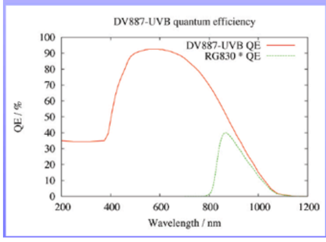
AstraLux SNR and DR considerations

Stefan Hippler, hippler@mpia.de, March 2008

AstraLux Homepage: `http://www.MPIA.de/ASTRALUX`

Commercial camera DV887-UVB from Andor Technologies:

- Back illuminated, QE>90% at 600nm and 40% at 900nm
- 512x512 pixels, 16μm pixel size
- Peltier cooling down to -75°C, no LN_2 necessary
- Up to 34Hz frame rate with full FOV, or several 100Hz using subarrays
- Shortest exposure time is 20μs
- EM- and conventional amplifier
- Adjustable EM-Gain, readout clock and voltages



Contents

1 Signal to Noise (SNR) considerations for AstraLux

AstraLux uses an electron multiplying CCD (EMCCD) based camera from Andor Technologies, type iXon DV 887-UVB. The detector used in this camera is an E2V CCD 97 device.

The most relevant noise factors with this EMCCD device are the readout noise σ_{RON}, the dark current noise σ_{DCN}, and the clock induced charge noise σ_{CIC}. Quite often one can find the latter noise source referenced as spurious charge noise or charge transfer noise. For our camera the readout noise at 10 MHz pixel clock and electron multiplying gain of 1, is typically 80 electrons per pixel rms for a system gain of approx. 24 electrons per ADU. The dark current DC measured at a CCD temperature of -75 degrees centigrades was found to be 0.009 e^-/pixel/s. The clock induced charge probabilty, ie the probabilty to generate one extra electron, can be as low as 1% for maximum ADU values around 1000, again for the 10 MHz pixel clock. A reasonable number for σ_{CIC} is 0.1 e^-/pixel/readout.

The total noise σ_{total} can be expressed as:

$$\sigma_{total} = \sqrt{\sigma_{RON}^2 + \sigma_{DCN}^2 + \sigma_{CIC}^2 + \sigma_{SHOT}^2} \quad (1)$$

with $\sigma_{DCN} = \sqrt{DC \cdot t_{exp}}$ and the signal shot noise $\sigma_{SHOT} = \sqrt{D_{QE} \cdot P}$. Here D_{QE} stands for the detector quantum efficiency, P for the number of incident photons, and t_{exp} for the exposure time. So far, there is no difference between EMCCDs and normal CCDs. For EMCCDs another noise source comes into play which is called excess noise F. This is a result of fluctuations of the signal multiplying gain M. This signal multiplying gain noise effects also other detected electron charges except the readout noise. Therefore for EMCCDs eq. 1 becomes:

$$\sigma_{total} = \sqrt{\sigma_{RON}^2 + F^2 M^2 (\sigma_{DCN}^2 + \sigma_{CIC}^2 + \sigma_{SHOT}^2)} \quad (2)$$

F^2 can be well estimated with 2 and typical gains used with Astralux are $M = 1000$. Now we can calculate the signal to noise ratio SNR for an EMCCD. Writing the signal as $S = M \cdot D_{QE} \cdot P$, we get:

$$SNR_{EMCCD} = \frac{M \cdot D_{QE} \cdot P}{\sqrt{\sigma_{RON}^2 + F^2 M^2 (\sigma_{DCN}^2 + \sigma_{CIC}^2 + \sigma_{SHOT}^2)}} \quad (3)$$

$$SNR_{EMCCD} = \frac{D_{QE} \cdot P}{\sqrt{\frac{\sigma_{RON}^2}{M^2} + F^2 (\sigma_{DCN}^2 + \sigma_{CIC}^2 + \sigma_{SHOT}^2)}} \quad (4)$$

If we neglect the small contributions of σ_{CIC} and σ_{DCN} we can write:

$$SNR_{EMCCD} = \frac{D_{QE} \cdot P}{\sqrt{\frac{\sigma_{RON}^2}{M^2} + F^2 D_{QE} \cdot P}} \quad (5)$$

For high multiplication factors the RON term becomes negligible and we can write:

$$SNR_{EMCCD} = \frac{D_{QE} \cdot P}{\sqrt{F^2 D_{QE} \cdot P}} = \frac{D_{QE} \cdot P}{1.41\sqrt{D_{QE} \cdot P}} \quad (6)$$

which is in the shot-noise limited regime obviously lower by a factor of $\sqrt{2}$ compared to normal CCDs.

Figure 1 clearly shows that an EMCCD outperforms a low noise CCD in the low signal regime, ie photon numbers below the reference flux of 100 photons. To detect faint sources with Astralux one strategy is to find a reference star as close as possible to the faint source such that you can use the highest electron multiplication gain without saturating the reference within the exposure time. The exposure time for Astralux observations is mainly determined by the Seeing, ie coherence time of the optical turbulence of the atmosphere. This means values larger than 30 ms are in most cases disadvantageous because the Strehl in the individual images will drop. To achieve a certain SNR of the faint object, the number of frames has to increase, keeping in mind that the SNR is proportional to the square root of the number of frames.

More information can be found for example at the the e2v web site, `http://www.e2v.com`, in particular L3Vision technical notes number **2**and **4**.

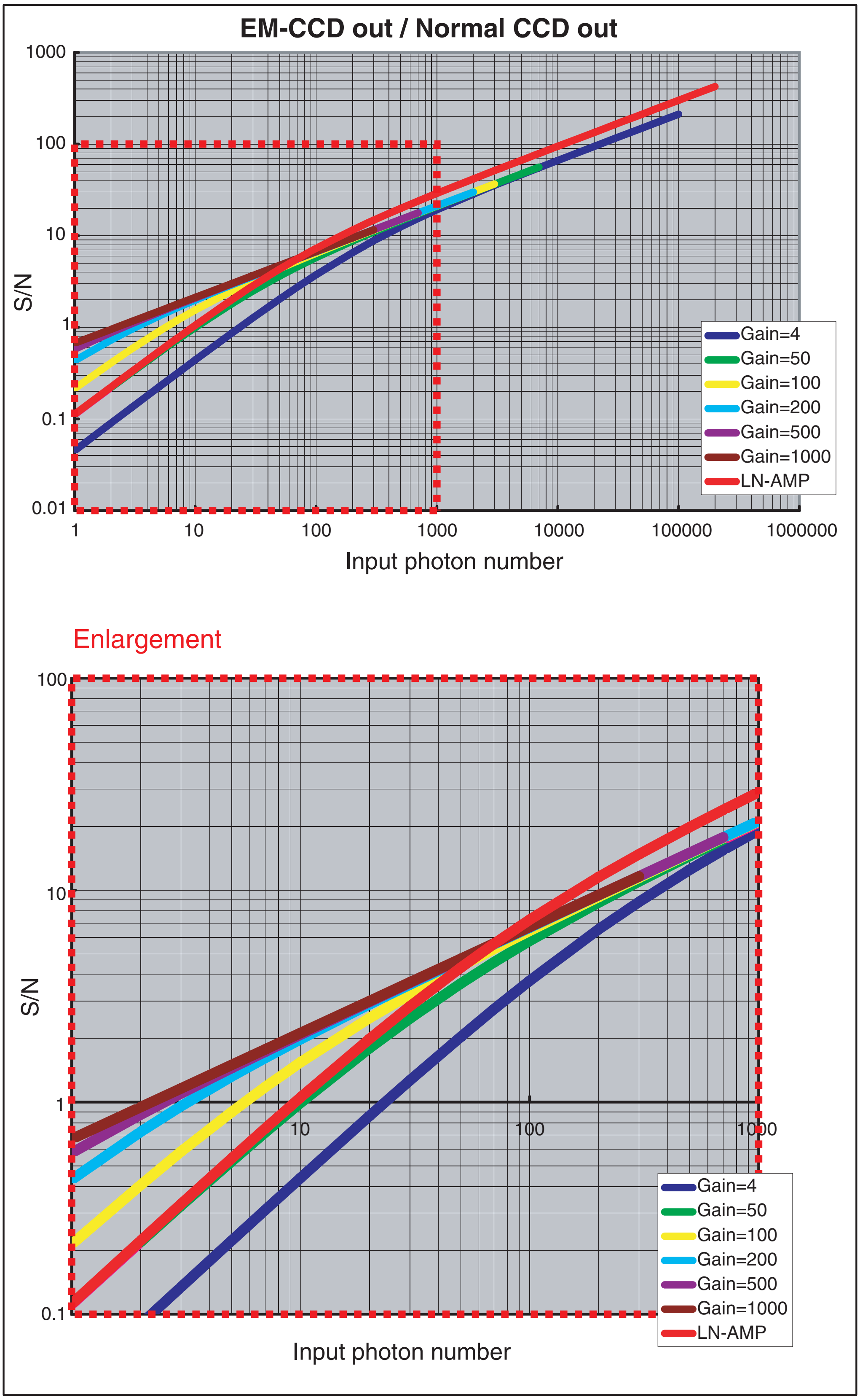


Figure 1. *Figure taken from Hamamatu's EM-CCD technical note. Signal to noise, S/N, as a function of incoming photon number for EMCCDs operated with various multiplication gains (4–1000) and for a regular low noise (LN) CCD. (For this plot the reference flux is 100 photons per pixel per frame with an exposure time of 100 ms).*

2 Dynamic Range (DR) considerations for AstraLux

This is an excerpt from an Andor Technologies Technote about iXon+ EMCCD (but also valid for the Astralux iXon Model without +).

Dynamic Range (DR) is given by:

$$DR = \frac{\text{Full Well Capacity}}{\text{Detection Limit}} \tag{7}$$

Calculating Dynamic Range in an EMCCD camera is a slightly more complicated story than for conventional CCDs. This is because of the favourable effect of EM gain on the detection limit vs. the limiting effect of EM gain on the full well capacity. The easiest way to address this is to first take each parameter separately:

Detection Limit and EM Gain –
The main function of EMCCD is to eliminate the read noise detection limit and enable detection of weak photon signals that would otherwise be lost within this noise floor. With EM gain, the detection limit is given by the Effective Read Noise, i.e. the read noise divided by the gain multiplication, down to one electron! Why never less than one? This stems from the definition of detection limit, which is essentially the signal equal to the lowest noise level. Since you cant get a signal less than one photon, then the detection limit should never be taken as less than one electron. For example, the iXonEM+ DU-897 has a read noise of 50 electrons @10MHz with EM Gain off. At EM gain x2, the new detection limit can be considered to be 25 electrons effective read noise; at x5 it will be 10 electrons; at x50 it will be 1 electron. At x100, the Effective Read Noise will be 0.4 electrons, but as far as the Detection Limit is concerned, this must still be taken as 1 electron!

Full Well Capacity and EM Gain –
One might imagine that applying EM gain will decrease the full well pixel capacity proportionally. This is indeed the case, but a buffer has been built into EMCCD cameras to enable at least some EM gain to be applied while maintaining the original well capacity. This buffer is in the form of a higher capacity in the gain register pixels, where the multiplication actually takes place. So, the true capacity is given by the capacity of the pixels of the sensor, but as you apply EM gain this holds only up until the point where the larger capacity of the gain register pixels also become saturated by applied EM gain. After that point, you have to correct the effective full well of the sensor to be equal to the full well of the gain register divided by the gain.

Dynamic Range and EM Gain –
These above factors combined means that as EM gain is increased, Dynamic Range will increase to a maximum, level off and then reach a point at which it begins to fall again with further gain. Phew! This can seem complicated we know, but fortunately these DR vs EM gain relationships can be readily plotted out and visualized in graphical form, as exemplified in Figure 2.

There are a number of interesting points to note from these plots:

1. The rationale behind offering readout speeds slower than 10MHz through the EM-amplifier is so that frame rate can be traded of against dynamic range. You can see that the highest dynamic range through an EM amplifier comes from the slowest 1MHz readout speed.
2. At any readout speed through the EM-amplifier, the best combination of dynamic range and sensitivity can be obtained at a EM gain setting equal to the readout noise at that speed. At this point the DR is at maximum and the effective readout noise is 1 electron (i.e. just on the verge of single photon sensitivity).
3. At x1000 EM gain the dynamic range is only 400:1. Excessively high EM gain can also accelerate EM gain ageing in backilluminated EMCCDs. EM gains of x300 or less are more than sufficient to optimize sensitivity, while ensuring dynamic range is not excessively compromised. The only occasions when Andor recommend extending EM gain to x1000, is for single photon counting experiments.
4. The highest dynamic range is through the conventional amplifier at 1MHz.

5. It is clear that the actual sensor dynamic range only exceeds 14- bits @ 1MHz, through either EM or conventional amplifier. Therefore, it is at 1MHz that we require an option to match this higher dynamic range output with a scientific grade, noise free 16-bit A/D digitization. The iXonEM+ is uniquely designed to do just that, making use of a real scientific grade A/D that is optimized for 1MHz readout.

Note: There is a direct relationship between readout noise and maximum dynamic range at a given readout speed. Lower readout noise affords higher dynamic range. The readout noise specification used in calculating dynamic range must be with EM gain turned off, as quoted in all iXonEM+ spec sheets. We note, however, that another prominent EMCCD provider chooses to quote their lowest read noise value, not for EM Gain-off, but for EM Gain x4. In this case, you would have to multiply this quoted figure by x4!

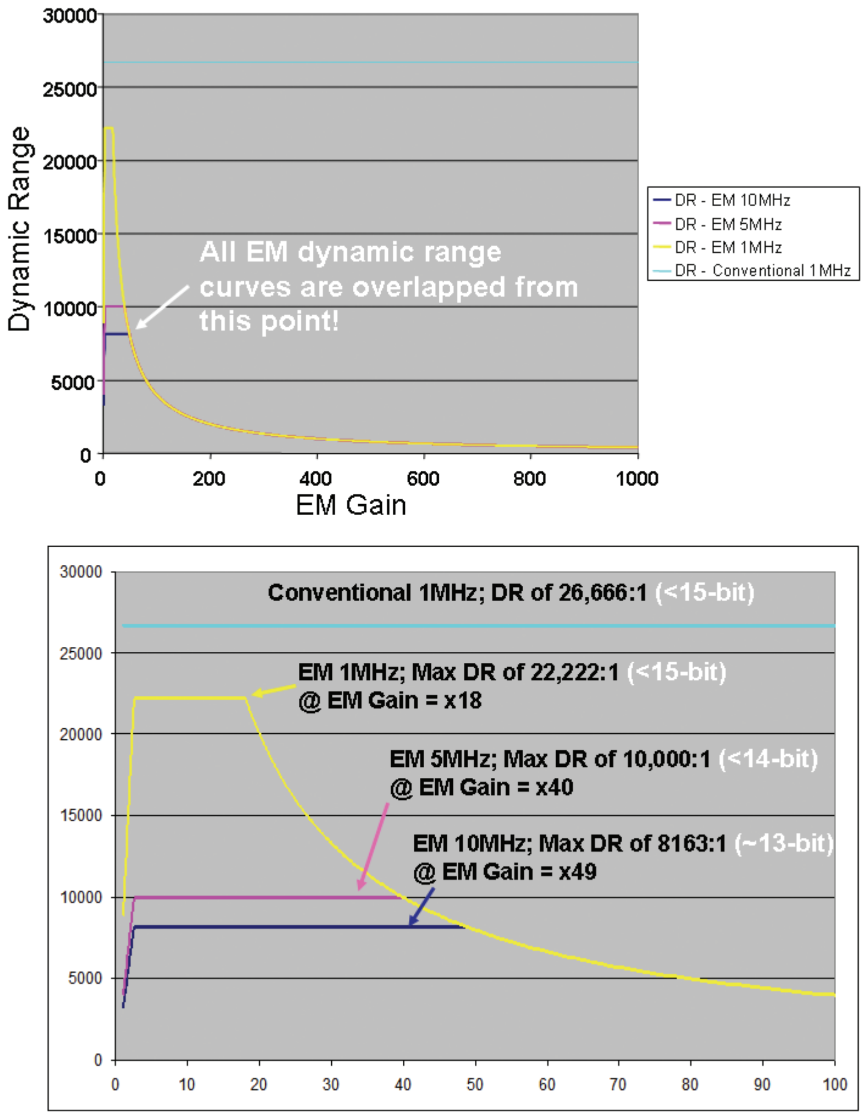


Figure 2. *Dynamic Range vs EMCCD Gain for iXonEM+ DU-897. Shown for EM amplifier @ 10, 5 and 1MHz readout speed and for Conventional amplifier at 1MHz readout speed. Well capacities used in DR calculation are characteristic of the CCD97 512x512 back-illuminated L3 sensor from E2V. Dynamic range only exceeds 14-bits max @ 1MHz, through either amplifier.*

For the Astralux detector, the full well capacity of an active pixel is around 200000 electrons. The gain register has a four times higher capacity, ie approx. 800000 electrons.