Seam Correction for Sensors with Multiple Outputs

ON Semiconductor®

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APPLICATION NOTE

Introduction

Image sensor manufacturers are continually working to meet their customers' demands for ever-higher frame rates in their cameras. To meet this need, ON Semiconductor produces image sensors with multiple outputs, currently making sensors with two and four outputs. Increasing the number of CCD output amplifiers, combined with splitting the vertical and/or horizontal registers, allows higher frame rates while still keeping the fundamental image quality unchanged.

While ON Semiconductor image sensors have very good correlation of output characteristics between the individual outputs of its multi-output sensors, there will still be small differences between the outputs on the same image sensor. These are due to small differences in lithography, doping or other aspects of the semiconductor manufacturing process. When the images from such a sensor are reconstructed, these small differences, if left uncompensated, may be noticeable at the boundaries where the channels meet producing a "seam" in the image.

In some applications these seams may need correction above what can be provided by electronic gain and offset. This application note explores the theory behind these seam errors and provides techniques to correct them.

SEAMS DUE TO MULTIPLE OUTPUT CCDS

Linear Detector Output

When characterizing the complete signal path of a CCD camera, the CCD output signal for a given pixel, expressed in ADU (Analog to Digital Unit as output from the Analog to Digital Converter, ADC), is related to the detected light by this formula:

$$OutSignal(I) = off + G \cdot I \quad \text{(eq. 1)}$$

Where:

I − the input signal can be either expressed in electrons per pixels or relative illumination.

off − black level offset, expressed in ADU.

G − the gain expressed in ADU per electrons.

The CCD exhibits a linear behavior with respect to the incoming light.

This application note assumes that this basic linear behavior is not jeopardized by other factors (such as temperature, electronic instability, etc.). The camera should have a sound electronic design.

For a CCD with N (1, 2, 3, 4…) outputs where k = 1…N, each output of the CCD device can be expressed as:

$$OutSignal(I)^k = off^k + G^k \cdot I \quad \text{(eq. 2)}$$

With multiple output CCDs, each output will have very small lithographic and process mismatches and will be slightly different from the other outputs, therefore:

- CCD Outputs Do Not Have the Same Offset Level (off^k)
- CCD Outputs Do Not Have the Same Gain (G^k)

If identical signals appear in areas of the sensors that are read through different outputs, the results in the image will be slightly different. This leads to areas of image non uniformity. Since the number of outputs (N) is usually equal to 2 or 4, the overall image will exhibit either 2 or 4 areas having brightness and contrast differences. The seams effect refers to the boundaries where the areas meet.

The image of Figure 1 shows the seam effect (located vertically in the middle of the image) provided by a dual output CCD. All off^k are identical, but with different gains: $G^2 / G^1 = 0.95$

NOTE: The seam effect is not as visible in image areas where there is a large amount of detail; it is more visible in uniform image sections, such as the sky.

Figure 1. Dual Output CCD (Left/Right) Image with No Seam Correction

How to Correct this Effect

Before any correction can be applied all output of the CCD must be characterized. The output response, off^k and G^2 for each detector will need to be measured.

This paper presents two techniques that could be used to do this. In each case the method should be performed on all outputs of the detector.

The first method requires only a flat field illumination source and the ability to sweep the integration time of the camera.

1. Place the CCD detector in front of a constant and flat illumination source.
2. Start with the integration time set such that the CCD output is zero.
3. Incrementally increasing the integration time and record an image at each increment.
4. When the output reaches the saturation collect the data from the stored images and plot as shown in Figure 2.

NOTES: The number of frames captured will determine the accuracy of the results.
Exposure time and the light source must be very stable (0.1%) during the measurement.

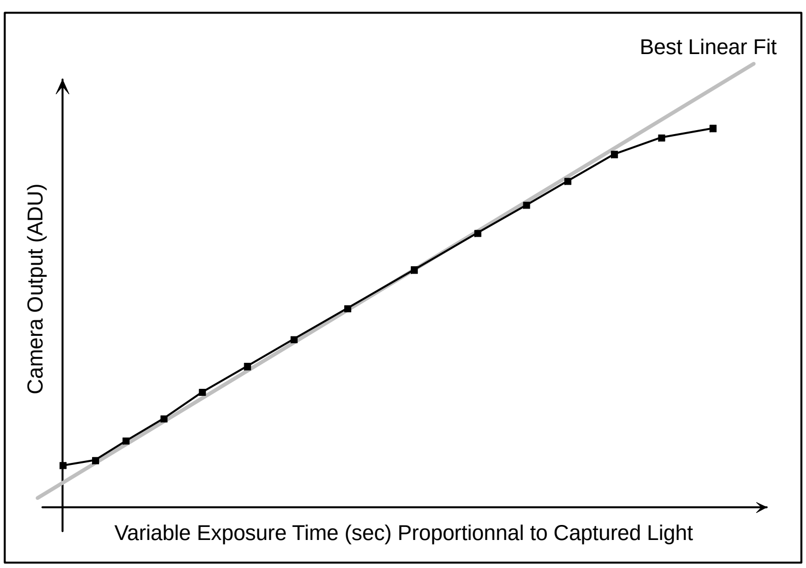

Figure 2. Detector CCD Output vs. Exposure Time

The second requires a variable intensity flat field illumination source with a range of no light to detector saturation. Place the detector in front of the illumination source. Records various frames with a constant exposure time by only changing the illumination level.

1. This requires the relative amount of light to be known and to be stable (0.1%) during the measurements.
2. Knowledge of the absolute output of the light source is not necessary for this method.
3. Relative illumination can be used without any impact on the final result.

Collect the data from the saved images at the completion of all captures, and plot as in Figure 3.

NOTE: This method is much closer to the usual operational condition and could, therefore, be more representative. It also eliminates any artifacts that may be induced by the cameras integration control circuitry.

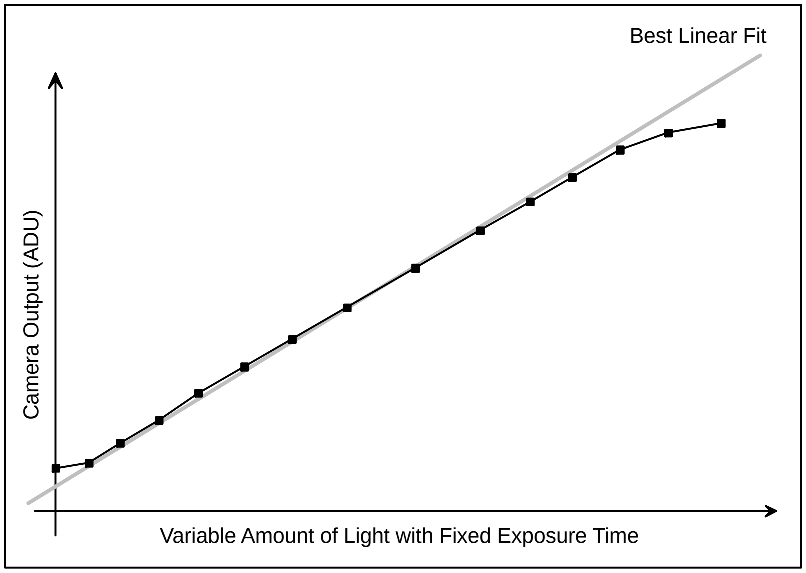

Figure 3. Detector CCD Output vs. Illumination Sweep and Constant Exposure Time

To confirm that the measured results are stable and representative, it is suggested that the process of collecting results is repeated several times.

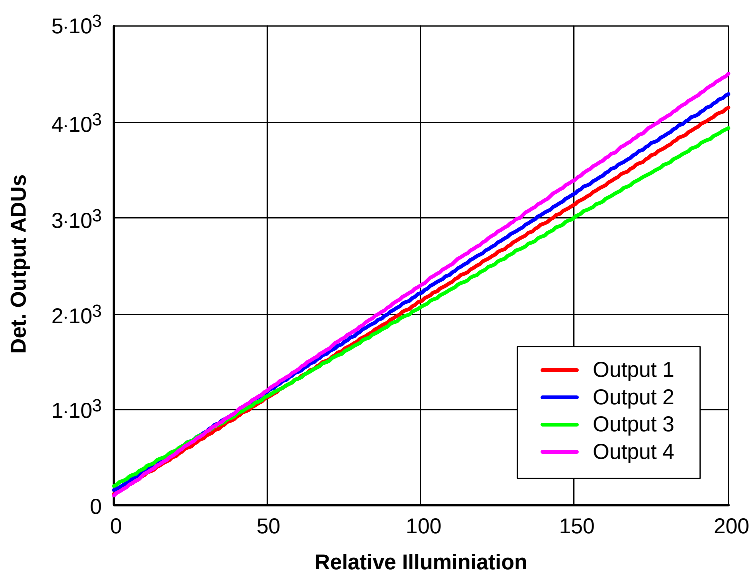

Figure 4. The 4 CCD Output Signal vs. Different Illumination Levels

Correction for Linear CCD Outputs

With linear output CCD response, the correction is straightforward. The goal is to make all outputs (1…k) behave the same by matching their output characteristics to the channel that best matches the expected performance.

This translates mathematically to:

$$off^1 + G^1 \cdot I = \left(off^k + sh^k\right) + H^k \cdot G^k \cdot I \quad \text{(eq. 3)}$$

Where:

off^k are the offsets at zero illumination.

G^k is the slope for each output.

Here, off^1, G^1, off^k *and* G^k are known, because of the previous measurements and H^k and sh^k can be calculated by:

$$sh^k = off^1 - off^k$$
$$H^k = \frac{G^k}{G^1} \quad \text{(eq. 4)}$$

Correction for Non-linear CCD Outputs

As the detector and its analog electronic signal path do not have perfect linear characteristics, some applications need to take this into account. This is especially the case at low lights levels and also levels close to the sensor saturation.

The output signal can be modeled as a polynomial function:

$$OutSignal(I)^k = off^k + G_1^k \cdot I + G_2^k \cdot I^2 + G_3^k \cdot I^3 + \ldots \quad \text{(eq. 5)}$$

Which can be generalized to:

$$OutSignal(I)^k = off^k + \Sigma_{i=1}^{i=m} G_i^k \cdot I^i \quad \text{(eq. 6)}$$

G_i^k are non-linear terms, and the output signal is being modeled to a polynomial function. *m*, the degree of the polynomial can be a figure up to the 7−9th degree but as *m* becomes larger more processing is required and also the accuracy of the measurements may not be sufficient to justify this effort. The more linear the CCD output, the closer to zero are the G_i^k terms.

G_i^k are regarded as constant terms in this equation. However they can also be affected by changes in temperature *T* (or other parameters):

$$OutSignal(I, T)^k = off^k(T) + \Sigma_{i=1}^{i=m} G_i^k(T) \cdot I^i \quad \text{(eq. 7)}$$

Note that other factors contributing to the non-linear behavior of a CCD output amplifier and its external signal path such as temperature stabilization issues, jitter in CDS timing, poor linearity near CCD saturation, and insufficient dark pixel used for black level measurement will all have an impact on system performance. Care should be taken to minimize any variation of the output linearity caused by them given the engineering constraints of the camera design. This approach can be difficult to implement in a practical system. A more experimental approach follows.

Once CCD output behavior is stable, the correction process can be put into effect.

For reference the Figure 5 illustrates a simulated non-linear output characteristic from a CCD and its external signal path as measured at the ADC.

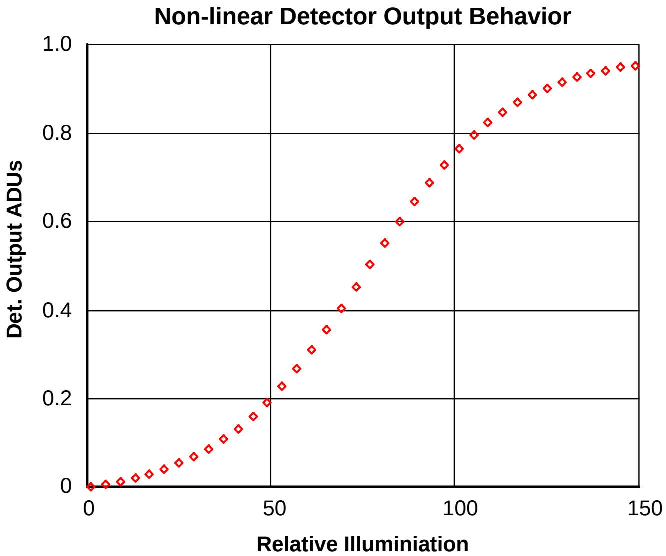

Figure 5. Simulated Non-linear CCD/Detector Output Behavior

The measurement of the CCD output and its respective readout chain linearity is best achieved using automated tools and software. The system used must be able to illuminate the CCD with different lights levels, perform the readout and compute automatically the final digitized signal coming from a small window inside the image.

This measurement allows N number of, $OutputDect_i$ discrete values to be retrieved from the CCD output and a plot of the output versus relative illumination to be made. The offset for no illumination has been removed to simplify computations.

The final output signal needs to be linear:

$$\text{Line (illumination)} = A \cdot \text{illumination} \qquad \text{(eq. 8)}$$

Each previously measured point (i = 1 to N) is then matched according to the data shown in Figure 6, using a discrete or point to point approach:

$$\text{Line}_i = A \cdot \text{illumination}_i \qquad \text{(eq. 9)}$$

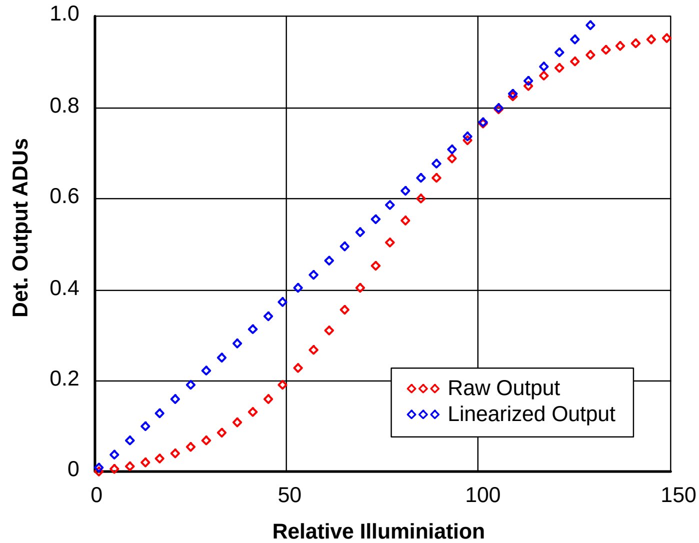

Figure 6. Non-linear Output to Be Corrected

The correction factors ($Fact\_corr_i$) can be now be computed for each measured point, by using Equation 10:

$$Fact\_corr_i = \frac{(A \cdot \text{illumination}_i)}{OutputDect_i} \qquad \text{(eq. 10)}$$

The A factor is chosen to minimize the $Fact\_corr_i$. This is done by minimizing the Error figure in Equation 11:

$$\text{Error} = \Sigma_{i=1}^{N} (1 - Fact\_corr_i)^2 \qquad \text{(eq. 11)}$$

The Error figure should be minimized using iteratively, or with a least square straight fit algorithm.

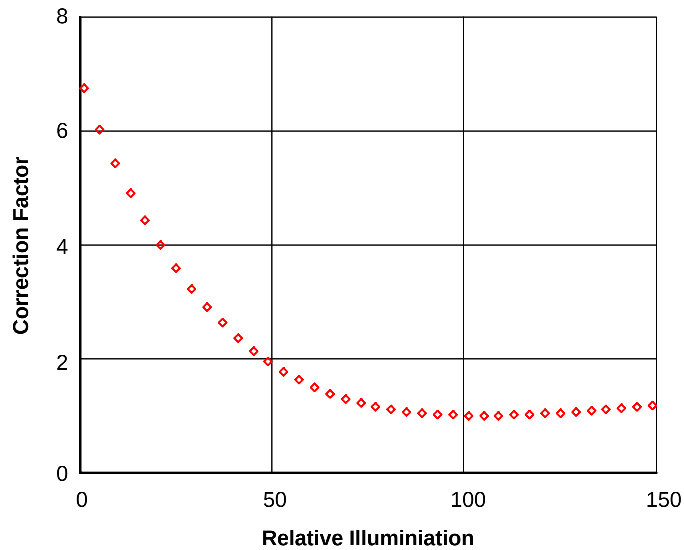

Figure 7. $Fact\_Corr_i$ vs. Relative Illumination

As can be seen in Figure 7, $Fact\_corr_i$ can be large at small illuminations, so measurements have to be accurate in this range.

The $Fact\_corr_i$, a discrete set of numbers, can also be fitted (using the least square method) to make a continuous function. This will help to smooth the data, and it will provide a continuous Fact_corr(x) function figure whatever the x illumination level.

The linearized corrected signal is then:

$$\text{Linearized\_OutputDect(illumination)} = \text{Fact\_corr(illumination)} \cdot \text{OutputDect(illumination)} \quad \text{(eq. 12)}$$

Once each CCD output is linearized, the final correction consists in matching all detector channels by setting Gain and Offset corrections with respect to the first (or one of the other) CCD outputs. This is an arbitrary choice.

This final correction stage is exactly the same process as described earlier (See Correction for Linear CCD Outputs).

Color Images

For color images, the same method applies. Fortunately, due to the color Bayer filters spread throughout the whole CCD surface; all the green, blue and red pixels will have the same linear/non-linear behavior versus illumination: All pixels are going through the same output amplifier. The green pixels can be used to perform the linearity measurement and follow the process as previously presented in this document.

Summary of Steps Required to Correct Seam Artifacts

1. Measure CCD output signal levels (including its signal path electronics) versus illumination, for each output. For color devices, select the green pixels, discarding the red and blue pixels.
2. Verify that measurements are stable and not temperature dependent as consistent with your design specification.
3. Measurements need to be performed for each device; factory tooling should to be set up to perform measurements of each device as explained in Step 1.
4. If the plots are sufficiently linear for your application, only offset and gain correction are required, store these numbers into camera memory and apply them after digitization.
5. If the plots are not sufficiently linear for your application, the outputs will need to be linearized prior to offset and gain correction being applied. All the figures need to be stored inside camera memory and applied in real time after digitization.

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