A New Digital CCD Readout Technique for Ultra–Low-Noise CCDs

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ABSTRACT. We present a completely new technique to read out the CCD matrix that can achieve much lower noise than classical techniques used since the 1970s. This technique is based on digital analysis of the CCD’s output signal instead of analog filtering coupled to an original filtering method. Despite several attempts carried out in the past to implement digital correlated double sampling, this is the first time that a radical improvement in readout noise performance is shown. This is highly interesting for low light level conditions, where the detector works in the readout-noise regime and not in the photon-noise regime. This is particularly the case when carrying out medium- to high-resolution spectroscopy or multiplex (scanning) observations.

1. INTRODUCTION: READOUT NOISE LIMITATIONS WITH CLASSICAL TECHNIQUES

The problem of readout noise affects CCDs at low light levels. Despite the remarkably high quantum efficiency achievable, up to 95%, and the very low noise, down to 2–3 $e^-$, this is largely insufficient in high-resolution spectroscopy where the observations are often detector noise limited. The problem is even more critical with multiplex instruments (e.g., scanning instruments), where large numbers of images are produced. This problem has been widely discussed in Gach et al. (2002).

Usually, CCDs are read out with correlated double sampling (CDS) devices. The goal is, for each pixel, to measure the difference between a reference level, called the black level, and the pixel level itself that are voltages sequentially present at the output of a CCD. This is made necessary by the pixel charge conversion method used inside the readout circuit of the CCD. There are also other techniques, such as double ramp integration, clamp-and-sample, etc., but all are equivalent to the CDS system in terms of transfer function and signal processing. To limit readout noise, a first-order low-pass prefilter with correctly matched bandwidth is placed before the CDS device. The output signal of the CDS is then converted into a digital signal with an analog-to-digital (A/D) converter when this difference has been done (once per pixel) for computer acquisition.

In this bandwidth-limited system, the total noise $e_n$ obtained at the output of the device could be expressed as

$$e_n = \sqrt{\int_{f_1}^{f_2} e_n(f)^2 df}$$

(1)

where $f_1$ and $f_2$ are the low and high $-3$ dB cutoff frequencies and $e_n(f)$ is the voltage noise density of the CCD’s output stage. It is possible to show that with a CDS,

$$f_1 = \frac{1}{2}f_c,$$

(2)

$$f_2 = \frac{1}{2}f_c,$$

(3)

where $f_c$ is the CDS rate (or also the pixel clock rate). The gain of a perfect CDS system is 2, with a peak gain at $f_c$.

When looking to a typical $e_n(f)$ shape, there are two different regions. For the high frequencies, $e_n(f)$ is nearly constant, meaning that the noise has a “white” characteristic. For the lower frequencies, $e_n(f)$ has a $1/f$ component, meaning that the noise has a “pink” characteristic.

In the case of white noise with constant spectral density $e_n^2$, a good approximation of the total noise is then

$$e_n = 2e_n\sqrt{f_c}.$$  

(4)

In the case of $e_n^2$ $1/f$ noise (pink noise), the total noise becomes

$$e_n = 2e_n\ln(3) \approx 2e_n.$$

(5)

This shows clearly that at high frequencies, reducing $f_c$, the pixel clock, diminishes the readout noise of the CCD. But for lower frequencies, this readout noise tends to become constant, meaning that reducing the readout speed of the CCD will not reduce the readout noise any more. Figure 1 shows the expected readout noise for different CCD readout circuit capacitances (giving different conversion factors, electrons to voltage, of the CCD output) with respect to the readout speed.
The curves show clearly that the decreasing readout noise at high frequencies becomes nearly constant for lower ones. Usually, a CCD manufacturer gives as CCD readout noise performance the best readout noise achievable with a “perfect” CDS system for a given readout frequency, meaning without any noise, distortions, gain, or offset errors introduced by the CDS. There is then a physical barrier (the noise floor) within the CDS that cannot be crossed whatever the quality of the electronics used, which is intrinsic to the CDS readout technique.

2. BREAKING THE NOISE FLOOR

To reach a lower readout noise at the same readout frequency, and mainly to have much lower readout noise than the noise floor expected with a given CCD, it is then necessary to use a radically different readout technique. We removed completely the CDS and converted directly the signal of the CCD into digital information to feed a digital signal processor (DSP). This method is well known and was introduced to read out infrared arrays in the early 1990s (Fowler & Gatley 1990, 1991). More recently, Markelov et al. (2000) developed a DSP-based CCD controller, but it still used a straightforward digital CDS (subtraction of two samples taken on the black level and pixel level, respectively) or a classical filtering technique based on the Hegyi & Burrows (1980) optimal filter concept at lower readout rates. In the case of our system, the A/D conversion rate is much higher (10 megasamples per second) since we have to sample several times (100–250) the reference level and the pixel level in order to have sufficient material for further digital processing. The digital flow is then processed in real time by a high computing power embedded DSP board (based on a Texas TMS320C6201), and the evaluated pixel value given by this process is returned to the classical CCD controller. This system was designed to be completely transparent to older CCD controllers in order to avoid useless developments and to get an exact comparison base with an existing CCD system developed by the Observatoire de Haute Provence. Therefore, swapping from a classical CDS system to this digital readout system is very simple. Figure 2 gives the system’s synoptic.

The first step has been to analyze the output signal of the CCD carefully. Figure 3 shows a typical signal we obtained with this system and an EEV 42-20 CCD previously used in the Observatoire de Haute Provence with a “classical CDS” controller. This graph shows clearly that samples very near to the reference level/pixel transition are much more correlated than the ones at the opposite side of these (theoretically constant) levels.

Therefore, one could say that the samples near the reference level/pixel transition (central samples) have a much higher quality than the other ones. One possibility to decrease readout noise is then to give more “weight” to the samples near this transition. When making the mean of all the samples of a given
level (black or pixel), one realizes a simple first-order filter. It is then possible to digitally compute the subtraction of the black level with the pixel level, thus obtaining a "digital double ramp integration," which is equivalent to a CDS, as said before. To give more weight to the central samples, it is necessary only to give a coefficient to the samples, sum up, and normalize with the sum of all the coefficients to maintain the system's gain at the same value. Each pixel value is then computed by the following formula:

\[
\text{pixel} = \frac{\sum_{0}^{2n-1} \alpha_i S_i}{\sum_{0}^{2n-1} \alpha_i} - \frac{\sum_{0}^{n-1} \alpha_i S_i}{\sum_{0}^{n-1} \alpha_i},
\]

where \(\alpha_i\) is the \(i\)th coefficient, \(S_i\) is the \(i\)th sample, and \(n\) is the number of samples for each level (black or pixel) giving \(2n\) samples per pixel. This formula can be simplified, especially for algorithmic reasons and code efficiency, giving negative coefficients for the first \(n\)th coefficients (corresponding to the black level samples) and adopting symmetrical coefficients values, by

\[
\text{pixel} = \frac{\sum_{0}^{2n-1} \alpha_i S_i}{2 \sum_{0}^{2n-1} \alpha_i}.
\]

The first coefficients tested are plotted in Figure 4. This shape is based on a Gaussian centered on the black/pixel level transition where the first \(n\)th coefficients were inverted as explained above. When varying the width of the Gaussian, we then looked at what the effect was on the readout noise of the CCD. We obtained the results shown in Figure 5, which plots the readout noise as a function of the Gaussian width.

When the Gaussian width decreases, the readout noise diminishes as well to go through a minimal value (\(\approx 2.2 \ e^-\) ) and increases again. This is because the central samples get more weight than the ones located at the edges of the black or pixel levels. For very small values of the Gaussian width, the readout noise increases since only a few samples are taken into account, and then the bandwidth of the system increases dramatically, increasing also the readout noise as a side effect.

The Gaussian shape was chosen randomly; therefore, there was almost no chance that this shape minimized the readout noise. To find the best coefficients, we ran a simulated annealing program with the readout noise as cost function. We obtained the coefficients plotted in Figure 6, which shows that this co-
efficient’s shape cannot be described by a simple mathematical function.

Using these coefficients, the readout noise has been reduced to $1.7 \ e^-$. This is to be compared with the classical Observatoire de Haute Provence’s controller, which reads out the same CCD at $\approx 5 \ e^-$ noise exactly in the same environmental conditions (same Dewar, same location, etc.). The linearity of the camera has been measured at 100 ppm versus 1000 ppm with the classical controller. This is interpreted by the fact that the CCD’s signal is digitized very near to the CCD’s output and does not go through any complex device. Therefore, it is less affected by distortions and other classical analog errors found in CDS systems. We exposed first a stochastic explanation of the noise reduction process, but a deterministic approach could also be given when looking at the frequency transfer response of the different systems (plotted in Fig. 7).

Compared to a normal CDS filter, the peak response of the digital filters is not centered on the pixel frequency $F_{\text{CDS}}$, but at $3F_{\text{CDS}}$. The optimized filter even has several components at $F_{\text{CDS}}, 3F_{\text{CDS}}$ (peak), $F_{\text{CDS}}$, etc. Since the CCD’s signal is supposed to have a square shape, this signal is rich in odd harmonics. The conclusion is that the digital filters use more of the high harmonics of the CCD’s signal to evaluate the pixel charge (whereas the CDS uses only the fundamental). Since these harmonics have a higher frequency, they are less affected by the CCD’s output pink noise, and this reduces the readout noise.

3. ZERO NOISE CCD CONCEPT

The device we presented here has a reduced readout noise (1.7 $e^-$). When a 0.2–0.3 $e^-$ readout noise is possible, it will be possible to remove the noise completely. Since the photons (and electrons) are discrete elements (2.5 photons is obviously a nonsense), the signal produced by a single electron will be above 3–5 $\sigma$, and it will then be possible to determine precisely the exact number of electrons present on 1 pixel. This is equivalent to a digital nonlinear filtering that will completely remove the remaining noise of the image.

To achieve this, the actual readout noise must be decreased by 5, which is still a big step. There are various technical solutions to reach this level.

First, it is possible to use a more recent CCD that has a lower intrinsic noise. The CCD technique is still evolving, and now 2 : 1 electron devices (with CDS) are foreseen or already proposed.

4. CONCLUSIONS

We presented a promising completely new filtering technique to read out CCDs. This technique has a real improvement potential since it is highly versatile and permits extremely complex digital processing. We can expect to decrease the readout noise level in the future by improving the digital filtering method and by combining this technique with other ultra–low-noise ones.

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REFERENCES