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Space and scientific CMOS image sensors workshop
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A rad-hard, global shutter, true HDR, backside illuminated image sensor

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Purpose

To realize a family of image sensors particularly suitable for space missions

1. BSI (Backside illumination)
2. TID (total ionizing dose) radiation-hard design
3. “true” or “MAF-” **HDR** (Motion Artifact Free High Dynamic Range)
   ⇒By reading the same photocharge on two different conversion capacitances
4. IWR Global shutter using “**GS**” CMOS technology, which
   ⇒ Allows low noise readout using CDS (correlated double sampling)
   ⇒ Enabling Global Shutter without dark current penalty

In this paper we demonstrate the combined operation of GS and HDR

It is developed under ESA contract 4000116089 “**E**uropean **L**ow **F**lux **I**mage **S**ensor”, in collaboration with LFoundry (I) and Airbus (F)

Patent US9819882 granted

outline

1. Purpose
2. Principle of operation
3. How to create a High DR signal from two “normal” DR signals
4. Movie of simultanous GS and HDR operation
5. Conclusions

Key specifications as measured on ELFIS Rev.A

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Geometry

- ✓ 15µm pixel pitch
- ✓ 1920x1080 pixels
- ✓ Leftmost 16 columns are test pixels and reference pixels
- ✓ 16 parallel differential output channels
- ✓ BSI
- ✓ Stitching compatible

Electrical performance

- ✓ 40MHz nominal pixel rate per output channel
- ✓ 500mW at nominal speed

Electro-optical

- ✓ Two Q_{FW} ranges:
  1. 10000e (6000e)
  2. 160000e in IWR; 320000e in ITR
- ✓ Q_{noise} 6.5e_{RMS} at nominal speed, excl. DCSN
- ✓ Peak QE > 90%
- ✓ MTF >60% for thin layer BSI
- ✓ PLS >200:1 for thin layer BSI, >500:1 for thick epi*
- ✓ I_{dark} @RT: PPD:60e/s SN:80e/s FD=140e/s

Dynamic range in global shutter, nominal speed

- ✓ ITR, excl DCSN: 160000:6.5 = **87.8dB**
- ✓ IWR, excl DCSN: 320000:6.5 = **93.8dB**

* Estimated not measured

2.

Principle of operation

ELFIS HDR concept

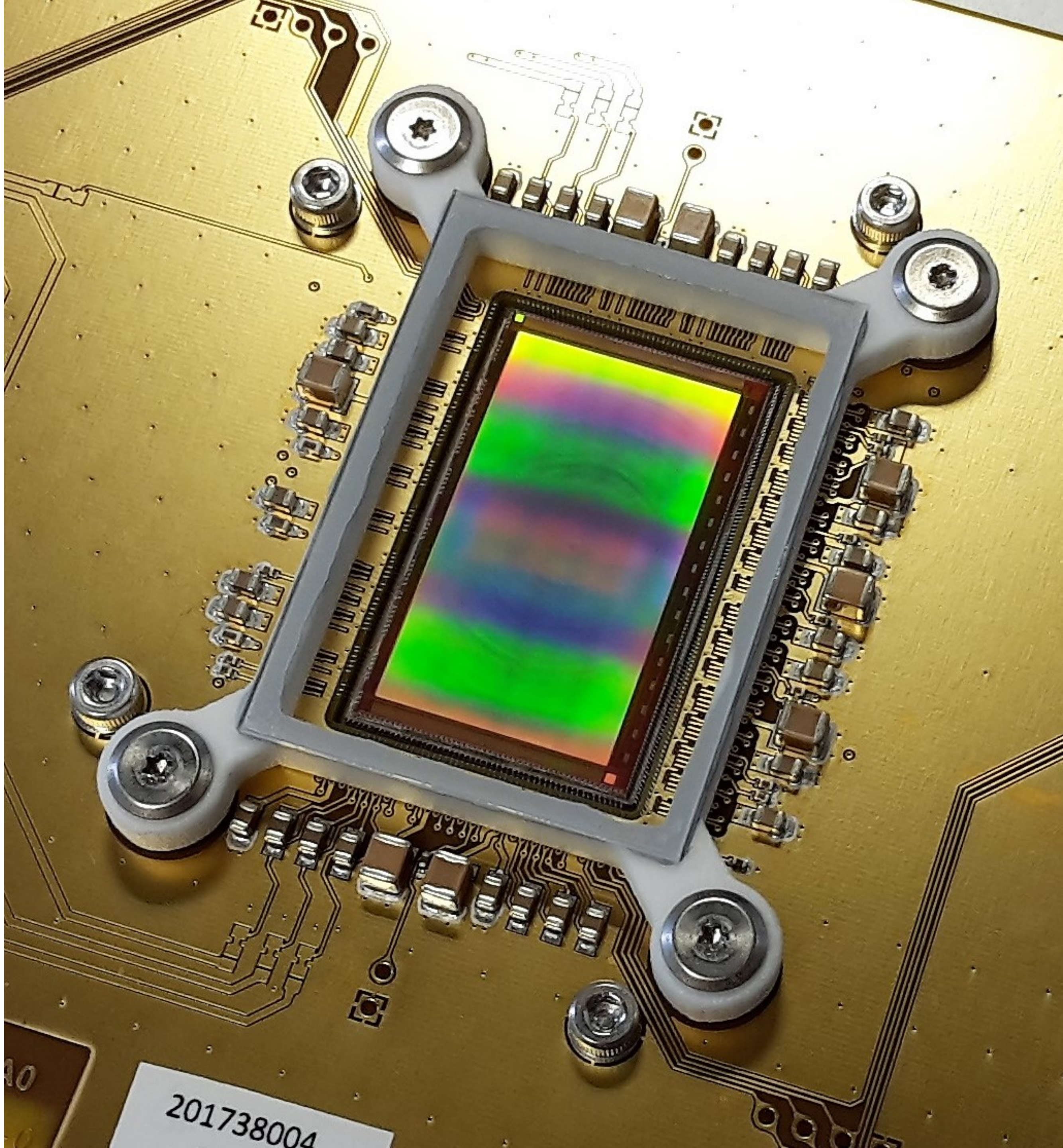
The high dynamic range is obtained by converting the photocharge of a given integration time to two signals (voltages).

A high and a low conversion capacitance is used, corresponding to two Q_{FW}:

1. Low Q_{FW} (high gain): ~10000e-
2. High Q_{FW} (low gain): ~320000 e-

The low Q_{FW} uses the “classic” **S**torage **N**ode of a GS CMOS technology.
The high Q_{FW} uses overflow capacitors to store an amount of charge that far exceeds the capacitance of the PPD.

In order to realize IWR (integrate while read) two sets of high Q_{FW} capacitors are used.



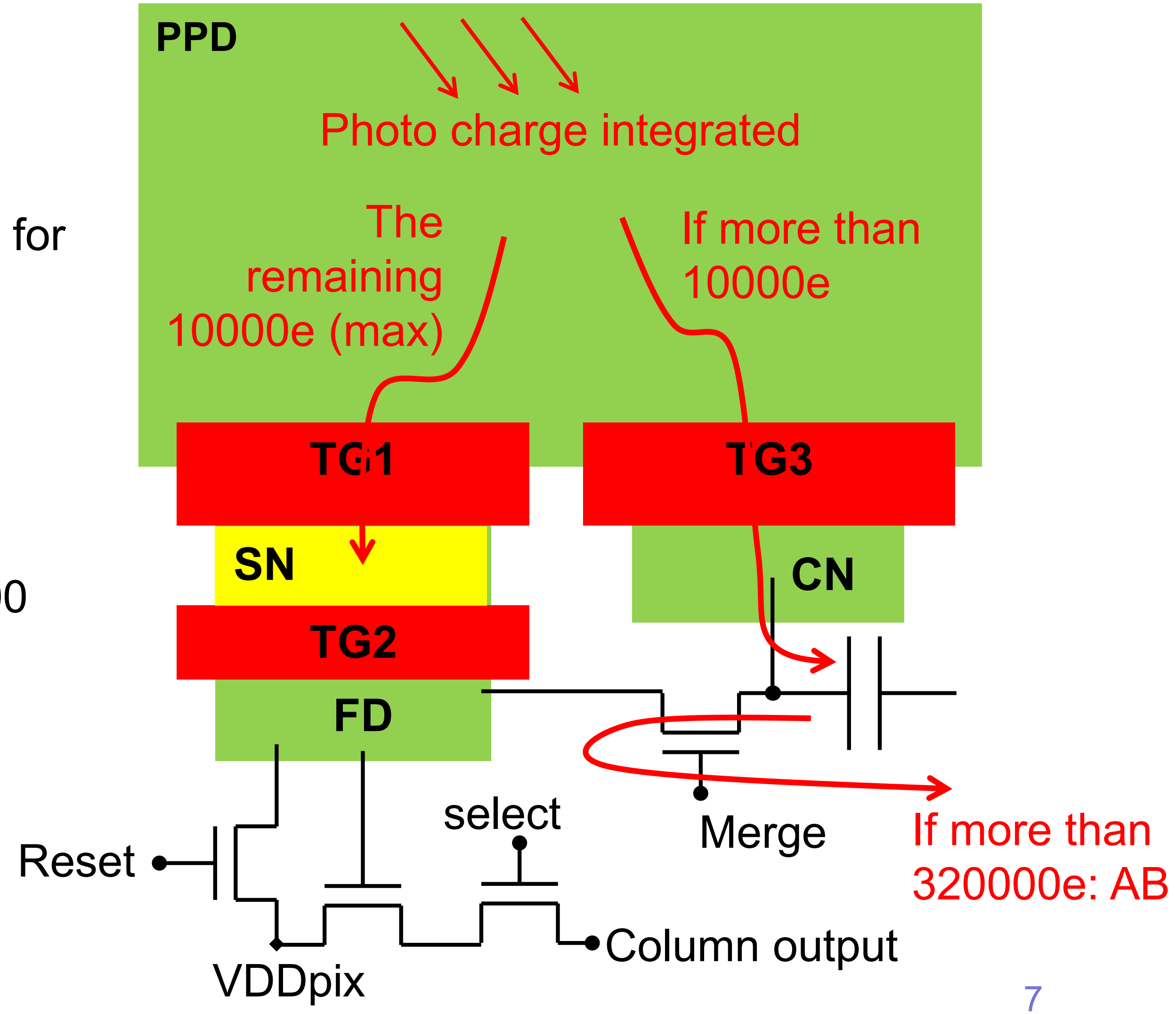
Operation of the ELFIS pixel:
how to read the same photo charge with two conversion gains

During the integration time photo-electrons are accumulated in the pinned photodiode (PPD)

If the amount of electrons in the PPD exceeds 10000, these overflow over TG3 into the capacitor node (CN) , for later use. There are two CNs with a total capacity for 320000 electrons

If the total charge exceed 320000 electrons, it goes to the anti-blooming drain.

At the end of the integration time, the (maximally) 10000 electrons still present in the PPD are transferred by transfer gate TG1 to the storage node (SN). The SN cannot contain more.



Operation of the ELFIS pixel: how to read the same photo charge with two conversion gains

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Just before the moment of readout, there are

- Between 0 and 10000 electrons in the SN
- Between 0 and 320000 on the CN(s)

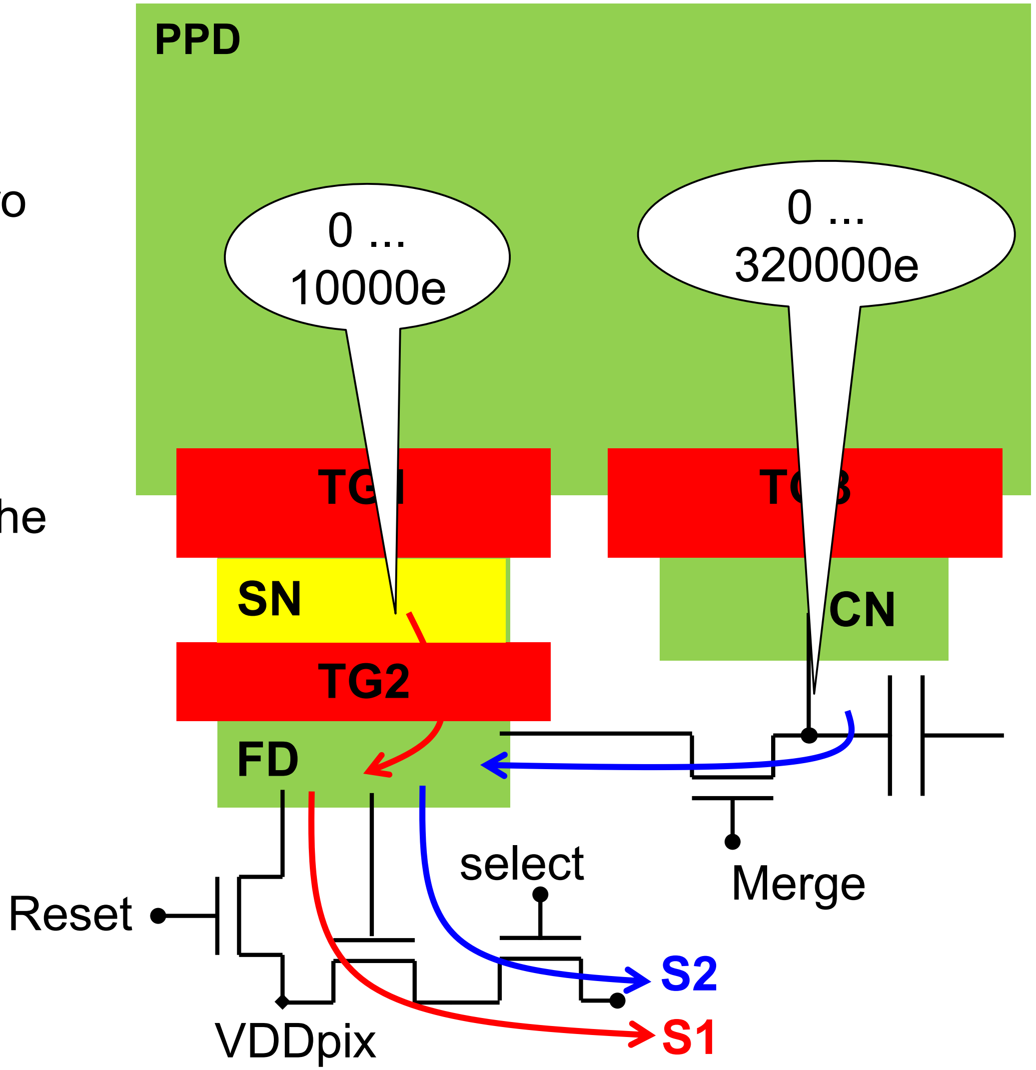
The total integrated photocharge is the sum of those two

TG2 is toggled and transfers the SN charge to the FD, where is it read out using correlated double sampling (CDS), yielding a signal "S1"

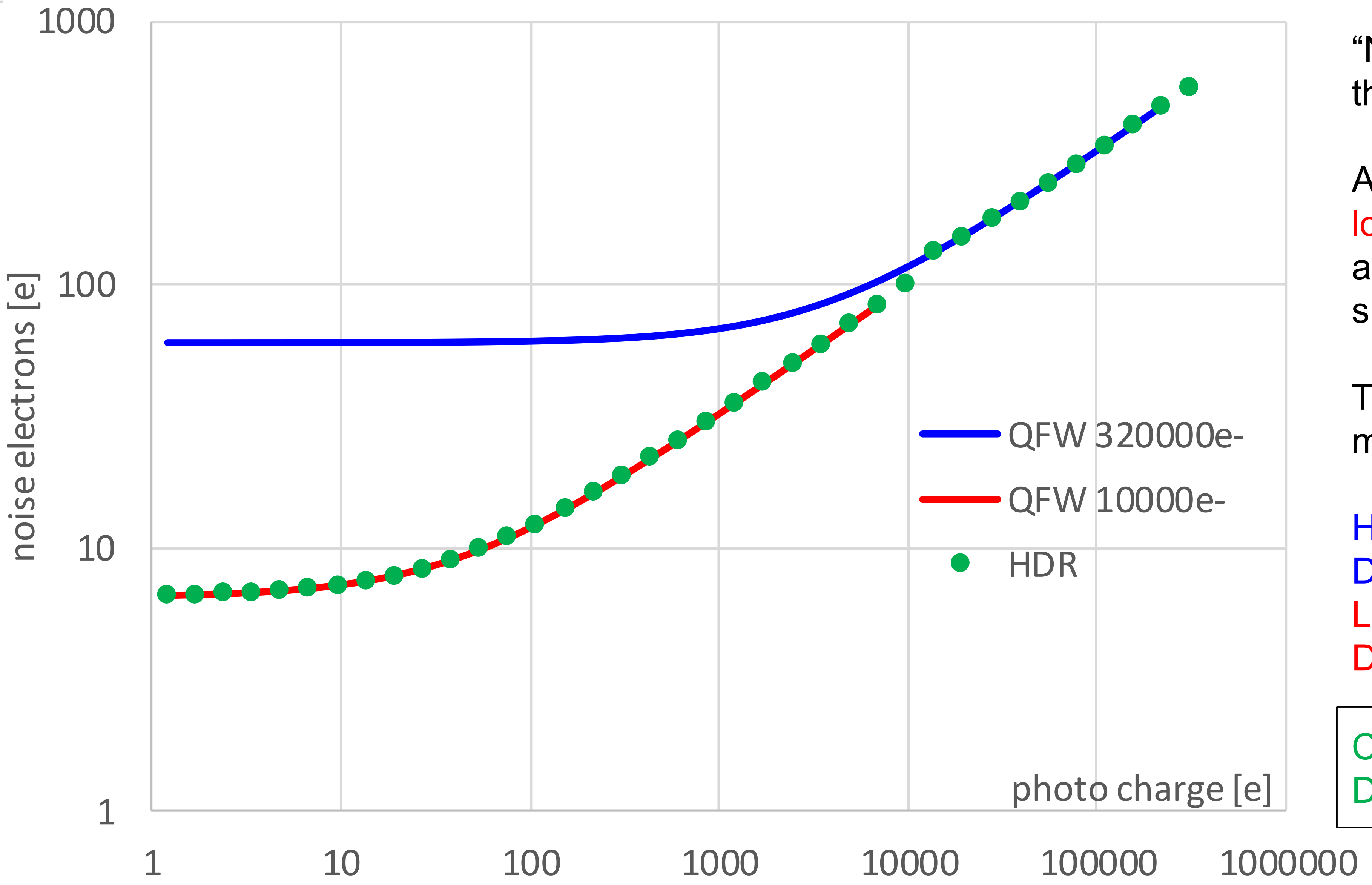
Then "Merge" is closed, shunting the FD and the CN. The sum of both charge packets is on FD, and is read out, yielding a signal "S2"

S1 is the "high gain" signal, with small Q_{FW}

S2 is the "low gain" signal, with large Q_{FW}



HDR by combining two “normal” DR ranges



“Noise versus Signal” relation of the ELFIS pixel.

At each illumination level both low Q_{FW} and high Q_{FW} signals are measured. The **“HDR”** signal is a combination of these

The new dynamic range is the max Q_{FW} / min Q_{noise}

High Q_{FW} range:
DR=320000/60 ≈ 5000:1

Low Q_{FW} range:
DR=10000/6,5 ≈ 1500:1

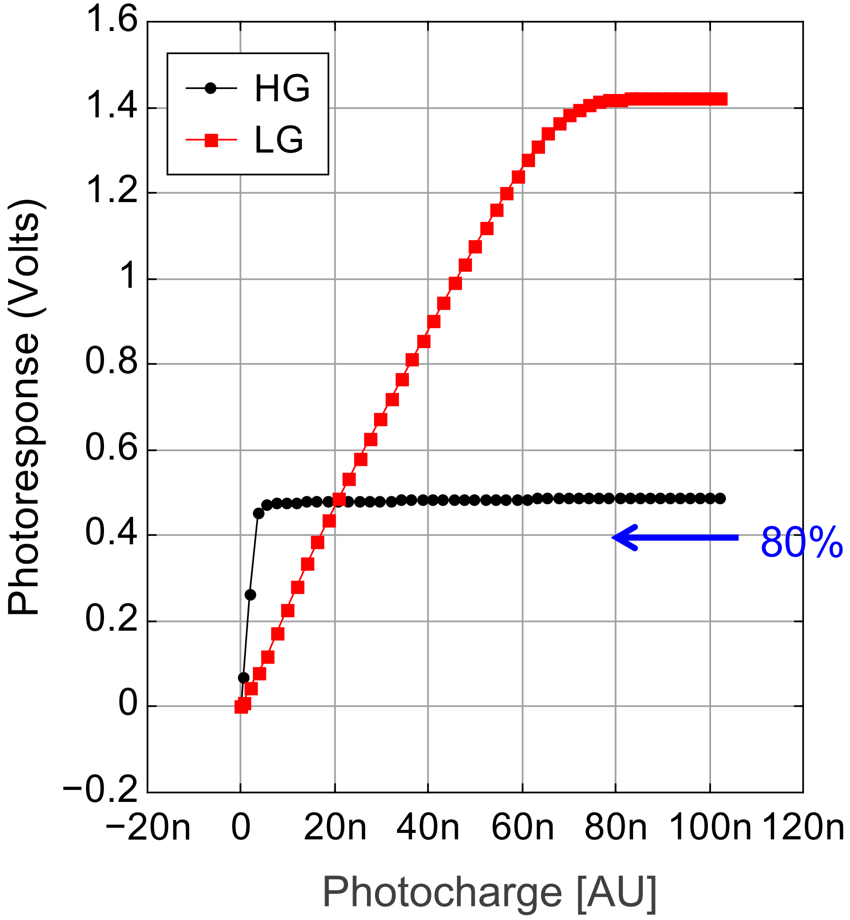
Combination
DR=320000/6,5 ≈ **93.8dB**

3.

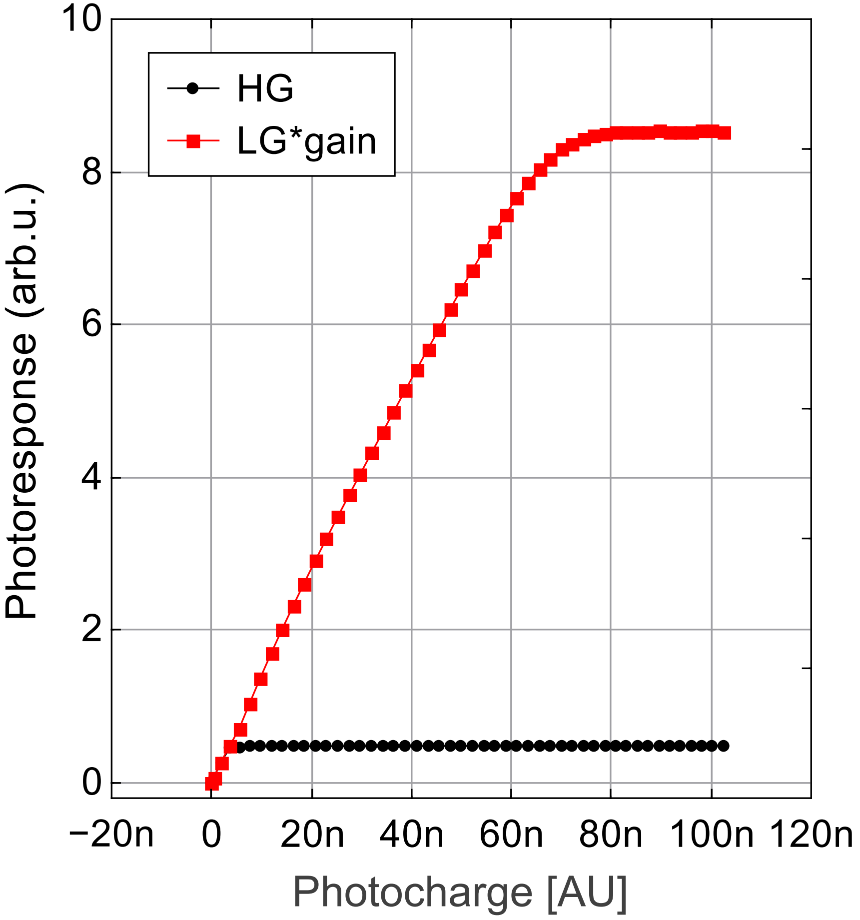
How to create a High DR signal from two “normal” DR signals

ELFIS photo response of HG and LG signals

Raw data of both signal ranges
After CDS & Offset corrected



After applying a gain factor on the LG data



ELFIS pixels convert the integrated photocharge almost simultanously on two conversion capacitances.

These are read out over the same channels time-multiplexed within the row time.

high gain = “low Q_{FW} range”
low gain = “high Q_{FW} range.

Avoid discontinuity when merging of HG and LG signals

smooth interpolation:

When HG signal is above 75% of HG saturation

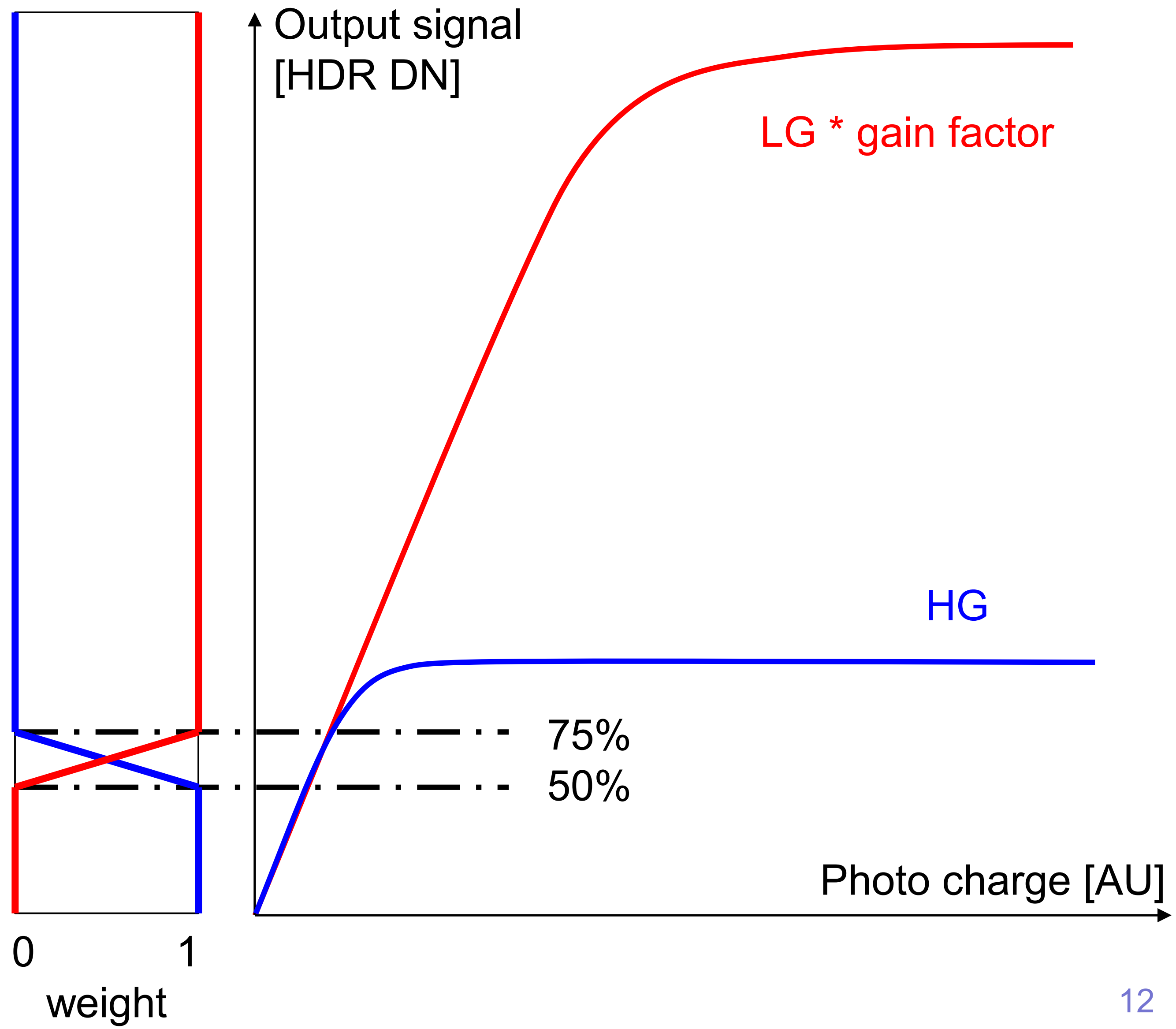
→take the LG signal

When the HG signal is below 50% of HG saturation

→ take the HG value.

Between 50% and 75%:

→ apply a weighted average.



4.

HDR images and movies

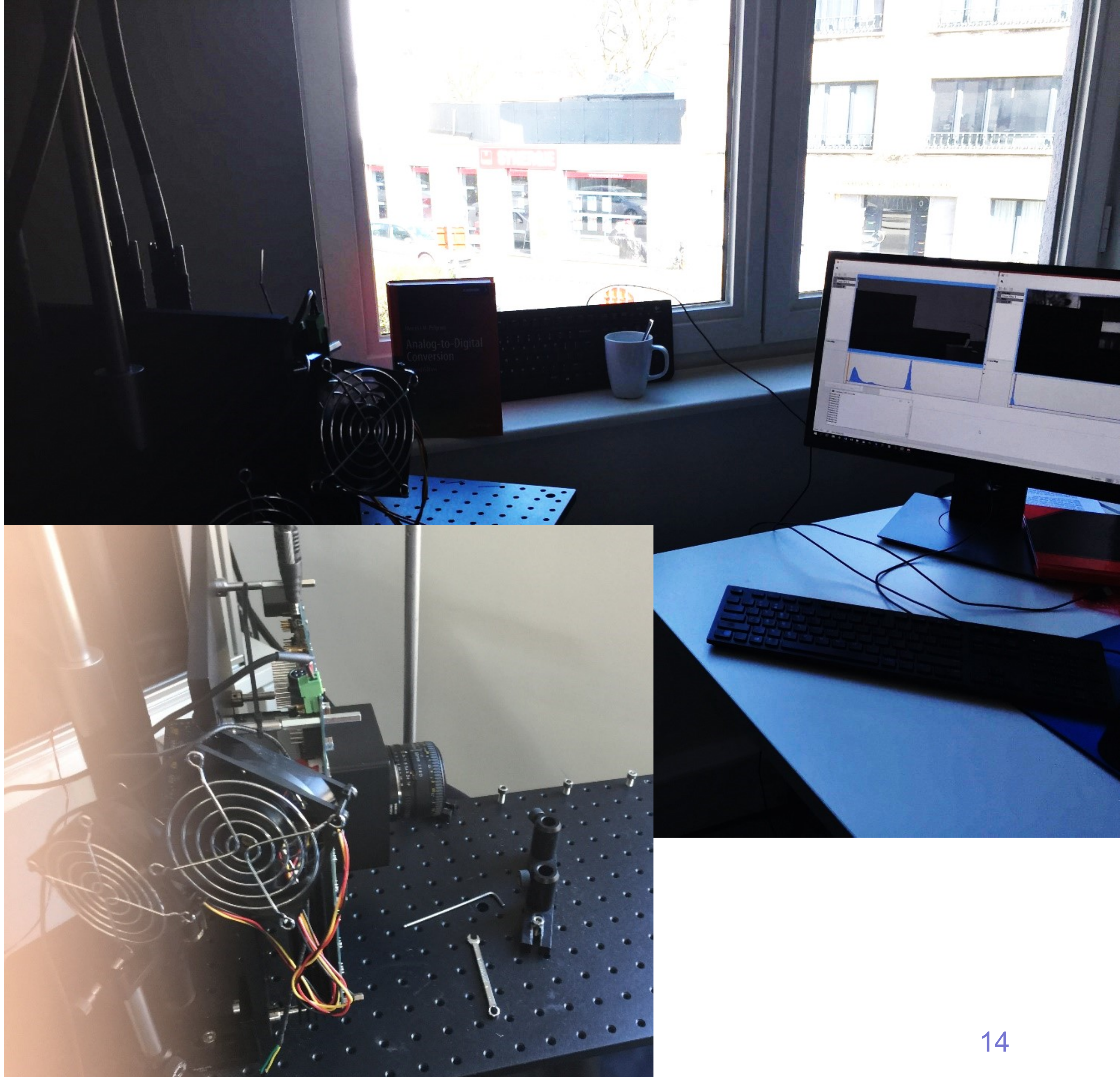
See also https://www.youtube.com/watch?v=_SUg1v9ZSjI

Setup

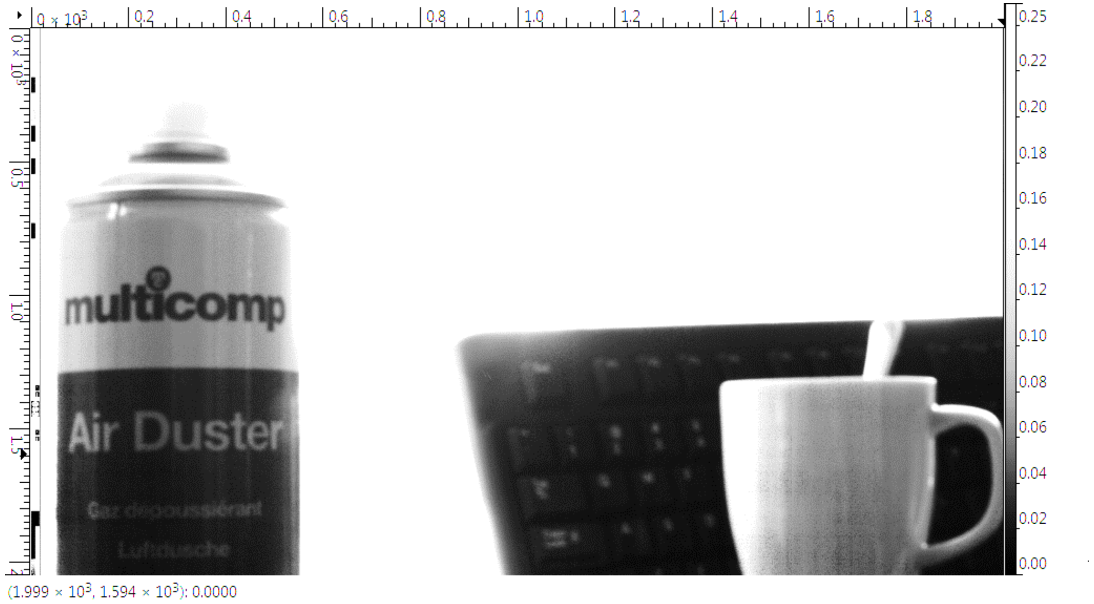
High dynamic range scene:
- ✓ Outdoor sunlit buildings
- ✓ Inside lab environment
- ✓ black PC keyboard.

The ELFIS breadboard:
- ✓ lens mount with a Nikon 55mm lens
- ✓ Aim for minimal internal reflection in the camera
- ✓ diaphragm set to 22 (! Indeed this 15µm BSI pixel is really light sensitive).

Nominal operation conditions
- ✓ IWR (global shutter “integrate while read”)
- ✓ $t_{frame} = t_{int} = 30ms$.



Processing the LG and HG (sub-)frames into a HDR frame



High gain (HG) sub-frame

Low gain (LG) sub-frame

Here we show the two simultanous frames of one image, being the HG and LG “sub-frames” of the same integrated photocharge.

Image processing done here:
In the HG sub-frame on-chip CDS and off-chip dark frame subtraction is done. In the LG sub-frame only dark frame subtraction is done.
No PRNU calibration, no linearity correction, no bad pixel or cosmetic corrections are executed.

The HDR frame is calculated pixel per pixel as follows:

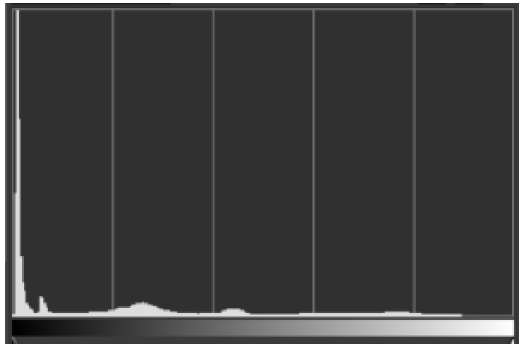
→ If HG pixel value < 80% of saturation, use that HG value

→ Otherwise use LG * gain factor

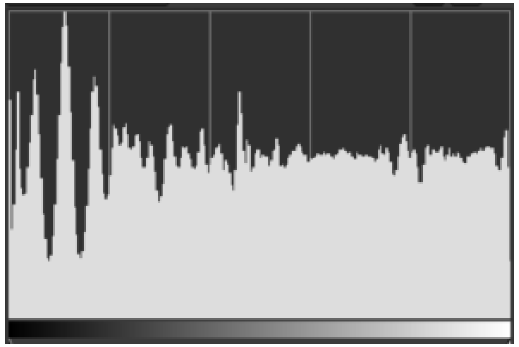
For demonstration; smoother algorithms exist see further

Displaying the HDR frame

The resulting HDR image (HDR frame) is stored in floating point format. However, when displaying it by truncation to 8 bit values, the dark parts of the resulting image display as very dark grey or black



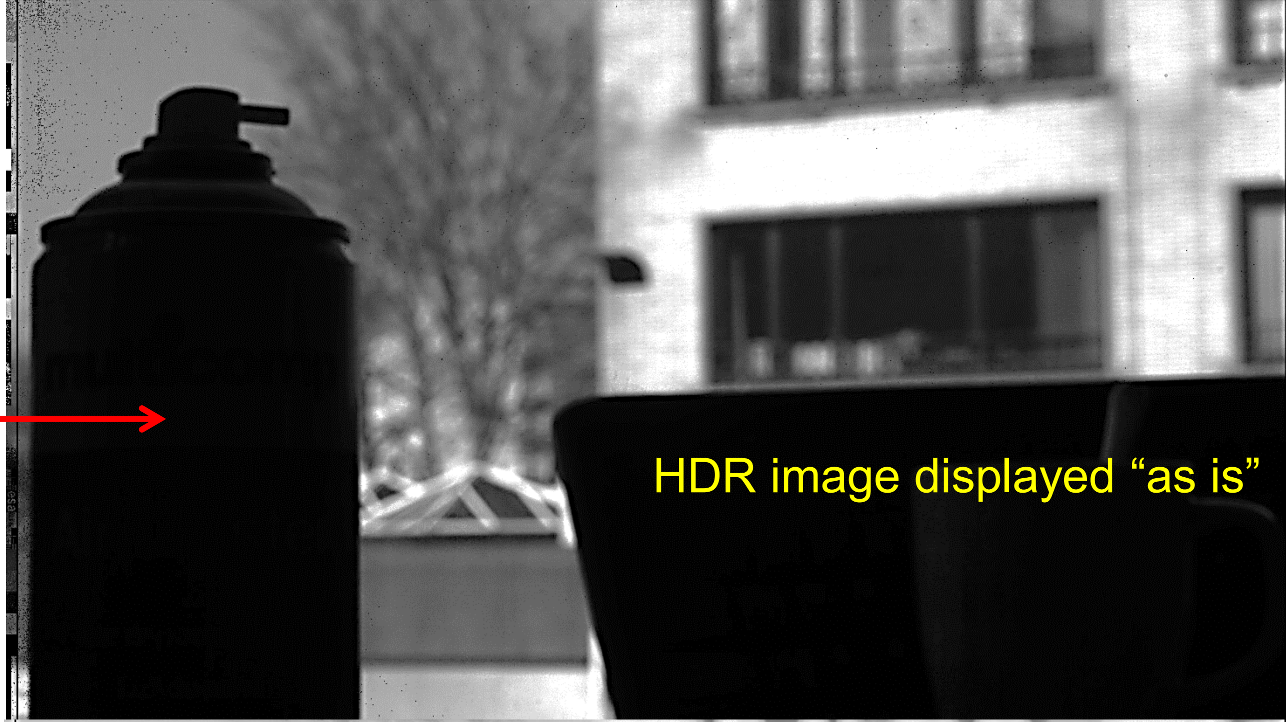
The “raw” histogram



The “equalized” histogram

For display purposes one does “histogram equilization”, resulting in a +/- constant distribution of grey values over the image.

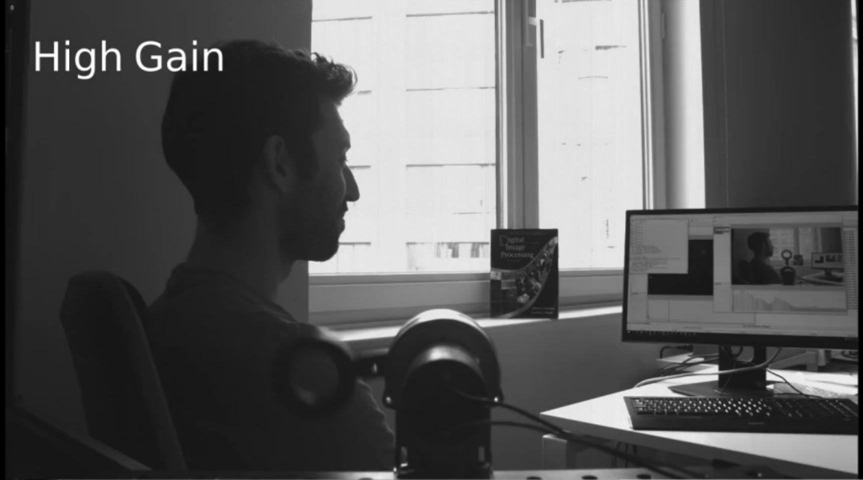
Better alternatives exist depending on the purpose and application.



"Moving" HDR scene
the rotating black ring "cuts through" the dark interior background as well as through the sunlit outside background. The motion blur is not affected by the local light intensity.

- ✓ IWR $t_{frame}=t_{int}$ = 30ms
- ✓ Nikon 28mm lens, diaphragm set to 22 (sic!)
- ✓ CDS & dark frame subtraction
- ✓ No PRNU correction, no linearization.

- ✓ The HDR image created by weighted interpolation between the HG and the LG frames
- ✓ The image is "histogram equalized" for display



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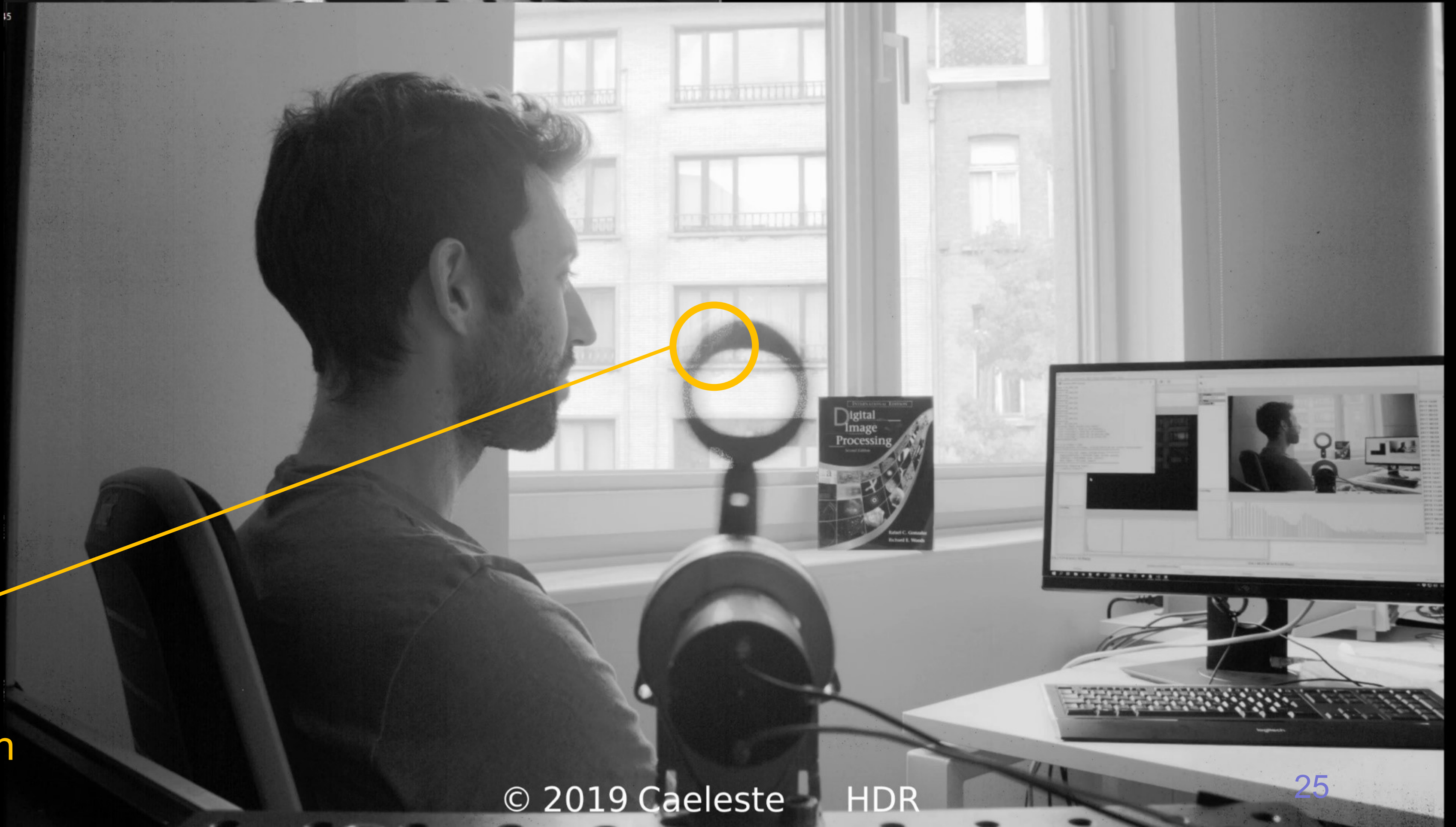
Artifact is explained by partly illuminated scene non-linearly emphasized by histogram equilization



5.

TAKE HOME MESSAGE

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- The combination of true HDR and Global shutter is proven, both as circuit and as technology

- Suitable for imaging high dynamic range scenes, with co-registration of all intensity levels and integration times
  - Star stracker, attitude control, AOCS: global shutter and high dynamic range
  - Earth observations over highly different and unpredicted varying scenes: No gain programming or shutter time adaptation needed by the HDR.
  - Astronomy: high QE by Backside illumination, large range of magnitudes by the HDR concept.