Read Noise Modelling of Skipper CCDs

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Introduction

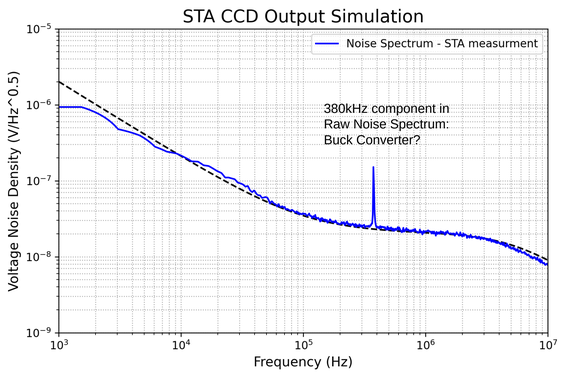
We developed a simulation tool to predict total integrated noise of a Skipper CCD. The tool ingests any arbitrary readout waveforms in the time domain and real-value noise spectrum. We show that the tool successfully predicts total integrated noise of an STA CCD. We then explore uncharted territory of Skipper operation making a few informed assumptions about actual Skipper source follower gain.
We draw requirements for a future Skipper CCD to be able to readout a 128-channels 4k x 2k in less than 2 minutes.

Simulation tool features:

- **Arbitrary time-domain waveform definition**
- **Analytical CDS and Skipper transfer functions**
- **Arbitrary noise distribution or 3-parameters model**
- **Total noise computation**

MOSFET Source Follower Noise

The source follower FET is the main source of noise in the video chain. While semiconductor theory and modelling can predict its noise characteristics, we do not attempt to tie each noise contribution to a physical transistor parameter.



Our tool can use continuous noise spectrum model or real-data spectrum.

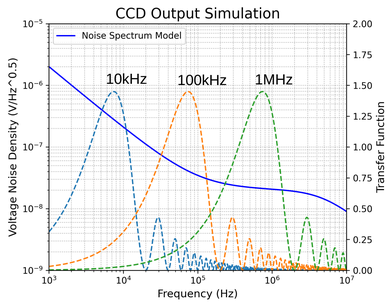
Greg Bredthauer collected 100MHz time-series voltage samples from an STA CCD and extracted its spectrum via FFT. We have fitted a curve using the following parameters.

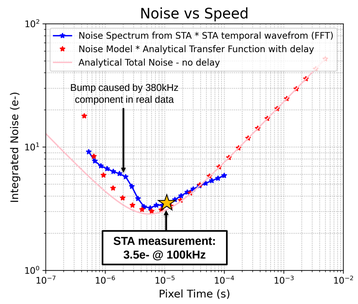
Noise Model parameters are:

- **White Noise floor. ~20nV/√Hz**
- **1/f noise corner. ~100 kHz**
- **1/f² noise corner. ~100kHz**

Correlated Double Sampling

Correlated Double Sampling (CDS) is a differential averaging technique that suppresses DC offset and low frequency fluctuations at CCD output. The averaged (integrated) post reset value is subtracted from the averaged signal after charge dump. The CDS transfer function is a band pass filter with peak near the pixel frequency, shifting to lower frequency when the transfer gate dead time is interleaved between samples. This causes a noise penalty.





$$H(f) = \frac{2\sin^2(\pi f \tau_{pedestal})}{\pi f \tau_{pedestal}}$$

$$\sigma_{CDS} = e_{wn}\sqrt{\frac{1}{\tau_{pedestal}} + 4 * f_{nc,1} * \ln(2) + \frac{4}{3} * \pi^2 * f_{nc,2}^2 * \tau_{pedestal}}$$

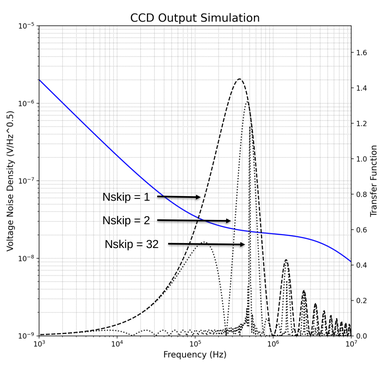
The Total Noise is found by integrating the product of readout transfer function and noise density. $\sigma^2 = \int_0^\infty [N(f).H(f)]^2 df$

1/f noise creates a noise floor: noise reduction to sub-electron levels cannot be achieved by simply extending the averaging time indefinitely.

Our tool can compute the transfer function of any time-domain readout waveform or use continuous analytical transfer function.

Skipper Operation

By repeating and averaging non-destructive readout of the same pixel at high cadence, Skipper Sampling narrows the filter bandwidth around the sampling frequency.



The total integrated noise reduces as $\sqrt{\text{nskip}}$ regardless of the noise regime it operates at.

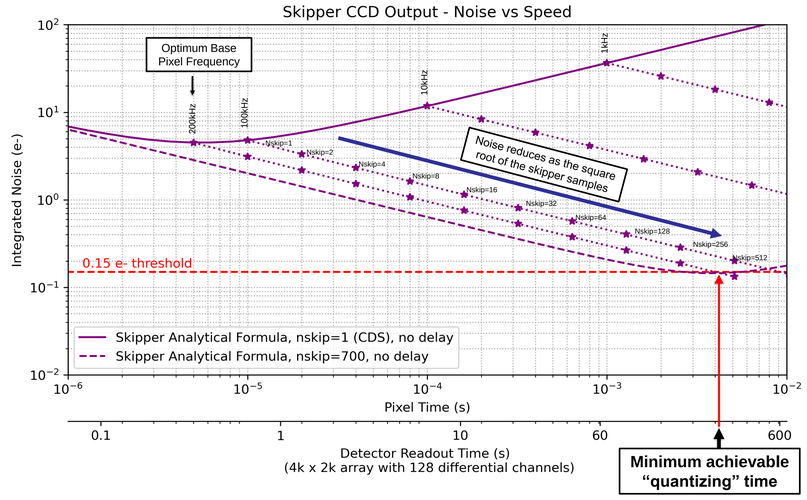
Skipper timing circumvents 1/f noise limit and reduces noise by $\sqrt{N_{skip}}$ into the sub-electron regime

$$\sigma_{skipper} = e_{wn}\sqrt{\frac{1}{\tau_{pedestal} * n_{skip}} + \frac{4 * f_{nc,1} * \ln(2)}{n_{skip}^{1.145}} + \frac{4 * \pi^2 * f_{nc,2}^2 * \tau_{pedestal}}{3 * n_{skip}}}$$

Skipper CCD - Total Noise

A realistic Skipper CCD is modeled to predict what noise can be achieved and conversely how a Skipper source follower must perform to achieve quantization at a given readout speed

Weaker coupling from the skipper channel to the source follower gate reduces system gain by factor of 1.6 compared to a regular CCD output stage (when using same pixel buffer transistor)



The base pixel frequency is chosen such as the single readout (CDS) noise is minimized. It is then possible to infer the number of skipper operation before reaching the 0.15 e- noise threshold. Using a slower or a faster base pixel frequency only leads to longer time spent to achieve a same noise.

0.15 e- * noise is achieved in ~5min readout time assuming 128 channels and a 4k x 2k array.

* ***threshold at which electrons can be discriminated with 99.9% confidence***

Conclusion

Our simulation tool predicts the total noise achievable with a Skipper CCD.

Being able to readout a 4k x 2k detectors in less than 2 minutes requires some optimization of the output transistor geometry.