Zero noise CCD : a new readout technique for extremely low light levels

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Abstract. Since the beginning of the CCDs, the only readout technique used up to now is the correlated double sampling scheme with bandwidth limitation. We developped a totally new technique based on the real time treatment of the output signal of the CCD by a digital signal processor: this allows complex filtering and better evaluation of the pixel charge. This technique is much more noiseless than the previous one and allows to read CCDs at a much lower readout noise, even without any noise in the near future. This is of prime importance for observations at very faint fluxes, dominated by detector noise and not shot noise. That kind of CCD systems could be used for medium to high resolution (both spatial and spectral) 3D spectroscopy of faint sources, and is unbeatable with scanning instruments such as FTS and Fabry Perot spectrographs. Since 8-10m class telescopes are pushing ground observations to fainter and fainter limits with higher and higher spatial resolution, noiseless detectors will become necessary to push even more away the limits.

1   The readout noise problem

One could demonstrate that with a Correlated double sampling (hereafter CDS), usually used to read out CCDs and to remove reset noise, the total noise e_{nt} in a band-limited system is:

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

where $e_n(f)$ is the noise spectral density of the output amplifier, f_1 and f_2 the frequency range of use. With appropriate pre-filtering, the bandwidth of a CDS is effectively $f_c/2$ to $3f_c/2$ with a gain of 2, where f_c is the CDS rate (twice the pixel rate). In the case of white noise with constant spectral density e_{no}, a good approximation of the total noise is then :

$$e_{nt} = 2e_{no}\sqrt{f_c}$$

As all electronic systems, the output noise of a CCD amplifier has a pink shape, meaning that it has a $1/f$ component for low frequencies. In the case of e_{n1}^2/f noise, the total noise becomes:

$$e_{nt} = 2e_{n1}\sqrt{\ln(3)} \simeq 2e_{n1}$$

This shows that any $1/f$ component produces a fixed value of total noise whereas in the case of white noise, it increases with the square root of readout frequency. In othe words, this means that when lowering the readout speed, the readout noise comes to a "floor" value which is usually the readout noise given by the chip manufacturer.

2   The digital alternative

2.1   System description

We replaced the classical analog CDS by a digital filter on a CCD camera based on the EEV 42-20 chip. The game is to digitize the signal from the CCD a large amount of times (typically 512 samples in our application) instead of once per pixel. The digital signal then feeds a high performance DSP (TMS320C6201) that makes the digital filtering. This is possible then to use more complex filtering than the usual 1st order filter used with CDS. The signal is only limited to the nyquist frequency of the A/D converter (10 MSPS in our case giving a 5 MHz full power bandwidth). The converter used has 14 bits resolution since no 16 bits are avalaible at this speed at that time, lowering then the dynamics of the system. This is not a real problem since this technique has an advantage only for low light level observations, where the images are detector noise limited and not photon noise limited.
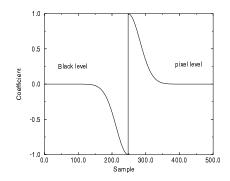
2.2   The results

The first idea we got was to give more weight to the samples which were at the end of the black level reference and at the beginning of the pixel level. This is driven by the idea that these samples are more correlated than the samples that are more spaced in time. In a comparable scheme as in a CDS, the black level was substracted from the pixel level according to the weight they recieved. The result is then normalized by the filter gain. The output could be written then as:

$$Pixel = \frac{\sum_{n+1}^{2n} \alpha_i S_i}{\sum_{n+1}^{2n} \alpha_i} - \frac{\sum_{0}^{n} \alpha_i S_i}{\sum_{0}^{n} \alpha_i}$$

the coefficients used are simply a gaussian centered on the black level - pixel value transition. Coefficients for the black level samples are negative to include the substraction and to make the code more efficient. By varying the width of the gaussian, we noticed that the readout noise was going thru a minimal value (figure 1). One could notice that when the width is increasing, all coefficients tend to have the same value, simply making a 1st order filter and simulating

numerically a perfect CDS. Taking the shape giving the lowest readout noise as a base, we ran a simulated re-cooking program to minimize the readout noise and to find the best coefficient shape which is not necessarilly a gaussian. We obtained then a readout noise of 1.8 e$^-$ to be compared to the 6 e$^-$ of the used controller and the 3 e$^-$ CCD chip. The linearity was measured at 10^{-4}, 10 times better than all CCDs cameras. This could be explained by the extrmely small amount of components before the A/D converter polluting the signal and adding non linearity.
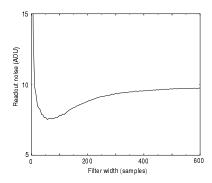

Fig. 1. Left : the used coefficients based on a gaussian function. Right : the readout noise obtained when varying the width of the coefficients' shape.

2.3   To the zero noise CCD

At this time, our CCD still has a readout noise. We will test other techniques, in particular non linear and predictive ones in the future to decrase the readout noise to a level of 0.2 to 0.3 e$^-$. At this level, it will be possible to measure exacly the amount of photons on one pixel. Doing this quantification, it will be then possible to convert the image into "number of photons" removing the remaining noise. At this time we will have a noiseless detector.

3   Astronomical interest

When used in the case of photon noise limited applications, this system has no interest. Whereas, when used at low fluxes, one could demonstrate that it could permit observations with a SNR 10 times greater than a 3 e$^-$ readout noise CCD. This is even more evident for scanning instruments which produce a large amount of images such as CIGALE [1], TAURUS [2], BEAR [3] or PYTHEAS [4] . In this case, increasing the amount of scanning steps (ie: higher spectral resolution) does no more means a loss in SNR and information.

4   Conclusion

A new CCD readout concept which is only at its beginning has been presented. Only one short way has been explored for the moment, giving interesting results, and this technique shows a large potential for the future. We hope to increase largely its performance in order to give the best detectors for the future large telescopes.

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