Comparative Analysis of SNR for Image Sensors with Enhanced Dynamic Range

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Motivation

Dynamic range is synonymous to imager quality

- True for conventional CCD or CMOS imagers

- Not necessarily true when dynamic range enhancement schemes are used, e.g.,
  - Well capacity adjusting (Decker’98)
  - Multiple sampling (Yadid-Pecht’97, Yang’98)

SNR plot is a better indicator of imager quality
Outline

• Dynamic range and SNR in integration mode

• Enhancing dynamic range by adjusting well capacity

• Enhancing dynamic range via multiple sampling

• Comparisons of the two enhancement schemes
Simplified Photocurrent to Output Sensor Model

Direct integration

\[ i_{ph} + i_d = C_d \]

Charge collected vs. time

Charge collected over time for high and low illumination.
Sensor Noise Model

Sensor model

Equivalent model with input referred noise

Need $N_i$ to compute SNR and DR
SNR and Dynamic Range in Integration Mode

\[ f_0(i + N_i) \approx f_0(i) + N_i f'_0(i) \]

\[ \sigma^2_{N_i} = \frac{\sigma^2_N}{f'_0(i)^2} = \frac{\sigma^2_N}{t_{int}^2} \]

\[ \text{SNR}(i_{ph}) = \frac{(i_{ph} t_{int})^2}{q(i_{ph} + i_d) t_{int} + \sigma_r^2} \quad \text{for} \quad i_{ph} \leq i_{max} \]

\[ \text{DR} = \frac{i_{max}}{i_{min}} = \frac{q_{max} - i_d t_{int}}{\sqrt{q i_d t_{int} + \sigma_r^2}} \]
Dynamic Range = Sensor Quality (Integration Mode)

$q_{max} = 125000$

$\sigma_r = 20 \, e^-$

$t_{int} = 30\text{ms}$
Shuttering Does Not Affect Dynamic Range

Dynamic range vs. integration time $t_{int}$

- $q_{max} = 125000$
- $\sigma_r = 20 \text{ e}^{-}$
- $i_d = 1 \text{ fA}$
Shuttering Matches Dynamic Range to Scene Illumination

$q_{max} = 125000$

$\sigma_r = 20 \text{ e}^-$

$i_d = 5 \text{ fA}$
Outline

- Dynamic range and SNR in integration mode
- Enhancing dynamic range by adjusting well capacity
- Enhancing dynamic range via multiple sampling
- Comparisons of the two enhancement schemes
Enhancing DR by Adjusting Well Capacity

Compress the sensor’s current versus charge response curve using a lateral overflow gate (Sayag’91, Decker’98)

Well capacity is monotonically increased to its maximum value
\( f_0(i) \) for the Well Adjusting Scheme

\[
i_1 = \frac{q_{max} \theta}{t_1}
\]

\[
\frac{q_{max} \theta t_{int}}{t_1}
\]

\[
\frac{q_{max} (1-\theta)}{t_{int}-t_1}
\]
Dynamic Range and SNR for Well Adjusting

\[ \text{SNR}(i_{\text{ph}}) = \begin{cases} \frac{i^2_{\text{ph}} t^2_{\text{int}}}{q(i_{\text{ph}}+i_d)t_{\text{int}}+\sigma^2_r} & \text{if } 0 \leq i_{\text{ph}} < \frac{q_{\text{max}} \theta}{t_1} - i_d \\ \frac{i^2_{\text{ph}} (t_{\text{int}}-t_1)^2}{q(i_{\text{ph}}+i_d)(t_{\text{int}}-t_1)+\sigma^2_r} & \text{if } \frac{q_{\text{max}} \theta}{t_1} - i_d \leq i_{\text{ph}} < \frac{q_{\text{max}} (1-\theta)}{t_{\text{int}}-t_1} - i_d \end{cases} \]

\[ \text{DRF} = \frac{1-\theta}{1-\frac{t_1}{t_{\text{int}}}} \]
SNR vs. $i_{ph}$ for the Well Capacity Adjustment Scheme

$q_{max} = 125000$

$\sigma_r = 20 \text{ e}^-$

$t_{int} = 30\text{ ms}$

$i_d = 1\text{ fA}$
Enhancing DR by Multiple Sampling

Dual sampling is the simplest case of multiple sampling (Yadid-Pecht’97)

- A scene is imaged twice, at a short and long integration times

- Two sampled images are combined into a high DR image
$f_0(i)$ for Dual Sampling
Dynamic Range and SNR for Dual Sampling

\[ \text{SNR}(i_{ph}) = \begin{cases} 
\frac{i_{ph}^2 t_{int}^2}{q(i_{ph}+i_d)t_{int} + \sigma_r^2} & \text{if } 0 \leq i_{ph} < \frac{q_{max}}{t_{int}} - i_d \\
\frac{i_{ph}^2 (\frac{t_{int}}{a})^2}{q(i_{ph}+i_d)\frac{t_{int}}{a} + \sigma_r^2} & \text{if } \frac{q_{max}}{t_{int}} - i_d \leq i_{ph} < \frac{aq_{max}}{t_{int}} - i_d 
\end{cases} \]

\[ \text{DRF} = \frac{aq_{max}}{t_{int}} - i_d \approx a, \text{ for small } i_d \]
SNR vs. $i_{ph}$ for Dual Sampling

$q_{max} = 125000$

$\sigma_r = 20 \text{ e}^-$

$t_{int} = 30 \text{ ms}$

$i_d = 1 \text{ fA}$
SNR vs. $i_{ph}$ for Both Well Adjusting and Dual Sampling

$q_{max} = 125000$

$\sigma_r = 20 \, \text{e}^-$

$t_{int} = 30\,\text{ms}$

$i_d = 1\,\text{fA}$
SNR vs. $i_{ph}$ for Well Adjusting and Multiple Sampling

$q_{max} = 125000$

$\sigma_r = 20 \text{ e}^{-}$

$t_{int} = 30 \text{ ms}$

$i_d = 1 \text{ fA}$
Conclusion

Dynamic Range as a measure of imager quality

- Good for conventional CCD and CMOS imagers
- Does not tell the full story when dynamic range enhancement schemes are used

SNR plot is a better indicator of imager quality

Multiple sampling achieves higher SNR than well adjusting