Noise performance comparison of ICCD with CCD and EMCCD cameras

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ABSTRACT

High quality imaging is a key parameter in many scientific applications. CCD and ICCD cameras have proven to be powerful tools and are consequently used in a wide range of fields such as engineering research and physical or biological sciences. The very new Electron Multiplying CCD technology seems now to provide the most sensitive detection capabilities. Here we compare analytically the signal-to-noise performance of the three systems and identify the most influencing parameters. The SNR provided by CCDs is strongly influenced by the readout noise and is also a significant function of the pixel rate. ICCD cameras are practically not at all affected by the CCD chip temperature and are shown to be mostly shot-noise-limited because readout and dark current noises are negligible. Therefore no cooling is needed for ICCDs. Although EMCCDs unite the quantum efficiency of CCDs and the gain of ICCDs, their performance is constricted by charge transfer and dark current noises which will be multiplied up along with the signal by the gain register. Therefore, EMCCDs must be strongly cooled (down to -70°C) and slowly read out in order to get rid of any unwanted "pseudo signal". In addition, their properties limit exposure times to milliseconds time scales and longer. We conclude that ICCD cameras remain the most efficient systems in all gated experiments and perform very well in extreme low light situations. They still keep great advantages over standard CCDs and the new incoming generation of EMCCDs.

Keywords: CCD, ICCD, EMCCD, SNR, shot noise, dark current, readout noise, Clocking Induced Charge, Charge Transfer Efficiency.

1. INTRODUCTION

A charge-coupled device (CCD) is an array of photodiodes (light-sensitive pixels) that are electrically biased so that they generate and store electrons (electric charge) when exposed to light. The amount of charge trapped beneath each pixel directly relates to the number of photons illuminating the pixel. This charge is then "read out" by changing the electrical bias of an adjacent pixel so that the charge travels out of the sensor, is converted into a voltage and is then digitized into a numerical value. This action is performed for each pixel to create an electronic image of the scene. Electronics inside the camera controls the readout process.

In an intensified camera (ICCD), an image intensifier is placed in front of the CCD chip to enhance its light detection capability. These photon multipliers typically comprise three main components: a photocathode, a microchannel plate (MCP) and a phosphor screen as shown in **Figure 1 (a)** on next page.

The respective roles of these devices are to convert the incident photons into electrons which are then multiplied to a number that is dependent on the gain voltage (600-900V typically) applied to the MCP, and finally converted (by the phosphor screen) back into photons ready for the CCD to detect. The phosphor screen is usually coupled to the CCD by a fiber optic bundle. Some manufacturers use high numerical aperture coupling lenses. They provide superior distortion-free image quality when compared to taper-coupled systems.

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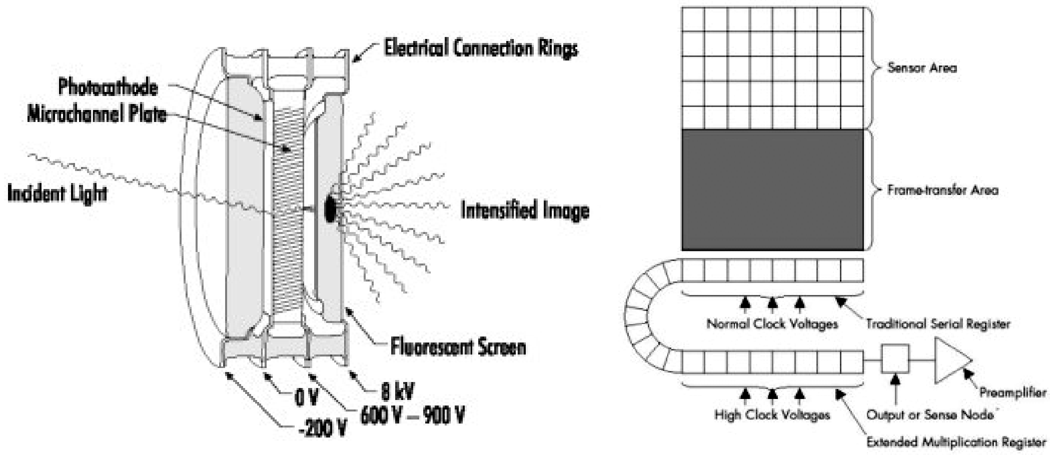


(a) **(b)**

Figure 1. a) Components of an image intensifier tub ; b) Structure of an EMCCD sensor.

Electron Multiplying CCD (EMCCD) cameras are an alternative approach that do not use a standard image intensifier. Instead an electron multiplying structure (called a gain register) is inserted between the end of the shift register and the output amplifier (see **Figure 1. (b)**). The design of this gain register is such that its high voltage causes impact ionization that generates new electrons. Consequently, this technique enables charge (photon induced but also unwanted thermally generated charge) from each pixel to be multiplied on the sensor before it is read out.

Due to these different processes, CCD, ICCD and EMCCD systems behave differently in terms of resolution, speed, sensitivity, and noise. Noise characteristics are probably the most important criteria when comparing imaging systems because they determine the detection limit. Here we address the theoretically calculated signal-to-noise ratio (SNR) characteristics of CCD, ICCD and EMCCD cameras.

2. NOISE SOURCES

Let us enumerate the noise sources which limit the performance of scientific grade CCD, ICCD and EMCCD cameras. The potential noise sources in such systems are the signal inherent shot noise (sometimes called input or photon noise), plus dark current noise and readout noise which is generated in the detector [1]. All following calculations relate to number of electrons at the CCD sensor output node which is consecutively always called signal or noise.

2.1. Shot noise

Shot noise is a fundamental property of the quantum nature of light and arises from statistical fluctuations in the number of photons emitted from the object. This noise source is unavoidable and always present in imaging systems. In terms of signal-to-noise ratio, the best a detector can do is to approach the shot-noise limit. The pseudo signal produced by shot noise (N_{shot}) can be described by Poisson statistics:

$$N_{shot} = G \times F \times \sqrt{\eta \phi_p \tau} \qquad (1)$$

where G is the overall electron (or multiplication) gain (for a non intensified CCD, G=1), and takes, for an ICCD, all system conversion and coupling efficiencies into account ; η is the quantum efficiency (QE) that characterizes the photoelectrons generation process at a given wavelength ; Φ_p is the mean incident photon flux in photons per second per pixel ; τ [s] is the integration time in seconds ; and F is the noise factor which quantifies the noise that is introduced by the gain process itself. For an ICCD or EMCCD system, F is gain dependent and falls within the range $1.3 < F < 2$ [3]. In a non intensified CCD, G=F=1, and the shot noise is equal to $(\eta\Phi_p\tau)^{1/2}$, which is the square root of the number of photoelectrons collected per pixel during the integration period.

2.2. Dark current and its noise

Dark current is caused by thermally generated electrons in the silicon substrate of the CCD. The dark current is often incorrectly confused with its noise, but since the constant pattern signal part is repeatable, this can be subtracted from image data. If not subtracted, it does add its own typically noisy-looking contribution to the image, but almost all of this disappears when a dark field subtraction is performed. Superimposed on this signal is statistical modulation in the form of shot noise (the same as in the photon signal we want to measure). In any CCD sensor, dark current noise (N_{dc}) is given by the square root of the dark current signal:

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

where N_{dc} is in electrons per pixel; N_{dc0} is the dark current in nA/cm² at 300K; d_{pix} is the pixel size in cm (here, for better comparison, we assume that $d_{pix} \approx 9\mu m$ for CCD, ICCD and EMCCD systems); T is the operating temperature in K; k is the Boltzmann's constant ($8.62 \cdot 10^{-5}$eV/K); E_g is the bandgap energy in eV given by the following relation:

$$E_g = 1.1557 - \frac{7.021 \cdot 10^{-4} T^2}{1108 + T} \qquad (3)$$

Cooling a CCD greatly reduces the dark current. For example, a non cooled CCD might generate a dark current of 300e/s/pixel at 20°C, but only 1e/s/pixel at -40°C.

In the particular case of EMCCD cameras, note that any dark current still remaining will be multiplied up along with the signal. Consequently, when calculating the signal-to-noise ratio, the dark current noise must be multiplied by the on-chip multiplication gain of the EMCCD. That's why EMCCD chips must be ideally strongly cooled (down to -73°C) thus drastically increasing the cost of such a device.

We found a high variance of dark current data in the literature. All of the numbers given by CCD and EMCCD manufacturers were only "calculated by design". We found no measured information, this may partially be due to the fact that correlated double sampling is applied to most CCD systems for readout which makes measurement difficult. Therefore we made calculations with two extreme values, 0.1nA/cm² and 3.0nA/cm², respectively. Only the latter did lead to significant changes in SNR numbers with temperature.

2.3. Readout noise

Readout noise (N_r) is generated by the electronic circuitry that converts the charge from each pixel into a digitized light-intensity proportional number that is displayed in the image. When the accumulated charges are shifted on the CCD-chip, electrons may be left behind or jump ahead. Readout noise is always present and also includes "reset noise", output amplifier noise and quantization noise. It is strongly frame rate dependent but independent of integration time. Typical numbers are given later in this article.
For EMCCD detectors, we separated the readout noise into two components: N_{r0} and N_{ct}. As any noise generated by the charge transfer process across the chip area before reaching the gain register would also be multiplied, we include this effect in our analysis as Charge Transfer Noise (N_{ct}). Two typical values as given in reference [6] were taken for N_{ct}: 2.2e^- rms (31kHz) and 5.4e^- rms (1MHz). N_{r0} represents all other non-multiplied readout noises.

The Clocking Induced Charge (CIC) and Charge Transfer Efficiency (CTE) are additional limiting factors in EMCCD cameras. They are gain and signal dependent and occur as a result of impact ionization during charge transfers. These phenomena are described in more details in reference [3].
We did not integrate these effects in our simulation because N_{ct} has a very severe impact on the SNR already at low pixel clock frequencies. Charge transfer noise can be considered as upper performance limit, whereas the CIC and CTE are not well documented and would further decrease the SNR features.

2.4. Total noise

For "white noise" the mean square fluctuations do add, so the overall noise generated by CCD, ICCD or EMCCD cameras is then given by:

$$N_{tot} = \left(N_{shot}^2 + N_{dc}^2 + N_r^2\right)^{1/2} \tag{4}$$

Shot noise and dark current noise are both functions of the integration time τ. For convenience let us group these noise sources together and write:

$$N_\tau = \left(N_{shot}^2 + N_{dc}^2\right)^{1/2} \tag{5}$$

Consequently, the total noise N_{tot} generated by CCD, ICCD or EMCCD can now be expressed as:

$$N_{tot} = \left(N_\tau^2 + N_r^2\right)^{1/2} \tag{6}$$

with:

$$N_r = \left[N_{r0}^2 + (G \times N_{ct})^2\right]^{1/2} \tag{7}$$

for the particular case of EMCCDs.

3. SIGNAL-TO-NOISE RATIO

We compare the SNR performances of CCD, ICCD and EMCCD cameras by first calculating the SNR obtained within a single frame in a quasi-video mode and then its increase through frame adding or extended integration time.

3.1. Single frame operation

The signal-to-noise ratio (SNR) for a single frame is given by:

$$SNR_{unit} = \frac{G\eta\phi_p\tau}{(N_\tau^2 + N_r^2)^{1/2}} \tag{8}$$

When the signal is dominated by shot noise, we have $N^2_{shot} >> N^2_{dc}$ and $N^2_{shot} >> N^2_r$. This shot-noise-limited operation of the camera occurs when either the readout and dark current noises are small or when the signal is high. Moreover we can obtain shot-noise-limited operation by increasing the gain (only possible with an ICCD or EMCCD camera) until we have N^2_{shot} dominating all the other noise sources. This is the main advantage of ICCD and EMCCD over CCD for low signals. They can generate a very high electron gain and thus cause the shot noise to overwhelm the noise generated by the camera electronics. At low gain, the signal will be detector-noise limited and as the gain is increased to arbitrarily high levels, the SNR continues to improve until it reaches the shot noise limit, beyond which the SNR is constant.

We use an integration time of 20 ms for the following analysis. **Figures 2** and **3** show the SNR variation as a function of the number of photons per pixel ($\phi_p\tau$) for cooled and non cooled CCD, ICCD and EMCCD cameras. A CCD was chosen with the following parameters: quantum efficiency η=50%, noise factor F=1, electron gain G=1. In order to analyze the limitation of readout noise, we took two extreme values as given in **Figure 2** and **3**: N_r=25e$^-$ and N_r=5e$^-$. The ICCD camera is assumed to have filmless GaAsP image intensifier with a peak quantum efficiency of 50%, an electron gain G of 500, a noise factor F of 1.6 and a readout noise N_r of 25e$^-$ at 250K and 300K. Both front-illuminated (FI) and back-illuminated (BI) EMCCD cameras have also been simulated. Whereas FI sensors offer a typical peak quantum efficiency of 50%, the quantum efficiency provided by BI formats can reach up to 90%. Furthermore we chose an on-chip multiplication gain of 500, a noise factor of 1.4, and a readout noise N_{r0} of 25e$^-$ at 300K, 250K and 200K.

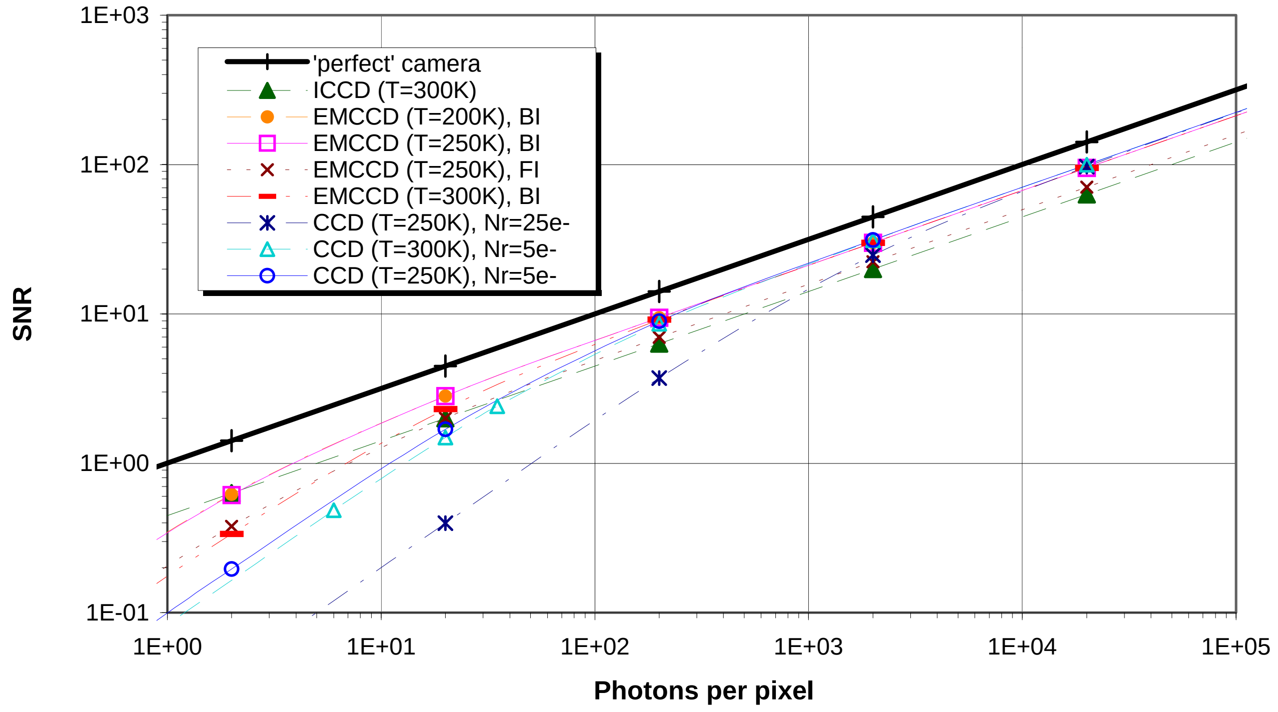


Figure 2. Variation of the SNR vs. signal ($\Phi_p\ \tau$) for CCD, ICCD and EMCCD (BI and FI) systems at 20ms integration time, with low camera noise (N_{dc0}=0.1nA/cm² and N_{ct}=2.2e^- rms).

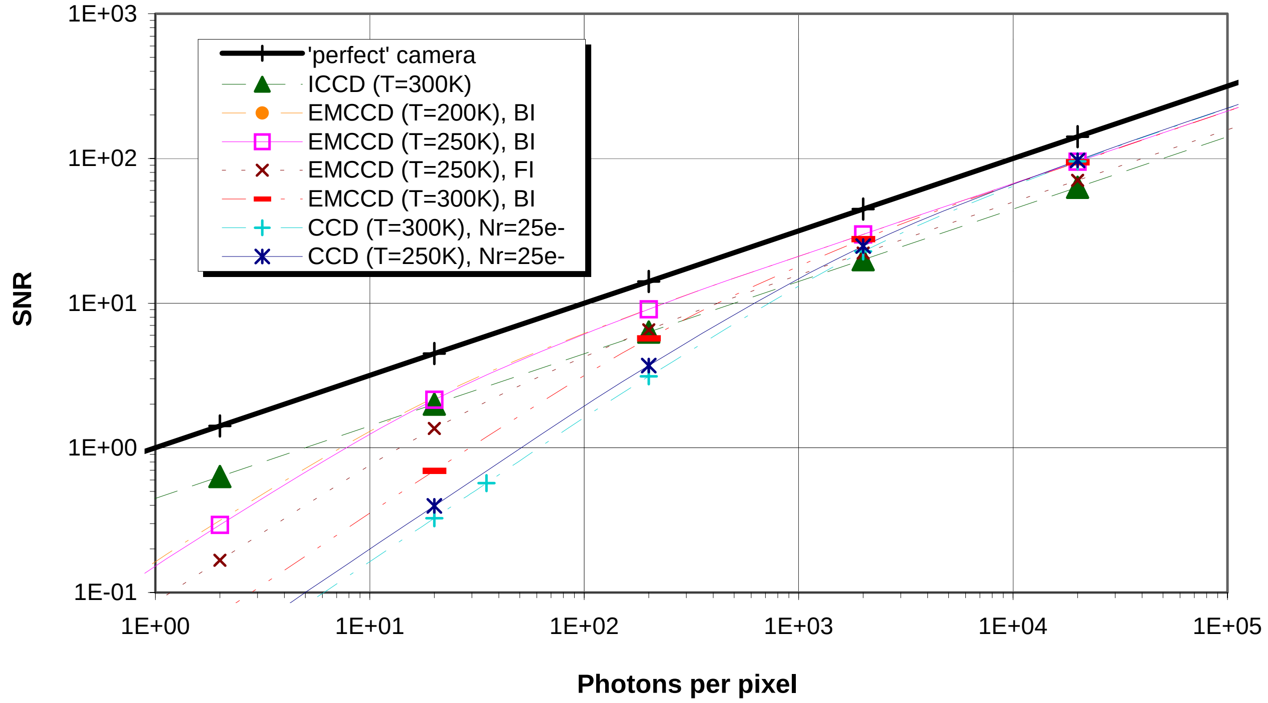


Figure 3. Variation of the SNR vs. signal ($\Phi_p\ \tau$) for CCD, ICCD and EMCCD (BI and FI) systems at 20ms integration time, with high camera noise (N_{dc0}=3nA/cm² and N_{ct}=5.4e^- rms).

In **Figures 2** and **3**, the upper black line represents the ideal case of a shot-noise-limited imaging system with a QE of 100%. The maximum attainable SNR of such a 'perfect' camera is 3 for a signal of 10 photons per pixel and 300 at 10^5 photons per pixel.

Figure 3 shows that the SNR provided by the cooled CCD is only very slightly higher than for the non cooled CCD camera even for high dark current. Furthermore, comparing **Figures 2** and **3**, the CCD seems to be only very little affected by the dark current variation. It turns out that the readout noise is the dominant limiting factor in non-intensified CCD systems. It has a much stronger influence on the SNR than dark current noise and shot noise especially in low light levels. That is the reason why CCD must preferably operate at very low readout rates (<50kHz).

A somewhat surprising result of this analysis does show no significant improvement of the SNR when cooling the sensor of an ICCD system. Indeed it was observed that, beyond an electron gain of roughly 100, the non cooled ICCD operates in the shot-noise-limited mode. Hence we consider chip cooling of an ICCD camera as being unnecessary and a useless cost increase of the system. Furthermore the ICCD camera clearly outperforms the cooled CCD in low light conditions but, for a number of photons per pixel greater than about 400, the cooled low noise CCD (**Figure 2**) gains the advantage over the ICCD.

EMCCD systems do amplify the dark current and provide very poor SNR when not cooled deep enough, especially in low light situations. Even if the dark current at room temperature N_{dc0} is as low as 0.1nA/cm² (**Figure 2**), the back-illuminated EMCCD detector is at low light levels not shot-noise-limited but is constricted by the Charge Transfer Noise (CTN). In this example, cooling the EMCCD sensor to extremely deep temperatures does not significantly influence the SNR. In order to achieve a totally shot-noise-limited operation the readout rate of the EMCCD sensor must be decreased as for a standard CCD system. Only then CTN would be covered by shot noise and would only have a very low impact on the SNR. In that case, due to its 1.8 times higher quantum efficiency, the SNR provided by the BI EMCCD technology would be 50% higher than that of an ICCD at medium to high light levels.

Finally, depending on the systems' settings and by operating at appropriate wavelength, exposure time and signal level, either the ICCD or EMCCD performs better in terms of SNR and sensitivity.

3.2. Long frame integration versus frame adding

For a constant illumination, the SNR generated by a single frame (**Equation (8)**) can easily be improved (i.e. increased) by taking longer frames or adding successive single frames [1]. Indeed, we can demonstrate that, when taking longer frames, the SNR is given by:

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

or

$$SNR_{long} = \sqrt{n_l}\,\frac{G \eta \phi_p \tau}{\left[N_\tau^2 + \left(N_r^2 / n_l\right)\right]^{1/2}} \tag{9}$$

where n_l is the factor by which the integration time τ is increased. Obviously, this n_l factor only affects the integration time dependent terms that is the input signal, shot noise and dark current noise (N_τ).

Frame adding leads to the following relation:

$$SNR_{add} = \frac{n_a G \eta \phi_p \tau}{\left[n_a \left(N_\tau^2 + N_r^2\right)\right]^{1/2}}$$

or

$$SNR_{add} = \sqrt{n_a}\,\frac{G \eta \phi_p \tau}{\left(N_\tau^2 + N_r^2\right)^{1/2}} \tag{10}$$

where n_a is the number of unit frames that are added together. In that case, the n_a factor applies not only to the integration time dependent terms but also to the readout noise. This leads to a SNR improvement of $(n_a)^{1/2}$ over the unit frame and approaches the long frame SNR.

The results of the simulation are displayed in **Figures 4** and **5**. It shows the observation time needed to obtain an unity SNR at a given photon flux Φ_p when performing long time frame integration or frame adding with CCD, ICCD and EMCCD systems. This graph was plotted by using **Equations (9)** and **(10)**. The values of n_a (for frame adding) and n_l (for long frame) that are necessary to maintain an unity SNR were calculated. These values were then multiplied by the single frame integration time (τ=20ms) in order to obtain the total observation time. The CCD, ICCD and EMCCD were chosen with the same parameters as in section 3.1.

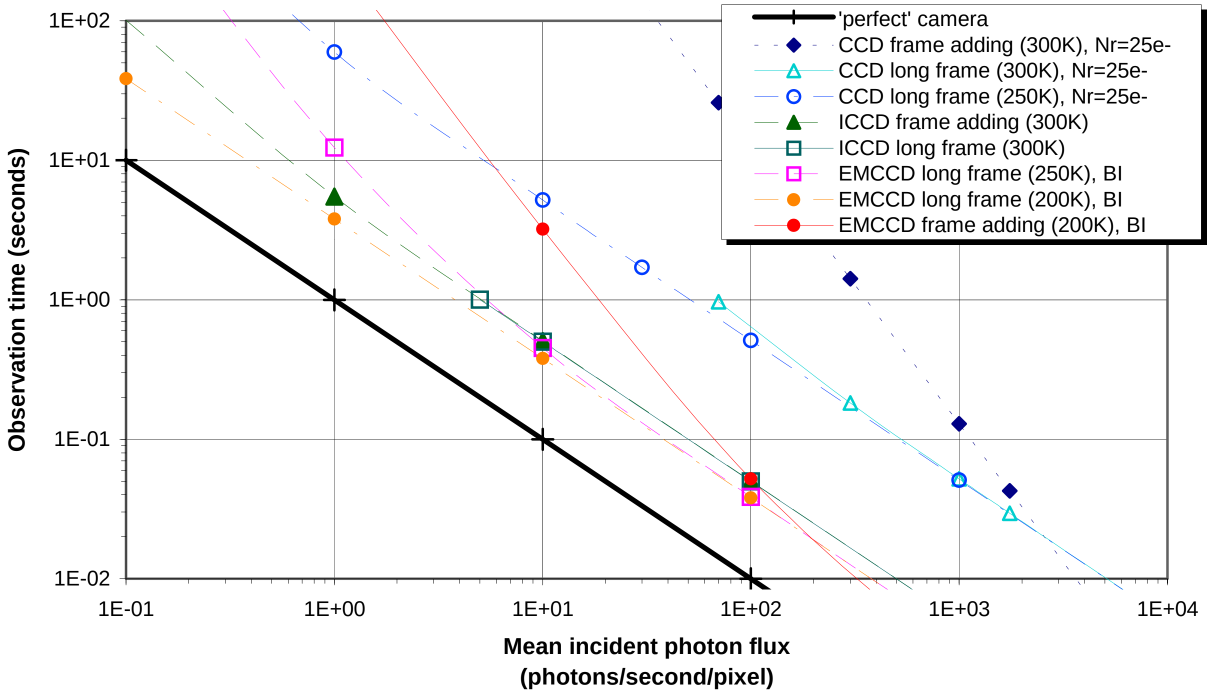


Figure 4. Observation time for frame adding and long frame as a function of mean incident photon flux (Φ_p) for CCD, ICCD and EMCCD cameras with low camera noise (N_{dc0}=0.1nA/cm² and N_{ct}=2.2e$^-$ rms).

For CCD cameras in which we cannot increase the electron gain G (G=1), the long frame would provide substantially better results as compared to frame adding. Indeed taking long frame multiplies the SNR by a factor of $(n_l)^{1/2}$ and divides the N^2_r term by a factor of n_l thus making eventually the shot noise dominate the camera output noise N_r (see **Equation (9)**). However, frame adding does increase the effective full well capacity and the sensitivity of the imaging system without any hardware modification and thus can also improve the SNR through a longer observation time. This numerical operation can be performed in real time by any modern PC.

Furthermore, not only do **Figures 4** and **5** show the substantial improvement when reducing internal noise (dark current and readout) of an EMCCD camera, it illustrates that in the case of ICCDs, frame adding and long frame integration result in very similar observation times to obtain an unity SNR. In contrary to this, EMCCD cameras behave very similar to CCDs, i.e. frame adding is much less effective than for an ICCD detector.

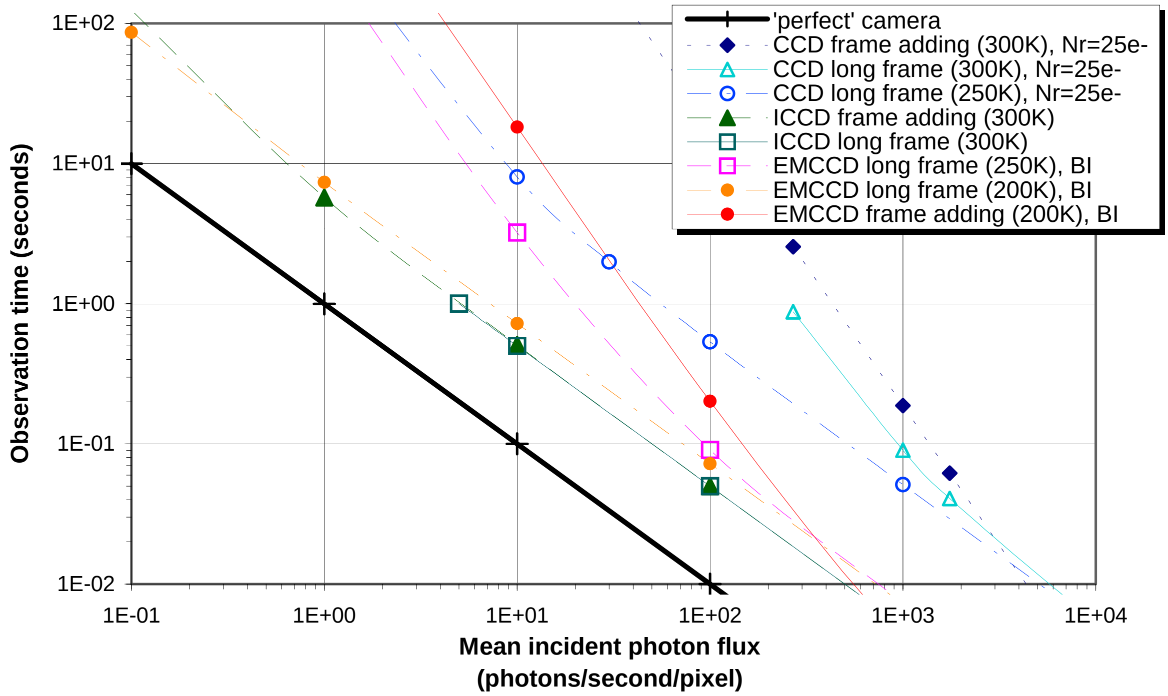
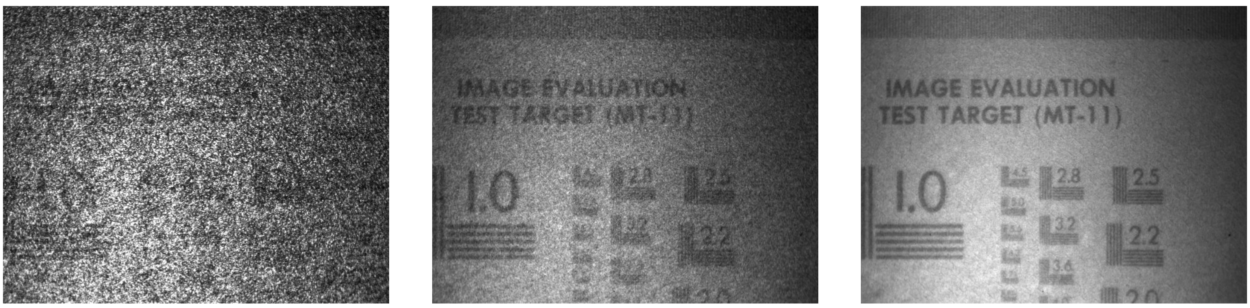


Figure 5. Observation time for frame adding and long frame as a function of mean incident photon flux (Φ_p) for CCD, ICCD and EMCCD cameras with high camera noise (N_{dc0}=3nA/cm² and N_{ct}=5.4e⁻ rms).

As illustration of the above theoretical work, the three images of **Figure 6** do show the very pronounced SNR improvements provided by frame adding in an ICCD system that was operated at room temperature. These pictures were taken by using a 4 Quik E camera with the test target being inside a completely blackened test-box. The only illumination was the short wavelength fraction of the black body radiation inside the box. From the left to the right we can see an obvious improvement in the SNR when adding more and more frames together (1, 25 and 250 frames with an exposure time of 40ms each). We would have obtained very similar results by taking long single frames (40ms, 1s, and 10s, respectively) in a cooled, very slow scan CCD or EMCCD camera.



a) b) c)

Figure 6. Example of the effect of frame adding: a) 1 frame, 40ms, b) 25 frames, 1s effective exposure time, c) 250 frames, 10s effective exposure time.

The following set of pictures (**Figure 7**) is a camera comparison made on 6/23/2003 at Live Cell Confocal course Vancouver. The target is a chair draped with newspaper in low ambient light conditions. Sequence shows F stops of 5.6, 8, 11 and 16 using the same camera lens on all three cameras.

The top row corresponds to a Stanford Photonics XR-Mega-10 Extreme 1400 x 1024 ICCD detector with 33msec exposure time and no binning. The pictures shown in the middle row were taken with an Andor EEV iXon EMCCD camera (512 x 512 pixels) with 33msec exposure time and no binning. The third set of pictures was made using a Roper Cool Snap 1400 x 1024 CCD detector from Roper Scientific. The three cameras have roughly the same quantum efficiency specifications. In this example, the ICCD detector clearly outperforms the EMCDD and standard CCD systems and provides a much clearer image of the scene.

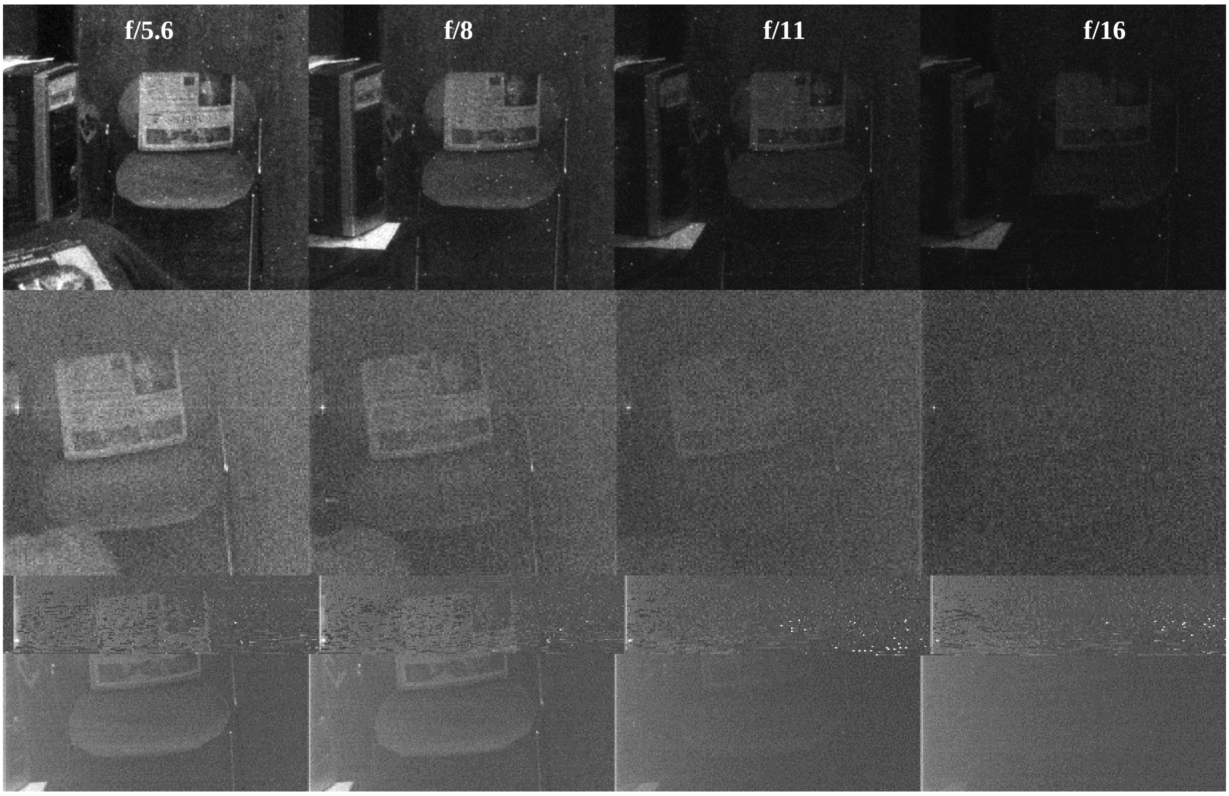


Figure 7. Camera comparison in low ambient light conditions. (Courtesy of Solamere Technology Group, Inc.)
Top row: Stanford Photonics XR-Mega-10 Extreme 1400 x 1024 pixels ICCD detector, 33 msec exposure, no binning.
Middle row: Andor EEV iXon EMCCD camera (512 x 512 pixels), 33 msec exposure, no binning.
Bottom row**:** Roper Cool Snap 1400 x 1024 CCD, 33 msec exposure, binned 2x2.

4. CONCLUSIONS

In spite of the expectation of significant performance improvements fed by their high QE, CCD and EMCCD systems seem not to be superior to ICCD at low light levels. They provide better SNR only at light levels that do not require cooling or slow scan readout.

In order to achieve a very high sensitivity with a CCD, the sensor must not only be cooled but also operate at very low pixel clock frequencies. The same applies to EMCCD systems because any CCD noise (dark current and readout) is multiplied up along with the input signal. Indeed, charge transfer noise exponentially increases with pixel rate and can strongly worsen the detection limit of EMCCDs.

EMCCD cameras seem to be a credible alternative to ICCDs for some applications but their theoretical capabilities must not be over-estimated because, in practice, Charge Transfer Noise greatly reduce their noise performances even at low frame rates and in low light situations. And due to the internal structure of their CCD chips, EMCCDs can absolutely not compete with ICCDs in applications which require gating faster than a few milliseconds.

What clearly emerges from the presented simulation is that it is unnecessary to invest any special efforts into the CCD sensor cooling and readout in an ICCD camera. As a matter of fact, dark current and readout noise do only have an insignificant effect on the SNR of ICCDs.

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(Excel spread sheets are available from the author via e-mail).