A Programmable Digital Camera Architecture

Multiple Capture Single Image

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http://smartcamera.stanford.edu/pdc.html

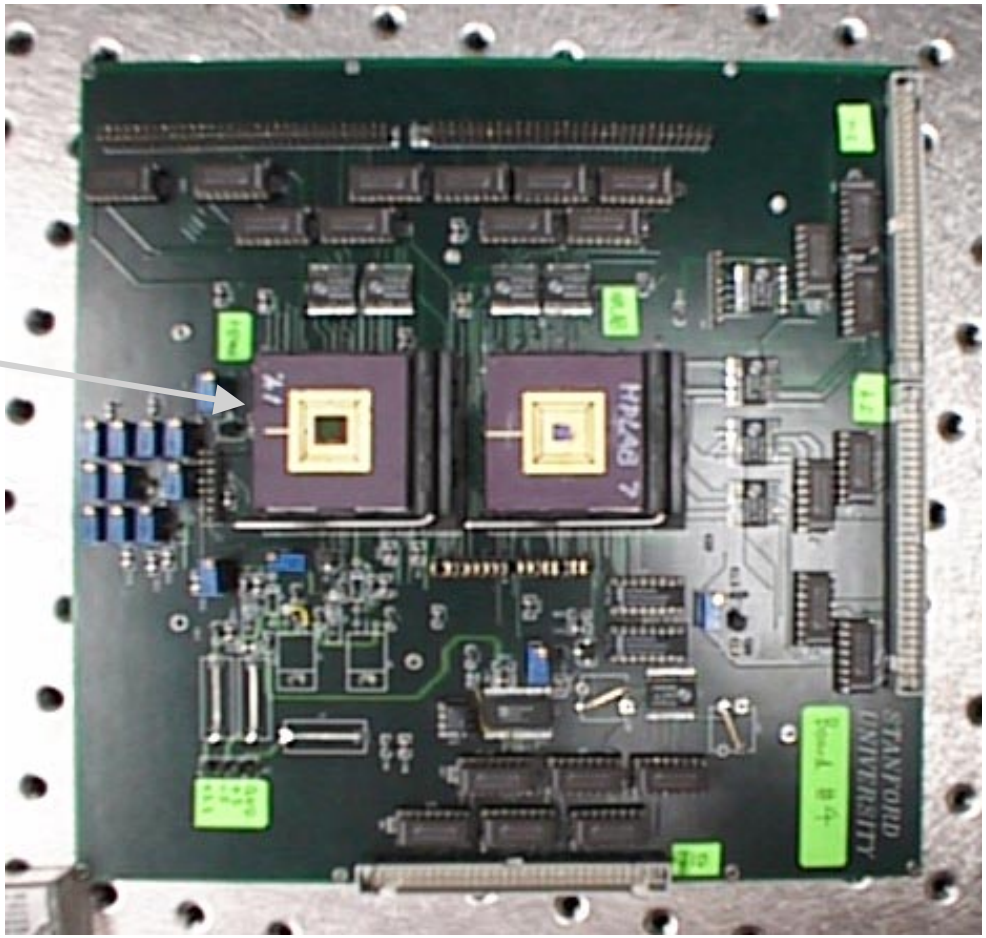
Outline of the Presentation

- Camera architecture lab
- CMOS sensor (PDC ‘98)
  - Pixel-level ADC
  - Programmable features
- Programmable digital camera architectures
  - Transduction
  - Temporal programming: Dynamic range
  - Spatiotemporal: Intensity resolution

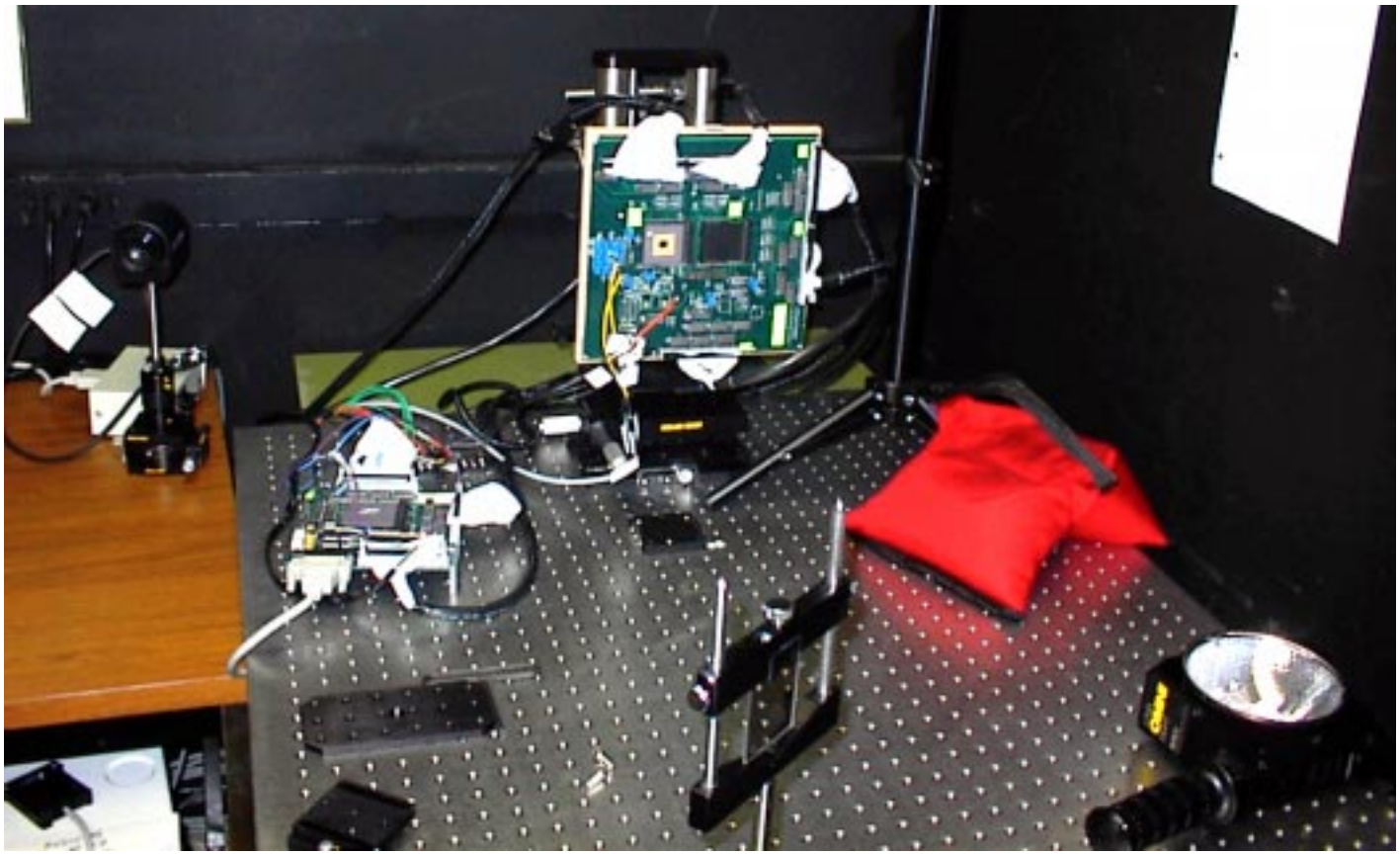
Experimental Lab: Overview

Experimental Lab: Sensors

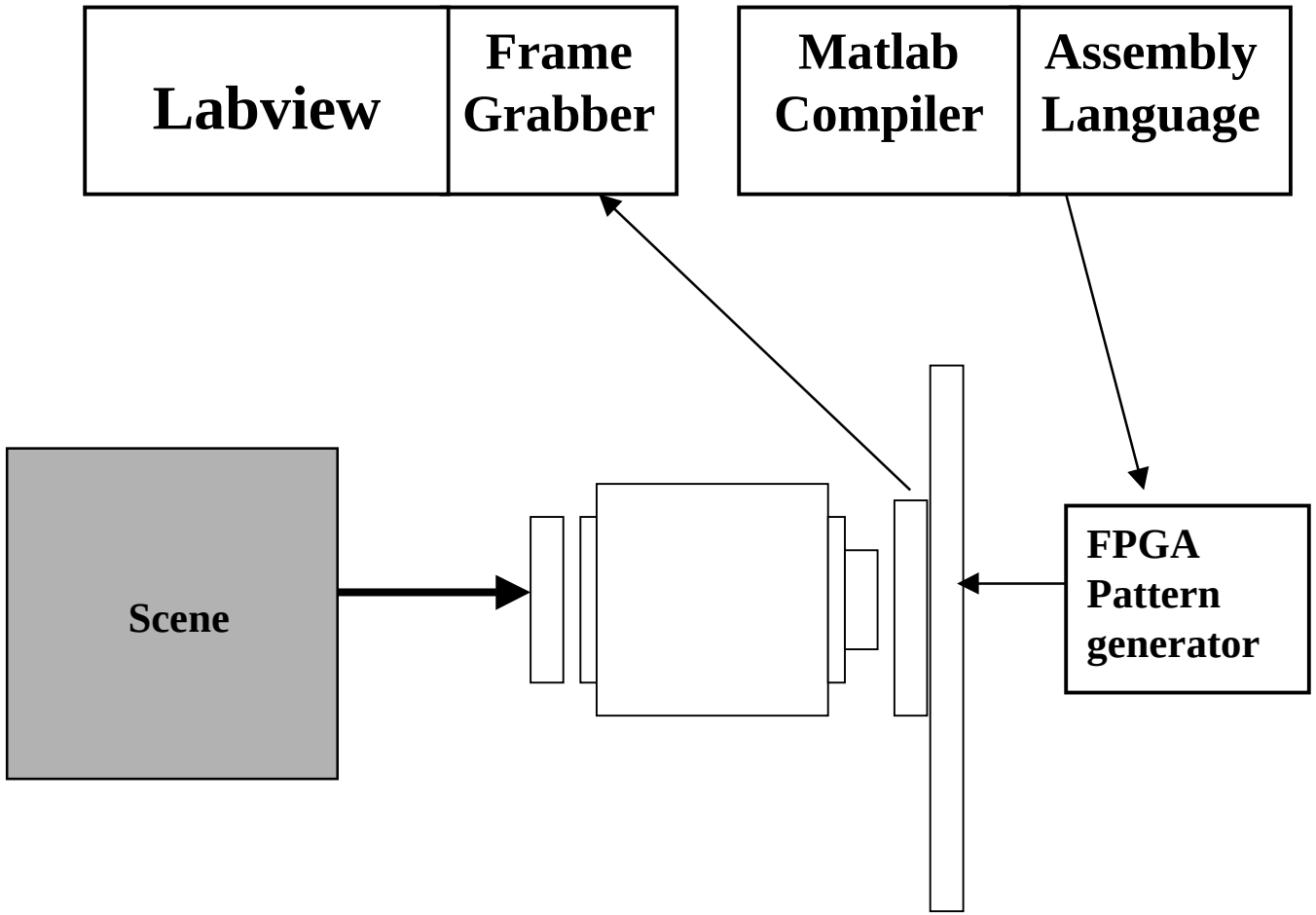
HPMosis
640*512



Experimental Lab: FPGA



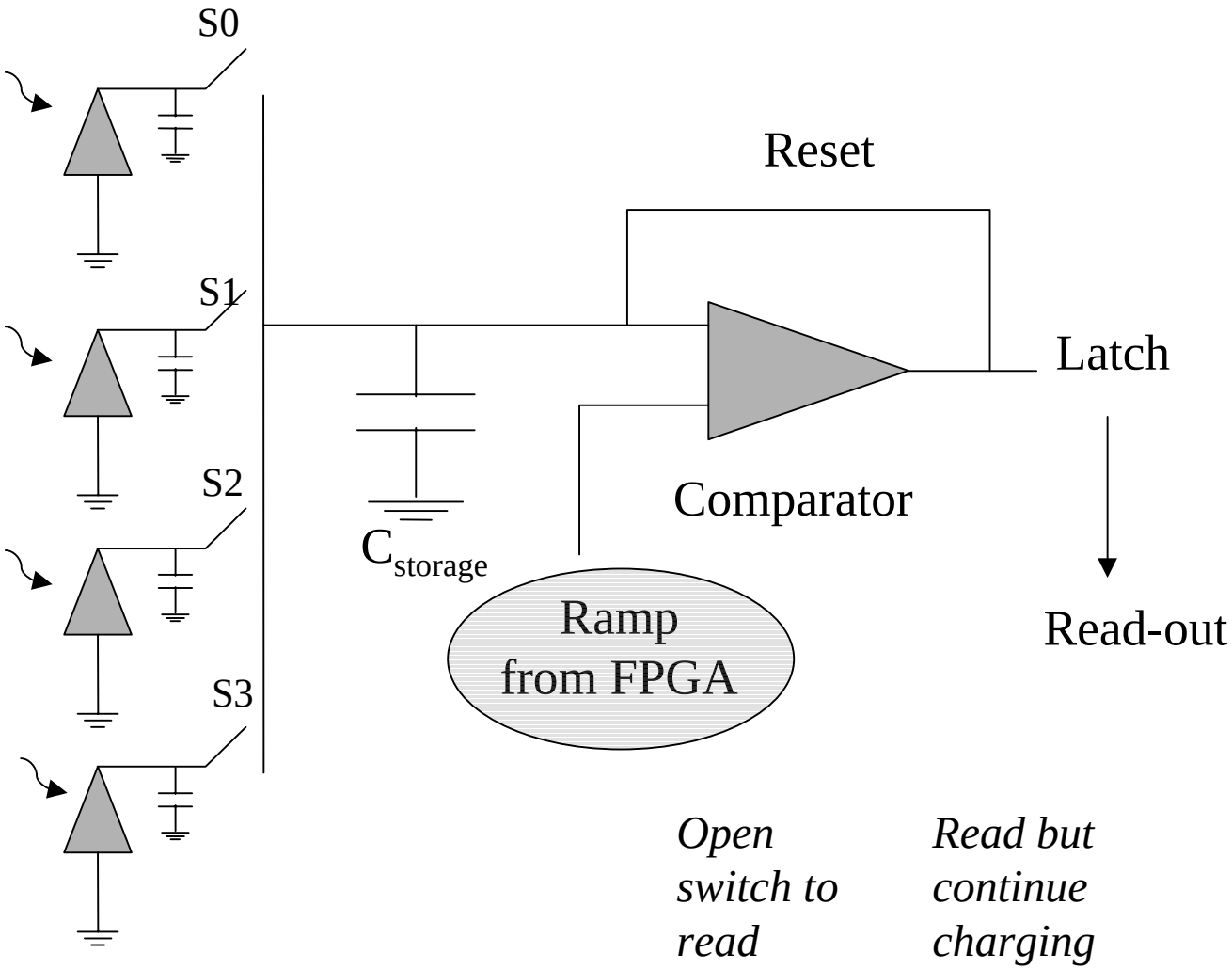
Programming overview



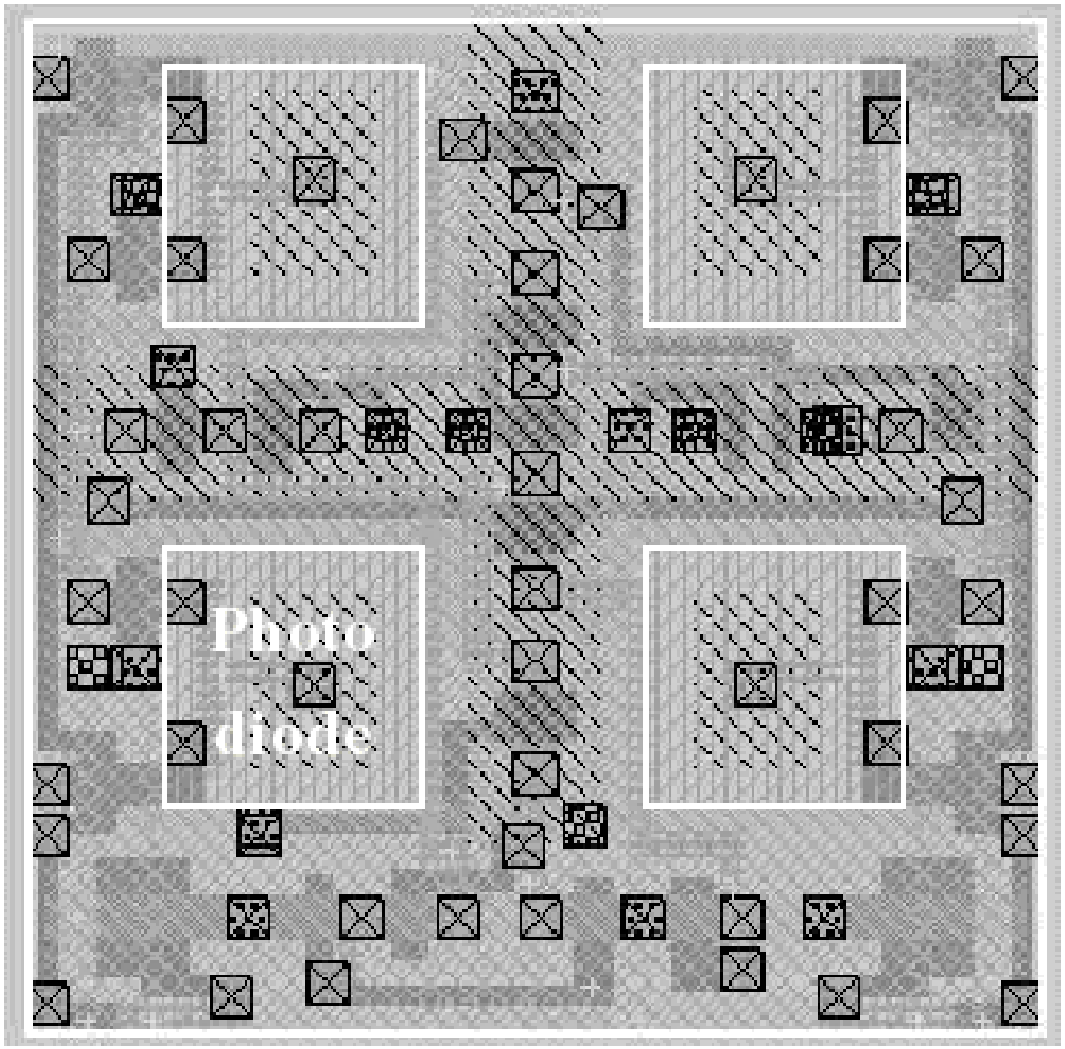
PDC Sensor ‘98

- Pixel-level ADC
- CMOS (4.5 transistors/pixel)
- Feature size: 0.35 μ
- Pixel size: 10 μ
- Light Sensitivity
  - Fill factor: 23 percent
  - QE: 4 percent

Sensor: Pixel-level architecture



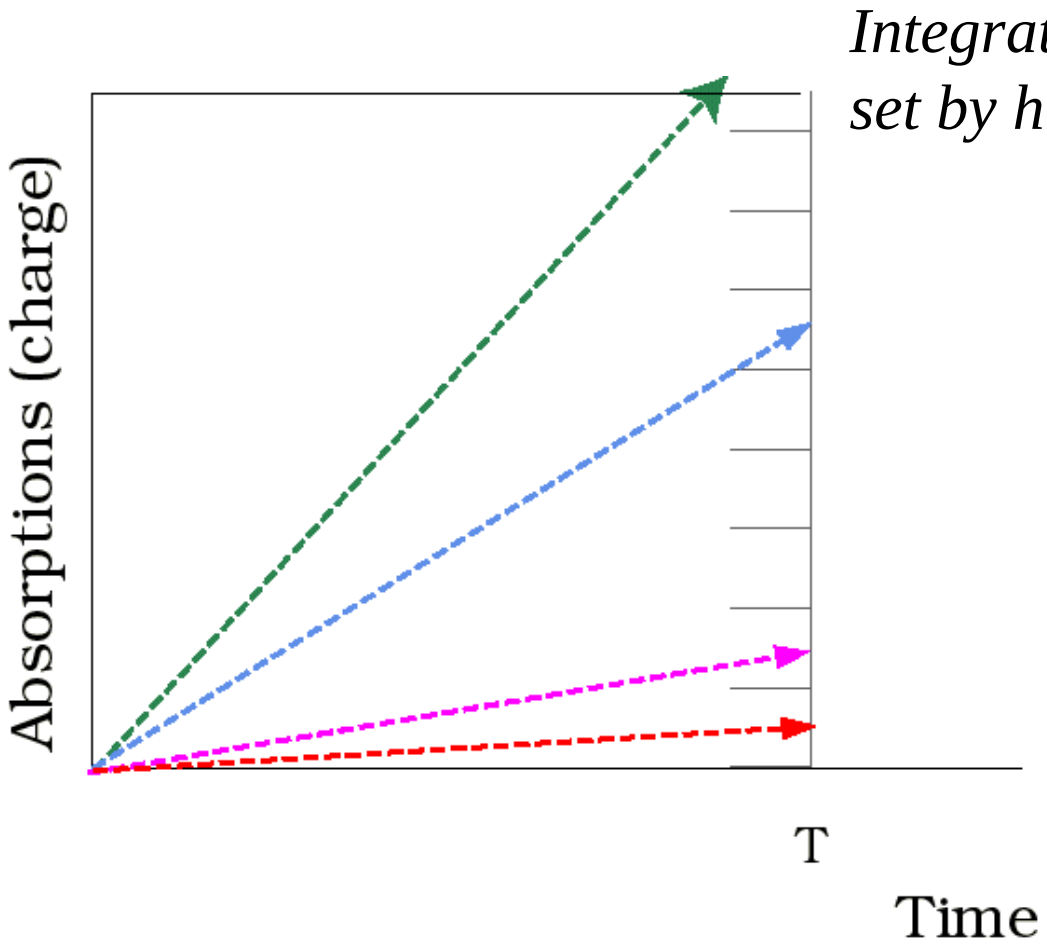
Sensor: Quad pixel layout



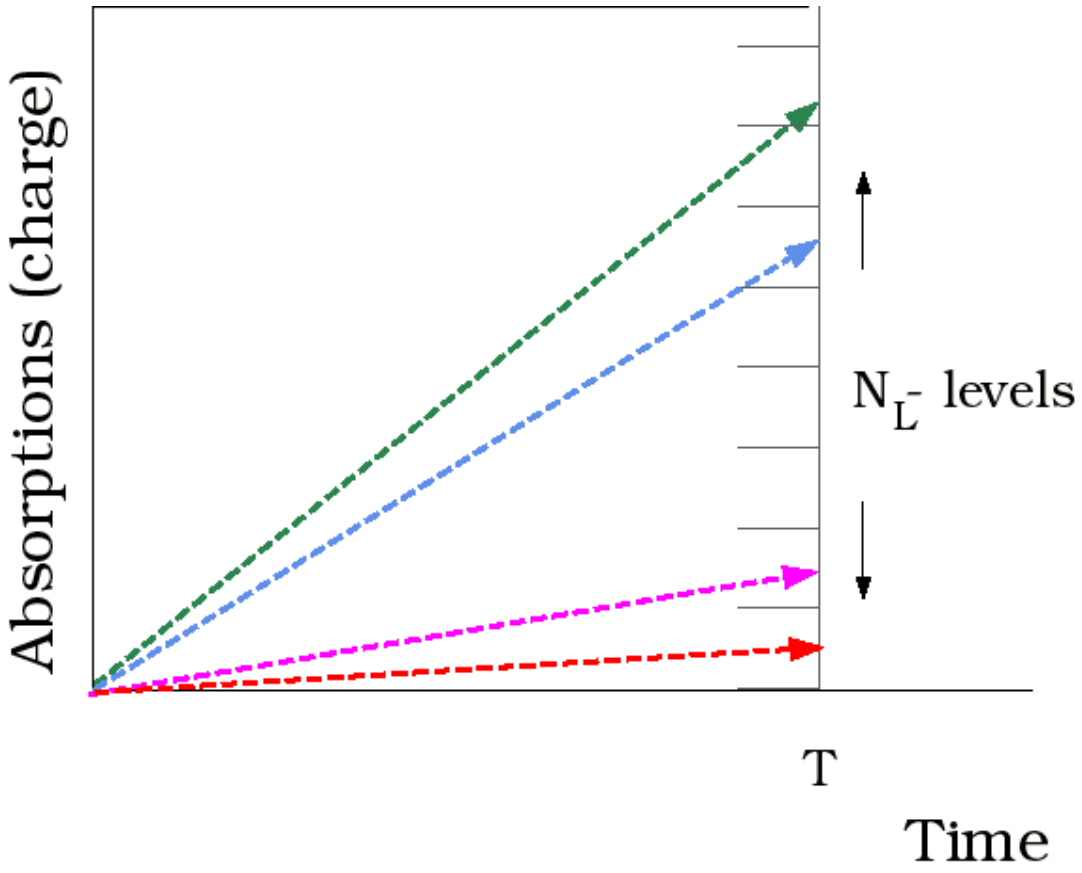
Programmable Digital Camera Algorithms

- Single Capture temporal integration
- Multiple Capture Single Image (MCSI)
  - Transduction
  - Temporal programming: Dynamic range
  - Spatiotemporal: Intensity resolution

Single Capture: Integration Time



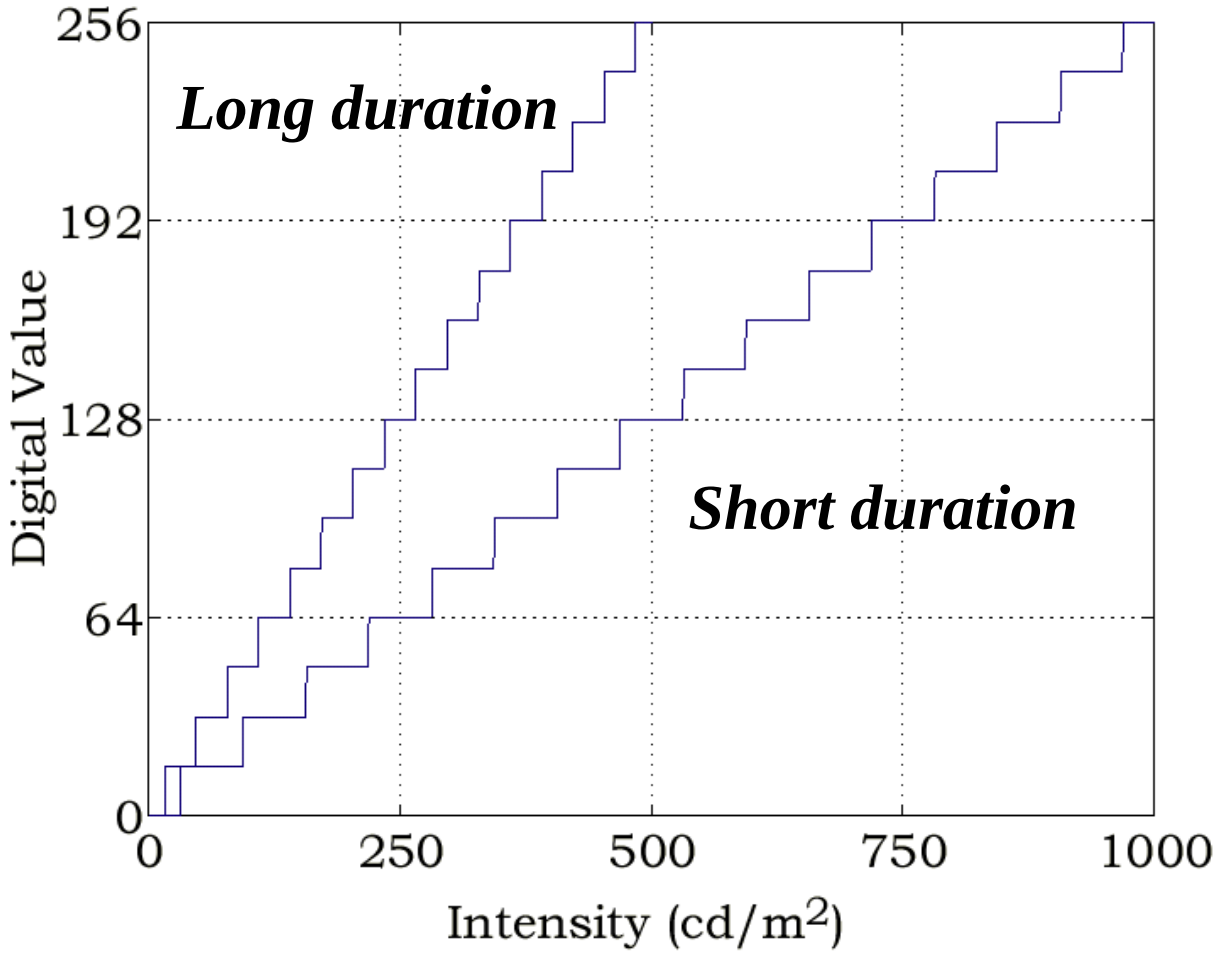
Single Capture: Digital encoding



Format: integer

Number of bits to encode $\log_2 N_L$

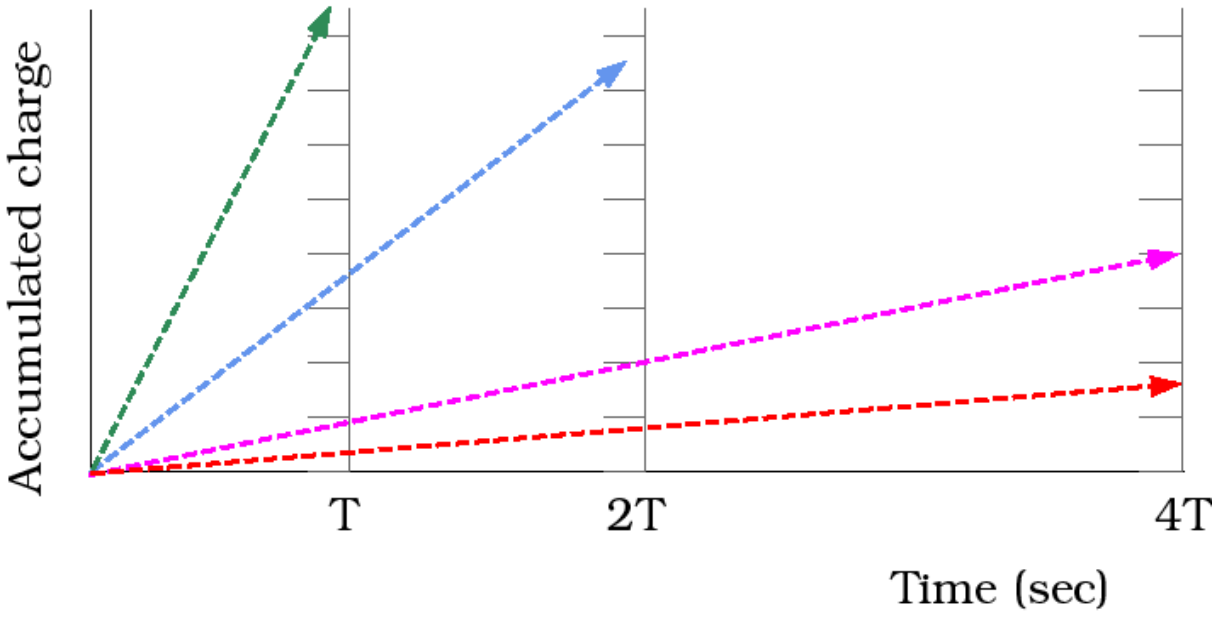
Single Capture: Transduction



MCSI: Integration Times

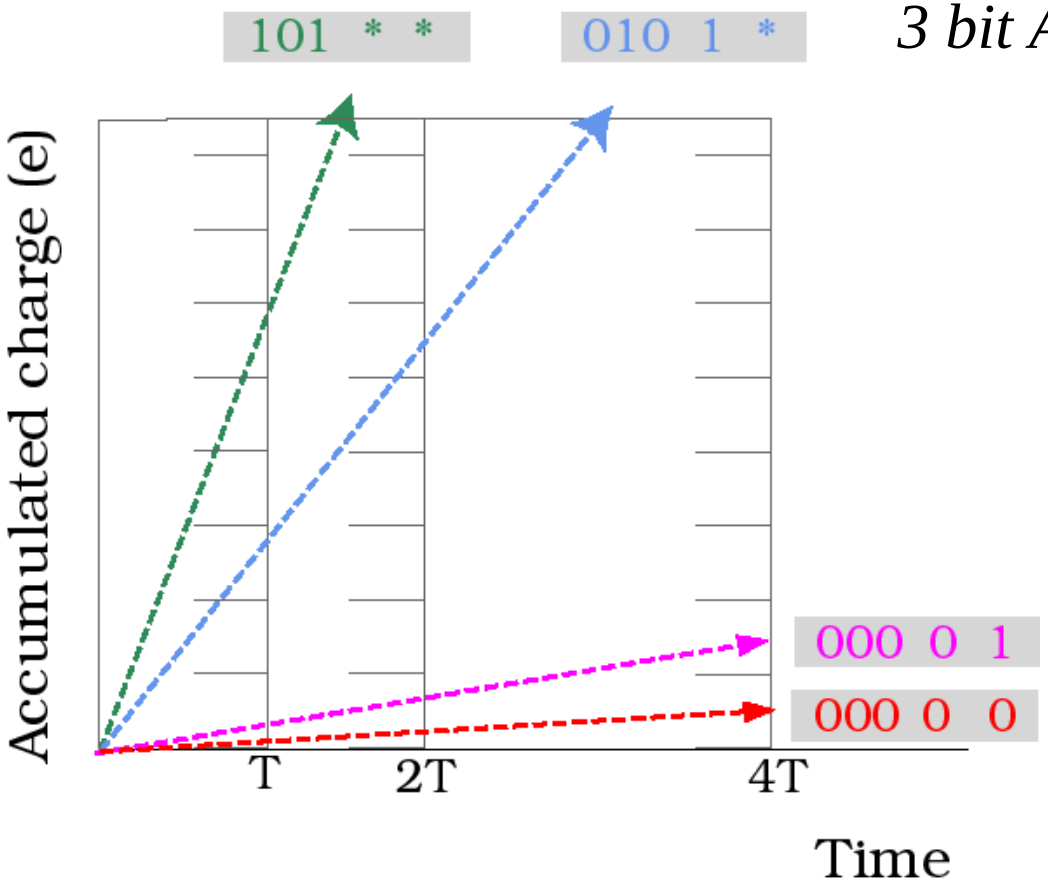
First sample time set by highlights

Final sample time set by lowlights

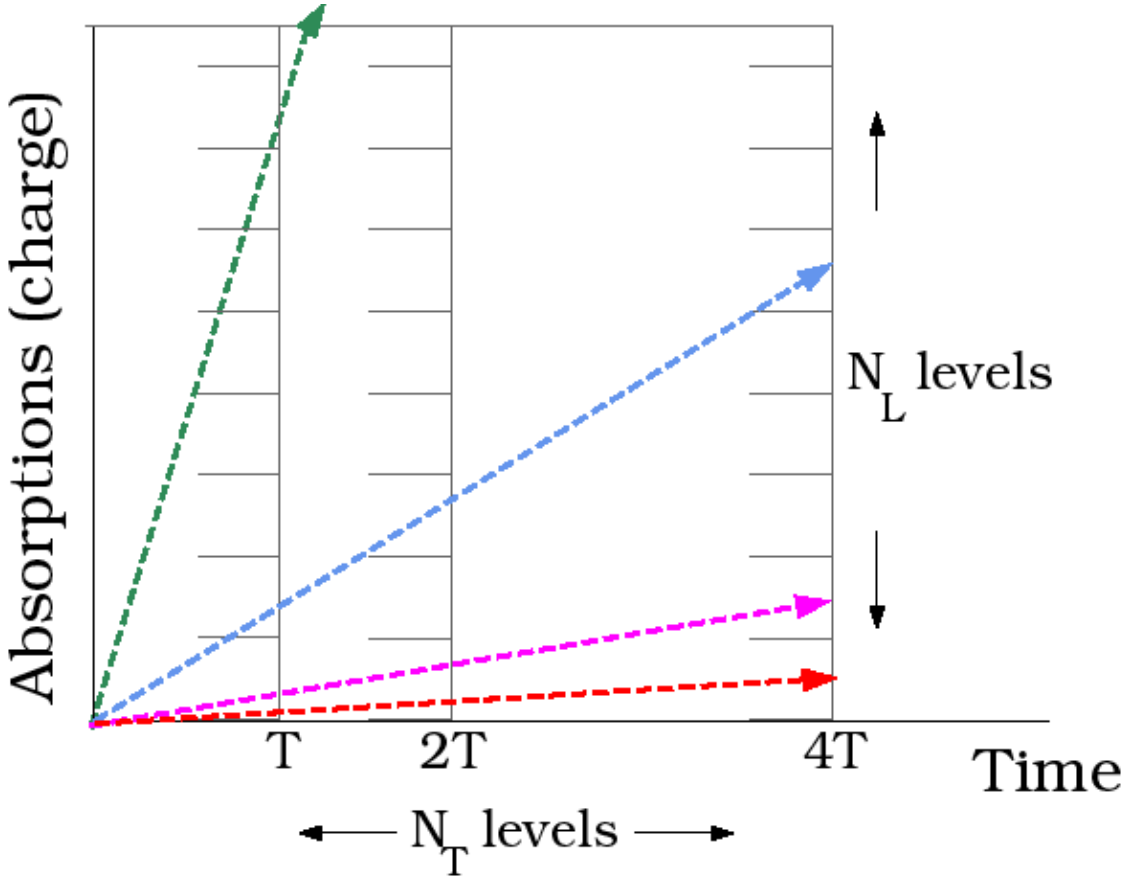


MCSI: Digital Encoding

3 bit ADC example



MCSI: Digital Encoding



$dc = L*2^{-T}$

Format: floats

Number of bits
$\log_2 N_L + \log_2 N_T$

MCSI: Dynamic range

256ms

1024ms

Multiple integration times increases dynamic range

16ms

64ms

MCSI: Dynamic Range

Integrated image using DiCarlo Algorithm

MCSI: Transduction

- The FPGA timing and comparator levels can be controlled, so
  - The transduction function can be varied between frames
  - The quantization levels can be selected freely (up to noise considerations)

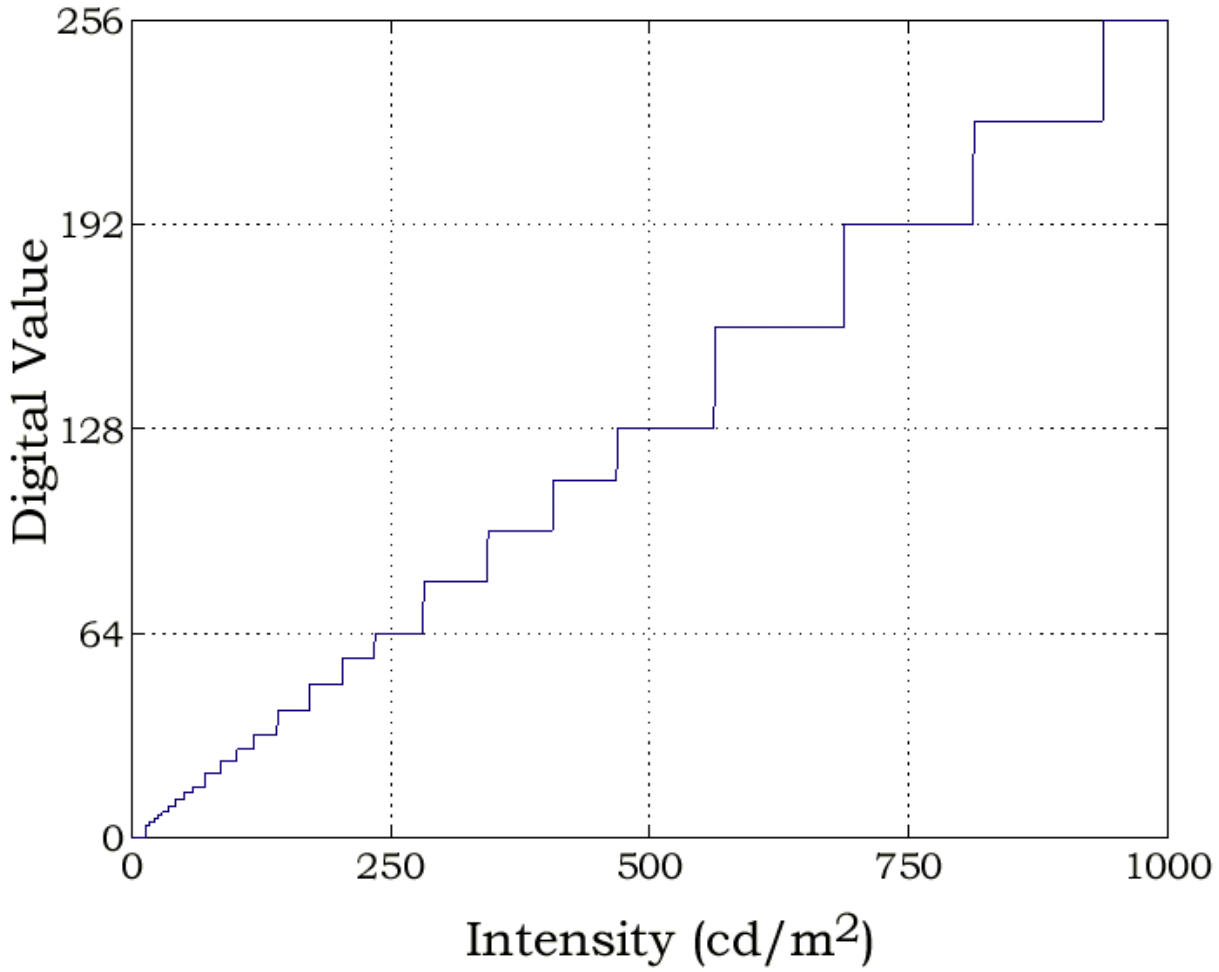
MCSI: Example Transduction

$\gamma = 0.5$

$\gamma = 1.0$

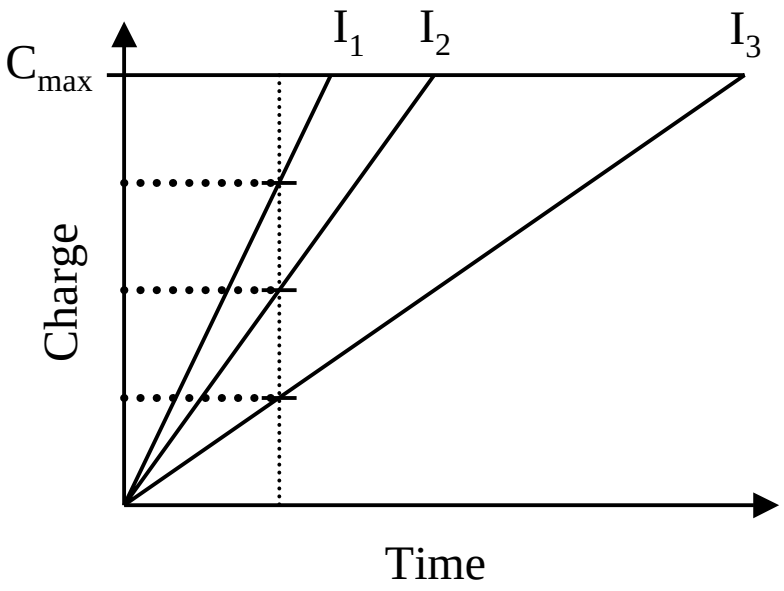
$\gamma = 2.0$

MCSI: Standard transduction

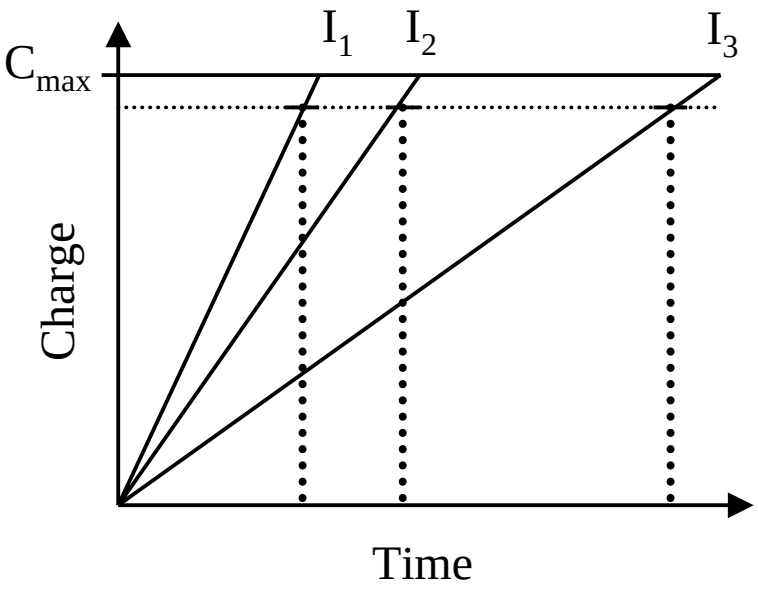


MCSI: Programmable Transduction

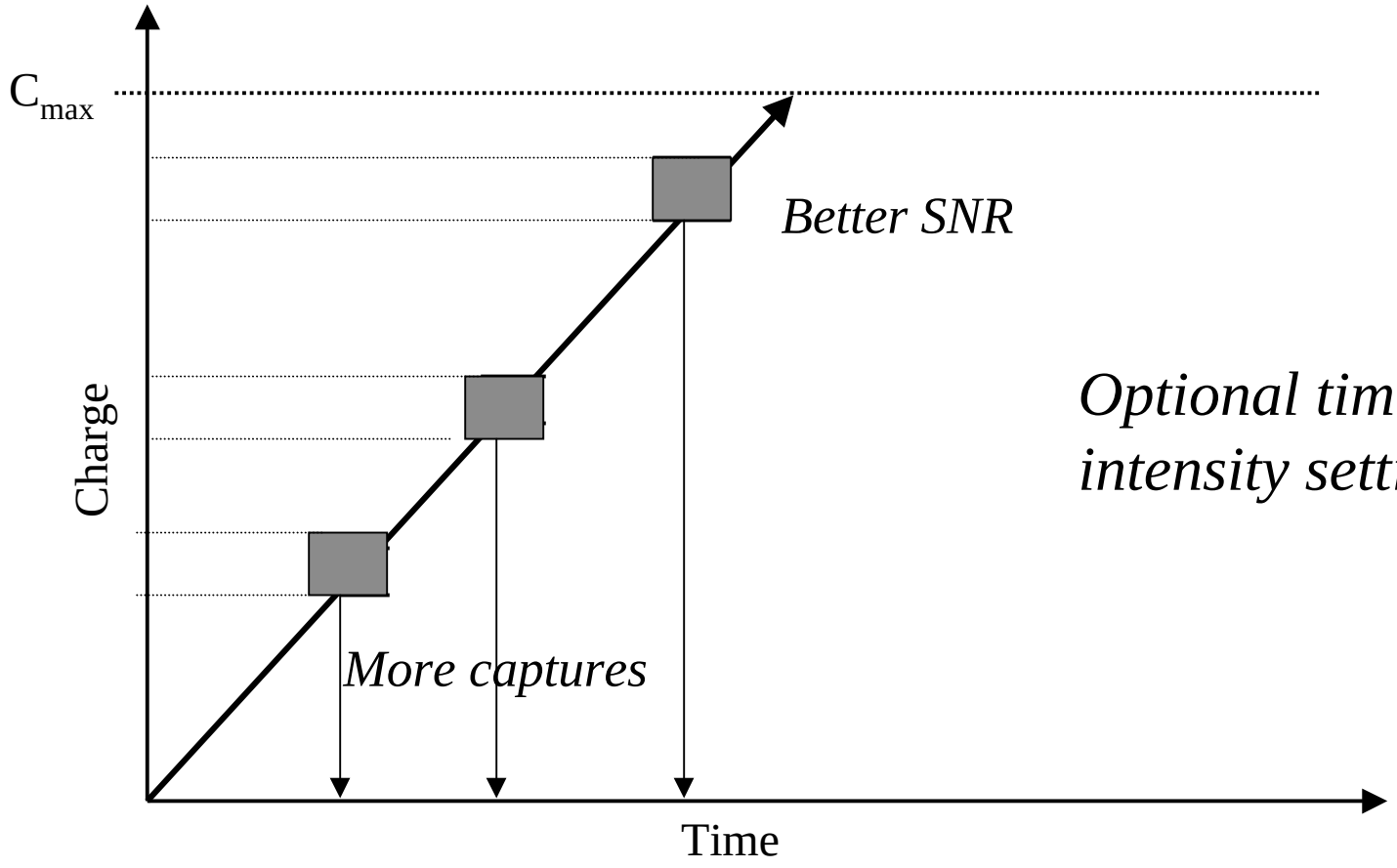
Level method



Timing method

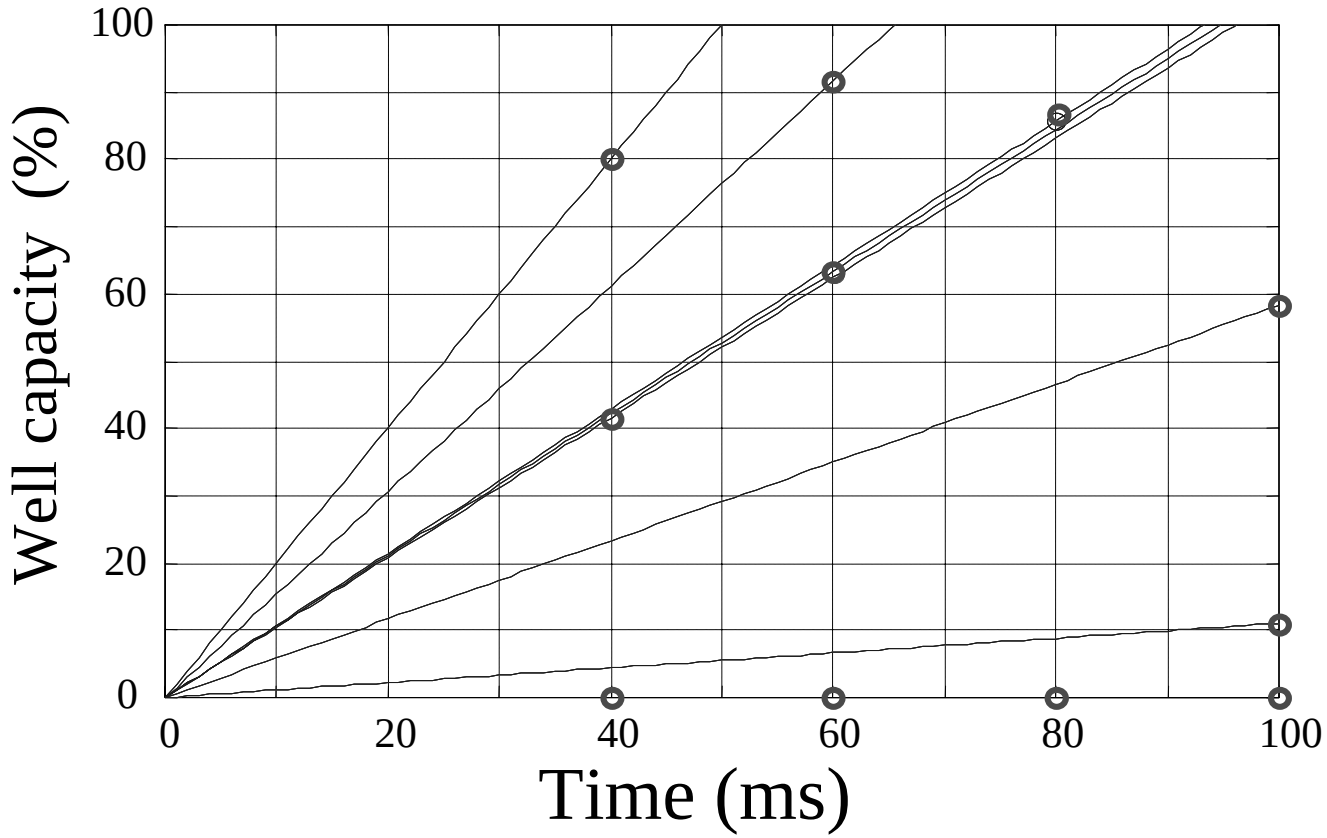


MCSI: Time/Level Tradeoffs

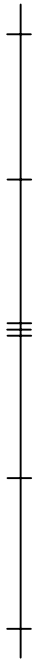


MCSI: Time/Level Optimization

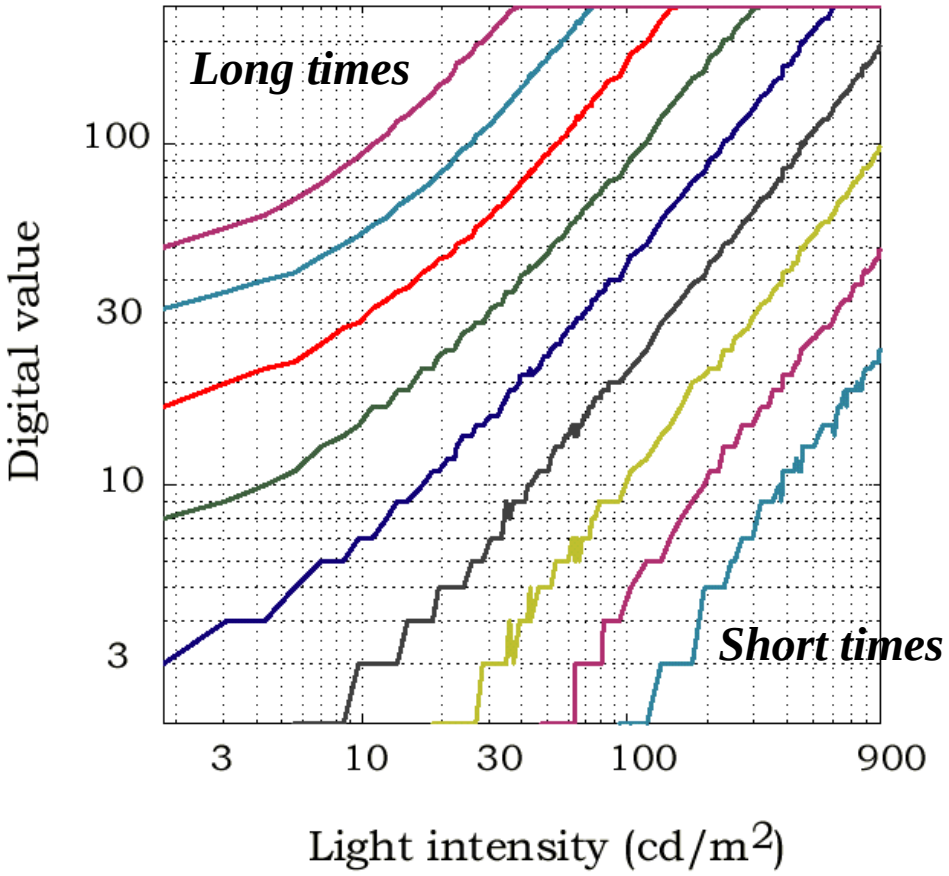
2-bit device, 25ms Sampling separation
7 bit (linear) device needed



Desired intensity quantization



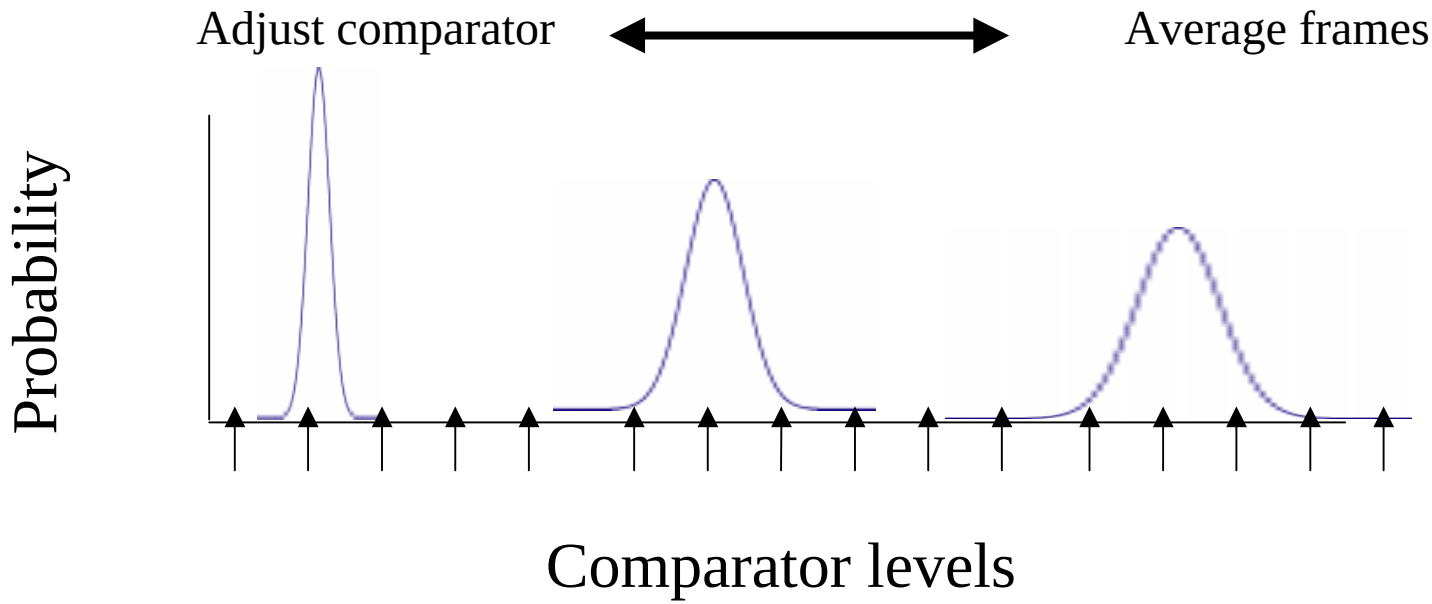
MCSI: Intensity resolution



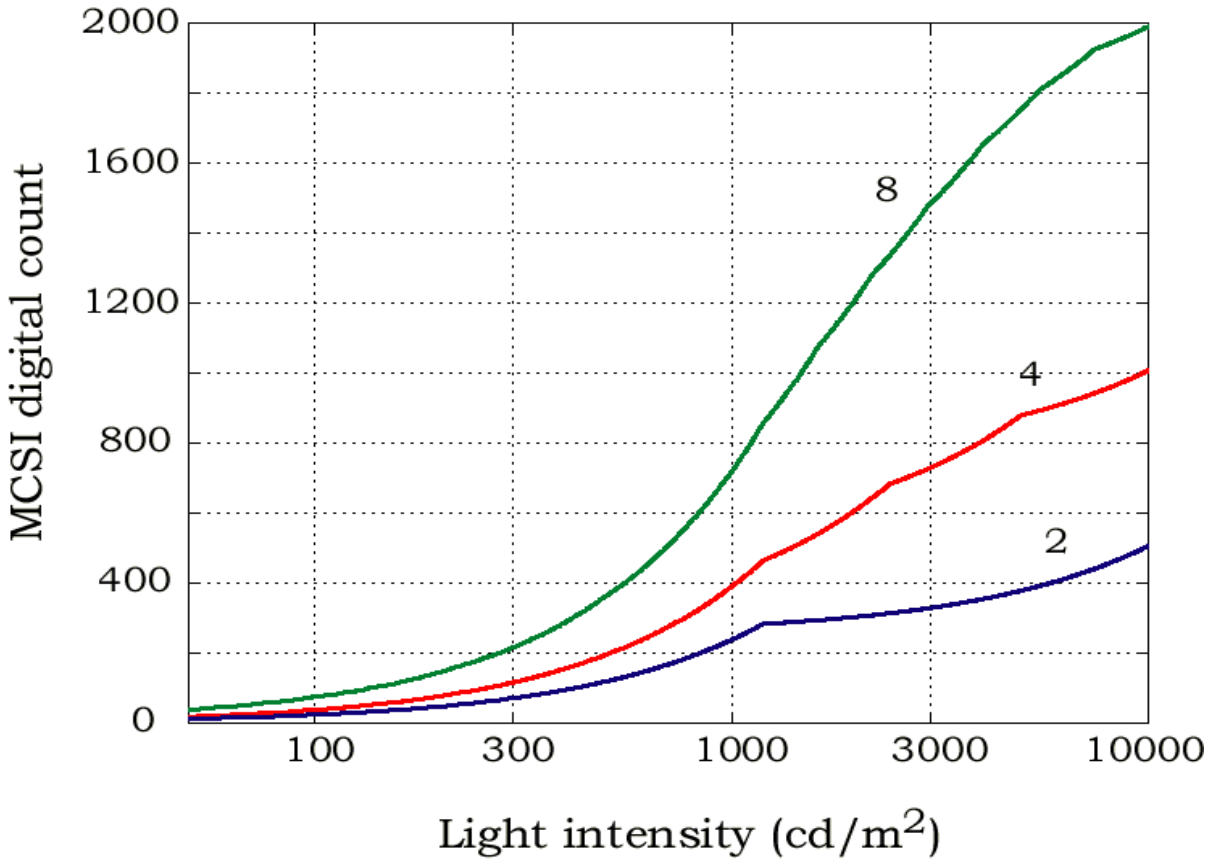
Multiple captures permits averaging for better SNR and for better range

MCSI: Intensity resolution

To improve to intensity resolution we must account for the noise and quantization bins

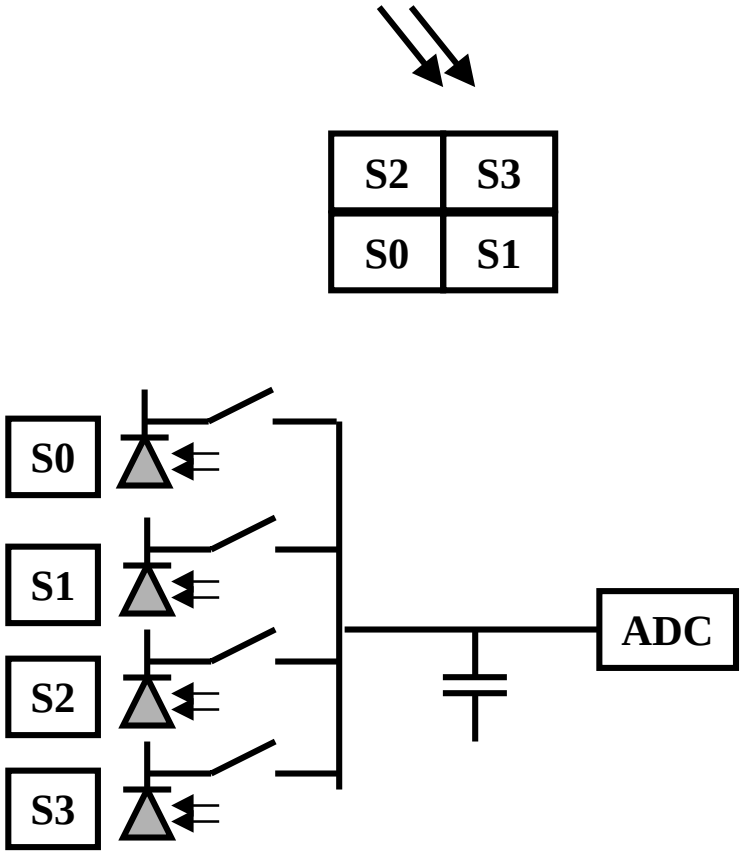


MCSI: Frame averaging



Averaging improves intensity resolution, as shown by increased slope

MCSI: Programmable Spatial Resolution



- The electrons collected in groups of four pixels can be read out separately or summed.
- Under low lighting conditions, one might sacrifice spatial resolution to increase sensitivity.

MCSI: Programmable Resolution

Trade spatial resolution against photon sensitivity by combining photons of combination of quarter images

Spatial resolution:
640*512

Spatial resolution:
320*256

MCSI: Spatial estimation

Camera measurements

Picture intensity

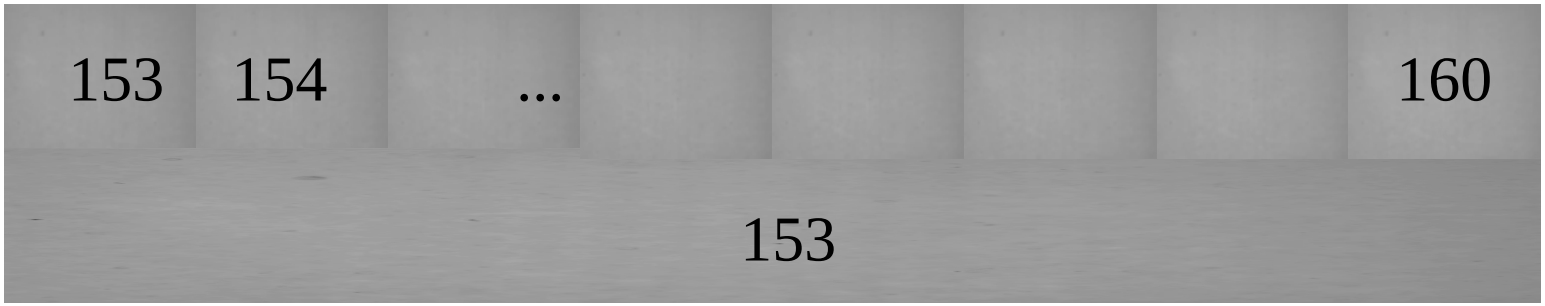
Hi-res mode
16 ms

4 ms

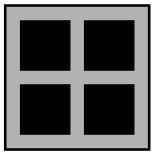
Hi-sensitivity mode

$$\begin{pmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ .25 & .25 & .25 & .25 \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{pmatrix}$$

MCSI: Contrast sensitivity

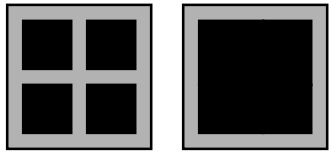


Single capture



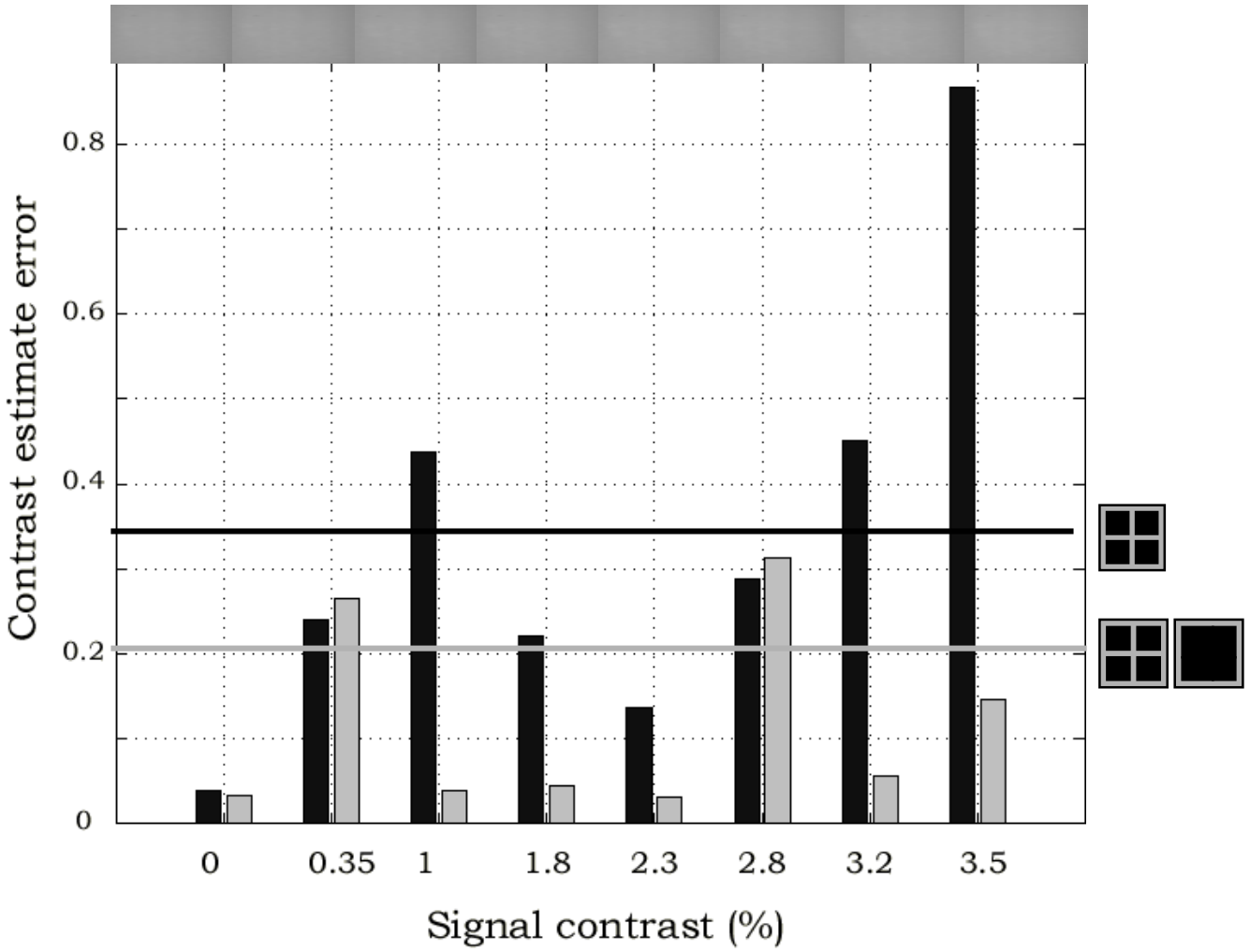
16 ms

Multiple capture

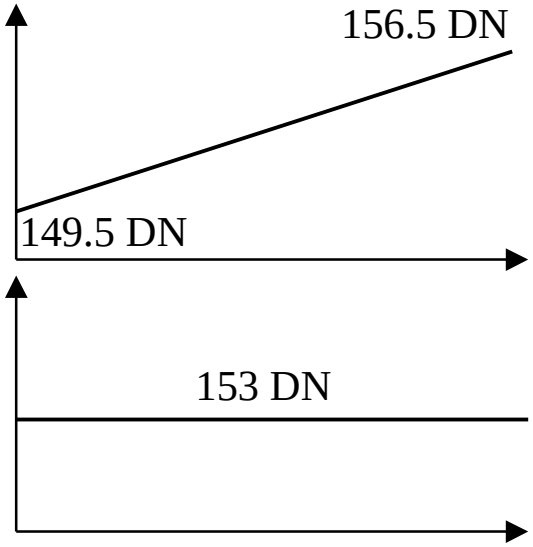


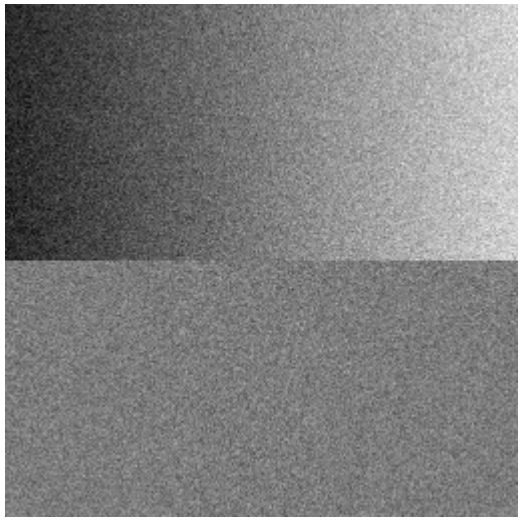
20 ms

MCSI: Contrast sensitivity

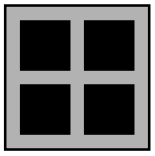


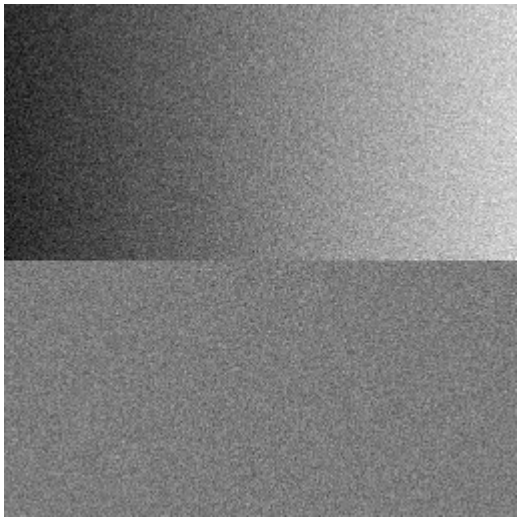
MCSI: Simulator



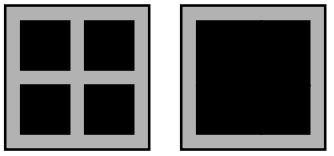


(a) Measured Image

based on 



(b) Estimated Image

based on 

Continuous Contrast Ramp = -0.0225 $\rightarrow$ 0.0225

Summary and Conclusion

- New sensor technology requires new algorithms
- Programmable to optimize for applications
- CMOS pixel-level ADC
  - Frame rate
  - Memory
  - Integrated processing