The International Symposium on

Optical Science and Technology

Noise performance comparison of ICCD with CCD and EMCCD cameras

Paul Hoess, David Dussault
Stanford Computer Optics / Paul Hoess KG, Munich, GERMANY

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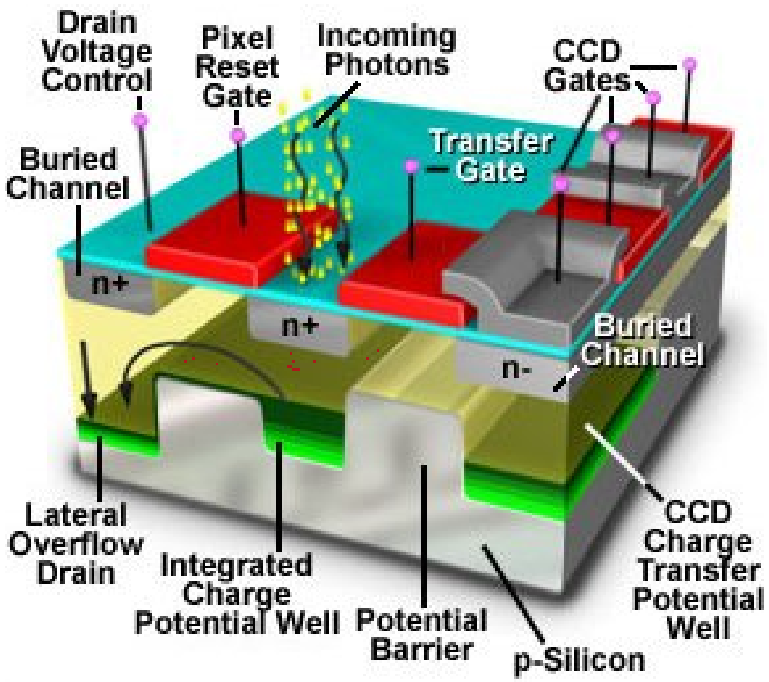
Topics

- **Introduction - 3 LLL sensing concepts**
  - CCD
  - ICCD
  - EMCCD
- **Noise sources**
  - Shot noise
  - Dark current noise
  - Readout noise
- **Signal-to-noise ratio**
  - Single frame operation
  - Long integration time versus frame adding
- **Discussion of the simulation results**
- **Conclusions**

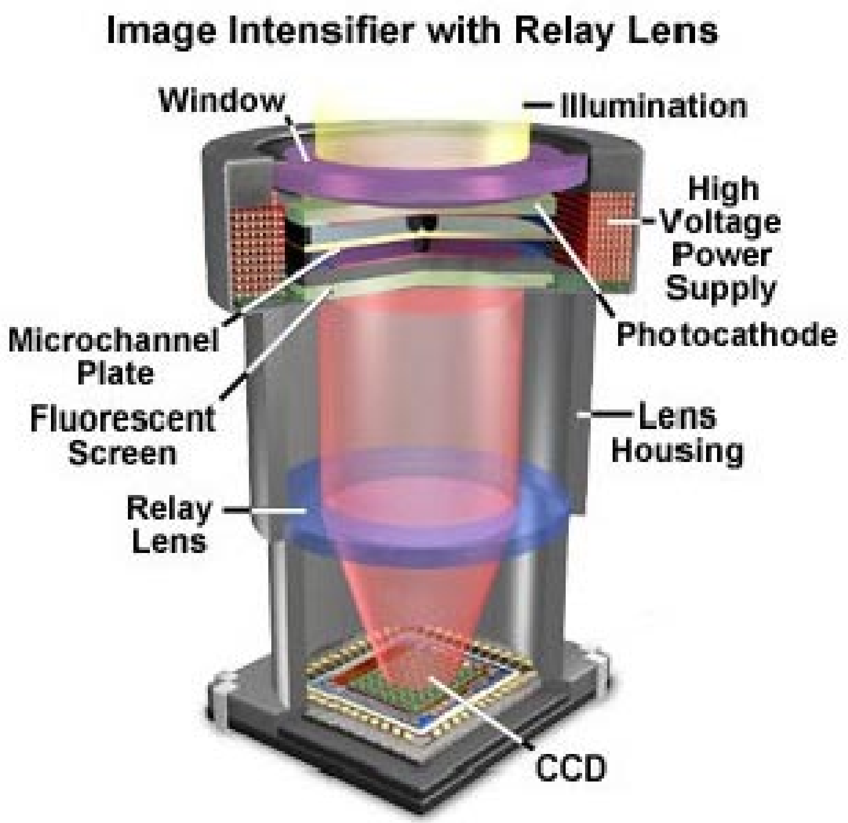
CCD (Charge-Coupled Device)



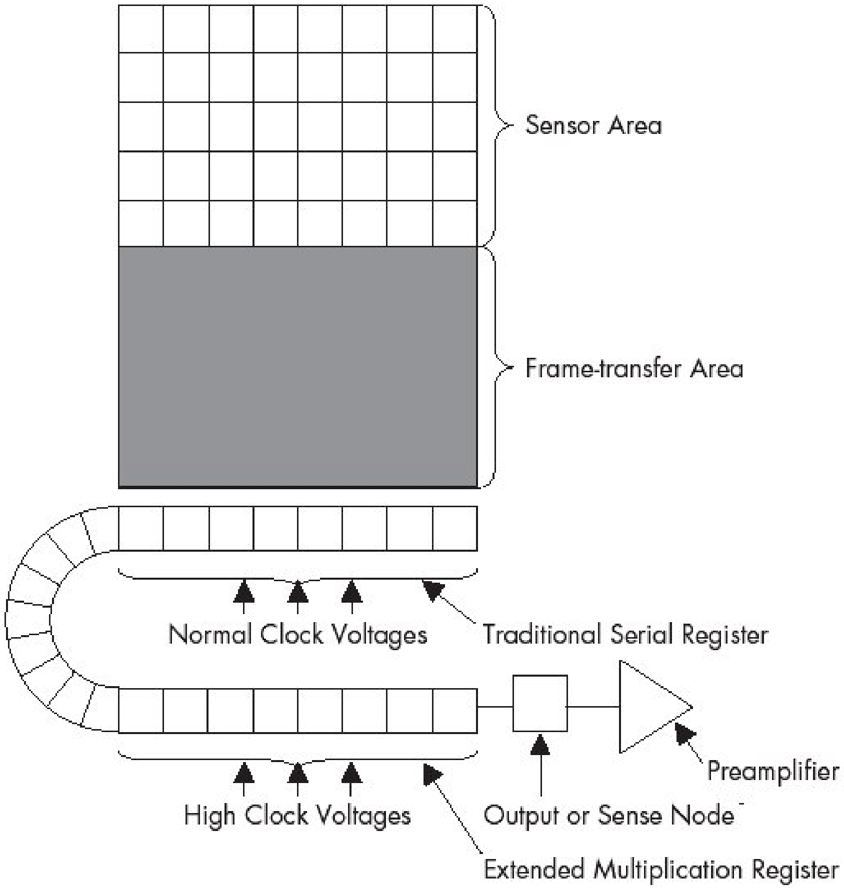
- CCD = array of photodiodes (light-sensitive pixels).
- **Generation** (high Q.E. η, 1e$^-$ per photon) and **storage** of electrons when exposed to light.
- Read-out of the charge by changing the electrical bias of an adjacent pixel.
- Charge to voltage conversion, digitization to numerical value by external circuitry.

ICCD (Intensified CCD)

- Photocathode: Generation (low Q.E. η, 1e$^-$ per hν) of photoelectrons.
- Microchannel plate (MCP): multiplication (G_{MCP}) of electrons.
- Phosphor screen: conversion (G_{screen}) of electrons back into highly increased (x10^4-10^6) number of photons.
- High numerical aperture lens-coupling for superior distortion free image quality.
- CCD: conversion of the very high number of photons to charge, readout and digitization.



EMCCD (Electron Multiplying CCD)



- Generation and storage of electrons (high Q.E. η, 1e$^-$ per photon), equivalent to CCD.
- Amplification by impact ionization in the gain register.
- Charge to voltage conversion, digitization equivalent to CCD.

Noise sources [1]

All signals and noises are calculated in equivalent number of electrons at system output.

- Shot noise N_{shot} [e^-/pixel]

$$N_{shot} = G \times F \times \sqrt{\eta \phi_p \tau}$$

G: multiplication gain

F: noise factor of gain

η: quantum efficiency

ϕ_p: mean incident photon flux per pixel

τ: integration time [s]

Noise sources [2]

- Dark current and its noise N_{dc} [e$^-$/pixel]

$$N_{dc} = \left[2.55 \cdot 10^{15} N_{dc0} \tau \cdot d_{pix}^2 T^{\frac{3}{2}} e^{\left(\frac{-E_g}{2kT}\right)} \right]^{1/2}$$

N_{dc0}: dark current at room temperature [nA/cm²]
d_{pix}: pixel size [cm]
T: operating temperature [K]
E_g: bandgap energy in eV
k: Boltzmann's constant
($8.62 \cdot 10^{-5}$eV/K)

Noise sources [3]

- Read-out noise N_r:
  - generated through charge transfers across the CCD.
    readout amplifier reset, "any other" electronic noises
  - Strongly pixel clock (frame rate) and slightly temperature dependent.
  - independent of integration time.
  - for EMCCDs:

$$N_r = \left[N_{r0}^2 + \left(G \times N_{ct}\right)^2\right]^{1/2}$$

where N_{ct} is the charge transfer noise that is multiplied in the gain register and N_{r0} is all other non-multiplied readout noises.

Noise sources

- Total noise N_{tot}:

$$N_{tot} = \left(N_{shot}^2 + N_{dc}^2 + N_r^2\right)^{1/2}$$

Signal-to-noise ratio [1]

- Single frame operation

$$SNR_{unit} = \frac{G\eta\phi_p\tau}{(N_{shot}^2 + N_{dc}^2 + N_r^2)^{1/2}}$$

- Shot-noise-limited operation if N_r and N_{dc} << N_{shot}:
  - high Φ_p,
  - high G,
  - or N_r and N_{dc} extremely small.

Signal-to-noise ratio [2]

- Long time integration (traditional approach):

$$SNR_{long} = \frac{n_l G\eta\phi_p\tau}{\left[n_l(N_{shot}^2 + N_{dc}^2) + N_r^2\right]^{1/2}} = \sqrt{n_l}\,\frac{G\eta\phi_p\tau}{\left[N_{shot}^2 + N_{dc}^2 + \left(N_r^2/n_l\right)\right]^{1/2}}$$

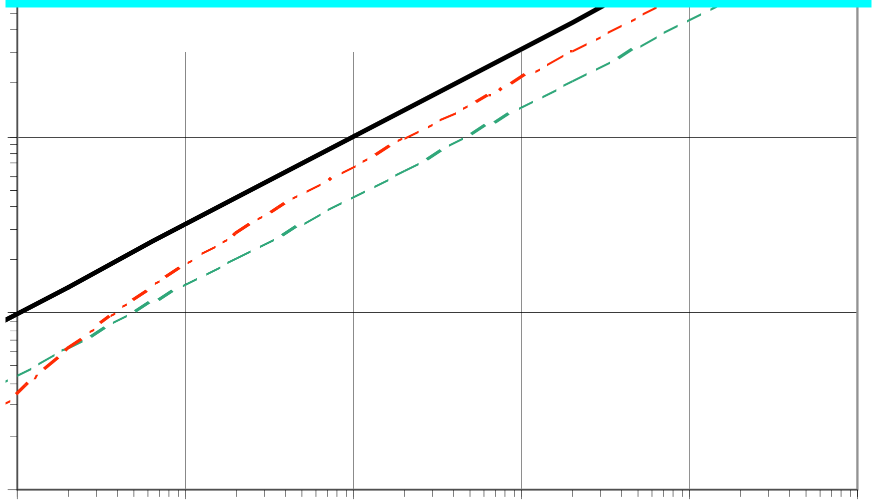
where n_l is the factor by which the integration time τ is increased.

Parameters of the simulation

- **CCD:**
  - η=50%, front-illuminated
  - G=F=1
  - N_r=25e$^-$ (5MHz) or 5e$^-$ (1MHz)
- **ICCD:**
  - η=50%
  - F=1.6
  - G=500
  - N_r=25e$^-$
- **EMCCD**:
  - η=50% (FI) or 90% (BI)
  - F=1.4
  - G=500
  - N_{r0}=25e$^-$
  - N_{ct}=2.2e$^-$ (31kHz) or 5.4e$^-$ (1MHz)

- τ=20 ms
- N_{dc0}=0.1 or 3nA/cm² @ 300K

short frame mode



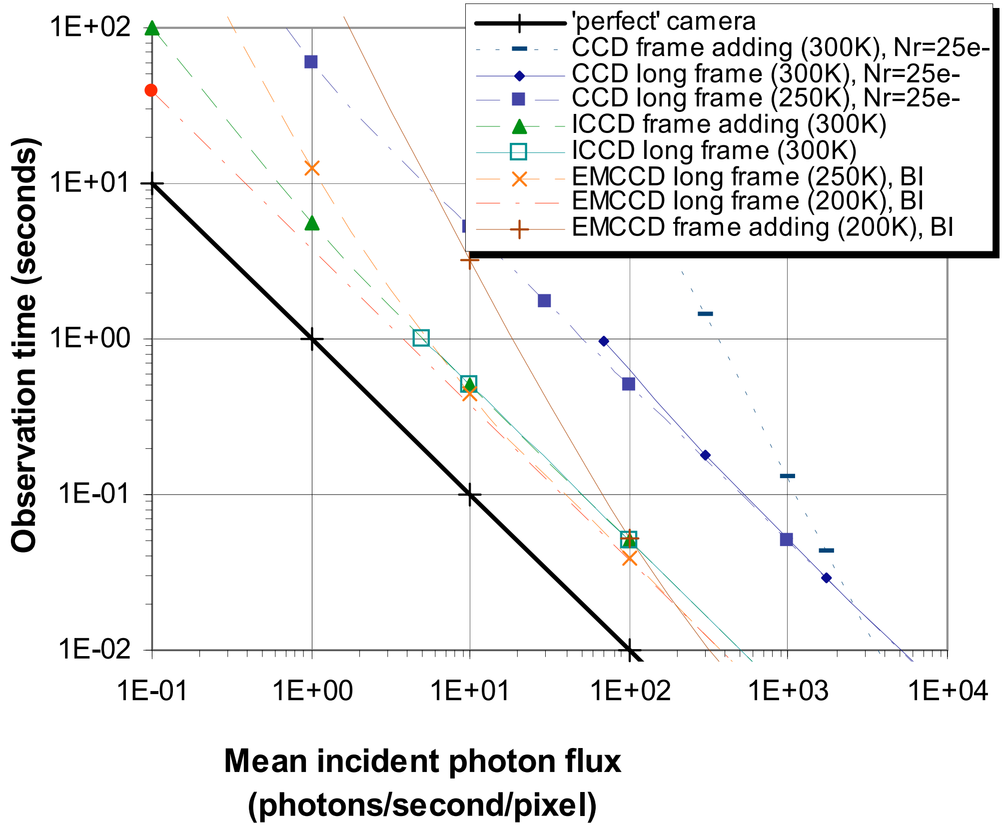
Simulation of extended integration time

low to very low Φ_p, low camera noise

- **CCD:**
  - Better SNR with long frame.
- **EMCCD:**
  - Clear influence of cooling in low light conditions,
  - frame adding not as effective as for ICCD.
- **ICCD:**
  - Same results with frame adding or long frame,
  - cooling not required.

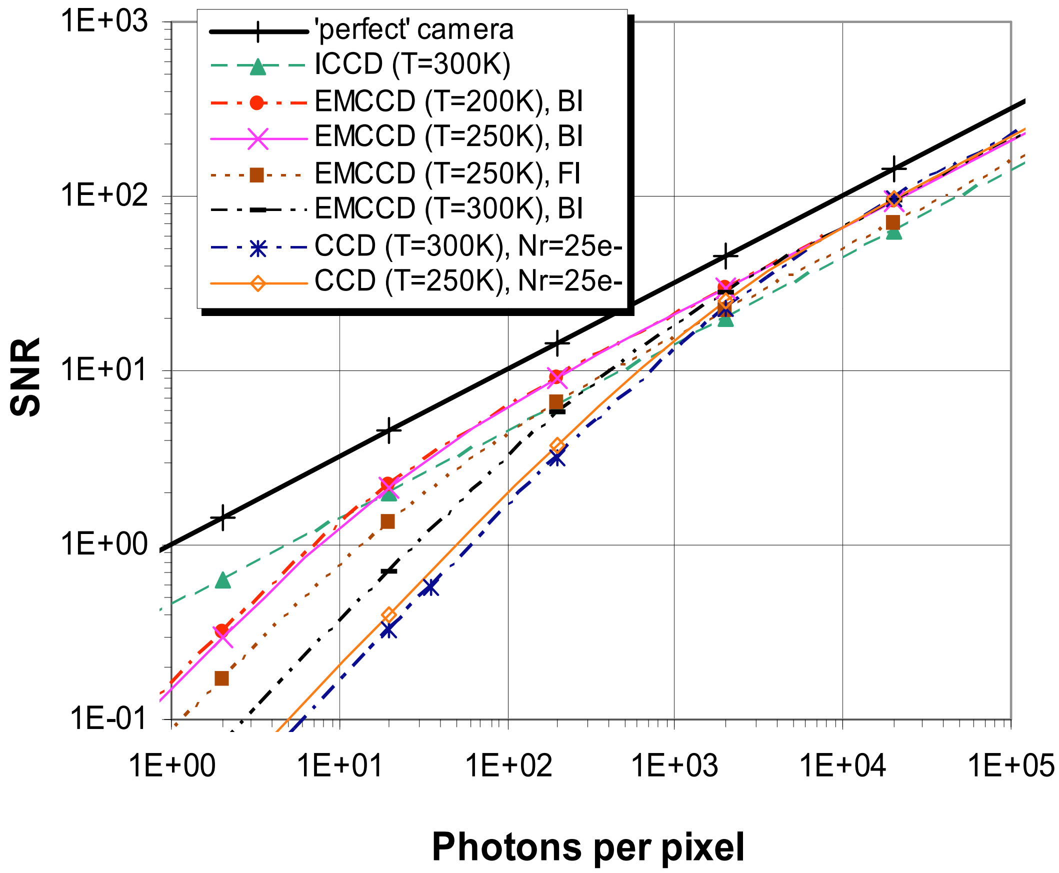
Parameters:

- τ=20ms
- N_{dc0}=0.1nA/cm²
- N_{ct}=2.2e$^-$



Simulation of single short frame mode

high to medium Φ_p, high camera noise, realistic operating conditions



- **CCD**:
  - Negligible temperature influence at 5MHz readout rate.
- **EMCCD:**
  - Still a decrease of the SNR in LLL,
  - Slightly superior to CCD at room temperature,
  - SNR improvement for lower temperatures,
  - BI: high QE, slight temperature dependence, readout dominated.
- **ICCD:**
  - Still in shot-noise-limited operation, unchanged.

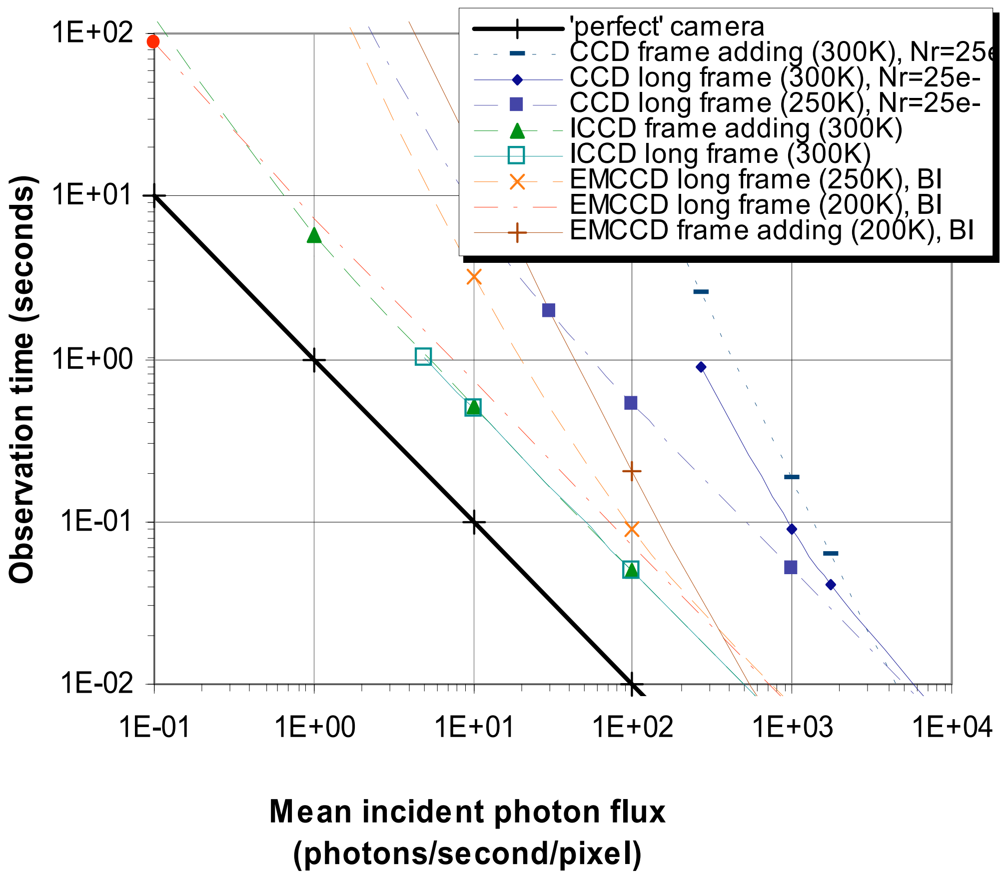
Parameters:

- τ=20ms
- N_{dc0}=3nA/cm²
- N_{ct}=5.4e$^-$

Simulation of extended integration time

low to very low Φ_p, high camera noise, realistic operating conditions

- **CCD:**
  - Long frame better than frame adding,
  - Frame adding: significant sensitivity increase without additional hardware.
- **ICCD:**
  - No influence of noises, better than EMCCD over a wide range.
- **EMCCD:**
  - Better than ICCD only at extremely low light levels (int. time ≥ 1min.)



Parameters:

- τ=20ms
- N_{dc0}=3nA/cm²
- N_{ct}=5.4e⁻

Conclusions

- Best SNR provided by CCD at high light levels, operating range extended to low light levels through slow scan and cooling.
- Need for strong cooling of EMCCD sensors to eliminate dark current.
- Need for very low frame rates operation for EMCCDs in order to minimize charge transfer noise.
- No cooling, no slow scan required for the CCD sensor of an **ICCD** system.