Lowering the noise in a CCD readout system

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Problem statement and chronology

- CCD readout noise is a limitation to achieve better physics/ astronomy in telescopes or CCD based detectors.
- Can this noise be lowered beyond the levels achieved by the traditional Correlated Double Sampling technique? (i.e. ~2e-)

- Approach:
  - Take N samples of each pixel at sampling frequency fs.
  - Digital Signal Process the data.

- We sampled CCD video data (few lines of an image) using an existing hardware (ESECON) developed in our ESE Dept in CD.
  - Data analysis is still in progress. Some preliminary results.

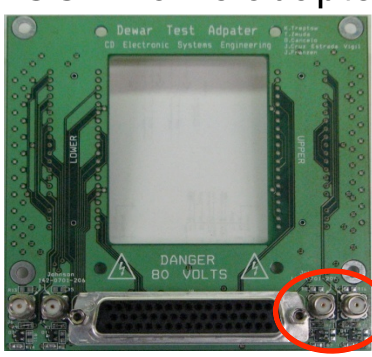
CCD noise and CCD readout noise

- CCD noise
  - Dark current is negligible at cryogenic temperatures.
  - Mainly shot noise from signal (Poisson).
- CCD readout noise:
  - 1/f noise.
  - Thermal (shot) noise (WGN), limited by high bandwidth amplifiers.
  - Analog to digital conversion noise (quantization noise).
- CCD readout noise sources
  - CCD internal electronics.
  - Readout amplifier chain.
  - Analog to digital converter and associated electronics.

CCD readout system

- CCD Picture frame adapter. It has a JFET amplifier.
- Flex or normal cable in the Dewar. Opportunities for crosstalk between higher voltage digital signals and clocks to the sensitive CCD video outputs.
- Preamplifier outside the Dewar.
- Digitizer and signal processing board.

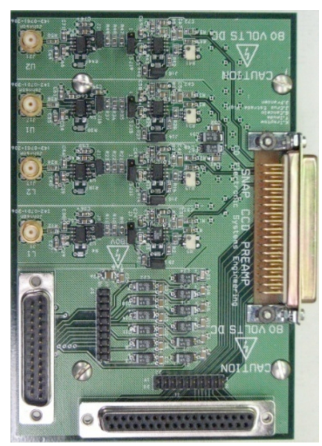
CCD frame adapter



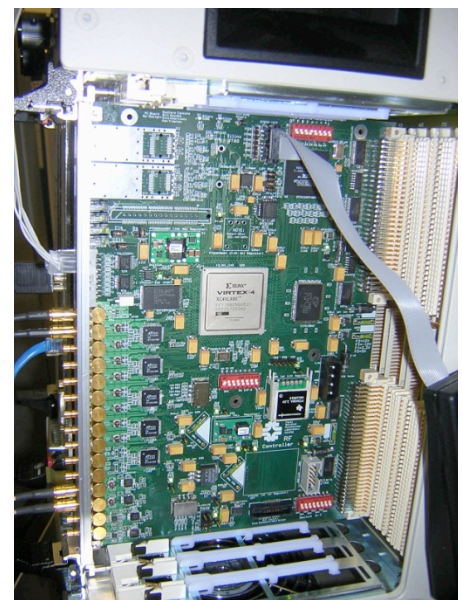
Video output and JFET

Cable inside the Dewar

Preamplifier



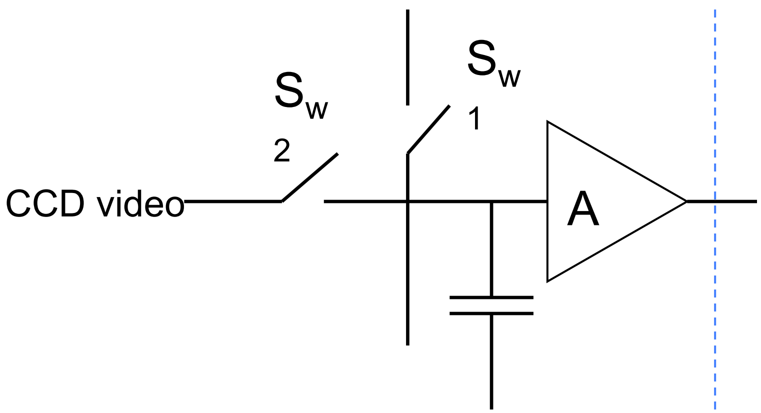
Digitizer (ESECON)



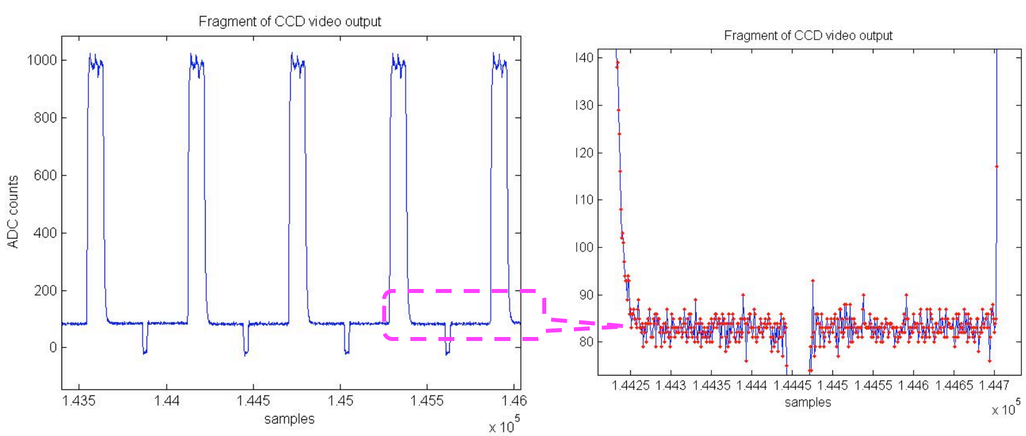
CCD readout

- CCD pixels are readout by transferring the pixel charge serially to one of the CCD's video outputs.
- The CCD uses timing signals (clocks) to do the charge transfer.
  - Timing signals can be of arbitrary length.
  - Unfortunately, the clocks show up in the video data stream.
- A pixel readout is done in two steps:
  - 1st the CCD video output capacitor is reset (CCD internal). This sets a pedestal value.
  - 2nd the pixel charge is transferred to the same capacitor.
- The actual pixel signal is calculated as a function of the difference between the pedestal charge and the pixel charge.

Simplified diagram of CCD video output



CCD video output with clocks



Most commonly used CCD readout system

- Correlated Double Sampling (CDS) performs

$$s(t)=\frac{1}{T}\int_0^T\left[x(t)-p(t)\right]dt \quad\Rightarrow\quad s(t)=\frac{1}{T}\left[\int_0^T x(t)dt-\int_{t0}^{T+t0}p(t)dt\right]$$

for an integration window T

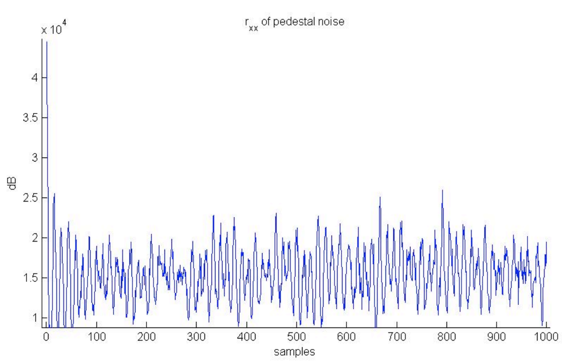
Where *x(t)* is the pixel and *p(t)* is the pedestal.

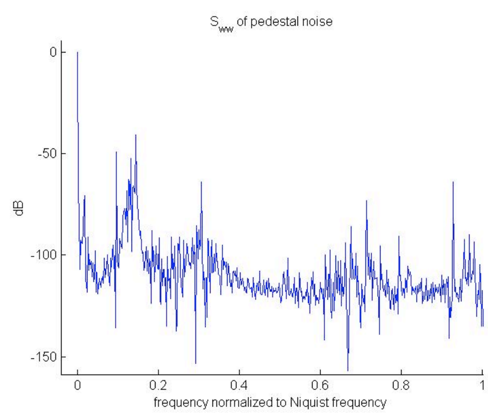
Let: $x(t)=x_0+n_x(t)\ \ and\ \ p(t)=p_0+n_p(t)$ n_x and n_p: signal and pedestal noise

If the noise is white and Gaussian ~ N(0,σ²) the CDS is the optimum estimator.

$$\hat{s}(t)=x_0-p_0\Big|_{T\to\infty} \quad \text{or} \quad \sigma^2_{\hat{\theta}_s}\to 0\Big|_{T\to\infty}$$

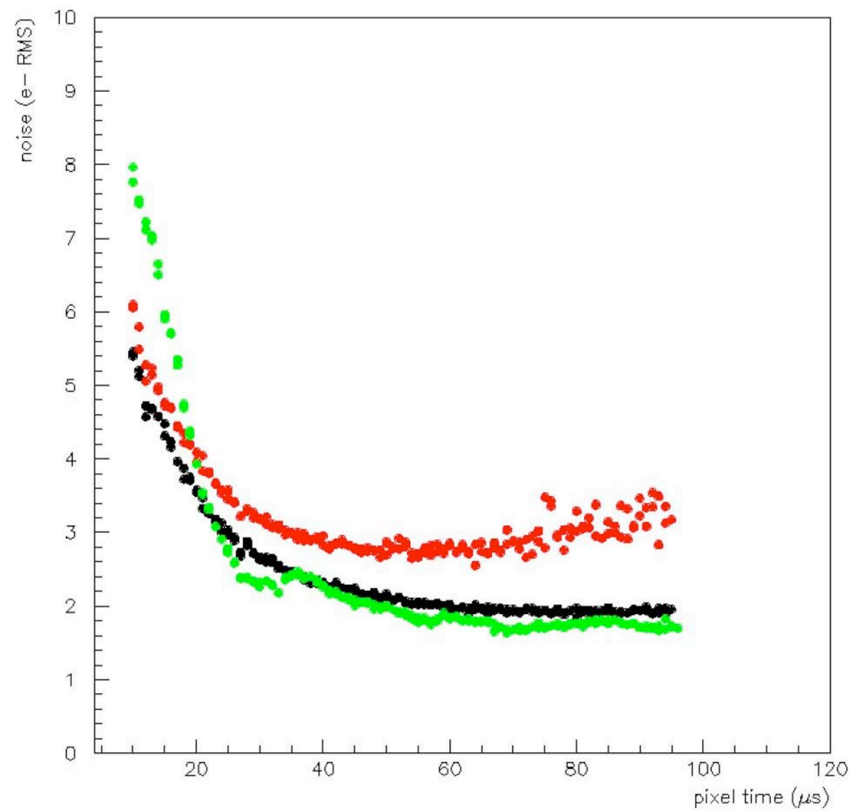
Unfortunately there is correlated noise in the low frequency spectrum. The noise does not integrate to 0 when T is made larger.





CCD noise measured with the Monsoon system

- The noise increases for long pixel observations T > 100 us.
- Besides it would be advantageous to have a low noise readout system that reads fast too.



The classical CDS

- Advantages:
  - Generates a single data point per pixel.
  - The pixel estimation gets rid of the pedestal value which is small but still a random number.
  - The CDS filtering is implemented by a simple analog circuit.

- Disadvantage:
  - CDS integrates the entire noise spectrum $[0,\infty)$ over a limited time T. Low frequency noise does not integrate to 0. The estimator variance does not go to zero as $T \to \infty$.

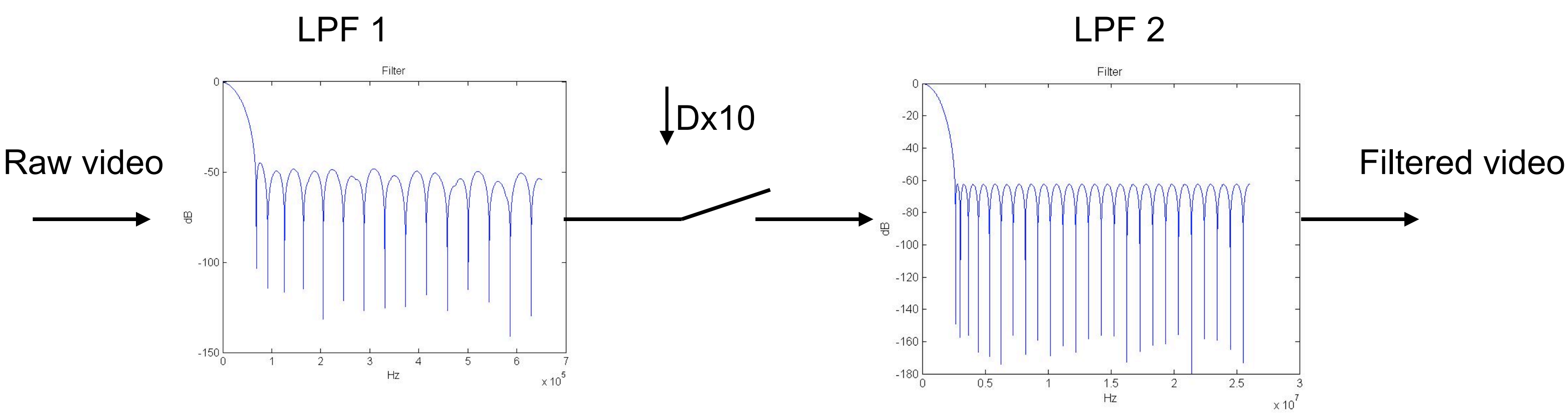
Alternative to the CDS CCD Readout

- Sample the video output.
  - Take N samples of the pedestal and the pixel value during the observation time T.
  - Digital Signal Process the data.
  - Apply a digital CDS to the processed data.

- Digital signal processing methods used:
  - Finite Impulse Response filtering.
  - Estimation using a linear model.
  - The pixel estimation problem is the classical problem of estimating a DC value in noise.

FIR filtering

- Two stage FIR filter with decimation.
  - Used to filter the high frequency noise content.
  - The data is oversampled and later decimated as a way to reduce the quantization noise of the analog to digital converter.
  - Lowers the noise of 97% of the spectrum (Nyquist domain) by at least 40dB (a factor of 100).
  - The FIR filters improve the estimation by only 30 to 40% with respect to CDS.

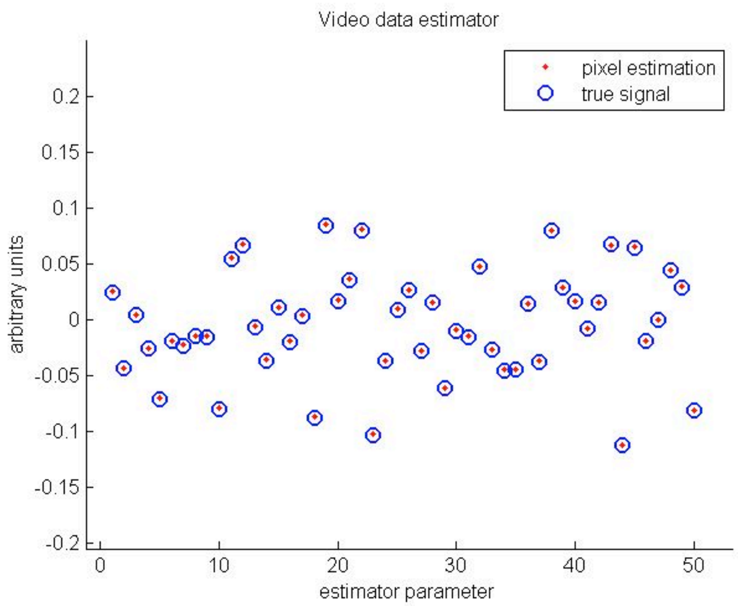


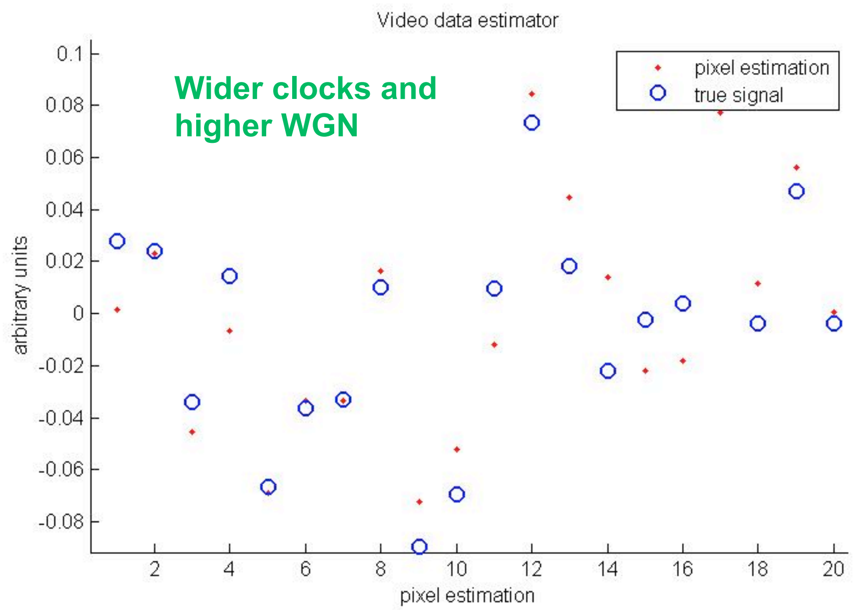
Estimators

- So far we used two estimators:
  - One estimates the low frequency noise content in the time domain and the second one in the frequency domain.
  - The estimation problem is linear and the inversion of the estimation matrix is done only once and a priori.
  - Both estimators were tested on simulated data. The time domain estimator was tested on a small set of real CCD sampled data.

Simulated data

- Random pixel data with additive noise.
- The noise follows an 1/f power spectrum with 500 to 1000 frequency components.
  - Amplitude and phases are randomized.
  - These are the noise components that we estimate.
- Small amplitude WGN noise, to test the robustness of the solution.
  - This is the high frequency noise that we are not estimating.
- We also include large the noisy clocks.

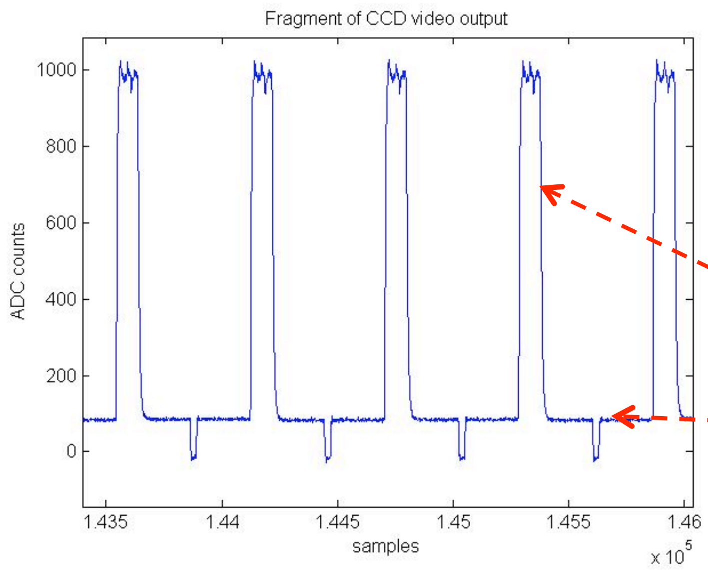




Observations

- The clocks are removed from the sampled data by skipping the points in time domain.
    - Clock gaps create numerical problems in the estimation process.
    - Clock gaps can become very large unless the pixel observation time is made longer.
- Some WGN is tolerated and the error increases linearly with the square root of the noise power.
- We must estimate all the frequencies in the filter’s bandpass.

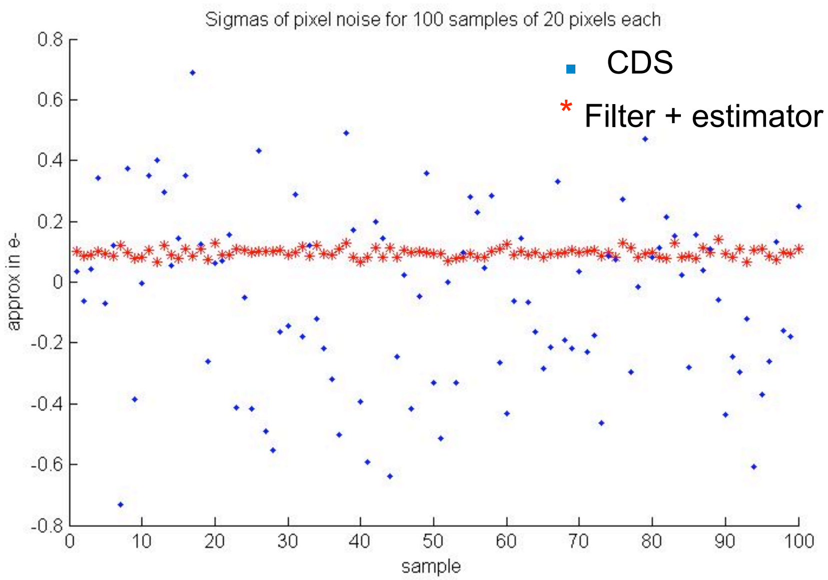
Real CCD data

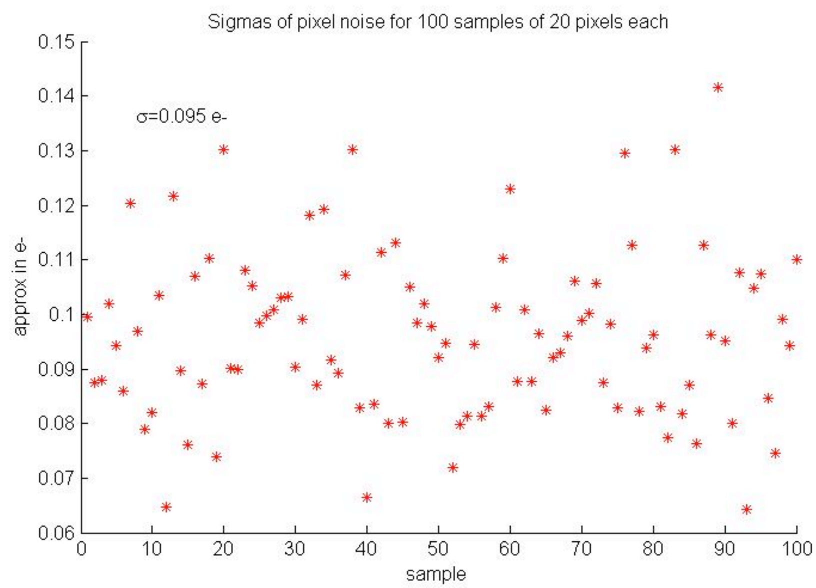


- What we see in simulation is verified.
- Clocks are huge compared to the signal levels that we are trying to measure.
  - Clocks~1000.
  - Signals ~ 0.01 in this arbitrary scale.
- Clocks gaps are too large.

Real CCD data

- Plots below show the sigma of the estimation error for and a comparison with the CDS (left).
- This is our current best results that could not be reproduced consistently in all our data.





Future work

- Make the filter-estimator work consistently.
- Process an entire image and see if it works for real.
- Hardware optimization.
  - Several noise reduction techniques.
  - I do not think that we need a new sampling card yet.