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DC and AC
High Dynamic Range pixels

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1. Why do we need a high dynamic range sensor?
2. Definitions of DR
3. Obtain a high DC dynamic range by non-linearity
4. AC high dynamic range pixel
5. Conclusions
Outline

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A high dynamic range scene

René Magritte, “l’ Empire des lumières” 1954

Ceci n’est pas une “High dynamic range scene”

100000 lx

100 lx

< 1 lx
Capture the whole scene, and then try to recover detail and contrast over the full scene dynamic range.

In the shadow of a dark scene

Highlight partly overexposed
Why do we need a wide dynamic range sensor?

DC

• To catch highlights
• To allow us to be lazy and not adjust camera speed to the scene
• To discriminate objects in any part (dark/bright) of the scene / picture

→ Catch the whole scene / range
AC high dynamic range

*Not:* capture the whole range ("DC")

*But:* capture the time varying small signal of interest in the presence of a large DC background
Why would we need a wide dynamic range sensor?

AC

• To extract *AC information only* from a scene
• To recover weak AC information buried in a large DC background
  – Narrow band: exchange noise ~ noise bandwidth
• For specific purposes
  – Distance ranging
    • time of flight method
  – Time gating
    • making the sensor sensitive during precise times spans
  – Patterned light; 3D imaging; …
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Dynamic Range definition?

DR_{wikipedia}

Wikipedia: “Dynamic range is a term used frequently in numerous fields to describe the ratio between the smallest and largest possible values of a changeable quantity, such as in sound and light.”

Applies to the scene, not to the sensor

- Our “changeable quantity” is “P”, “light” [W, W/m², photons, lux…]
- “signal”, “S”, is the measurement result [V, ADC bits…]
Natural scenes may have a huge dynamic range

- Sun illuminant
  - Sunlit average object (albedo) 18%
  - Sunlit charcoal 3%
  - Sunlit snow 95%
- Moon illuminant
- Office light illuminant (…)
- Indoor objects…
- Indoor shadow objects…
- Sunlit window illuminant (…)
- Outdoor shadow objects…
- Outdoor night objects…

Light power [W/m²]

1e-5 1e-4 1e-3 1e-2 1e-1 1 10 100 1000 1e4 1e5 1e6 1e7
“linear” dynamic range definition

**Linear response sensor:**
S/N or SNR = Dynamic Range?
- typical: Between 1000:1 = 60 dB
- extreme high end: 10000:1 = 80 dB

\[ S_{\text{max}} \approx 1 \text{V}, N \approx 1 \text{mV}_{\text{RMS}} \]
\[ S_{\text{max}} \approx 2 \text{V}, N \approx 200 \text{μV}_{\text{RMS}} \]

**Dynamic range definition no.1**
“DR is in light power domain what \( S_{\text{max}}/N_{\text{min}} \) is in voltage (signal) domain”
Image sensor detection chain

1m²

Illuminant
(illuminance)

Photons/s.m²
Lumen/m²=lux

1m²

object reflection
(emittance)

Scene

Pixel sees

P [W]
[Photons/s]
[Lumen]

Photodiode

I_{photo}[A]

Q_{signal}[F,e⁻]

Signal S

V_{signal}[V]
ADCbits

Charge
amplifier

V_{noise}

Q_{noise}

*1/4F

SR, QE

Conversion gain

C_{eff}

PR

Pixel

Signal S

V_{signal}[V]

ADCbits

Charge
amplifier

V_{noise}

Q_{noise}

*1/4F

SR, QE

Conversion gain

C_{eff}

PR
Image sensor detection chain

Illuminant (illuminance)

Object reflection (emittance)

Pixel sees

Photons/s.m²

[Lumen]

Photons/s

[Lumen/m²]

[Lux]

Signal

Noise

SR, QE

Conversion gain

C_{eff}

Charge amplifier

Pixel

Photodiode

I_{photo}[A]

Q_{signal}[F,e^{-}]

Signal S

V_{signal}[V]

ADCbits

Dynamic range of the Scene

1m²

W/m²

1m²

*1/4F

Pixel sees

P[W]

[Photons/s]

1m²

Object reflection

(emittance)

Lamp surface

(emittance)

Illuminant

(illuminance)

Scene

1m²

W/m²

Photon/s.m²

Lum/m² = lux

1m²

*1/4F
DR = S/N?

In a linear system
Dynamic Range = \( \frac{P_{\text{max}}}{\text{NEP}_{\text{min}}} = \frac{S_{\text{max}}}{N_{\text{min}}} \)
How to push DR beyond $S_{\text{max}}/N_{\text{min}}$

In a linear, DC coupled, system, Dynamic Range is very closely related to Signal/Noise

$$DR = \frac{P_{\text{max}}}{\text{NEP}_{\text{min}}} \approx \frac{V_{\text{signal}_{\text{max}}}}{V_{\text{noise}_{\text{min}}}} < \ldots 10000:1$$

Ways out:
- Non-linear response
- AC signal detection $\Rightarrow$ AC dynamic range
**Constant N.E. Contrast - linear**

Log Signal $S$, Noise $N$ [V, $V_{RMS}$]

$\text{NEC} = \text{SNR}$

Signal

Hypothetical noise for a constant noise equivalent contrast

Photon shot noise

Read noise

Log Illumination $P$ [W, W.s, W/m², lux, photons…]
Noise Equivalent Contrast - general

\[ NEC = \frac{P}{NEP} \]

\[ NEP = \frac{N}{Photoresponse} = \frac{N}{\frac{\partial S}{\partial P}} \]

\[ NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N} \]
DC Dynamic Range definitions

Further attempts for definition

- The range of light intensity levels that can be captured by the image sensor within a single frame

- The range of illumination levels on a similar object within the same frame, for which the object is recognizable (=decent contrast, after image processing)

- The range of intensities that can be captured, for which the SNR has at least a certain value

- The range of intensities that can be captured for which the Noise Equivalent Contrast (NEC) has at least a certain value
## Summary of definitions for [DC] dynamic range

<table>
<thead>
<tr>
<th>Definition</th>
<th>Symbol</th>
<th>How to obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal to Noise Ratio</td>
<td>$S/N_{\text{max}}$ $\text{SNR}_{\text{max}}$</td>
<td>sensor signal voltage range / sensor signal noise in the dark</td>
</tr>
<tr>
<td>Differential or small-signal signal to noise ratio</td>
<td>$dS/dN$ $d\text{SNR}$</td>
<td>signal voltage / signal noise at that same signal level</td>
</tr>
<tr>
<td>Noise equivalent contrast ratio</td>
<td>$\text{NEC}$</td>
<td>The ability to discriminate between nearby grey levels $=1/(d\text{SNR})*\text{PR}$ (where $\text{PR}$=photo response)</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$\text{DR}_{\text{max}}$</td>
<td>Saturation intensity divided by noise equivalent intensity in the dark</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$\text{DR}_{\text{SNR}1}$</td>
<td>the ratio between upper and lower intensities for which $d\text{SNR} \geq \text{[value]}$</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$\text{DR}_{\text{NEC}10}$</td>
<td>the ratio between upper and lower intensities for which NEC $\geq \text{[value]}$</td>
</tr>
<tr>
<td>Generalized dynamic range</td>
<td>$\text{LDR}_x$</td>
<td>$\text{DR}_x$ with largest intensity for which $d\text{Volt}/d\text{Intensity}$ is linear</td>
</tr>
<tr>
<td>ADC (E)NOB</td>
<td></td>
<td>Number of (effective) bits in the sensor’s digital output</td>
</tr>
<tr>
<td>bits</td>
<td></td>
<td>Number of bits after image processing</td>
</tr>
</tbody>
</table>
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Obtain high \textit{DC} high dynamic range by non-linearity

\textbf{non-linear response}

- a way to increase the sensor’s capability to capture a wide dynamic range scene

- a way to exploit the fact that the noise level depends on the scene contents
We do not need a high DR

We need a high NEC

Goals

1. make a pixel that can capture a high DC dynamic range – *means actually*
2. reach a constant or minimal NEC over the largest possible [dynamic range]_{wikipedia definition}

Assumptions

1. NEC is needed to allow recovery of details in all parts (dark, bright) of the scene
2. *Unproven underlying hypothesis:* the largest range is obtained when NEC is just large enough, i.e. constant

\[
NEC = \frac{P}{NEP} = \frac{P}{\partial P} = \text{constant}
\]
In search for a high DR

• Exercise of thought:
  – Obtain the constant NEC by exploiting non-linear response
    • Increase DR by sacrificing NEC where it is sufficient
  – Non-linear response is obtained by
    • A non-linear transconductance, gain or $C_{\text{effective}}$
    • A non-linear integration time $t_{\text{int}}$

$$V_{\text{signal}} = \frac{t_{\text{int}} \cdot I_{\text{photo}}}{C_{\text{eff}}}$$
\[ V_{signal} = \frac{t_{int} \cdot I_{photo}}{C_{eff}} \]

**Modulation of the integration time**
- Multiple slope response (piece-wise linear slopes)
- Non Destructive Readout

**Modulation of the time constant**
- Logarithmic response
- Lin-log

\[ V_{signal} = \frac{Q_{signal}}{C_{eff}} \]
\[ V_{noise} = \frac{Q_{noise}}{C_{eff}} \]
Non-linear $V_{\text{signal}}(Q)$

$$V_{\text{signal}} = \frac{t_{\text{int}} \cdot I_{\text{photo}}}{C_{\text{eff}}} \quad \text{(linear)}$$

$$V_{\text{signal}} = \sum t_{\text{int}} \cdot \frac{I_{\text{photo}}}{C_{\text{eff}}} = \frac{Q_{\text{photo}}}{t_{\text{int max}}} \sum \frac{t_{\text{int}}(Q)}{C_{\text{eff}}(Q)}$$

slope = $t_{\text{int}}(Q)/C_{\text{eff}}(Q)$
NEC as function of $V_{\text{signal}}(Q)$

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

$V_{\text{signal}} = S$

$V_{\text{noise}} = N$

$SR =$ Spectral Response $[A/W]$

$S = V_{\text{signal}} = \sum \frac{t_{\text{int}} \cdot I_{\text{photo}}}{C_{\text{eff}}} = \sum \frac{t_{\text{int}} \cdot P \cdot SR}{C_{\text{eff}}}$

$$\frac{\partial S}{\partial P} = \sum SR \cdot \left( \frac{t_{\text{int}} \cdot P}{C_{\text{eff}}} + \frac{\frac{\partial t_{\text{int}}}{\partial P} \cdot P}{C_{\text{eff}}} - \frac{t_{\text{int}} \cdot P \cdot \frac{\partial C_{\text{eff}}}{\partial P}}{C_{\text{eff}}^2} \right)$$

When one lets integration time depend on $P$ or $Q_{\text{photo}}$
Postulate NEC = constant

Hence

\[ NEC = \frac{P \cdot \frac{\partial S}{\partial P}}{N} = \text{constant} \]

Will impose a relation for S(P), via t_{int}(P) or C_{eff}(P)

This relation depends on N or N(P)

Note: S==V_{signal}, N==V_{noise}
keep NEC constant by varying $t_{\text{int}}$ or $C_{\text{eff}}$ during integration

Nature of noise $N$

- Noise sources that persist after calibration in high end imagers

<table>
<thead>
<tr>
<th>Nature of noise</th>
<th>Constant charge $_{\text{RMS}}$</th>
<th>kTC noise</th>
<th>Constant voltage $_{\text{RMS}}$</th>
<th>EMI, read noise, ADC...</th>
<th>$\sim \sqrt{\text{power}}$</th>
<th>PSN</th>
<th>$\sim \sqrt{t_{\text{int}}}$</th>
<th>DCSN</th>
<th>$\sim \text{power}$</th>
<th>PRNU</th>
<th>$\sim t_{\text{int}}$</th>
<th>DSNU</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{int}}$ varies</td>
<td>$t_{\text{int}} \sim 1/Q$</td>
<td>$C_{\text{eff}} \sim Q^2$</td>
<td>$t_{\text{int}} \sim 1/Q$</td>
<td>$C_{\text{eff}} \sim Q$</td>
<td>$t_{\text{int}} \sim 1/Q$</td>
<td>No solution</td>
<td>$t_{\text{int}} \sim 1/Q$</td>
<td>No solution</td>
<td>$t_{\text{int}} \sim 1/Q^2$</td>
<td>No solution</td>
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<td>No solution</td>
</tr>
</tbody>
</table>

The relations $t_{int} \sim 1/Q$ and $C_{eff} \sim Q$ found are essentially “logarithmic responses”

$$V_{signal} = \frac{1}{t_{int \ max}} \cdot \int_0^{Q_{photo}} \frac{t_{int}(Q)}{C_{eff}(Q)} \, dQ \sim \int_0^{Q_{photo}} \frac{1}{Q} \, dQ$$

$$V_{signal} \sim \log_n(Q_{photo}) + Cte$$

Is a consequence of imposing a constant NEC
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Examples of AC information

• Extract a modulated light source from a DC background
  – E.g. recognize an IR remote control or an IR transmitter in a scene
  – Artificial light source flicker detection

• Time of flight
  – Ranging: sample and time stamp the light returning from an illuminator

• Time gating
  – Acquire light only during precise fractional time spans
  – Acquire only light from a certain distance – as reflected from a short illuminator pulse – or signals at very precise moments – or an accurate global shutter.
Extract AC from DC

• How to extract AC information from a huge dynamic range scene

⇒ Brute force: acquire multiple DC frames, and demodulate off line

⇒ More subtle: Subtract DC part from the signal, acquire the AC part only and demodulate off-line or in electrical domain

⇒ Best: demodulate in optical or charge domain and acquire that image

Sensor must handle full DR; and many frames
Uncorrelated noise accumulates

Sensor must only handle AC
Uncorrelated noise accumulates

Sensor must only handle AC
No uncorrelated noise
Image sensor detection chain

DC illuminant

Object reflection

Scene

Pixel sees

$P \, [W]$

[Photons/s]

[Lumen]

Photodiode

$I_{\text{photo}} \, [A]$

$Q_{\text{signal}} \, [F, e^-]$

Signal $S$

$V_{\text{signal}} \, [V]$

ADCbits

Conversion gain

$C_{\text{eff}}$

SR, QE

Charge amplifier

Noise

$Q_{\text{noise}}$

$V_{\text{noise}}$

Charge

$Q$

Noise

$V$

Signal

$S$

Pixel

$t_{\text{int}}$
Image sensor detection chain:

1. DC illuminant
2. AC illuminant
3. Scene
4. Object reflection

Demodulation of the light

Demodulation of the photocharge

Demodulation of the output voltage

Conversion gain

SR, QE

Charge amplifier

AC signal

DC signal

ADC bits

Signal S

V_{signal}

V_{noise}

Q_{signal}

t_{int}

P [W]

[W/s/steradian]

[Photons/s]

[Lucem]

V

Q

Noise

F_e

C_{eff}

ADC bits

Conversion gain

SR, QE

Charge amplifier

AC signal

DC signal

ADC bits

Signal S

V_{signal}

V_{noise}

Q_{signal}

t_{int}

P [W]

[W/s/steradian]

[Photons/s]

[Lucem]

V

Q

Noise

F_e

C_{eff}
time gating pixel
demodulating in charge domain
Continuously tunable sensitive volume

Depletion layer
Continuously tunable sensitive volume

Patent pending
Time gating

1 integration time

illumination sensitivity

sensitivity

1 integration time

time

+ + +

+ + +

+ + +
## Preliminary device specs

<table>
<thead>
<tr>
<th>Geometrical</th>
<th>Electro-optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Array: 360x720 pixels</td>
<td>• Full well 50000 e-</td>
</tr>
<tr>
<td>• 30 fps nominal</td>
<td>• Read noise: 20e- (below kTC) per pixel/frame</td>
</tr>
<tr>
<td>• Pixel pitch 20 μm</td>
<td>• QE &gt; 80% visible range</td>
</tr>
<tr>
<td>• Technology: 0.35um CMOS</td>
<td>• $PS(\lambda)$ Parasitic sensitivity when gate is off &lt; 1% in BSI</td>
</tr>
<tr>
<td>• Substrate: backside thinned, 5E12/cm$^3$ p-type</td>
<td>• DC/AC suppression factor: minimum of $PS$ and duty cycle.</td>
</tr>
<tr>
<td>• Gating / switching speed: &lt;&lt;1ns effective</td>
<td>• Shortest global shutter time &lt; 1 ns</td>
</tr>
<tr>
<td>• Gating on/off cycle: &gt;100kHz</td>
<td></td>
</tr>
</tbody>
</table>
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2. Definitions of DR
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• **High dynamic range** is a property of the scene and light source.
  – The sensor has to accommodate.
• **DC**: When you want to acquire the “scene”:
  – One must apply some form of non-linear response
    ⇒ have a **sufficient NEC** in all parts of the image/scene
• **AC**: When you want to extract AC information from the large DC background:
  – Demodulate as early as possible: in optical or charge domain, better than in voltage domain or off-line
    ⇒ have **as high as possible NEC** for the AC signal only