Low Noise Wide Dynamic Range Image Sensor Readout using Multiple Reads During Integration (MRDI)

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ABSTRACT

Thermal noise sets the fundamental detection limit for silicon photodiode based image sensors. In this paper we present a technique for nondestructively reading PDI image sensors, called multiple read during integration (MRDI), which reduces thermal read noise by using oversampling.

This paper discusses the operation of MRDI, presents an illumination estimator, and analyzes the resulting noise and dynamic range of this estimator. We show that the dynamic range of an image sensor can be increased by $O(n^{\frac{3}{2}})$, where n is the number of times the sensor is readout while photocharge is being integrated. A real-time algorithm is presented for processing MRDI pixel data. Measured data from a PDI-CIS600B sensor is reported and compared with theory.

Keywords: Read noise, oversampling, APS, MRDI.

1. INTRODUCTION

Non destructive oversampling has been used for many years to reduce read noise in infrared image sensors.[2] This technique was developed to help improve the low light performance of image sensors used in telescopes and other scientific instruments. Oversampling has been shown to reduce read noise by as much as a factor of 4 in infrared telescope applications.

Due to the similarities between PDI image sensors and the readout circuits used in high end infrared sensors, oversampling should reduce the read noise of PDI image sensors. In this paper we present an oversampling method called multiple read during integration (MRDI) and show how it reduces read noise and increases the dynamic range of PDI sensors.

The remainder of this paper is organized as follows. Section 2 describes the operation of MRDI, presents an illumination estimator, and analyzes the noise and dynamic range of this estimator. Section 3 presents a real-time algorithm for processing MRDI pixel data. Section 4 presents measured results from a PDI-CIS600B sensor and compares it with theory.

2. THEORY

2.1. Operation

Figure 1 shows a simplified model of a PDI linear image sensor. In this model, each photodiode is connected to a low noise high gain pixel level amplifier, and each amplifier is noiselessly multiplexed to the output. The output multiplexer is selected using the data select shift register. This model assumes that the sensor is linear and that all of the noise in the system can be input referred to the photodiode.

Using MRDI readout, PDI image sensors can be nondestructively read out multiple times while photocharge is being integrated. This is possible with PDI sensors because pixel readout does not affect the state of the integrated photocharge at the pixel. This is not possible with CCD image sensors, because they transfer charge from the pixel to readout the sensor.

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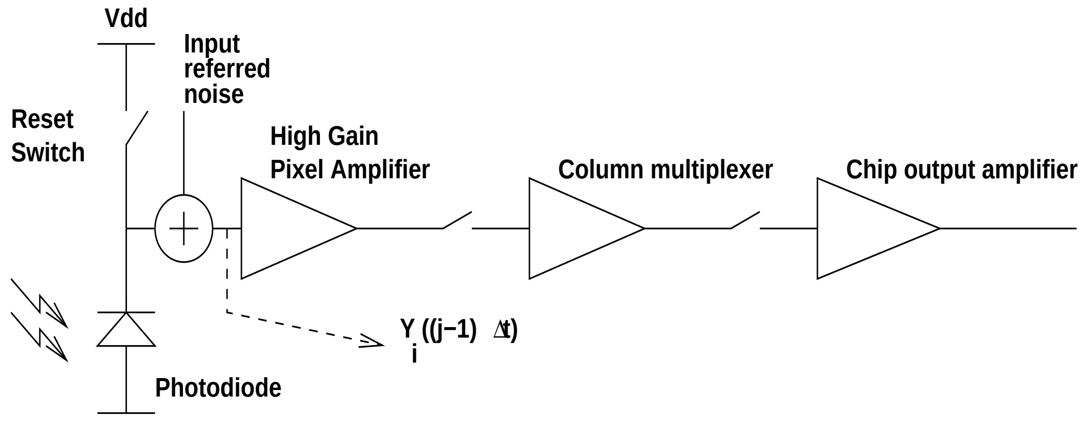

Figure 1. Simplified Sensor Model

MRDI operation begins by resetting all of the pixels. Then after allowing the pixel level amplifiers to settle, data is read out from the sensor multiple times. After completing the final readout, the sensor is again reset. Figure 2 shows the output waveform of a sensor operating in MRDI with 8 readouts during a single integration period. The gaps in the waveform represent the time between finishing a readout and starting the next readout. The pixels are not sampled and held between each readout and this causes the slope in the output waveform. Figure 3 shows the output waveform of a single pixel during MRDI. The arrows in this Figure represent the 8 sampling points during integration. The exact sampling points for each pixel in the array are slightly different because each pixel is readout at a different time. The time difference between each pixel's sample point is the same assuming the sensor is readout at a constant rate. For MRDI to operate correctly the photon flux must be constant during the entire integration period, since we are trying to measure the photon flux not the total integrated charge. Note that the amount of anti-blooming required in MRDI is proportional to the number of times the sensor is readout during a single integration period.

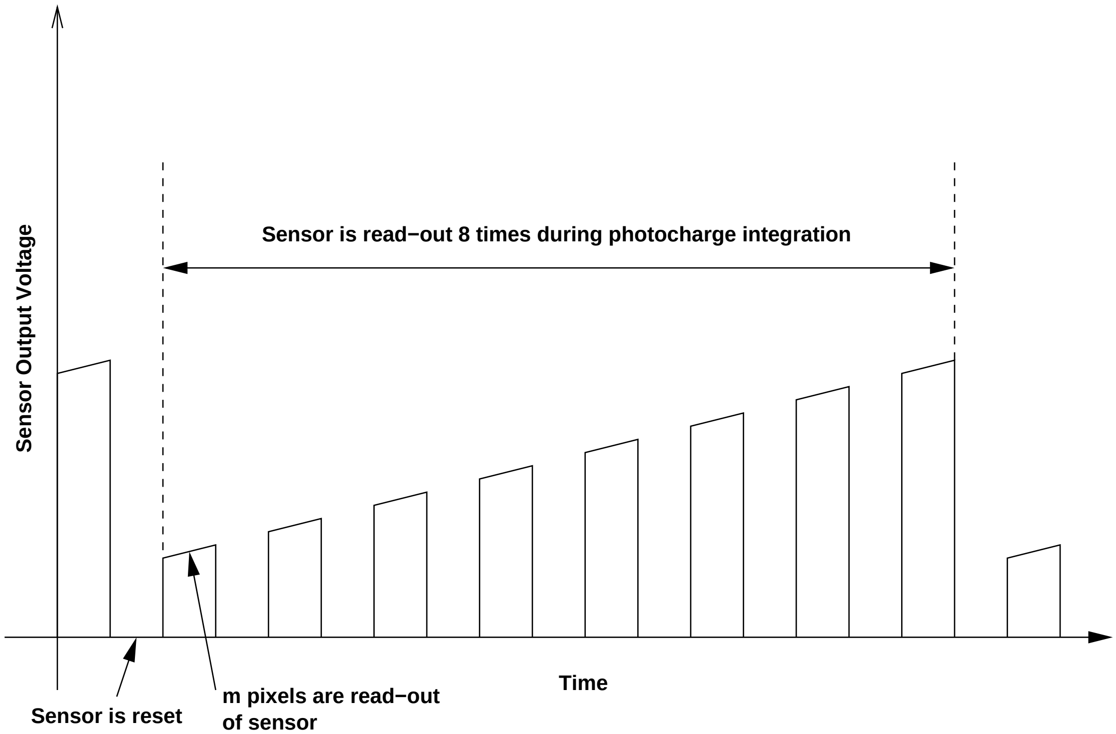

Figure 2. MRDI Sensor Output Waveform

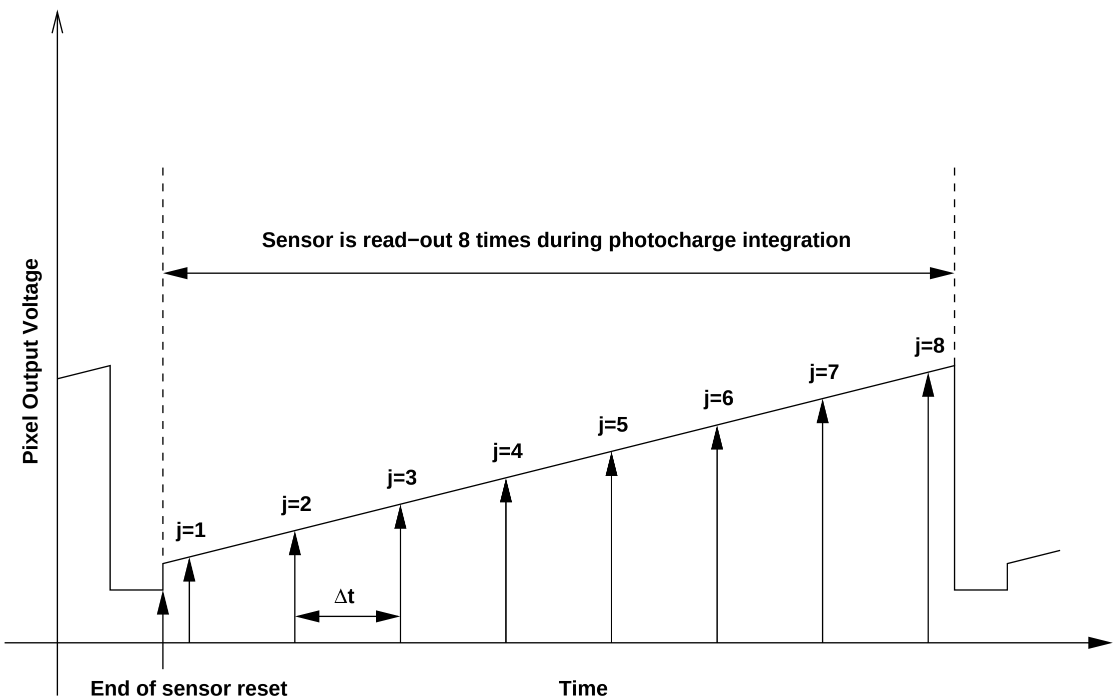

Figure 3. MRDI Pixel Amplifier Output Waveform

2.2. Notation

In order to analyze the dynamic range of an image sensor operated in MRDI we introduce the following notation: $Y_i((j-1)\Delta t)$ is the charge collected by pixel i at time $(j-1)\Delta t$, where j is an integer between 1 and n and Δt is the time between readouts. This includes photocharge, dark charge, time varying read noise, and pixel reset noise. This model does not take 1/f noise into account. Moreover,

$$Y_i((j-1)\Delta t) = X_i((j-1)\Delta t) + N_i((j-1)\Delta t) + O_i, \tag{1}$$

where $X_i((j-1)\Delta t)$ is the photo and dark charge at time $(j-1)\Delta t$, $N_i((j-1)\Delta t)$ is the read noise of the sensor at time $(j-1)\Delta t$. and O_i is the pixel reset noise*. We model each of these variables as random processes with the following properties: $X_i((j-1)\Delta t)$ is a Poisson process with mean and variance equal to $(j-1)\lambda\Delta t$, $N_i((j-1)\Delta t)$ is a white Gaussian process with zero mean and variance σ_N^2, and O_i is a Gaussian random variable with zero mean and variance σ_O^2. We assume all of the variables are statistically independent. Note that λ is the average arrival rate of electrons at the pixel.

2.3. Slope Estimator

The signal estimator we recommend is a straight line, least squares fit to the data $Y_i((j-1)\Delta t)\ \forall\ j = 1...n$, i.e. we will estimate the slope of the data

$$\overline{\lambda} = \frac{\sum_{j=1}^{n}(Y_i((j-1)\Delta t) - \hat{Y}_i)(j\Delta t - \frac{n+1}{2}\Delta t)}{\sum_{j=1}^{n}(j\Delta t - \frac{n+1}{2}\Delta t)^2}, \tag{2}$$

$$\overline{\lambda\Delta t} = \frac{\sum_{j=1}^{n}(Y_i((j-1)\Delta t) - \hat{Y}_i)(j - \frac{n+1}{2})}{\sum_{j=1}^{n}(j - \frac{n+1}{2})^2}, \tag{3}$$

where

$$\hat{Y}_i = \frac{1}{n}\sum_{j=1}^{n} Y_i((j-1)\Delta t). \tag{4}$$

The expected value of $\overline{\lambda\Delta t}$ is

$$E[\overline{\lambda\Delta t}] = \frac{\sum_{j=1}^{n}(E\left[Y_i((j-1)\Delta t) - \hat{Y}_i\right])(j - \frac{n+1}{2})}{\sum_{j=1}^{n}(j - \frac{n+1}{2})^2} = \frac{\sum_{j=1}^{n}\lambda\Delta t(j - \frac{n+1}{2})^2}{\sum_{j=1}^{n}(j - \frac{n+1}{2})^2} = \lambda\Delta t \tag{5}$$

This shows that this estimator is unbiased. Additional approaches for estimating $\lambda\Delta t$ can be found in the literature[1] and.[2]

2.4. Read Noise and Dynamic Range Analysis

We define the dynamic range of an image sensor as the ratio of the maximum non-saturated signal to the RMS noise under dark conditions. In order to find the RMS noise under dark conditions we start by determining the variance of the slope estimator, i.e.

$$\sigma^2_{\overline{\lambda\Delta t}} = E\left[\left(\frac{\sum_{j=1}^{n}(Y_i((j-1)\Delta t) - \hat{Y}_i)(j - \frac{n+1}{2})}{\sum_{j=1}^{n}(j - \frac{n+1}{2})^2}\right)^2 - (\lambda\Delta t)^2\right], \tag{6}$$

$$\sigma^2_{\overline{\lambda\Delta t}} = \frac{\sum_{j=1}^{n}\sum_{k=1}^{n} E[(Y_i((j-1)\Delta t) - \hat{Y}_i)(Y_i((k-1)\Delta t) - \hat{Y}_i)](j - \frac{n+1}{2})(k - \frac{n+1}{2})}{\alpha^2} \tag{7}$$

where

$$\alpha = \sum_{j=1}^{n}(j - \frac{n+1}{2})^2. \tag{8}$$

*Reset noise is generated while the photodiode is reset but it is fixed in time until the next reset.

It can be shown that

$$\sigma^2_{\lambda\Delta t} = \frac{6(n^2+1)\lambda\Delta t}{5n(n+1)(n-1)} + \frac{12\sigma^2_N}{n^3-n} \ \forall \ n > 1. \tag{9}$$

If we allow $\lambda \to 0$ the variance simplifies to

$$\sigma^2_{\lambda\Delta t} = \frac{12\sigma^2_N}{n^3-n} \ \forall \ n > 1. \tag{10}$$

Remember that σ^2_N is the sensor read noise power as defined in Section 2.2. Therefore the RMS noise under dark conditions is $\sqrt{\frac{12\sigma^2_N}{n^3-n}}$. The maximum illumination the sensor can measure occurs when $\lambda\Delta t$ is equal to the usable full well capacity (FWC) of the sensor†. The dynamic range (DR) of the sensor in MRDI with n readouts per integration period is

$$\mathrm{DR} = \frac{\mathrm{FWC}}{\sqrt{\frac{12\sigma^2_N}{n^3-n}}}. \tag{11}$$

This shows that the dynamic range of a PDI image sensor operated in MRDI can be increase by $\mathrm{O}(n^{\frac{3}{2}})$. For example, if $\sigma_N = 14$e- RMS, and the full well capacity of the sensor is 75ke- and Δt is constant then the noise and dynamic range of the sensor as a function of the number of readouts per integration period n is given in Table 1 ‡.

n	Noise RMS electrons	Dynamic Range
2	19.8	3788
4	6.26	11979
8	2.16	34718
16	0.75	98781
32	0.27	279800

Table 1. MRDI Dynamic Range (σ_N=14e- RMS and FWC=75ke-)

†This assumes that the first readout can be used to estimate $\lambda\Delta t$ even if the second sample is saturated.
‡Table 1 assumes that the dark current is small enough to be neglected.

3. REAL TIME ALGORITHM FOR MRDI

Figure 4 shows pseudo code for real-time processing of MRDI pixel data. `dark_pixel[i]` is a vector of MRDI pixel values from the first readout of a dark line. `ndeltat[i]` is a vector of normalized times from reset to each pixels sample time during the first readout, i.e. `deltat[i]`$= (\mathrm{TR}+\mathrm{TP}*i)/\Delta t$, where TR is the time between the end of reset and the beginning of the first readout, and TP is the pixel clock period. Note that `slope_estimate[i,line_number]` is a 2D vector that contains the final image data. If `slope_estimate[i,line_number]` is set to -1 this represents an overflow condition.

```
MultipleReadDuringIntegration(dark_pixel[],ndeltat[]) {
   n = MRDI OVERSAMPLING RATIO;
   line_number = 0;
   For (i = 1; i <= n; i++) {
      alpha[i] = 0.0;
      For (j = 1; j <= i; j++) {
         alpha[i] = alpha[i] + (j - (i+1)/2)*(j - (i+1)/2);
      }
   }
   While (SENSOR IS CAPTURING A FRAME) {
      RESET SENSOR;
      For (i = 1; i<= (NUMBER OF PIXELS); i++) {
         num_good_samples(i) = n;
      }
      For (j = 1; j <= n; i++) {
         For (i = 1; i <= (NUMBER OF PIXELS); i++) {
            pixel_value[i,j] = get_digitized_pixel();
            if (pixel_value[i,j] > (PIXEL SATURATION VALUE) && num_good_samples[i] > j-1) {
               num_good_samples[i] = j-1;
            }
         }
      }
      For (i = 1; i <= (NUMBER OF PIXELS) ; i++) {
         slope_estimate[i,line_number] = 0.0;
         if (num_good_sample[i] > 1) {
            For (j = 1; j <= num_good_samples[i]; j++) {
               slope_estimate[i,line_number] = slope_estimate[i,line_number] +
               pixel_value[i,j]*(j-(num_good_samples[i]+1)/2)/alpha[num_good_sample[i]];
            }
         } else if (num_good_samples[i] == 1) {
            slope_estimate[i,line_number] = (sum[i]-dark_pixel[i])/ndeltat[i];
         } else {
            slope_estimate[i,line_number] = -1;
         }
      }
      line_number = line_number + 1;
   }
}
```

Figure 4. MRDI Processing Algorithm

4. MEASURED RESULTS

Measurements were taken using a PDI-CIS600B operated at 27°C. The input control waveforms for the sensor are shown in Figure 13 of the PDI-CIS600B datasheet. Pixel data was collected by connecting the sensor output signal AOUTP to a high gain single ended low noise amplifier and then connecting the output of the amplifier to a high speed 12 bit analog to digital converter with an input range of 4 Volts. The sensor was operated with a pixel clock of 2.5MHz and power supply voltage of 5 Volts. Sixty lines were collected with 2, 4, 8, 16, and 31 readouts per integration period with $\Delta t = 102.4\mu$s. This data was used to estimate the average pixel noise power and dynamic range. The average pixel noise power was estimated by first estimating the noise power of each pixel and then averaging the noise estimates of every pixel.

Figure 5 shows the dynamic range of the PDI-CIS600B as a function of the number of readouts per integration period in MRDI mode. For comparison, this Figure also shows the theoretical maximum dynamic range of the sensor. We measured σ_N =14e- RMS and FWC = 75ke-. Note that the curves diverge as the number of readouts per integration period increases, this is caused by assuming that $\lambda = 0$ and neglecting 1/f noise in the pixel level amplifier.

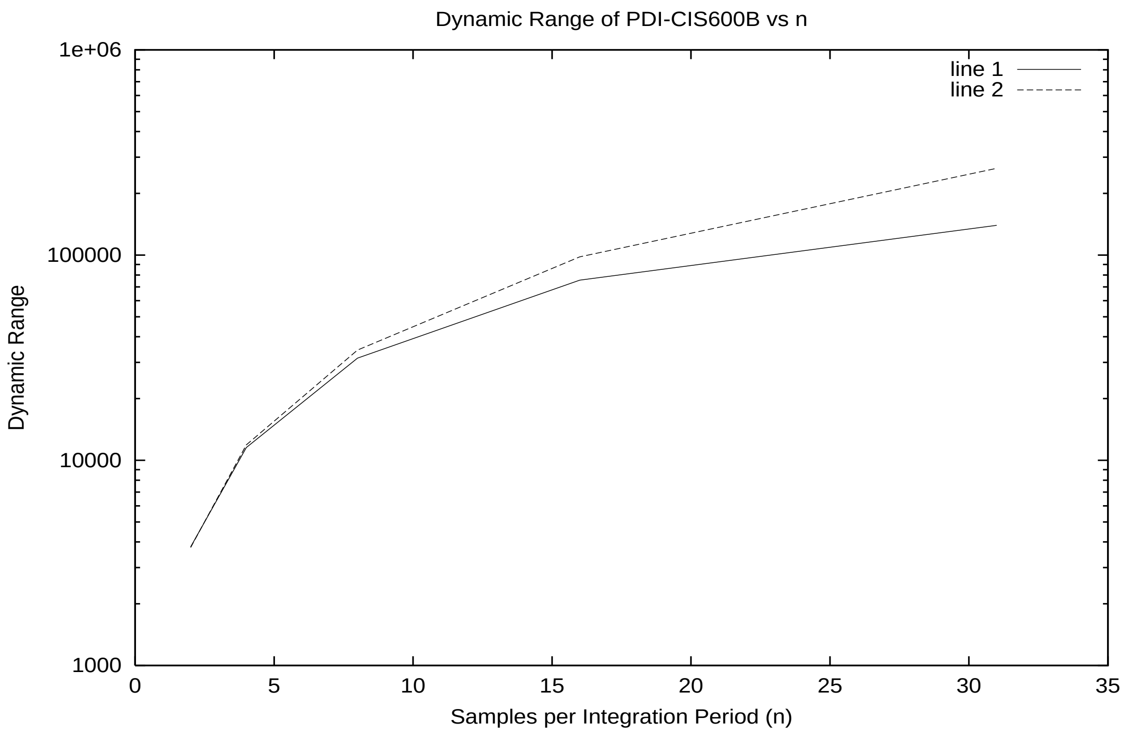

Figure 5. σ_N = 14e- RMS and FWC=75ke-. Line 1 is the measured dynamic range and line 2 is the dynamic range predicted by the theory developed in Section 2.

5. CONCLUSIONS

We have shown how reading a PDI image sensor multiple times during integration increases the dynamic range of the sensor. Moreover, the dynamic range an image sensor can be increased by $O(n^{\frac{3}{2}})$, where n is number of readouts during an integration period, by using MRDI.

APPENDIX A. MATLAB CODE

Figures 6 and 7 were used to process MRDI data captured from a PDI-CIS600B sensor to verify the algorithm presented in Section 3.

```
function [output] = mrdi(data,dark_pixel,ndeltat)
% data is a 2d vector of size 256x32
% dark_pixel is a vector of 256x1
% ndeltat is a vector 256x1
pixel_sat = 2500;
for i=1:256,
   num_good_pixels(i) = 32;
end
for i=1:256,
   for j=1:32,
      if data(i,j) > pixel_sat && num_good_pixels(i) > j-1,
         num_good_pixels(i) = j-1;
      end
   end
end
for i=1:256,
   if num_good_pixels(i) > 1,
      output(i) = slope_est2(data(i,:),0,num_good_pixels(i));
   elseif num_good_pixels(i) == 1,
      output(i) = (data(i,1)-dark_pixel(i))/ndeltat(i);
   else
      output(i) = -1;
   endif
end
```

Figure 6. Matlab code for MRDI Processing

```
function [output] = slope_est2(data,n,ms)
% data is a 256*32 x 1 array of pixel values
% n is the first readout
% ms is last non saturated readout
temp = [1:ms-n] - (ms-n+1)/2;
alpha = sum(temp.2̂);
output = (data(n+1:ms)*temp’)./alpha;
```

Figure 7. Matlab code for estimating slope

REFERENCES

1. X. Q. Liu and A. El Gamal, “Photocurrent Estimation from Multiple Non-destructive Samples in a CMOS Image Sensor,” in *Proceedings of SPIE*, vol. 4306, Jan. 2001.
2. J. D. Garnett and W. J. Forrest, “Multiply sampled read limited and background limited noise performance,” in *Proceedings of SPIE*, vol. 1946, 1993.