Electron-multiplying CCD astronomical photometry

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ABSTRACT

Electron Multiplying CCD is a CCD technology sensor reduces read-out noise to less than one electron. We study the way the usage of this technology affects to the astronomical photometry and to the improvement of the temporal resolution of the measurements. We show the effect of this technology on individual celestial sources and in the limiting magnitude. We propose a criterion to choose the optimal EM gain for a specific integration time. We explain a straightforward procedure to characterize the actual EM gain and the readout noise expressed in photo-electrons for every software-displayed gain, and we applied this procedure to the Andor Ixon DU-888E-C00-BV EMCCD.

Keywords: EMCCD, astronomical photometry

1. INTRODUCTION

EMCCD (Electron Multiplying CCD) or L3CCD (Low Light Level CCD) is a CCD technology sensor developed by Marconi Applied Technologies (Chelmsford, UK) which effectively reduces read-out noise to less than one electron.[1–4] It provides an internal gain within the CCD before the signal reaches the output amplifier. With reasonably high gain, sub-electron readout noise levels are achieved even at MHz pixel rates.

The detection limit of an astronomical measurement is imposed by the background noise or by the readout noise of the detector. EMCCD technology should be of a great importance in the astronomical measurements where the readout noise dominates the background noise (readout noise limited measurements). The background noise can be theoretically overcome by collecting more photons from the source than the shot noise of the background (in photons). In addition, collecting more photons always improves the signal-to-noise ratio (SNR) of any measurement. The two procedures to collect more photons are to increase the telescope diameter and to increase the exposure time. When there are temporal restrictions on the exposure time, the readout noise may impose the detection limit of a telescope. In these cases, the exposure time may be not long enough to increase the shot noise of the background above the readout noise and then the EMCCD plays an important role. The EMCCD multiplies the photo-electrons by a factor G (gain) before they reach the readout stage. Due to this multiplication the readout noise is G times smaller when is expressed in photo-electrons. Then, it is possible to overcome the readout noise G times faster than with a conventional CCD.

However the multiplication process increases the shot noise of the electrons by a factor $\sqrt{2}$ (noise factor). The consequence is that, using the same integration time and telescope, electron-multiplying (EM) provides a SNR $\sqrt{2}$ times smaller in a shot noise limited astronomical measurement. The EM reduces the readout noise but, when it is negligible respect to other noises, the performance decreases respect to a conventional CCD. On the other hand, the amount of photo-electrons that can be accumulated in an EMCCD is inversely proportional to the value of the gain used. Therefore, in order to keep a good dynamic range, it is important not to use a higher than the required gain to reduce the readout noise below the background noise.

The shorter the integration time and the smaller the telescope, the less background, then the improvement by using an EMCCD is higher at short integration times and small telescopes. Decreasing the integration time

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while increasing the gain may improve temporal resolution while keeping the detection limit, but the SNR will decrease for the not too faint sources because less photons will be collected, and it will saturate the brighter sources. This is something to have into account before using EMCCD technology.

This work gives insights on how the astronomical photometry is affected when using EMCCD and the readout noise becomes negligible respect to the background noise. It is discussed the effect of EM on the images of the individual sources, the SNR and the limiting magnitude. In addition, the improvement on this device on the temporal resolution is analysed, and a procedure to characterize the readout noise of the measurement (expressed in photo-electrons) and the actual gain is explained.

2. EMCCD VS. CCD

A CCD accumulates photogenerated electrons (photo-electrons) in the pixels during a time (integration time), transfers sequentially these electrons to the readout node and converts them into counts by an A/D converter.[5,6] The EMCCD follows almost the same steps, the only difference is that electrons are multiplied in their way to the readout node.[7,8] Therefore, since the measured electrons are not photo-electrons but multiplied electrons, the invariant readout noise in counts is smaller when it is expressed in photo-electrons.

The purpose of multiplying electrons is to make negligible the readout noise, but the cost is an additional noise associated to the multiplication (noise factor). This noise introduced in the additional multiplication channel does not affect readout noise, but shot noise. Because of this noise, when the measurement is shot noise limited, the SNR is $\sqrt{2}$ times lower than in CCDs, that is equivalent to use a CCD with half quantum efficiency.

When the readout noise decreases due to the EM, other noise sources begin to be important. According to Andor, unless an EMCCD is cooled below -95^oC, the limiting noise source is readout dark current, that is not so important in CCDs because in this case readout time are usually much smaller than integration time.[9] If an EMCCD is cooled below -95^oC, the limiting noise source is Clock-induced Charge (CIC) noise.[5]

In terms of incident photons, EMCCD has less capacity than CCD and, in consequence, a lower dynamic range (when the readout noise is lower than 1 photo-electron, a noise of 1 photo-electron is used to calculate the dynamic range, because the detection limit is defined as the signal equal to the lowest noise level and is not possible to get a signal lower than 1 photo-electron[10]).

3. CONSIDERATIONS ON EMCCD IN ASTRONOMICAL PHOTOMETRY

3.1 Pros and cons

Due to the negligible readout noise, an EMCCD allows to reach a higher limiting magnitude for the same exposure than a conventional CCD with the same external quantum efficiency, as long as the background shot noise was higher than the CCD readout noise. When the readout noise is not negligible, the addition of images decreases the SNR for readout noise limited sources in the images. Using an EMCCD, it is possible to add images improving the SNR for all the sources. As a consequence, the temporal resolution can be improved by acquiring images at shorter exposures times, and combining enough of them to achieve the SNR requirement for the target.

The main disadvantage is that the noise factor reduces $\sqrt{2}$ times the SNR for bright shot-limited sources, the same effect that using a detector with half sensitivity. Another disadvantage is that the EMCCD allows less capacity for photo-electrons: the brightest source in the image is GC_{CCD}/C_{EMCCD} times fainter than in conventional mode, where G is the multiplication gain, C_{CCD} is the active area pixel well depth and C_{EMCCD} is the EMCCD gain register pixel well depth. The brightest source achievable for a gain G and for a given integration time t_i is that not generating more than C_{EMCCD}/G photo-electrons at any pixel.

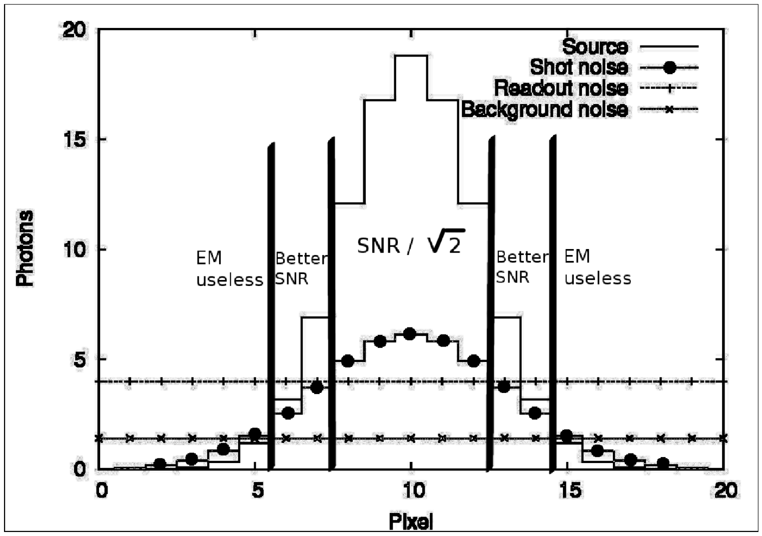

Figure 1. Different exposure levels in a source. Some pixels are favoured by EM, whereas the SNR of other pixels may decrease due to the EM.

3.2 EM effect on the images of the sources

Pixels that detect a celestial source are subjected to different exposure levels, usually according to a gaussian profile of the irradiance distribution. Regarding to the improvement of the measurement using EM, there are three different exposure conditions, shown in Fig. 1, where a 2D-profile of an usual source is plotted. In the central region of the source, when the source shot noise is above the readout noise, the use of EM reduces the SNR by $\sqrt{2}$. The intermediate region, where the readout noise is below the source shot noise but above the background shot noise, the SNR is favoured by the use of EM. Finally, it is impossible to improve the SNR of the measurement of the external region using EM, since there the background shot noise dominates the source shot noise.

In any case, since SNR of the brighter sources is always higher than the SNR of the fainter sources, whenever that a chosen gain allows to detect a faint star, it will not prevent from detecting the brighter sources, although the uncertainty will increase by a factor $\sqrt{2}$ for these ones.

Figures 2 and 3 show the theoretical effect of EM on a source at the detection edge (SNR$\sim$3). A 8 electrons readout noise, a plate scale of 0.5 arcsec/pixel, a seeing of 3.5 arcsec, a 40 cm-telescope, a 1 sec integration time, a unity quantum efficiency, a source photon flux of 0.1 photons/cm^2/sec ($\sim$ 17.5 mag) and a background photon flux of 8 photons/pixel/sec ($\sim$ 21 mag/arcsec) were assumed for this figure.

A 2D-representation of the source with a conventional CCD is shown in Figure 2. Left y-axis represents the number of incident photons, and right y-axis the measured electrons. The source SNR is 3.3, taking only into account pixels within 1σ in the gaussian shape. The noise is completely dominated by the readout noise, that is above shot and background noise. These noises are also plotted in the graph. Since no gain is applied in this case, incident photons and measured electrons are equivalent. A 2D-representation of the source using a gain of only 4 electrons/photo-electron is shown in Figure 3. The SNR becomes 4.7 now, but in this case is limited by the shot noise, that increases slightly due to the factor noise associated to the EM. The measured electrons are multiplied by 4, and the readout noise, expressed in photons is divided by 4. Again, the background noise level is slightly higher due to the factor noise. Since the readout noise is now well below the background shot noise, to increase the gain would not improve the measurement of this specific source.

3.3 Signal-to-noise Ratio and Limiting Magnitude

To optimise the parameters of the system it is necessary to know the expression of the SNR. This is calculated from the ratio between the measured photo-electrons and its uncertainty (readout noise, shot source and background

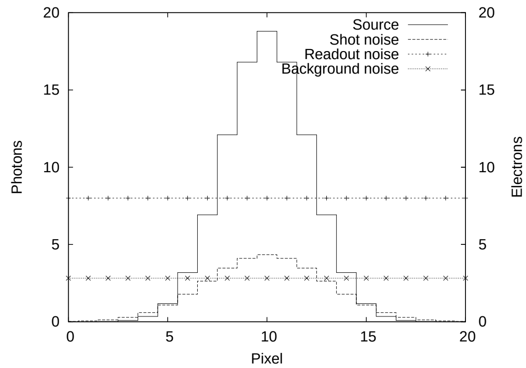

Figure 2. Theoretical effect of EM on a source in the border of the detection (SNR∼3).

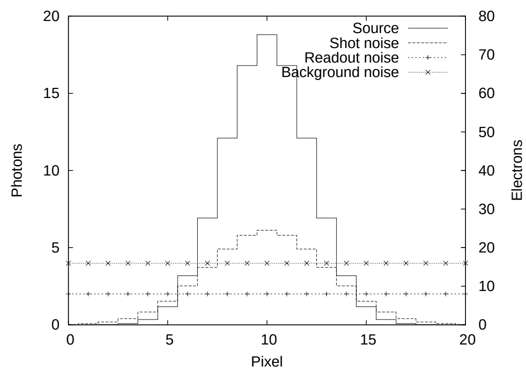

Figure 3. Theoretical effect of EM on a source in the border of the detection (SNR∼3).

noises). The resultant equation can be written as:

$$SNR = \frac{LAt_i\Gamma}{\sqrt{M(\frac{\sigma_{r,e}}{G})^2 + F^2At_i(L\Gamma + 2M < n_{b,pe} >)}} \tag{1}$$

where A is the area of the telescope, t_i is the integration time, Γ represents the fraction of photons flux from the source converted into photo-electrons [atmosphere (T_a) and telescope (T_t) transmittances and quantum efficiency (η_e), $\Gamma = T_aT_t\eta_e$], L is the photons flux from the source (photons/time/collection area], G is the EM gain (electrons/photo-electrons, $G = 1$ if EM is not applied), F is the factor noise ($F = \sqrt{2}$ with EM, $F = 1$ without EM), $\sigma_{r,e}$ is the readout noise expressed in multiplied electrons, $< n_{b,pe} >$ is the rate of background-generated electrons (photo-electrons/time/collection area/pixel) and M is the number of pixels used to measure the source. The factor 2 in the last addend in the denominator's root (background shot noise) is due to the way the source photons are measured: a background measurement is subtracted from a measurement that contains both source and background photons, so the background is considered twice. Apparent inconsistency in the units is due to the fact that shot noise variance is the same value than average, then L is expressed in photons in the numerator and in photons^2 in the denominator. Equation 1 is easily expressed in terms of digital counts (N) as:

$$SNR = \frac{\sum_i^M N_i - M < N_b >}{\sqrt{M\sigma_{r,N}^2 + F^2GK(\sum_i^M N_i + M < N_b >)}} \tag{2}$$

where the conversion from photo-electrons to counts is made by the product $G \times K$ (counts/photo-electrons), where K, known as conversion factor, is a constant of the A/D converter and is expressed in counts/electron.

Then, $LAt_i\Gamma$ photo-electrons are $LAt_i\Gamma GK$ counts, $\sigma_{r,e}$ electrons are $\sigma_{r,e}/K$ counts, and $< n_{pe,b} >$ photo-electrons are $< n_{pe,b} > GK$ counts. Equation 2 aims to be the practical way to calculate the SNR, therefore we have expressed the source flux as it is calculated, firstly summing the values of the N pixels where the source photons should be ($\sum_i^M N_i$), and secondly subtracting the value of the background for these M pixels ($< N_b >$ is the average background per pixel).

The limiting magnitude of a specific telescope and a specific observation is calculated working out Γ in equation 1 and usually using SNR=3. The resultant flux of photons, expressed in photon/cm^2/sec, as a function of SNR, is written thus as:

$$L = \frac{(SNR)^2 F^2}{2\Gamma A t_i}\Big\{1 + \Big[1 + \frac{4M}{(SNR)^2 F^2}\Big(\frac{\sigma_{r,e}^2}{G^2} + 2F^2 A t_i < n_{b,pe} >\Big)\Big]^{1/2}\Big\} \qquad (3)$$

Assuming that a magnitude 0 source has a photon flux of 10^6 photon/cm^2/sec, the limiting magnitude, m_L, for a configuration (G, t_i) is expressed as:

$$m_L = 2.5 \log_{10}\Big[10^6 / L(SNR = 3)\Big] \qquad (4)$$

The proper gain that should be used at a given integration time and background is the gain that allows to decrease the readout noise well below the background. Thus, it is possible to write the following condition, whose fulfillment implies that the background noise is lower than twice the readout noise:

$$\sigma_{r,N}(N) < \frac{F\sqrt{GKN_b(t_{int}, G)}}{2} \qquad (5)$$

where $N_b(t_{int}, G)$ is the background intensity in counts/pixel as a function of t_{int} and G, therefore, assuming linearity with G and t_{int} $N_b(t_{int}, G) = t_{int} \times G \times N_b(1, 1)$.

Rearranging terms and making $F^2 = 2$:

$$G = \frac{\sqrt{2}\sigma_{r,N}(N)}{\sqrt{t_{int} K N_b(1, 1)}} \qquad (6)$$

This equation allows to optimize the gain for a specific observation. Using a higher EM gain does not improve the measurement and reduces the dynamic range.

When the readout noise is overcome, the temporal resolution is limited by the background and source shot noises, as it is plotted in Figure 4. The theoretical SNR in absence of readout noise (for a 40 cm telescope and a sky brightness of 20 mag/arcsec) as a function of the magnitude to be measured for integration times of 0.01 sec, 0.1 sec, 1 sec, 10 sec and 100 sec (equation 1) is plotted in Figure 4. It was assumed that the flux of a zero magnitude is 10^6 photons/sec/cm^2, perfect transmittance and an ideal telescope (quantum efficiency is unity, and not losses in the mirrors and filters). The plot is a set of straight lines that are bent in the point where the background shot noise is comparable to the signal. In five decades of integration time the limiting magnitude ($SNR < 3$) varies from 15 mag (at 0.01 sec) to 21 mag (at 100 sec).

In Figure 5 the theoretical SNR is plotted for the same conditions, at 1 sec of integration time and for an EMCCD at G=1 and at G= 25. The use of the gain increases the limiting magnitude from 15 mag to almost 18 mag.

3.4 About the improvement of the temporal resolution

Temporal resolution improvement can be achieved by reducing either the readout time t_{read} or the integration time t_i. It is always counterproductive to decrease the integration time below the readout time, since it does not substantially improves the temporal resolution and worsens the measurement SNR. Therefore, temporal

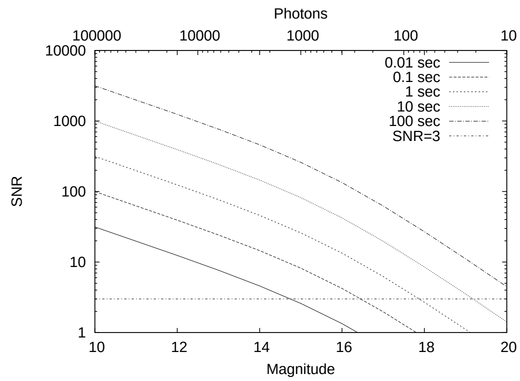

Figure 4. Theoretical SNR in absence of readout noise (for a 40 cm telescope and background brightness of 20 mag/arcsec) versus astronomical magnitude for different the integration times.

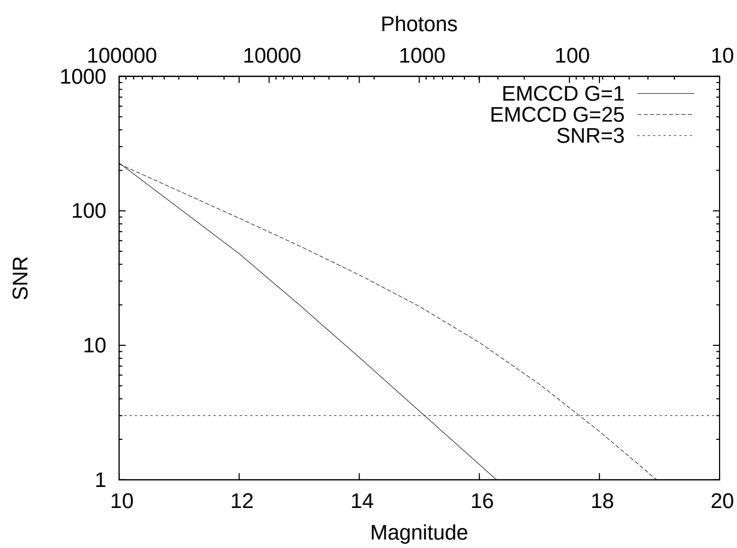

Figure 5. Theoretical SNR (for a 40 cm telescope and background brightness of 20 mag/arcsec versus astronomical magnitude for conventional mode and G=25.

resolution discussion on improvement should be centred around integration time, specifically around finding a compromise between the chosen integration time and the SNR of the image sources.

Once the readout noise is overcome, the background and source shot noises impose the usual restrictions on SNR. This means that to improve the SNR it would be necessary to collect more photons, not only for improving the shot-limited measurements, but also to overcome the background in cases where its shot noise is comparable to the source photon flux. The only way to collect more photons with a given telescope is to increase the integration time. This is something to remember when discussing the EMCCD capacity to improve the temporal resolution. Shortening the integration time has three effects:

Since using EM gain allows background limited images, it is possible to obtain an image by composing several images of shorter integration time, because other exposures can be recovered by addition of frames without propagation of the readout noise from every single frame. The idea is to be able to choose the length of the exposure regarding to the SNR required for a specific target or to the wanted limiting magnitude.The achievable temporal resolution usually depends on these constraints.

Hereafter we will denote Δ the temporal resolution, defined as the maximum frequency it is possible to use to acquire a frame with a specific photometric characteristics, and expressed as:

$$\Delta = \frac{1}{N(t_i + t_{read})} \tag{7}$$

where N is the number of combined frames. N is a function of our requirements (specific SNR for a specific target source), expressed in general terms as:

$$N = round_{+}\Big(\frac{SNR^2F^2[S + N_{ap}(s_{sky} + \sigma_r^2/t_i)]}{t_i S^2}\Big) \tag{8}$$

where $round_{+}$ means rounding to the upper integer, N_{ap} is the number of the pixels within the aperture, S is the number of photo-electrons generated by the target source by time unit, s_{sky} is the number of background photo-electrons per pixel and time unit, and σ_r is the readout noise.

There is a limitation in this addition technique: the better temporal resolution at high magnitudes, the worse temporal resolution at low magnitudes, and vice versa. The reason is that the shorter the integration time, the better temporal resolution for the bright sources that can be analyzed just from an image, but the more frames should be added to obtain the fainter magnitudes, increasing the temporal resolution due to the temporal gaps between single images, since the readout time can be very short, but never zero.

The inverse of the temporal resolution as a function of the achievable limiting magnitude for a conventional CCD [with readout noise (37 e^-)] and for a EMCCD (without readout noise) is shown in Figure 6. This figure was obtained by using the addition technique (equation 7). Temporal resolution for different exposure times (0.2 s, 0.4 s, 1.6 s and 6.4) is plotted, using a readout time of 0.246 s. The same effect is observed in Figure 7, but is it much more important in 6 (CCD) than in 7: the less temporal resolution at low magnitudes, the more at high magnitudes, and vice versa. With the EMCCD the effect is almost completely reduced. The flat part of the curves ends at the point where the addition of images is no longer adequate (analysis of single image, $1/\Delta = t_{read} + t_i$). Higher limiting magnitudes are obtained using EMCCD, and the improvement is better the shorter is the integration time.

G and t_{int} are the parameters to change in order to improve temporal resolution. When t_{int} decreases, G should be increased because the background noise becomes lower than the readout noise. However, the higher G, the more the aging. In addition, as previously mentioned, the usage of very high gains decreases the detector dynamic range, therefore the dynamic range required for the kind of measurement to be carried out will restrict the useful gain range. Restrictions on the t_{int} lower limit of are imposed by the CCD (because the accuracy of the measurement is increasingly spoiled under around 0.1 sec of integration time) and by the astrometry, that requires a minimum number of well confident detected sources in every single image to work properly.

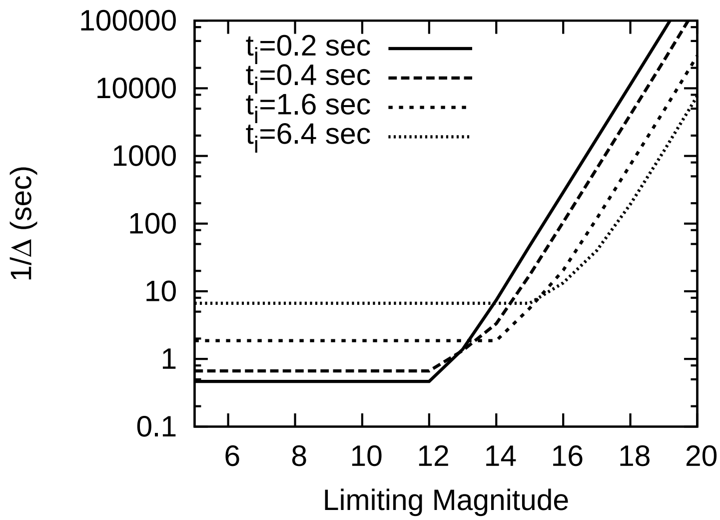

Figure 6. Temporal resolution as a function of the achievable limiting magnitude for a conventional CCD [with readout noise (37 e^-)]. Detector: 514×514 pixels, 1MHz, $t_{readout}$=0.264 sec. Telescope diameter: 40 cm. N_{ap}=68 pixels, s_{sky}=20 electrons/pixel/sec, Γ=0.46, magnitude 0 = 10^6 photons/sec/cm^2.

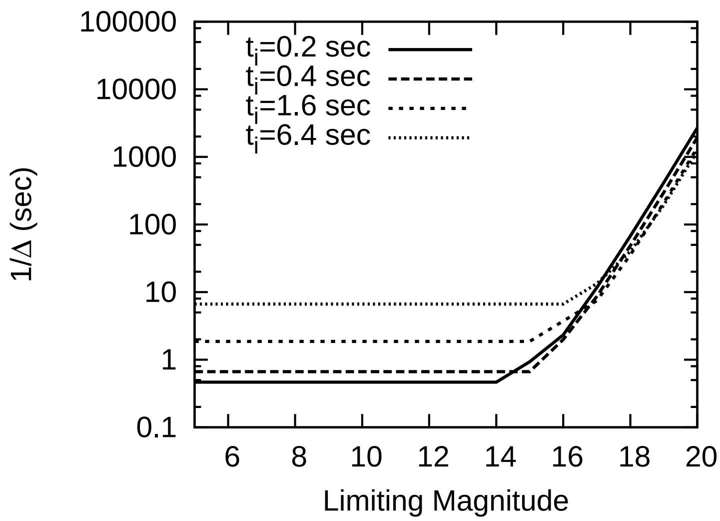

Figure 7. Temporal resolution as a function of the achievable limiting magnitude for a EMCCD (without readout noise). Detector: 514×514 pixels, 1MHz, $t_{readout}$=0.264 sec. Telescope diameter: 40 cm. N_{ap}=68 pixels, s_{sky}=20 electrons/pixel/sec, Γ=0.46, magnitude 0 = 10^6 photons/sec/cm^2.

3.5 Characterization of EMCCD readout noise

The most important parameter to be characterized in a EMCCD, apart from the well-known parameters of a conventional CCD, is the readout expressed in photo-electrons $\sigma_r(n_{pe})$ for every software-displayed gain. Two things are required: the count-expressed readout noise $\sigma_r(N)$, that it is invariant, and the relation between the number of counts and photo-electrons [product of factor of conversion K (expressed as number of counts by electrons getting the readout node, or, in EM case, multiplied electrons) by gain G (expressed as multiplied electrons by photo-electrons)]. Thus, $\sigma_r(n_{pe})$ is expressed as:

$$\sigma_r(n_{pe}) = \frac{\sigma_r(N)}{GK} \tag{9}$$

The count-expressed readout noise of a EMCCD should be calculated, like in the conventional CCD, as the temporal variation of the pixels' response in dark conditions, but at a low gain, because for high gains, the Clock Induced Charge (CIC), hidden by the readout noise at low gains and in conventional mode, takes part of this variation (the clocking of the CCD during readout can itself generate electrons, which in the case of those arising from the vertical clocks are indistinguishable from true photo-electrons. This electrons, known as Clock Induced Charge, are only dominant when the readout noise is much smaller than 1 photo-electron). CIC can be reduced using lower clock voltages (Vertical Shift Speed), but it would lower the well depth, reducing the dynamic range.[9]

The product GK at the software-displayed gain was measured using the photon transfer technique,[11] a technique that returns the relation between photo-electrons and counts from the relation between the response and its variation. The usual technique has to be slightly modified in order to apply it to the EMCCD, because this device, unlike CCDs, introduces the multiplication noise as additional noise source. The relation in which is based the technique is obtained as follows:

The variance of the pixels' response, expressed in photo-electrons, is written as:

$$\sigma^2(n_{pe}) = \sigma_r^2(n_{pe}) + n_{pe} + n_d + \sigma_C^2(n_{pe}) \tag{10}$$

where n_{pe} is the number of photo-electrons, n_d is the number of dark electrons before the multiplication and $\sigma_C(n_{pe})$ is the clock-induced charge noise in electrons before the amplification. Both n_{pe} and n_d in the equation are the variance of the shot noise of the photo-electrons and dark electrons, respectively. When the multiplication channel is added, the noise produced before this stage is amplified by factor a $\sqrt{2}$. Now, the variance expressed in multiplied electrons is calculated as:

$$\sigma^2(\frac{n_{me}}{G}) = \sigma_r^2(\frac{n_{me}}{G}) + \frac{2n_{me}}{G} + \frac{2n_{md}}{G} + (\frac{2\sigma_C(n_{pe})}{G})^2 \tag{11}$$

$$\sigma^2(n_{me}) = \sigma_r^2(n_{me}) + 2G(n_{me} + n_{md}) + 2\sigma_C^2(n_{me}) \tag{12}$$

where G is the gain (n_{me}/n_{pe}), $\sigma_r(n_{me})$ is the readout noise (in multiplied electrons), $\sigma_C(m_{pe})$ is the charge clock induced noise in multiplied electrons, n_{me} is the number of multiplied electrons and n_{md} is the number of multiplied dark electrons.

Since $K = N/n_{me}$ (where N is the bias-subtracted number of count, but not dark-subtracted), we can write:

$$\sigma^2(N) = \sigma_r^2(N) + 2GKN + 2\sigma_C^2(N) \tag{13}$$

and consequently:

$$GK = \frac{\sigma^2(N) - \sigma_r^2(N) - 2\sigma_C^2(N)}{2N} \tag{14}$$

where $\sigma_r(N)$ is the readout noise (in counts). $\sigma_r^2(N) + 2\sigma_C^2(N)$ is the variance of the temporal variation of the pixels' response in dark conditions, $\sigma_d^2(N)$. Then, we can rewrite equation 14 as:

$$GK = \frac{\sigma^2(N) - \sigma_d^2(N)}{2N} \tag{15}$$

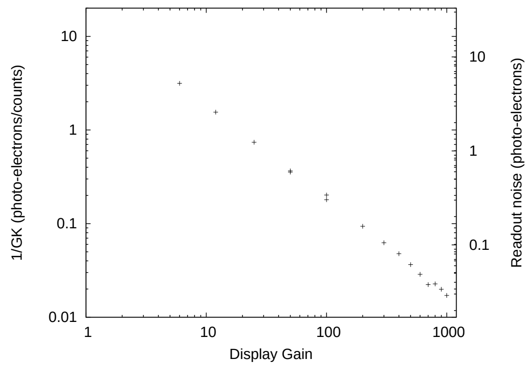

Figure 8. 1/GK and readout noise as a function of the software-displayed gain..

Equation 15 allows to obtain experimentally the relation between counts and photo-electrons (GK) at every software-displayed gain.

The more intuitive way of measuring $\sigma(N)$ is to study the variation with the time of the response (standard deviation) of every pixel at constant exposure (the same for $\sigma_d(N)$, but at dark conditions), and taking the average standard deviation over all the pixels. However that involves more many repetitions, because it is necessary to sampling correctly the CIC that has a low occurrence frequency. Instead of that, it is possible to assume that the majority of the pixels have the same behaviour and irradiate uniformly the CCD: in this case only two repetitions are required, the second one for correcting the non uniformity across the array. Thus, if F_1 and F_2 are two successive flatfield images, $F_1 - F_2$ represents a frame where the only variation is due to readout, CIC and shot noises. Then $\sigma(N) = std(F_1 - F_2)/\sqrt{2}$, where std means standard deviation across the frame. The division by $\sqrt{2}$ is required to avoid taking into account twice the noise.

Using this technique we measured the product $G \times K$ for the Andor Ixon DU-888E-C00-BV EMCCD (at 1 MHz and preamplified $\times 1$). Figure 8 shows $1/GK$ was plotted as a function of the software-displayed gain. The higher the gain, the lower the readout noise when expressed in photo-electrons (represented in a second y-axis). This noise is around 1 photo-electron at a gain around 20. The relation between G_D (display gain) and GK is almost linear ($GK = 0.05 G_D^{1.02}$, with a correlation coefficient of 0.99953). When the settings are changed (preamp and Horizontal Pixel Shift) K and the readout noise changes, and the GK factor should be proportionally corrected.

A uniform and stable source was used in this characterization. This source, that is described elsewhere[12] consisted, essentially, of a power-stabilized (0.02%) argon laser externally irradiating a 0.5 m-diameter integrating sphere. A rotating diffuser was placed in front of the entrance port to minimize the speckle pattern on the matrix detector.[13,14] This radiant source behaves as a lambertian spectral source[12] and ensures a uniform irradiance distribution over the array.

4. CONCLUSIONS

The EMCCD technology does negligible the readout noise in astronomical photometry measurements respect the background noise, allowing the background-limited astrometrical photometry. Therefore, this technology is relevant only in the measurements conditions where the readout noise is well above the background noise. Its usage produces an increase in the shot noise by a $\sqrt{2}$ factor and decreases the dynamic range of the detector. The best value for the EM gain at a specific integration time is the smallest one that lowers the readout noise well below the background noise. It is possible to improve the temporal resolution using EMCCD technology by dividing an image exposure in several frames of shorter integration time, because other exposures can be recovered by addition of images without propagation of the readout noise from every single image. The more important restrictions to the temporal resolution are the readout time, the loss of dynamic range, the accuracy of the CCD at very short integration times and the possibility of carrying out astrometry. The most important parameter to characterize from a EMCCD, apart from conventional CCD's parameters, is the readout noise expressed in photo-electrons as a function of the software-displayed gain. A readout noise characterization method based in the photon transfer technique is proven to be sound and technically straightforward.

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