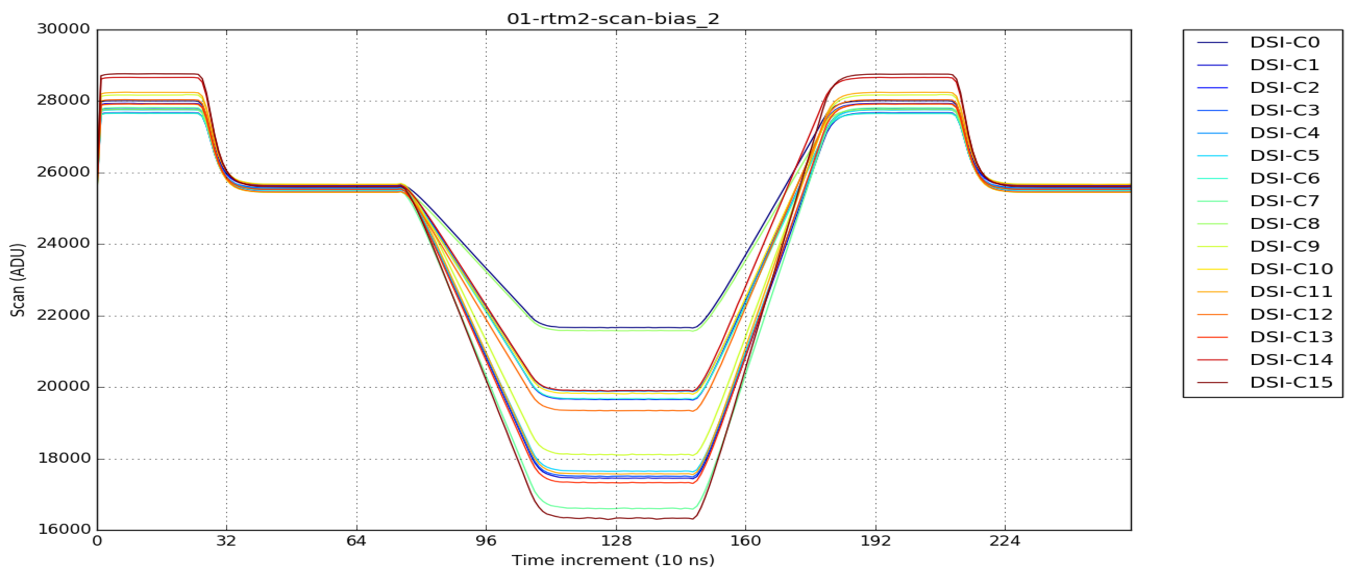
E field distortions are confined in the last 5 µm

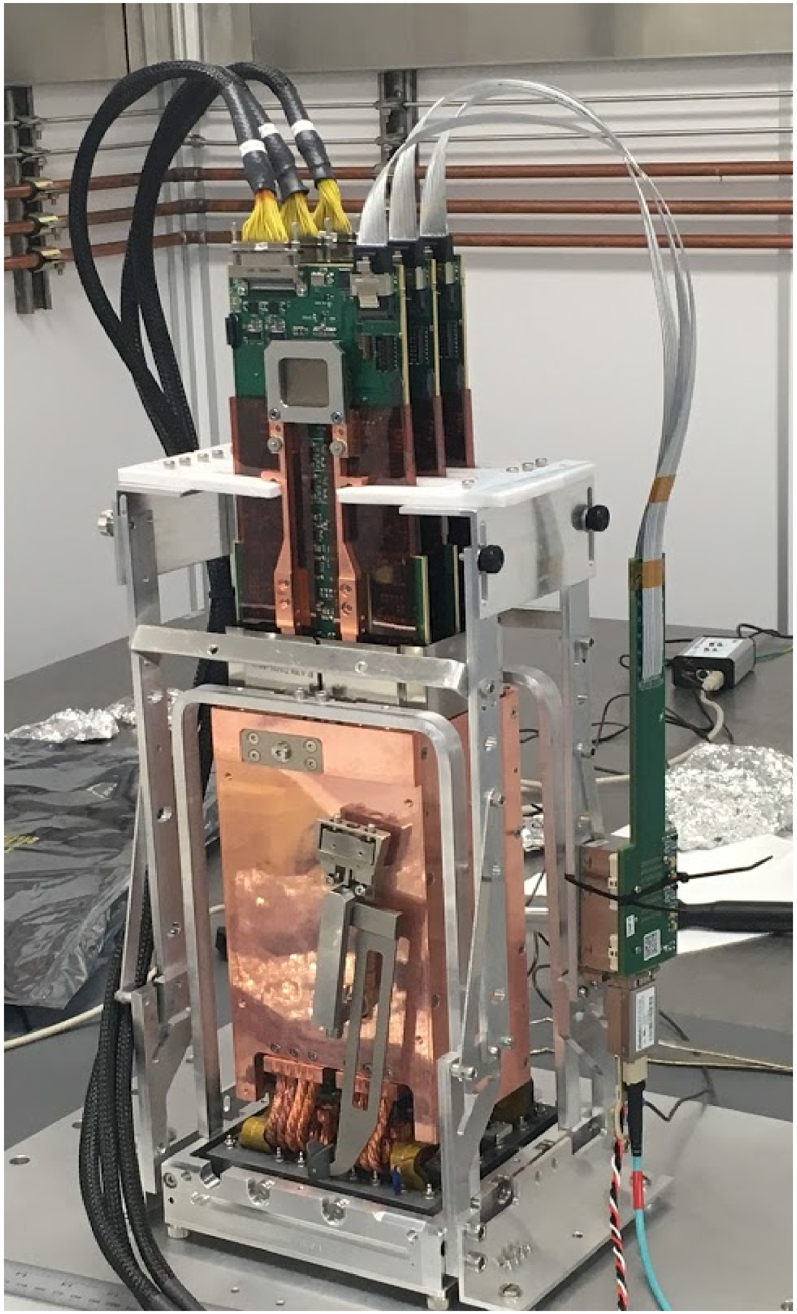
Lecture



Dual slope integration:

Un “pixel vide” est intercalé entre chaque vrai pixel et soustrait.

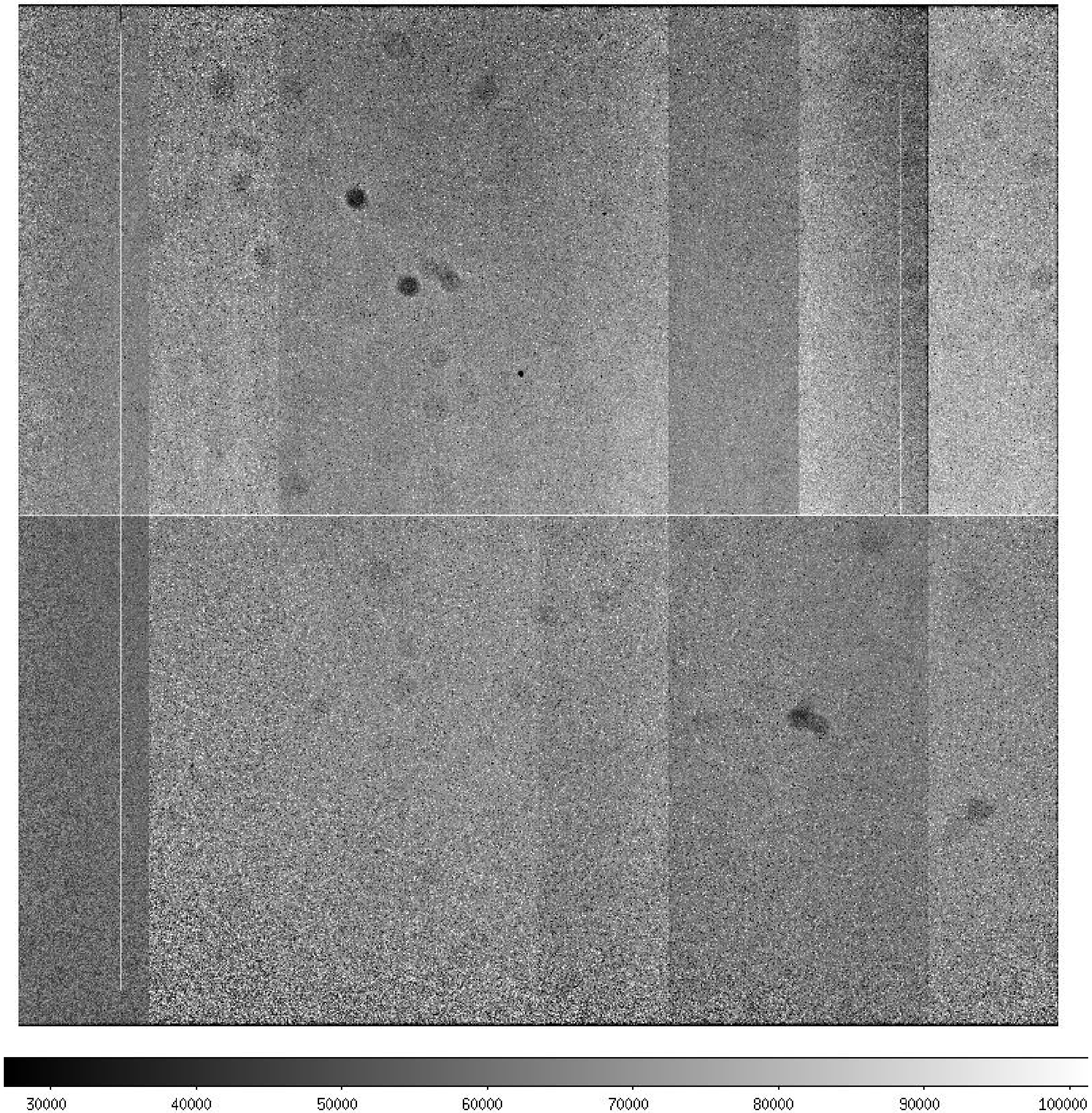




Modularity

- 1 raft = 9 CCDs
- 1 raft contains 3 REBs
- Each REB handles the clocking and read out of 3 CCDs (48 channels).
- The clocking is orchestrated by a program running on the REB FPGA. The name of the source file of this program is in the SEQFILE FITS keyword.

Raw image



One image = 16 amps.

In the raw image,
the 16 amps are stored in
16 fits (compressed)
extensions

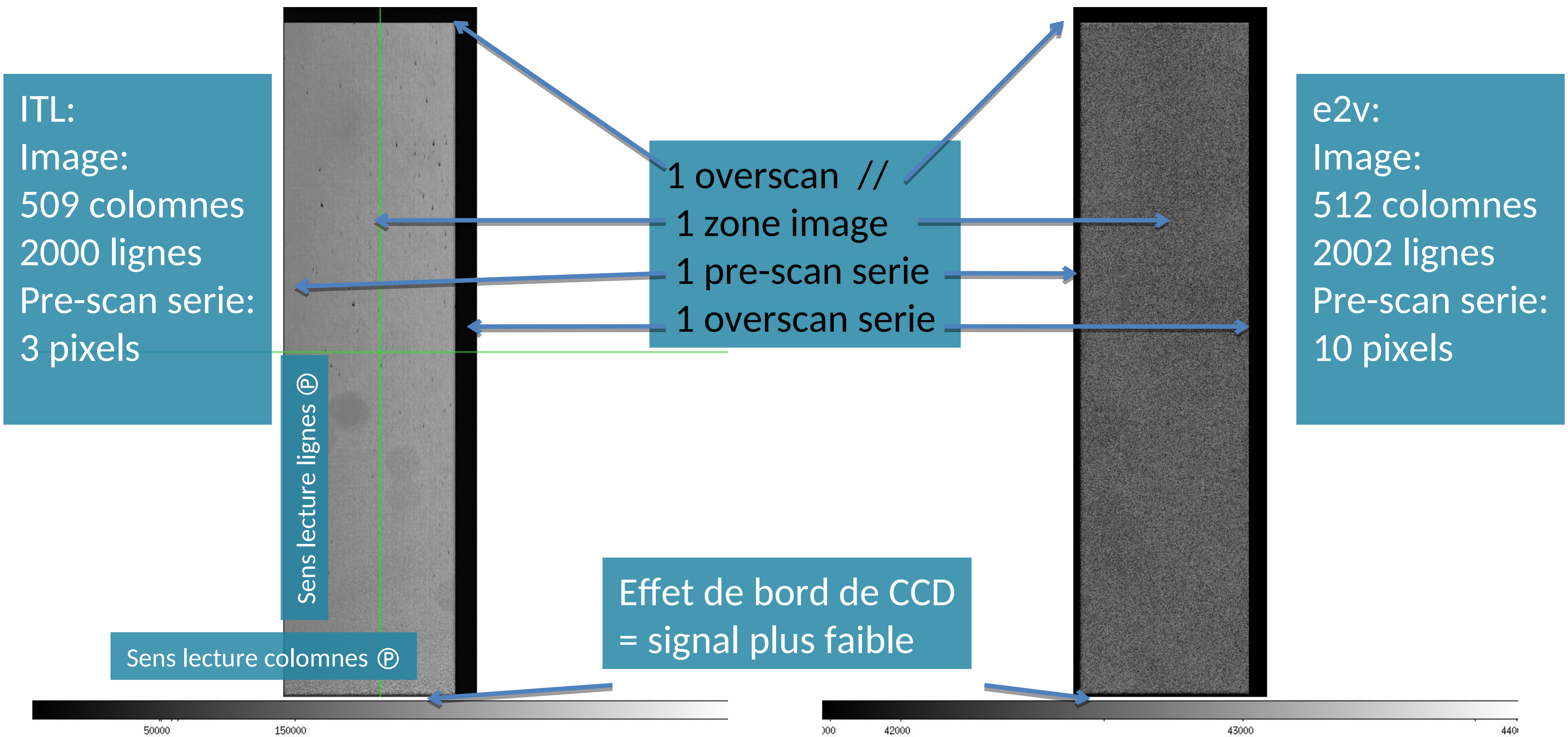
The informations that
allow one to place this
amp into the whole image
are in the fits headers.

This follows some standard,
so these images are well
displayed by ds9
(ds9 -mosaicimage iraf ...)

Two vendors ….

- e2v : industrial CCDs (Megacam, GAIA, Euclid, ZTF, Plato, …). Most of the delivered CCDs were accepted.
- ITL : Spin off from American labs. Heavy sorting among the delivered sensors.
- In the final camera, e2v goes in the center, ITL around. Rafts are not mixed.
- There are small geometrical differences between the two kinds.

Structure par ampli



FITS keys

```
CHANNEL =                    1
EXTNAME = 'Segment10'
CCDSUM  = '1 1      '
DATASEC = '[11:522,1:2002]'
DETSEC  = '[512:1,1:2002]'
DETSIZE = '[1:4096,1:4004]'
```

two different channel numbering schemes.

I image pixel = 1 physical pixel

DATASEC: area of the data array that addresses physical pixels.

DETSEC : Where these physical pixels should be placed in the whole image (beware: this amp should be flipped along X)

DETSIZE: Toal CCD size (just to allow you to allocate the image)

The difference between the data shape and datasec indicates where are the pre/over-scans.

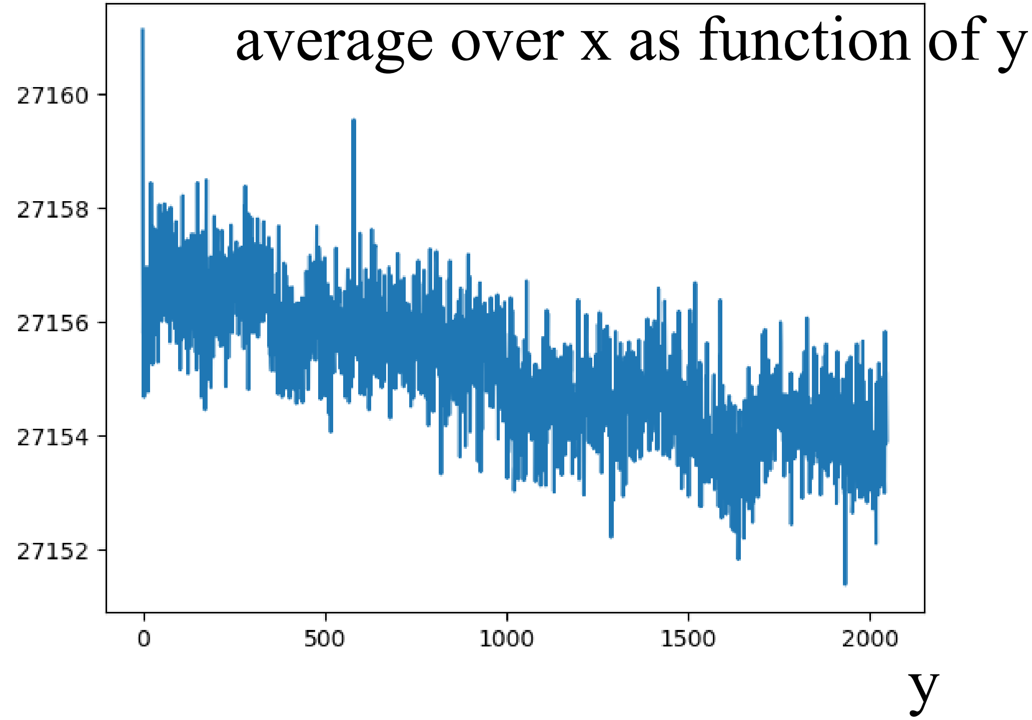
Overscan

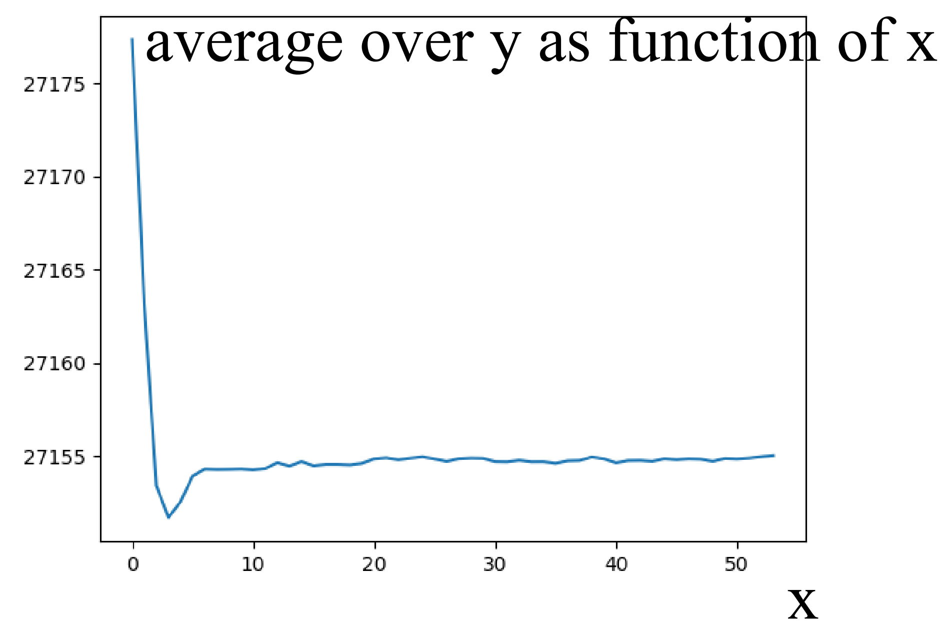
The overscan allows one to follow the evolution of baseline (zero charge) during the image readout.

The overscan is made from actual clock cycles corresponding to absent pixels.

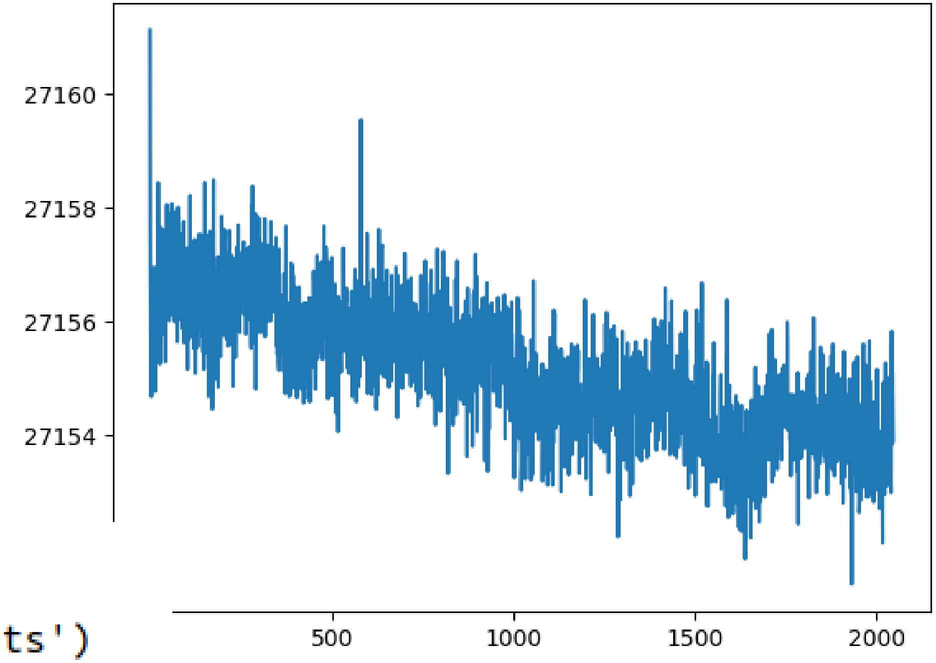
The first overscan pixels are affected by the (brutal) commutation but also by deferred signals.

To estimate the pedestal:
- skip a few pixels at the beginning.
- robust mean per line (along x)
- smooth along y in order to reduce the noise.

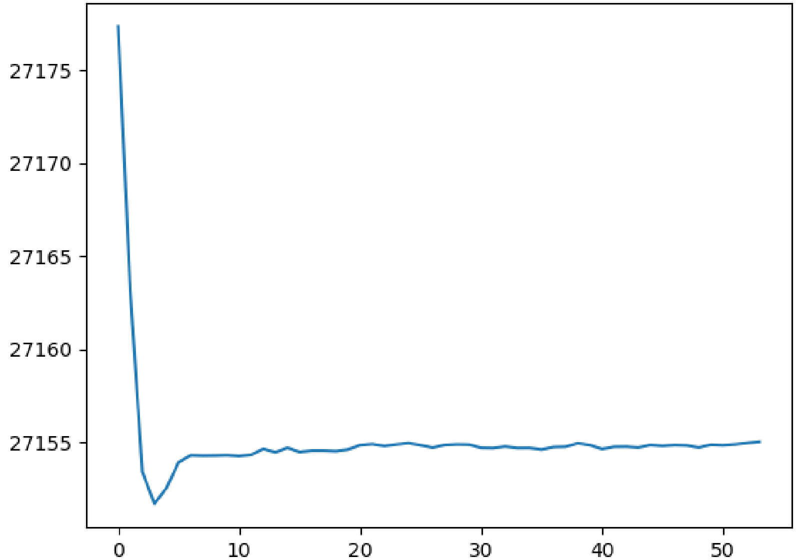




Serial overscan

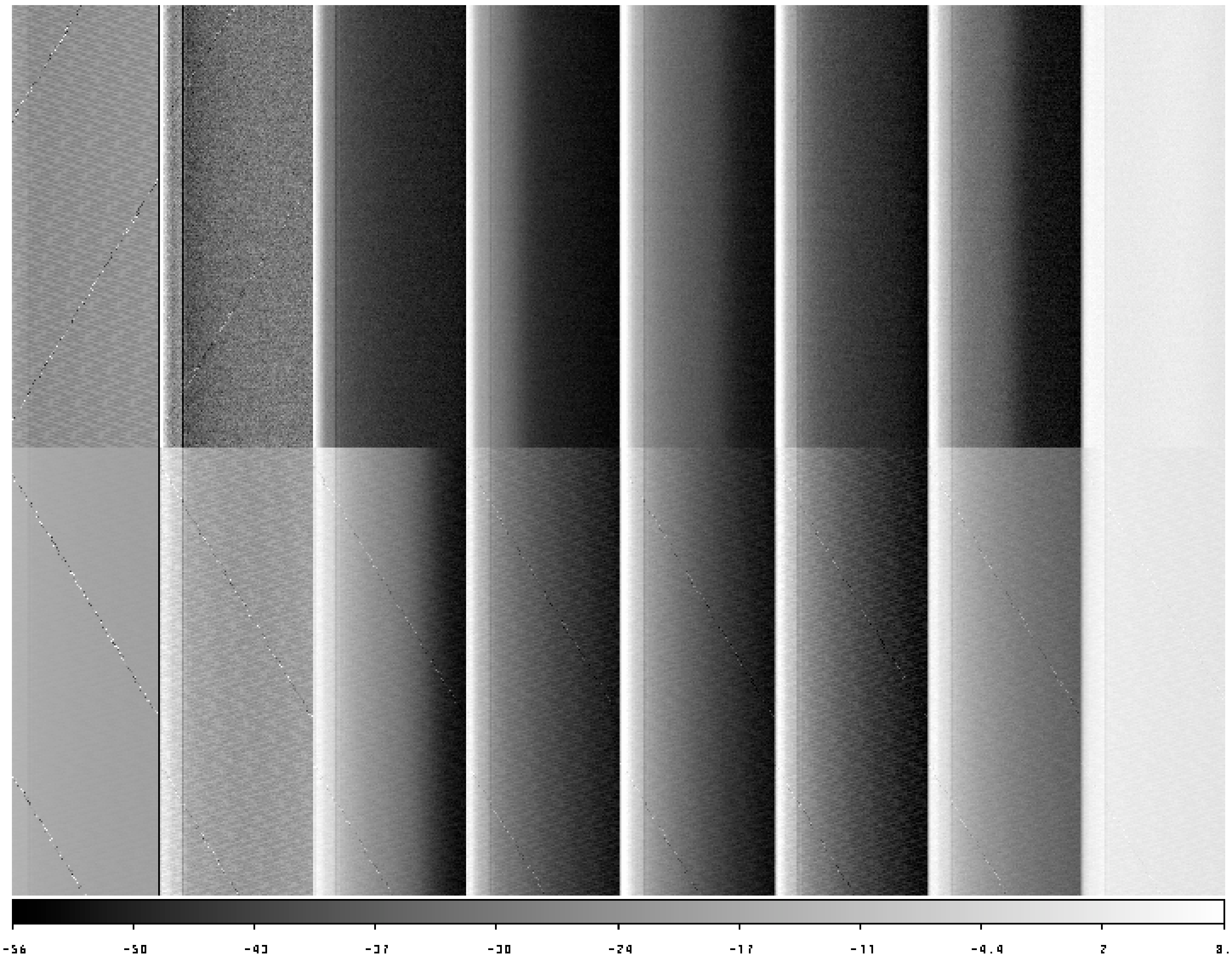



```
import astropy.io.fits as pf
import pylab as pl
f = pf.open('MC_C_20191012_000308_R22_S00.fits')
d = f[1].data.T
f[1].header['DATASEC']
o = d[522:,]
o.shape
pl.plot(o.mean(axis=0))
pl.plot(o.mean(axis=1))
```



FITS indexes à la Fortran,
Python prefers C mode:
- swap the indices,
- subtract 1 to DATASEC & Co

Biais

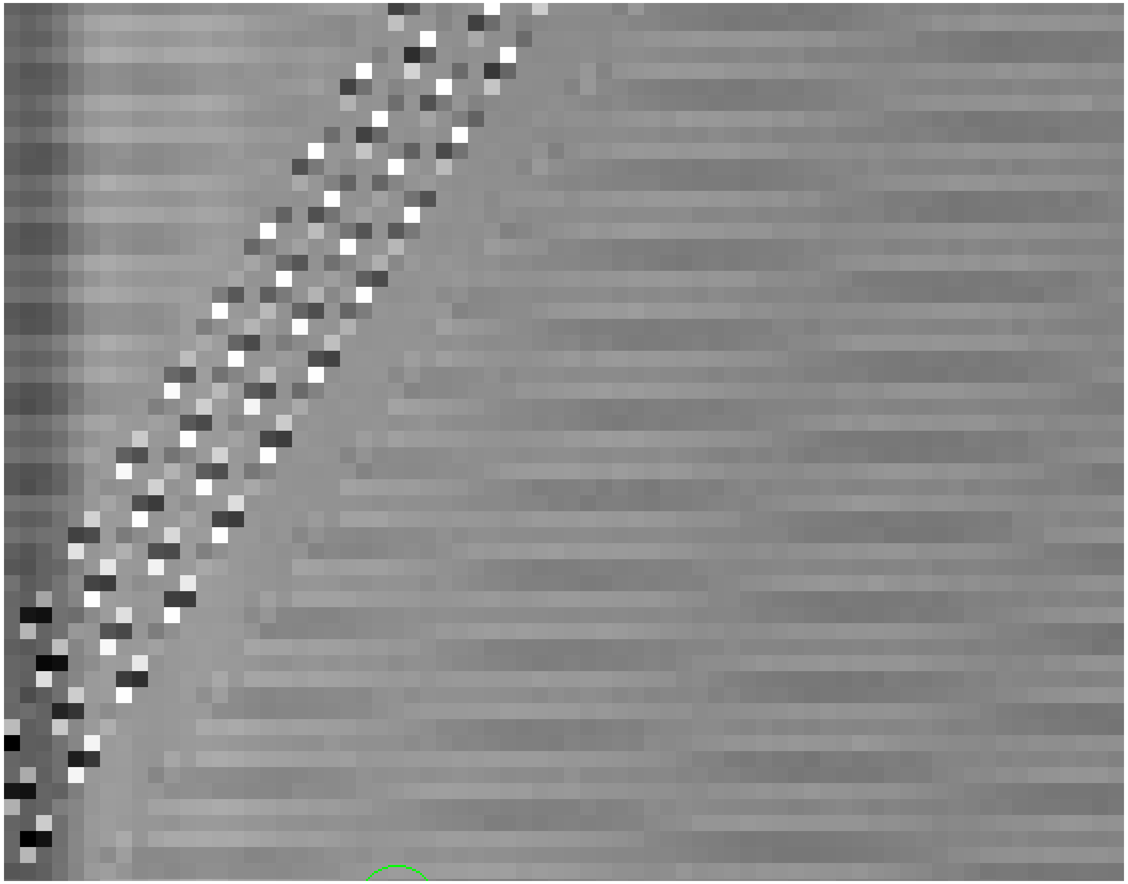


Light-free images.
zero integration.

"Average" of a ~100 bias frame (ITL CCD).

The structure (>20 ADU) imposes to subtract this masterbiais from images.

Biais (2)



In principle, the structures in biases are du to clock inductions.
Here, we see the induction of e2v clocks on an ITL CCD.
This was fixed at the middle of previous run, by synchronizing both sequencers : V1→ V2
In principle gains should not have changed.

Read out noise: 3 ways

- Evaluate the scatter of overscan pixels (around some reasonable average)
- Evaluate the scatter of biases (e.g. when assembling a master bias)
- Fit a PTC with a (good) model, and read the variance at zero flux.
- They should more or less agree….

CTE/CTI
(Charge Transfer (In)Efficiency)

- Manifest through charges than are are measured later than they should, i.e. in following pixels time-wise.
- Can be due to traps that release charges after some time.
- Can be due to clocks leaving some small fraction of the charge behind,
- Can be due to just electronics: the shaping of some preamp extends into the next pixel.

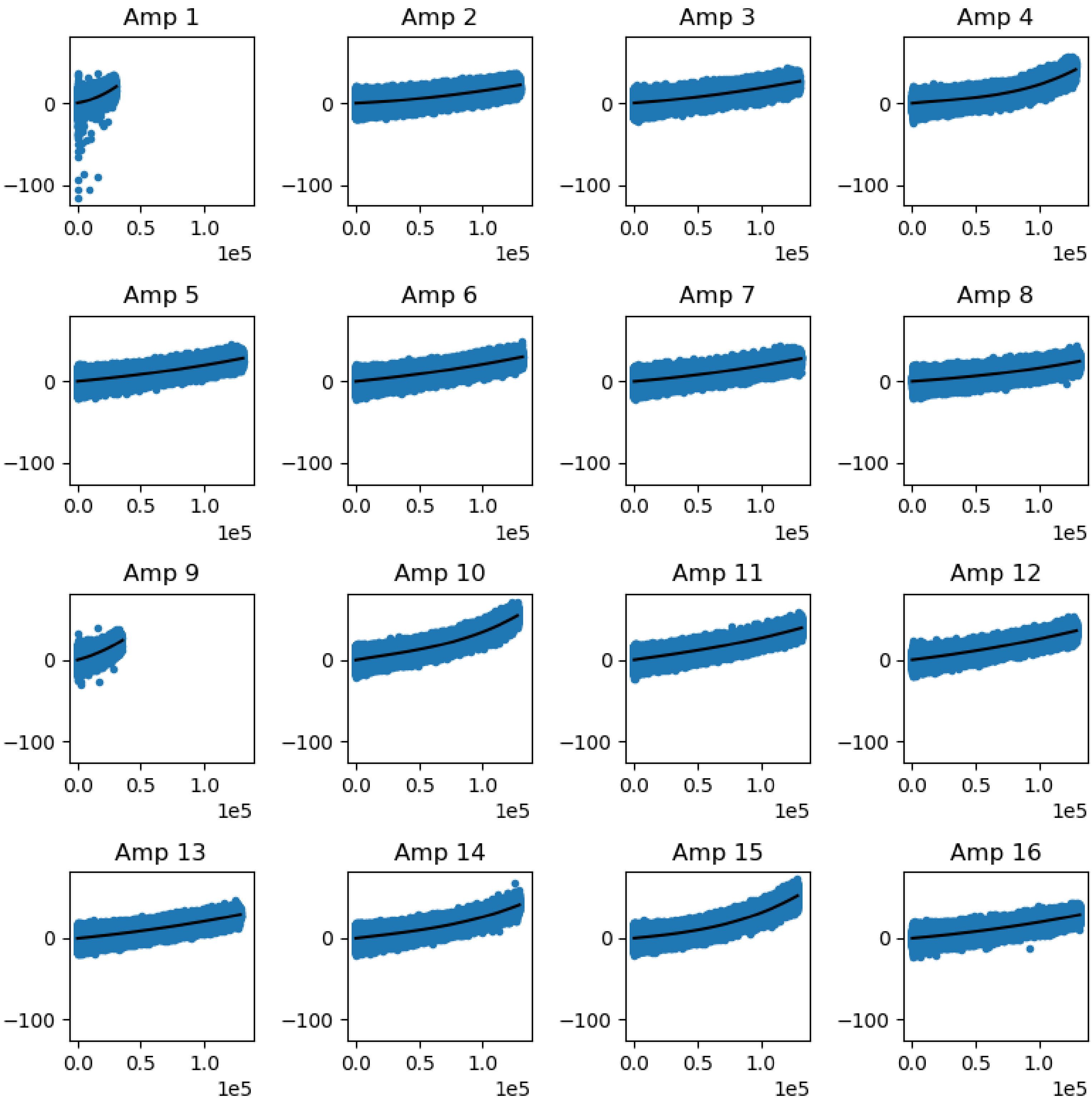
CTE/CTI

- CTI (1-CTE) is reported as if it was due to "clock leakage". One measures the first overscan pixel (O_1) and compares it to the actual signal level (S), in a flat image :

$$CTI = \frac{0_1}{S} \frac{1}{N_{transfers}}$$

- This is conventional. It is how CTI is reported.

Delayed signals



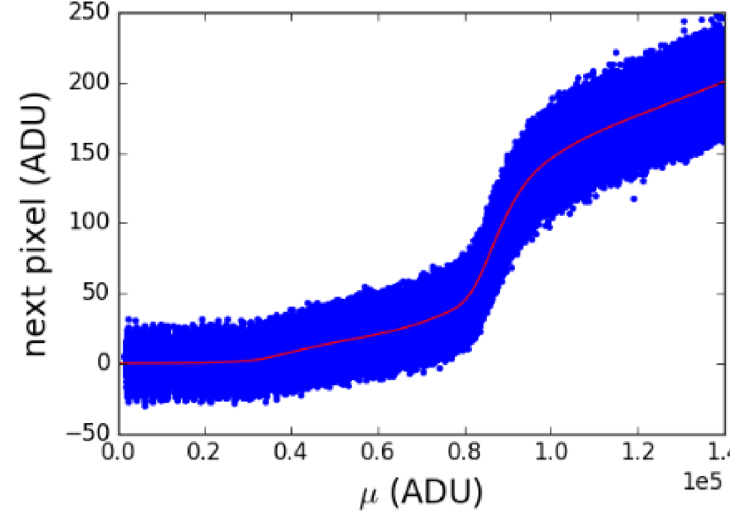
First overscan pixel as a function of the last physical pixel (e2v)

Segments 1 and 9 are special because the signal in the last physical column is lowered by electrostatic distortions that makes this column smaller.

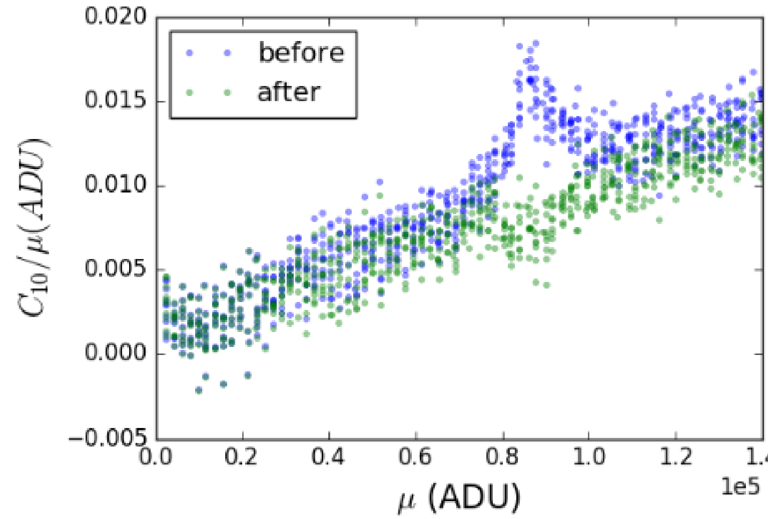
Delayed signals e2v, ~2 years ago

1905.08677

O_1 vs S

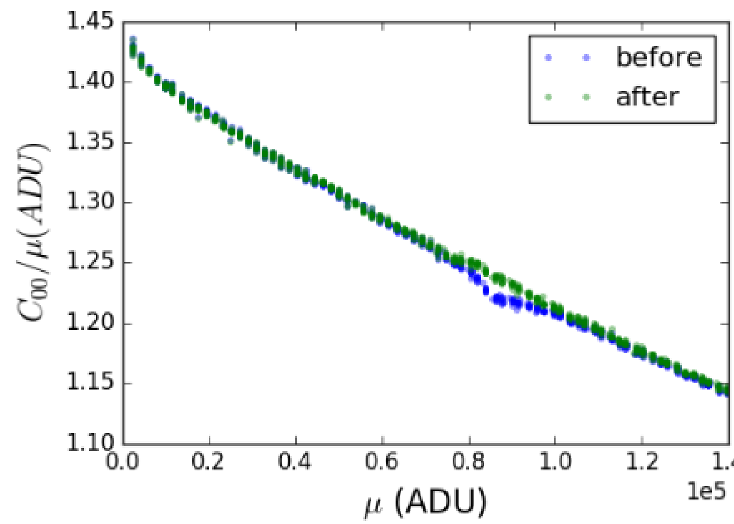


Covariance of nearest serial neighbors



Simplest correction:
put the charge back
into the previous pixel

Variance/average vs average (PTC)



This poor behavior
was cured by changing
the // voltage settings (!)
i.e. chosing "bipolar mode"

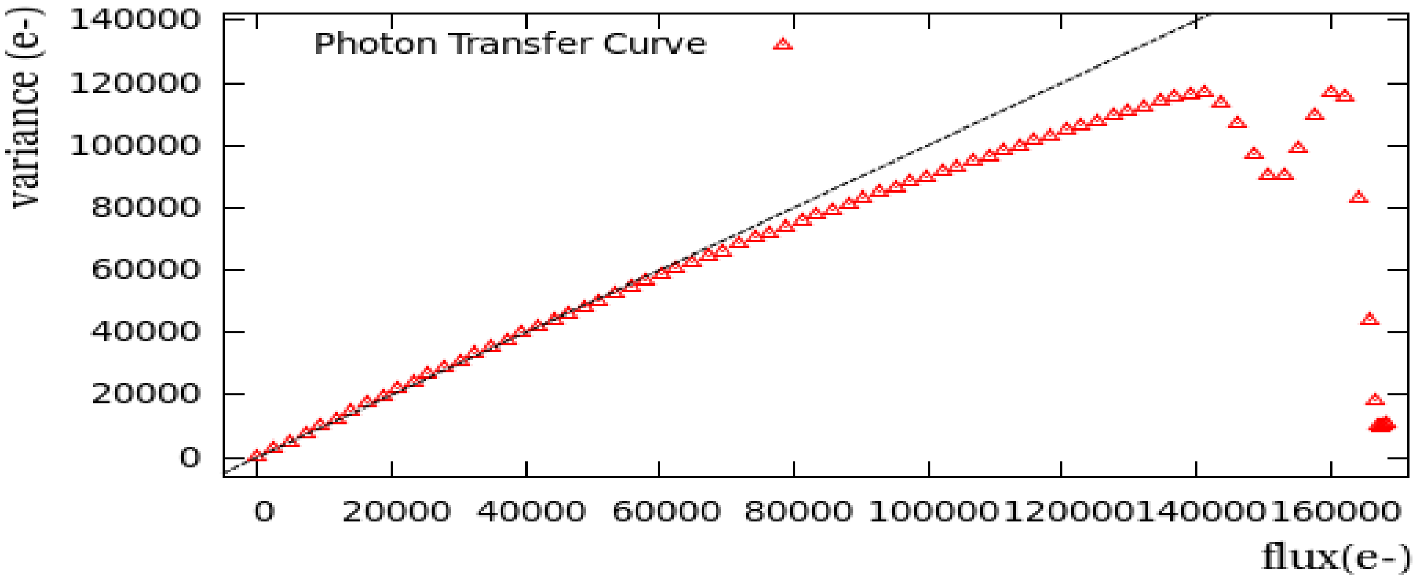
Characterization: Photon Transfer Curve (PTC)

- The PTC expression is misleading. It was introduced by Janesick. The idea is that in a flat exposure, one can measure the average (mu) and the variance (V). The “gain” is defined as the factor that expresses the image in unit charges, and then the variance is equal to the average. So:

$$g^2 V = g\mu \quad \rightarrow g = \mu / V$$

- At low flux, the electronic noise contributes and should be accounted for: $V = g\mu + (n/g)^2$

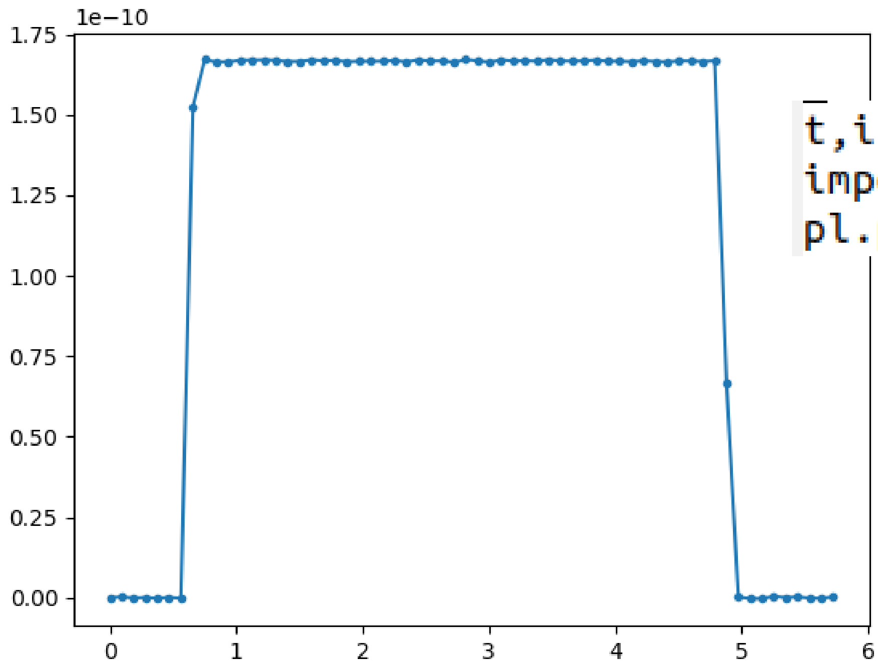
PTC : variance vs average in flats



If only Poisson was at play, this curve should be a straight line.
One can still use the tangent at 0 flux to define the (inverse) gain.

Non-linearity

- Use a stable lamp and vary the exposure time.
- Use a regular lamp, vary the exposure time, and monitor the lamp intensity with a photodiode.



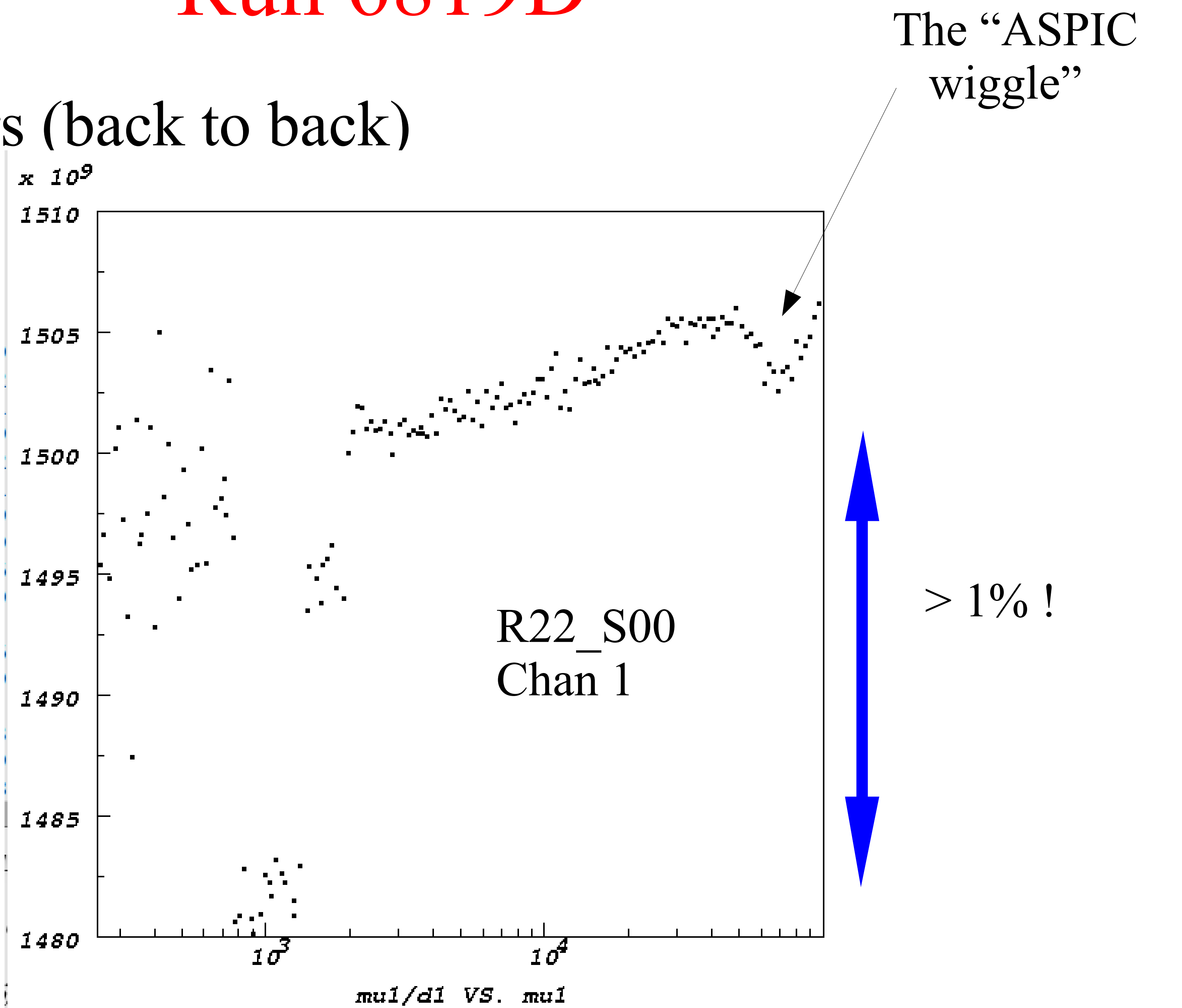

```
t,i = np.loadtxt('Photodiode_Readings.txt').T
import pylab as pl
pl.plot(t,i,'.-')
```

If one only varies the exposure time, the linearity of the photo diode and its electronic is irrelevant.

Run 6819D

- 211 flat pairs (back to back)

CCD/D vs D

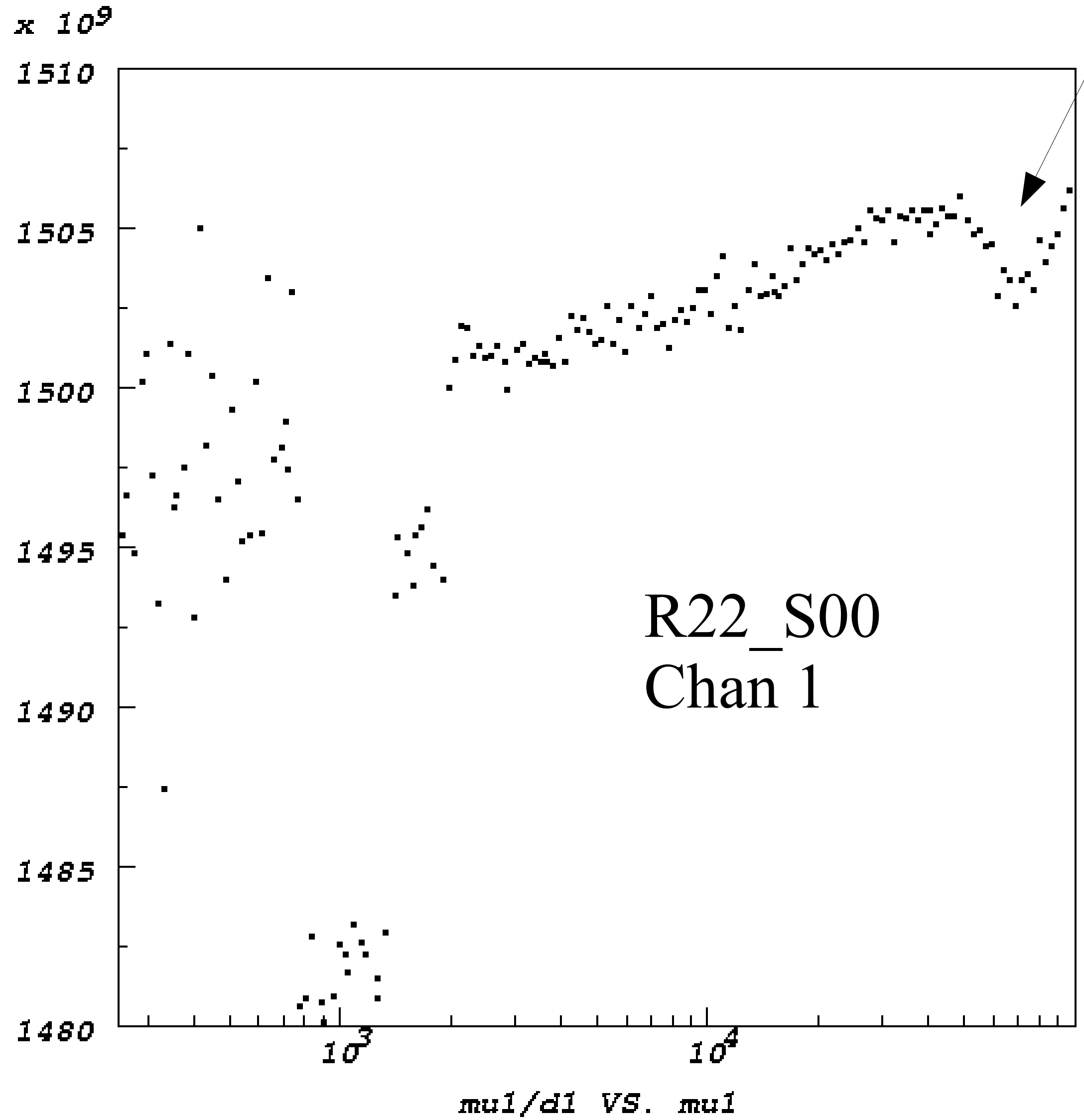


Run 6819D

- 211 flat pairs (back to back)

The "ASPIC wiggle"

CCD/D vs D



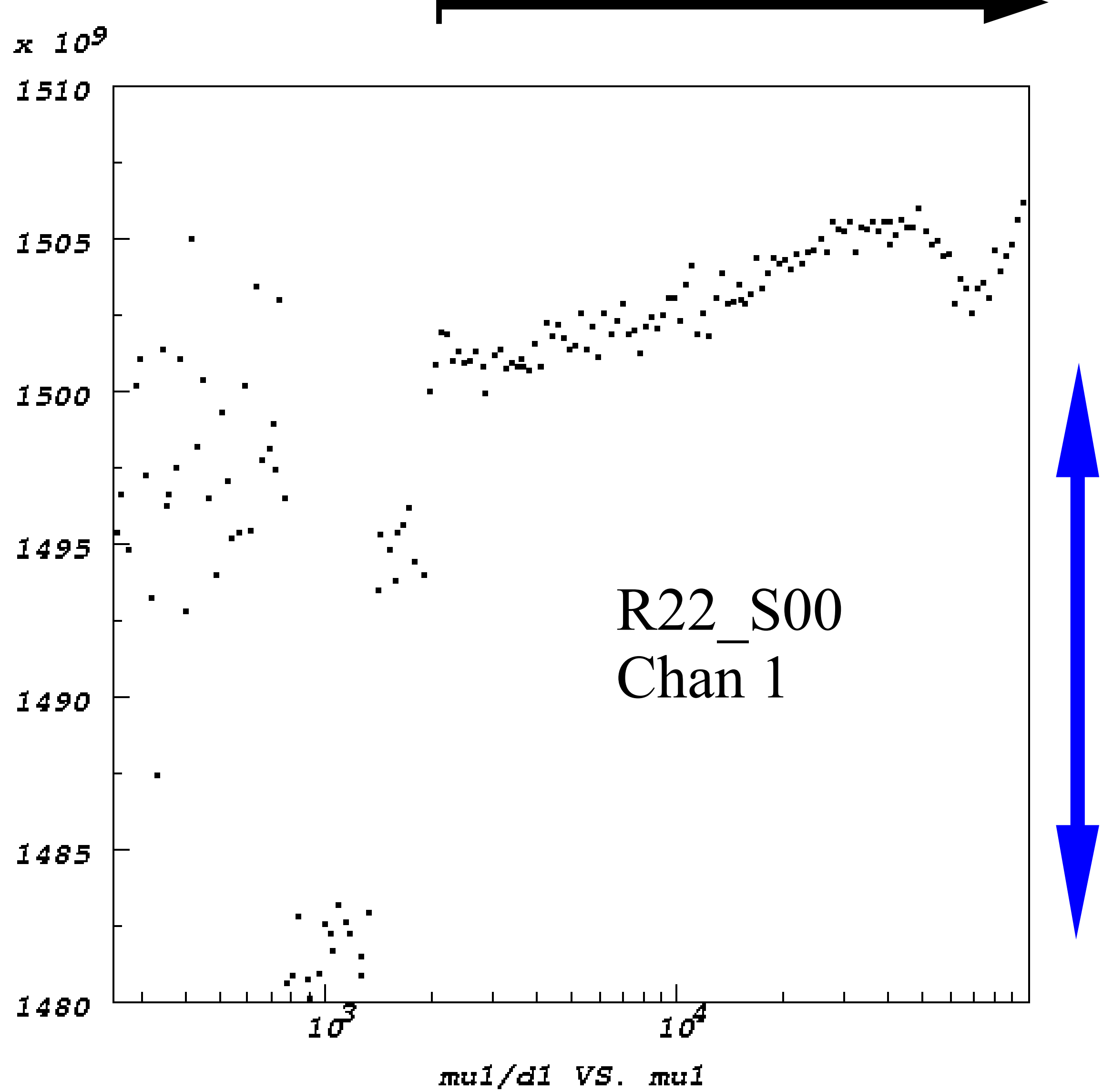
> 1% !

The 4 image sets were obtained using different incident fluxes, obtained by "neutral density filters". ?? To be redone, with overlaps

Run 6819D

usable range (about 98% of the whole range)

CCD/D vs D



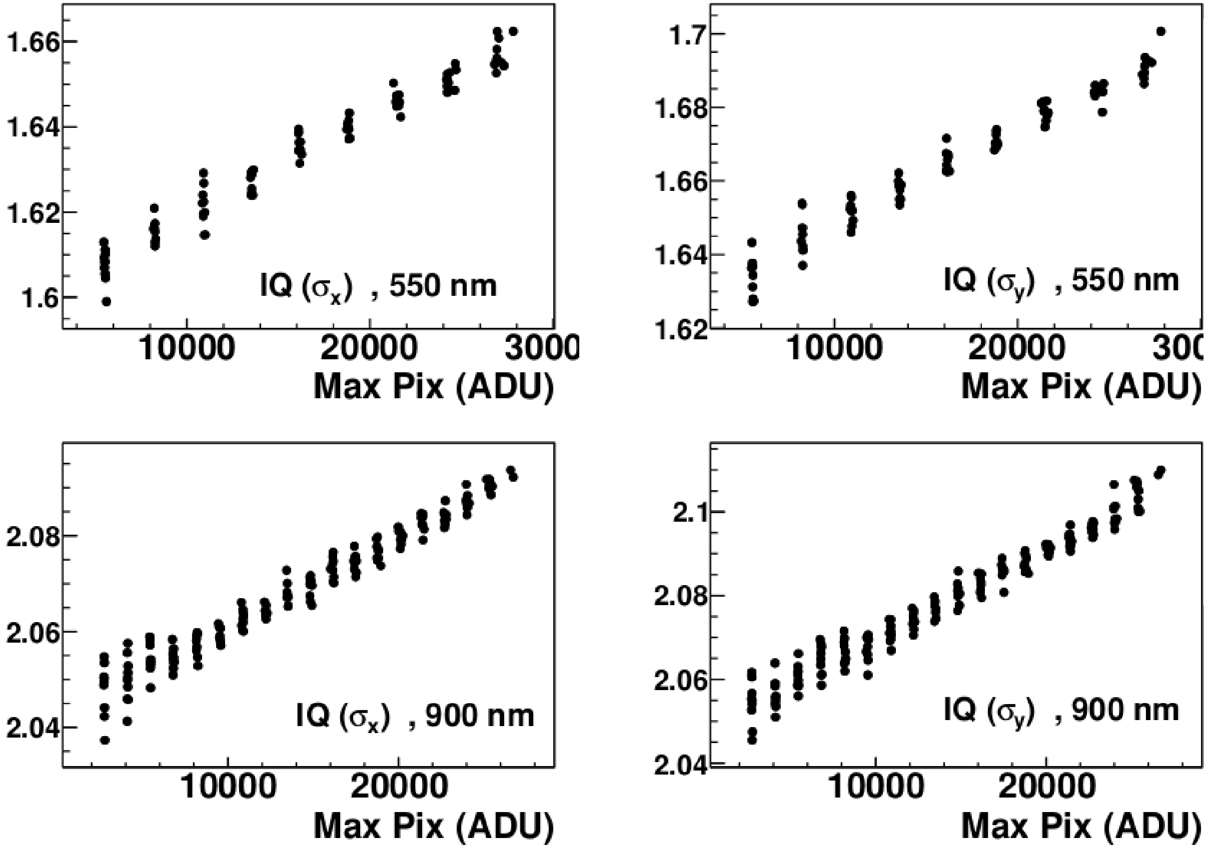
> 1% !

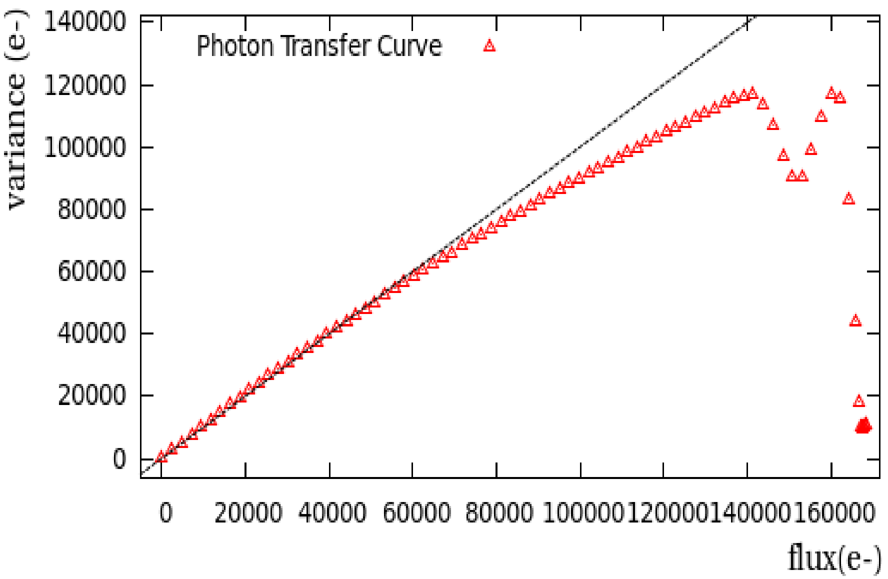
The flat pair series

- Acquire a large set (100s) of flat pairs ranging from zero to saturation.
- If possible, acquire photodiode signals monitoring the incident flux.
- It proved to be a good idea to shuffle the exposure times, or at least to acquire several ramps
- Then, model delayed signals and nonlinearity,
- You can then measure covariances in flats.

(

Intrinsic non linearity of CCDs



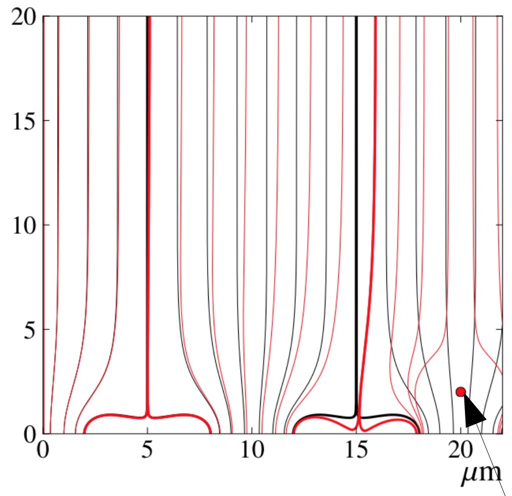


Variances of
flat fields
do not add up

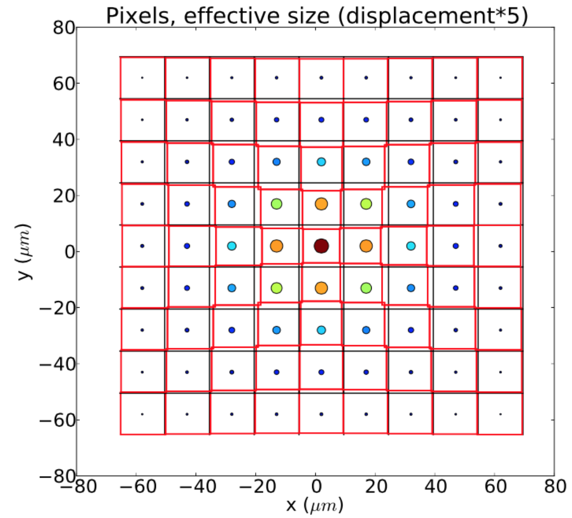
Spots get broader with flux:
brighter-fatter effect

(Guyonnet et al 2015)

Electrostatics



50 ke



Actual pixel boundaries with a star of 100 ke peak flux.
(Guyonnet et al 2015)

Charges already stored in the CCD source some extra electric field that alters pixel shapes

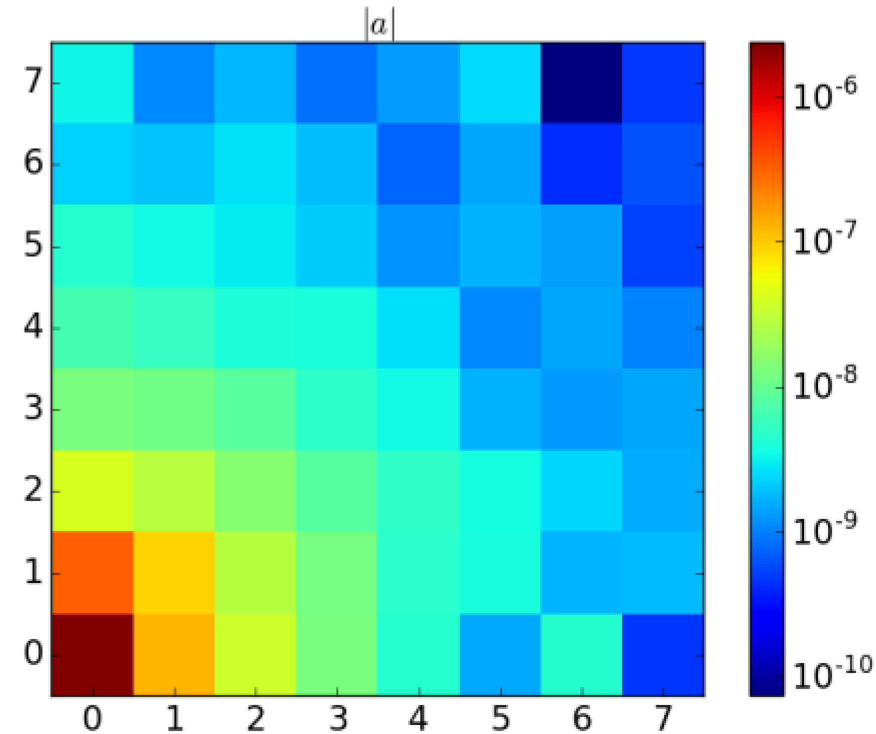
Electrostatics

1905.08677

- Key handle: correlation function of flats as a function of flux, see 1905.08677 and references therein.
- The electrostatic forces extend to ~ the sensor thickness, i.e. 10 pixels in our case.
- The outcome of the measurements is an array of values that describe the pixel area changes a_{ij} at a distance of i columns and j rows.

Pixel area change = a*Q

Measurable anisotropy at low distances, that vanishes farther away as expected.



1905.08677

These are measurements from a single test sensor, that will never go into the focal plane

)

ToDo list for constraining brighter-fatter effect

- Measure the covariance curves of all channels...
- ... after proper correction of disturbing effects:
  - non-linearity
  - delayed signals
- Fit the covariance curves
- We'll then know the demographics of our science chips.
- And possibly compare the outcome with spot data (on a few sensors)

Test data collected at SLAC

Up to date pointer list to documentation:
http://lsst.in2p3.fr/wiki/index.php?title=Commissioning_focal_plane

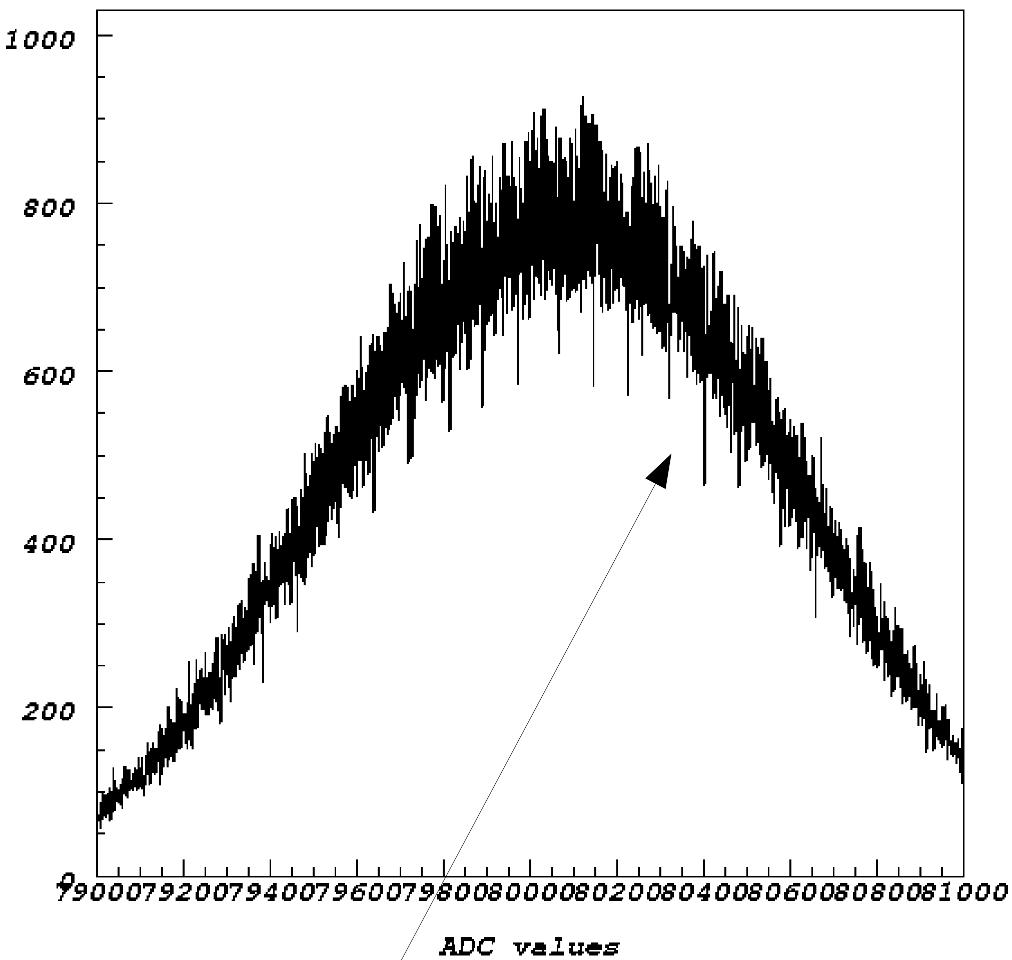
wiki readable only
from in2p3 IP addresses

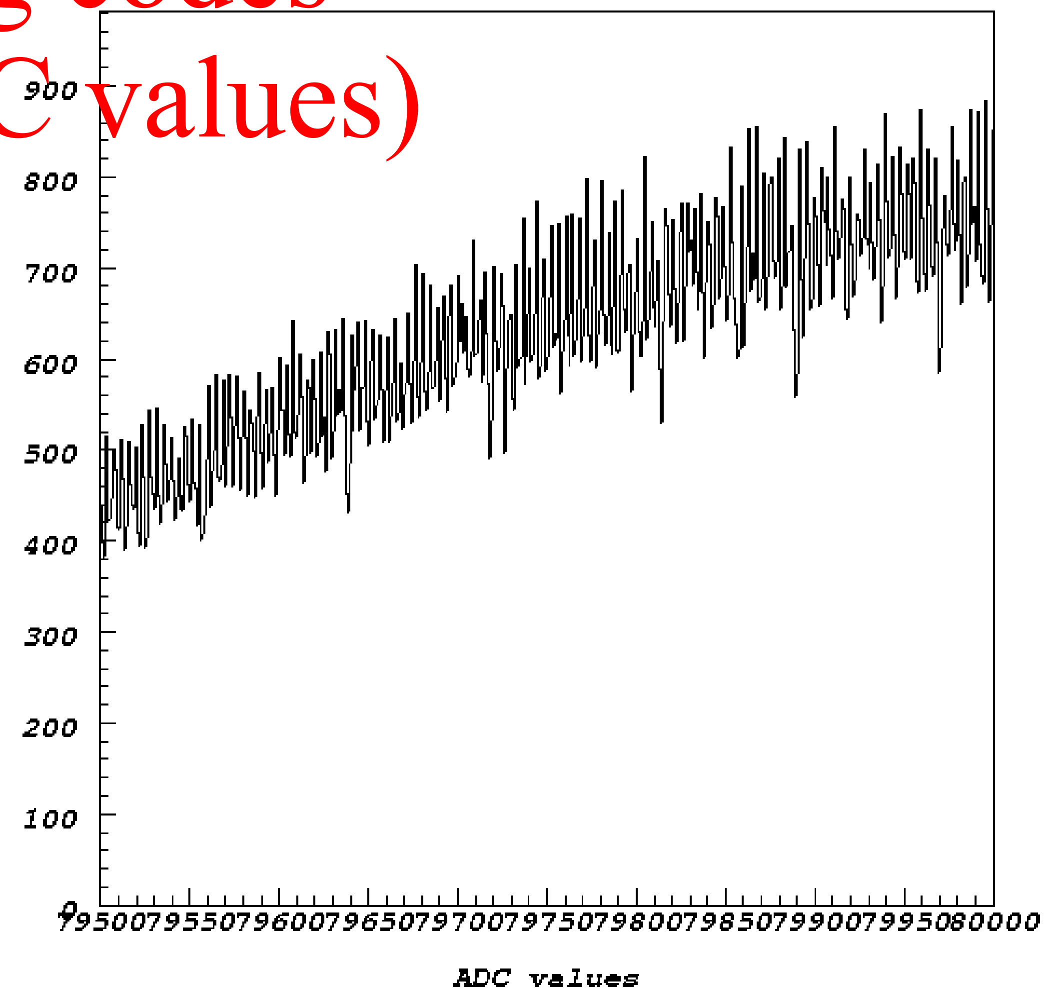
- Partial copy at CC:
  - /sps/lsst/SLAC/LCA-10134_Cryostat-0001/
- Full copy at NCSA, butler-based, but misses the photodiode data.
- notebooks are not the proper way to run on ~100 chips.
- Slack channel for analysis: “eochar”
- Teleconfs: Tuesday 5:15 pm SAWG/CVT alternating

A short list of possible studies

- CTE/deferred signals in particular for ITL sensors.
  - measurement
  - correction algorithm
- Non linearity: measure and model.
- Demography of BF parameters (beyond e2v/ITL)
- “Missing codes”
- Gain variations during the readout of flats (yes or no?)
- Flatfields using the CCOB. Seems under control (Céline ?).

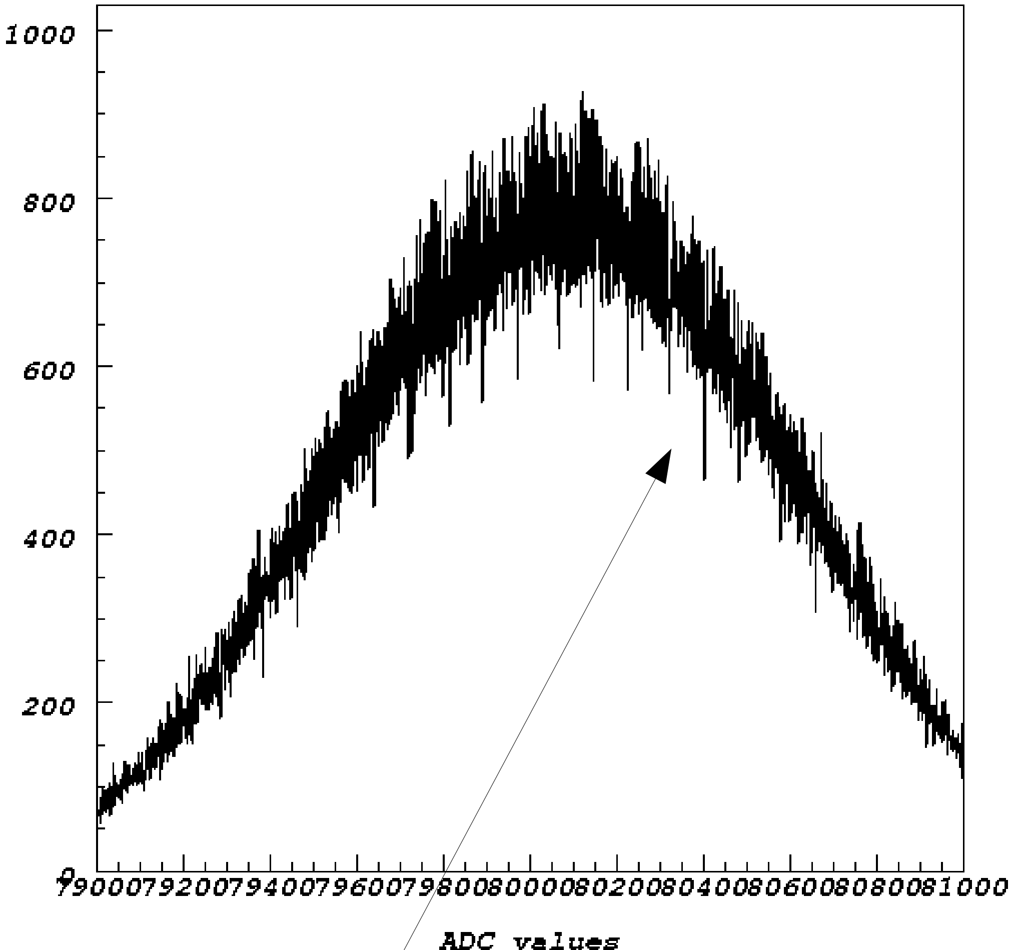
Missing codes (raw ADC values)

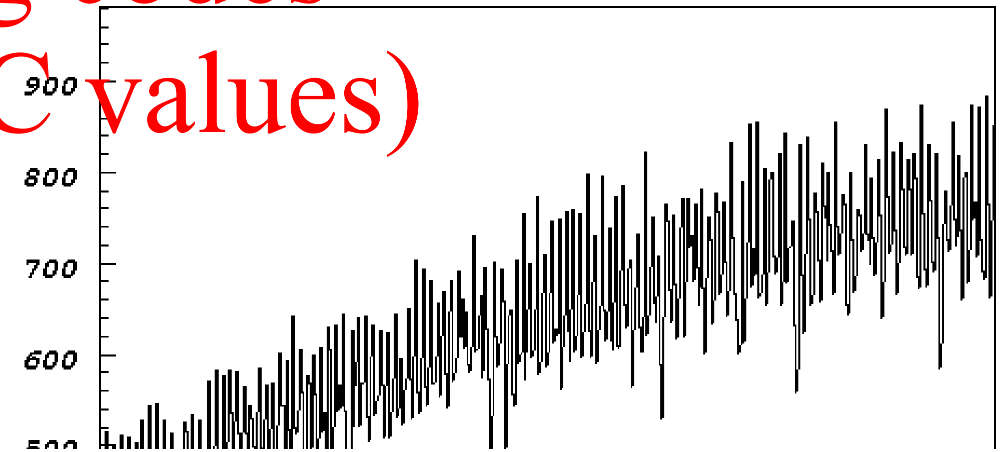


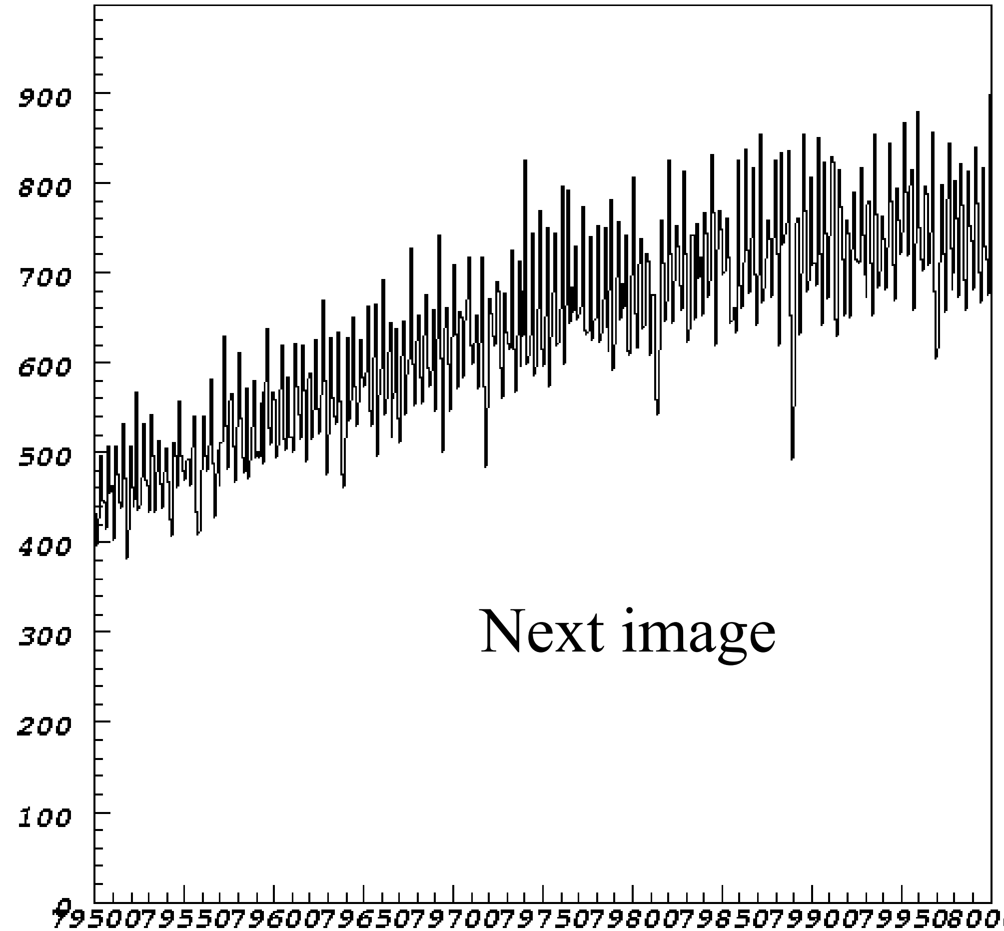


Missing codes : several hypotheses tested, none found to describe the data

Missing codes (raw ADC values)







Missing codes : several hypothes

Final focal plane tests at SLAC

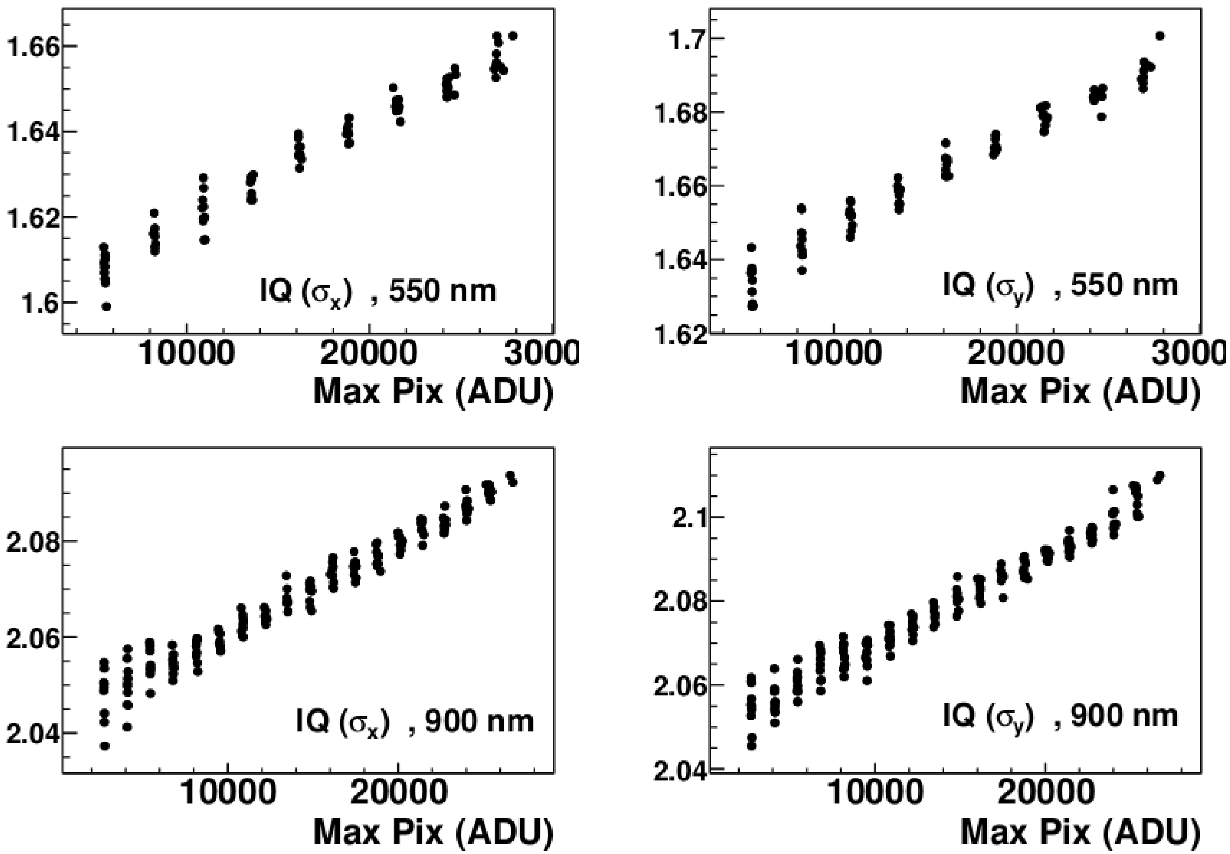
- Should start in a few days (cooling down by now)
- There are dedicated tests for voltage/sequence settings. Presumably, the "eotest" code can analyze this specific data.
- Data taking plan: here . Outcome may be different.
- You may need to be on the camera team to access the relevant confluence pages
  - Just ask, SLAC people welcome new workforce.

AuxTel

- AuxTel is able to image starlight.The sensor is an ITL.
- Commissioning of the sensor, observing procedures, reduction software are all to be done.
- There are good prospects for contributing to the definition of the observing program, if participating to the commissioning per se.
- We can even consider working on PSF and astrometry.
- This commissioning is (very) understaffed, even for observing.

END

Détail pénible : les CCD sont intrinsèquement non linéaires



Dimensions d'un « spot » comme fonction de son intensité.

Dimensions croissent de 2 à 3 % de 0 à la saturation

(Guyonnet & al, 2015)

Vitesse de lecture

- Gouvernée par le bruit tolérable
  - 500 kpix/s -> ~5 el de bruit par pixel (OK pour l'imagerie en général)
  - 100 kpix/s -> ~2-3 el de bruit : bien pour la spectroscopie
  - La plupart des CCD ont maintenant plusieurs voies de sortie (2,4, jusqu'à 16)