Simultaneous Image Formation and Motion Blur Restoration via Multiple Capture

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Programmable Digital Camera Project

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Background

- Most of today's digital cameras use CCD imagers
- CMOS imagers emerging as alternative
  - Low fabrication cost
  - Low power
  - Integration leading to digital-camera-on-chip
- CMOS imagers are capable of very high frame rate non-destructive readout
  - 10,000 f/s demonstrated (Kleinfelder ISSCC'01)
- Application to still and video rate imaging
  - Dynamic range enhancement
  - Motion blur restoration

Dynamic Range Enhancement via Multiple Capture

- Sensor dynamic range determines range of scene illumination that can be imaged
  - Saturation limits highest signal
  - Sensor read noise limits lowest signal
- Varying exposure time shifts dynamic range
  - Short exposure shifts it to high illumination end
  - Long exposure shifts it to low illumination end
- Multiple capture scheme: (Yang ISSCC99)
  - Capture several images at different exposure times, combine them into single high dynamic range image
  - Need high frame rate operation – CMOS imagers ideally suited

Multiple Image Capture Example

τ

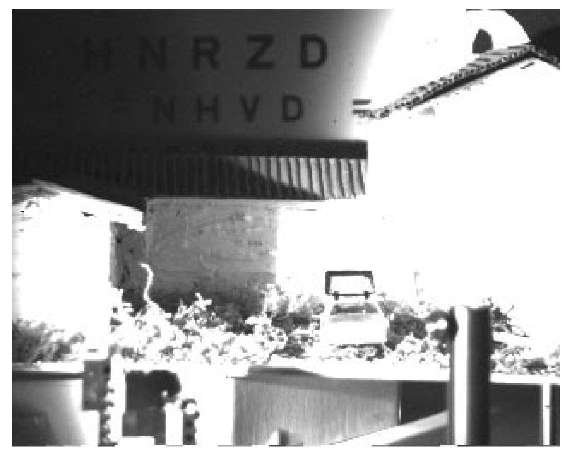
2τ

4τ

8τ

16τ

32τ



(Courtesy of J. DiCarlo)

High Dynamic Range Image Reconstruction

Simple Algorithm: use each pixel's last sample before saturation with appropriate scaling

Limitation of Simple Algorithm

- For a given maximum exposure time, it only enhances dynamic range at high illumination
  - Read noise is not reduced
- Increasing maximum exposure time limited by motion blur

This Work

- Method for simultaneously increasing dynamic range at low illumination end (in addition to high end) and preventing image blur
  - Linear estimation used to reduce read noise
  - Motion detection to prevent blur
- Blur prevention makes possible to further extend dynamic range at low illumination end
- Method is recursive and local (each pixel's samples processed separately)
  - Small memory (independent number of captures)
  - Low computational complexity
  - Well suited to camera-on-chip implementation

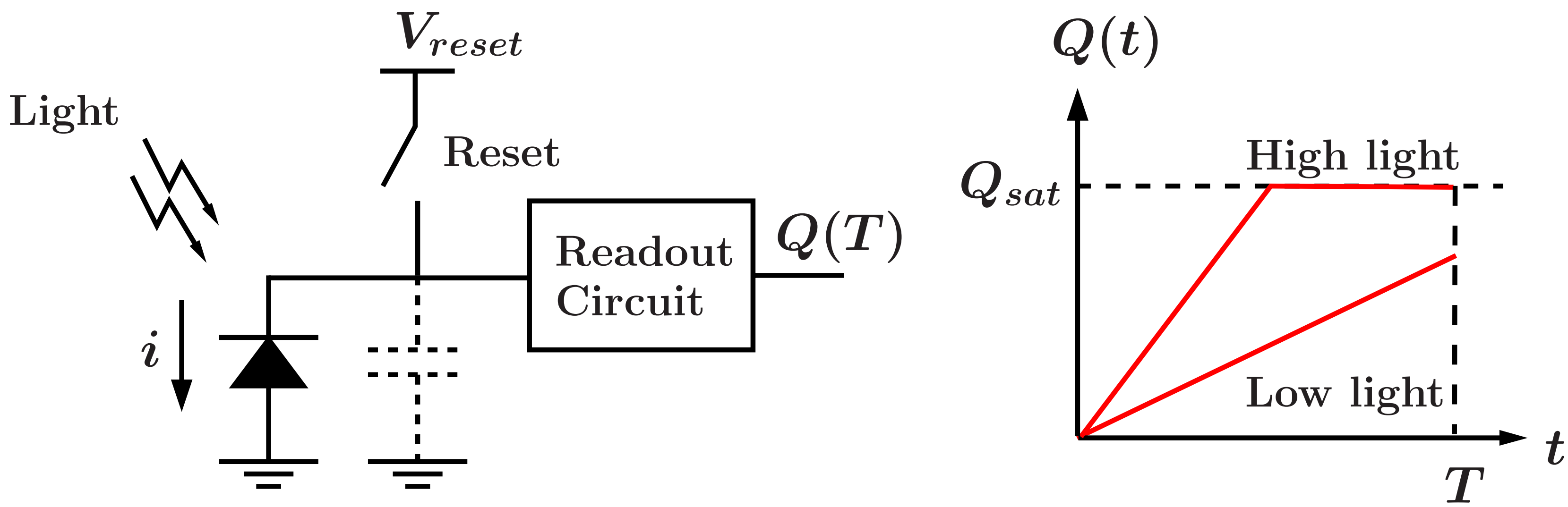
Our Method

- **Capture multiple images at times $\tau, 2\tau, \ldots, n\tau$**
- **After each capture, for each pixel:**
  - **Use the motion detection algorithm to check if motion or saturation has occurred**
  - **If motion or saturation detected, last estimate set as final estimate**
  - **Otherwise use the current estimation algorithm to update the photocurrent estimate**

Outline

- Image sensor operation and model
- Photocurrent estimation algorithm
- Motion detection algorithm
- Simulation results
- Conclusion

CMOS Image Sensor Pixel Operation



- Reset photodetector at beginning of exposure
- Photocurrent integrated into charge for exposure time T
- Charge sampled with two additive noise:
  - Shot noise
  - Read noise

Pixel Model

- Charge at exposure time T:

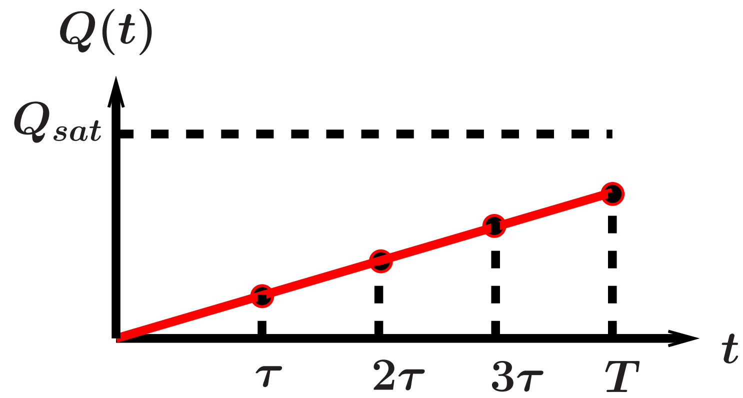
$$Q(T) = \begin{cases} \int_0^T i(t)dt + U(T) + V(T), & Q(T) \leq Q_{sat} \\ Q_{sat}, & \text{otherwise} \end{cases}$$

  - Q_{sat}: saturation charge
  - $U(T) \sim \mathcal{N}(0, q\int_0^T i(t)dt)$: shot noise
  - $V(T)$: read noise with zero mean and variance σ_V^2
  - q: electron charge $\sim 1.6 \times 10^{-19}$ Col.

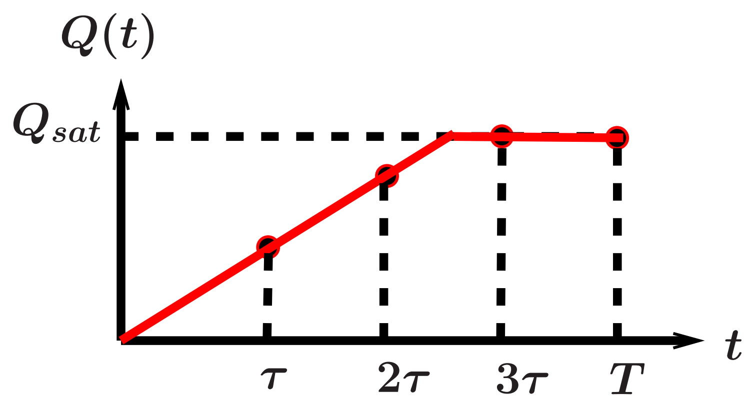
- If no saturation, SNR for constant i is:

$$\text{SNR}(i) = 10\log_{10}\frac{(iT)^2}{qiT + \sigma_V^2}$$

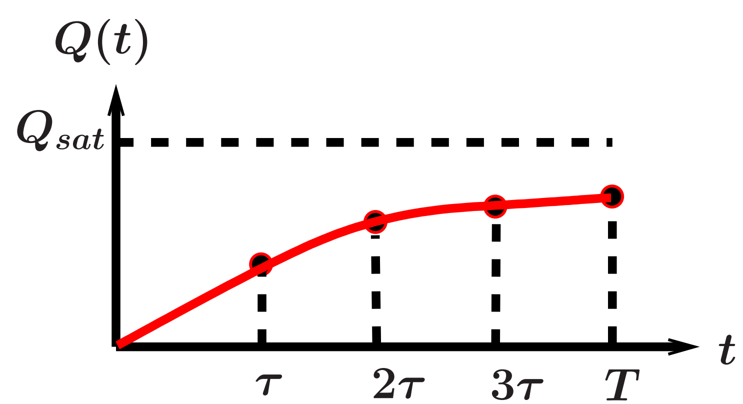
Multiple Image Capture



Constant low light



Constant high light



Changing light (motion)

Photocurrent Estimation

- Assume no motion or saturation, n images captured at $\tau, 2\tau, \ldots, n\tau = T$, for each pixel, the kth sampled current:

$$\tilde{I}_k \triangleq \frac{Q(k\tau)}{k\tau} = i + \frac{1}{k\tau}\left(\sum_{j=1}^{k} U_j + V_k\right),$$

  - i: signal to be estimated
  - V_k: read noise of the kth sample
  - U_j: shot noise during $((j-1)\tau, j\tau]$

- The noise terms all zero mean and independent

$$E(V_k^2) = \sigma_V^2 > 0,$$
$$E(U_j^2) = \sigma_U^2 = qi\tau$$

Estimation Problem

- Use linear MSE estimation to estimate signal i
- At time $k\tau$, find best linear unbiased estimate of i given $\tilde{I}_1, \tilde{I}_2, \ldots, \tilde{I}_k$, *i.e.*, find weights $a_1, a_2, \ldots, a_k$ such that

$$\hat{I}_k = \sum_{j=1}^{k} a_j \tilde{I}_j,$$

minimizes the MSE:

$$\Phi_k^2 = E(\hat{I}_k - i)^2,$$

subject to:

$$E(\hat{I}_k) = i$$

Solution

- Optimal estimate can be expressed in recursive form

$$\hat{I}_k = \hat{I}_{k-1} + h_k(\tilde{I}_k - \hat{I}_{k-1}),$$

  - h_k is a function of a_k, which is recursively computed

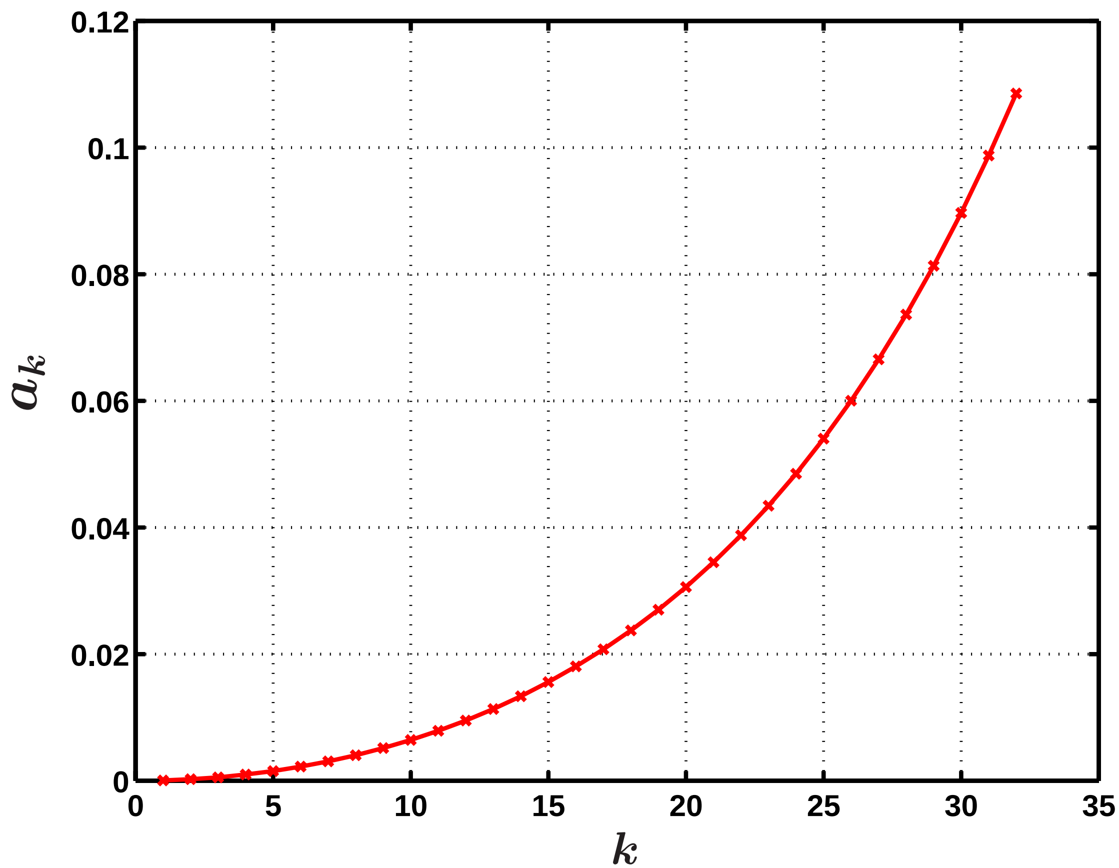
- The MSE of the estimator, Φ_k^2, can be expressed recursively using Φ_{k-1}^2 and a_k as well

  - Will be used in the motion detection step

- The shot noise variance is a function of i

  - Use the latest estimate of i, $\hat{I}_{k-1}$, to estimate it

Optimal Weights



Longer exposure time samples weighted higher than shorter exposure time samples

Motion/Saturation Detection

- Performed after each pixel sample
- Detection algorithm is heuristic due to
  - Incomplete noise statistics
  - Unknown motion model
- After each capture, for each pixel:
  - Compute best predictor, I_{k+1}^{pre}
  - Compute MSE of prediction error,

$$\Delta_{k+1}^2 = E\left((\tilde{I}_{k+1} - I_{k+1}^{pre})^2 | \hat{I}_k\right)$$

  - Perform soft decision to prevent error accumulation

Soft Decision

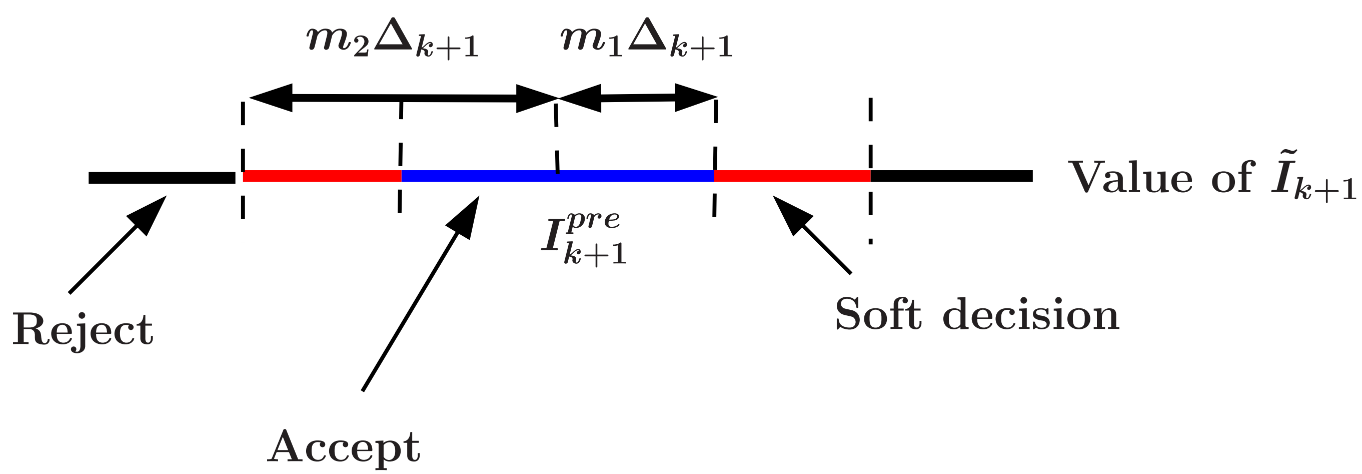
- Hard decision: declare motion occurred if

$$|\tilde{I}_{k+1} - I^{pre}_{k+1}| \geq m\Delta_{k+1}$$

  problem: gradual drift in i can cause error accumulation

- Soft decision: decision deferred if

$$m_1\Delta_{k+1} < |\tilde{I}_{k+1} - I^{pre}_{k+1}| < m_2\Delta_{k+1}$$



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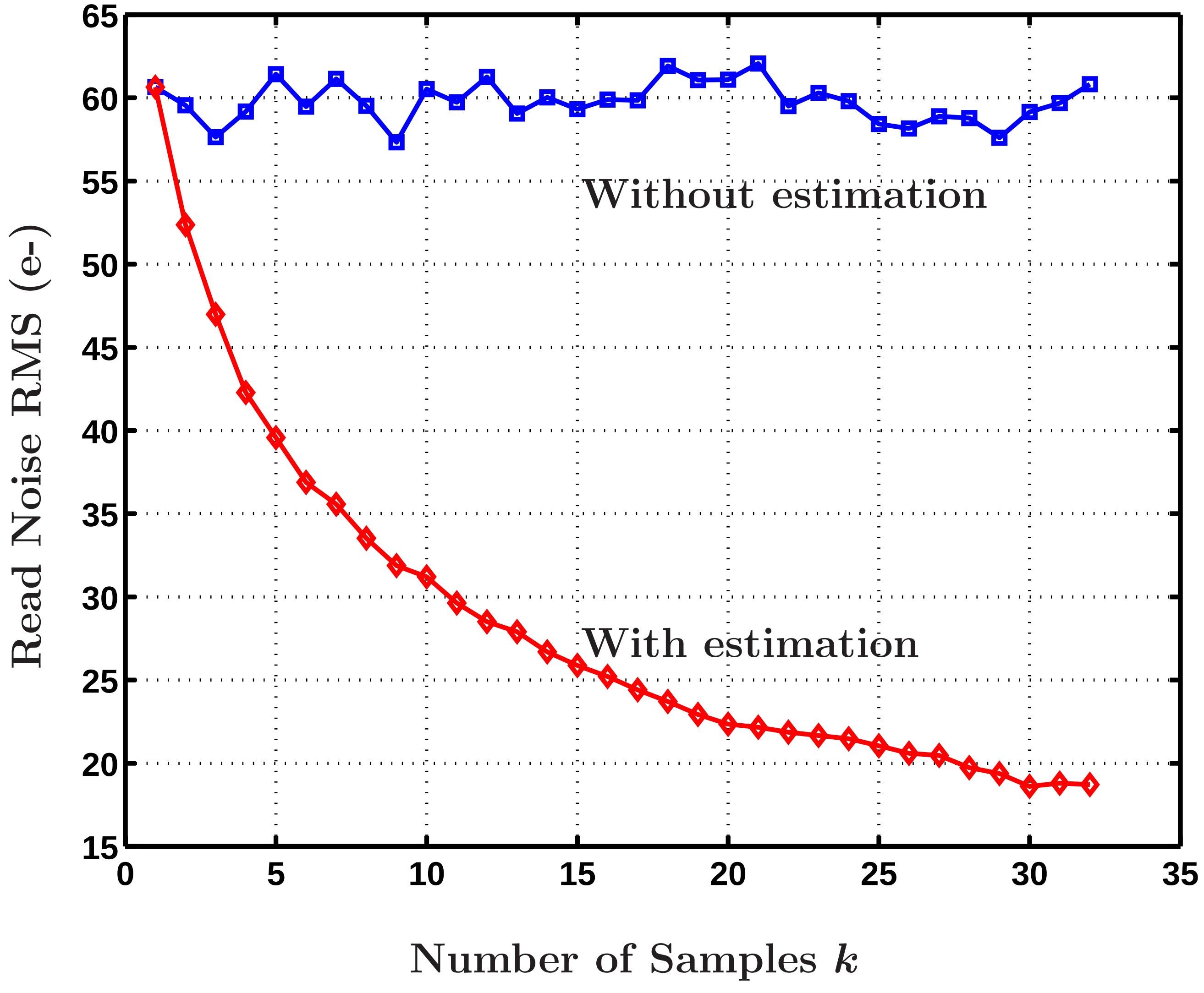
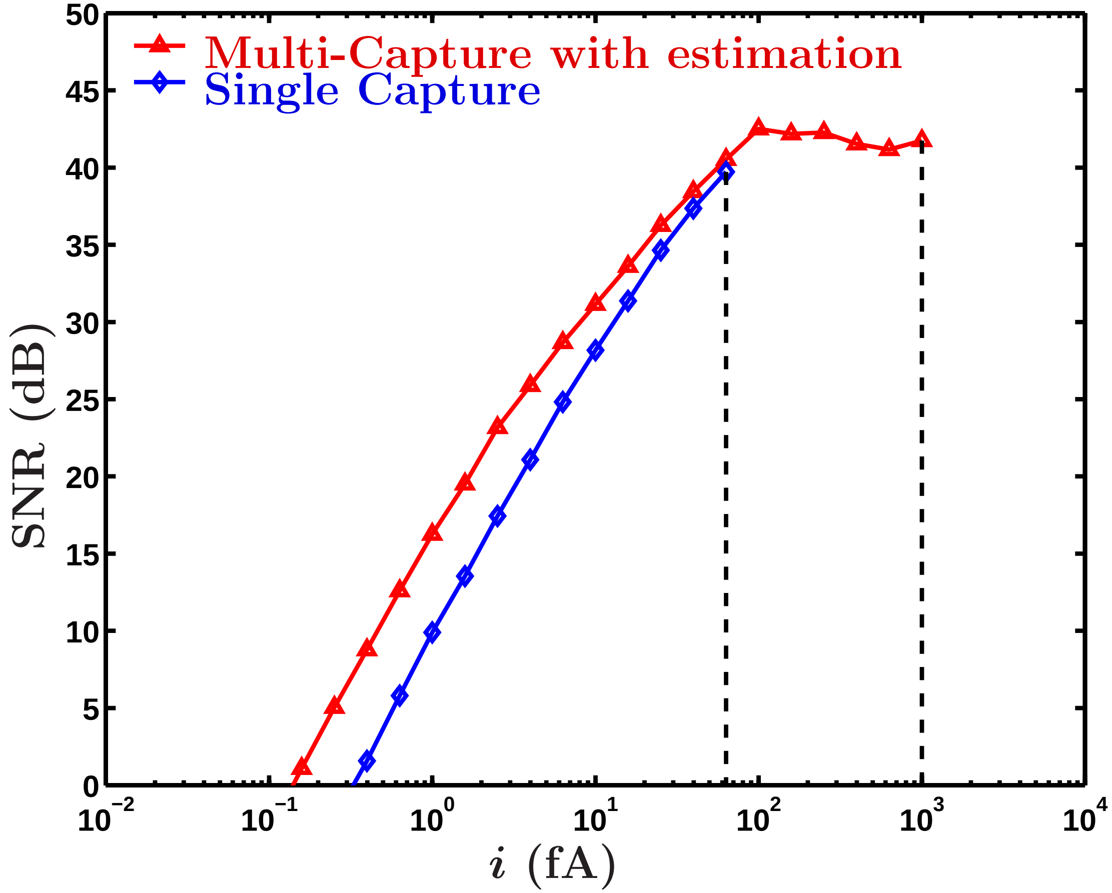
Read Noise Reduction (constant i)



Dynamic Range and SNR Improvements



Dynamic range improved from 47dB to 85dB (30dB improvement at high end and 8dB at low end)

Motion Blur Prevention Example

Frame 1

Frame 20

Conventional sensor

Our method

(Courtesy of C. Bregler)

Conclusion

- **Describe method for simultaneously increasing dynamic range and restoring image blur**
  - Linear estimation used to reduce read noise
  - Motion detection to prevent blur
- **Algorithm is recursive and local**
  - Small memory
  - Low computational complexity
  - Well suited to camera-on-chip implementation