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AN08: Polynomial Gain Correction for RadEye Sensors

Introduction

CMOS active pixel sensors are inherently less linear in their response to light than CCDs or passive pixel sensors. The basic detection process – the conversion of light photons to electric charge – is the same for all three detector types. Both CCDs and passive pixel sensors transfer the accumulated charge from the pixel to a readout amplifier before any charge-to-voltage conversion takes place. The active pixel sensor, on the other hand, measures a change in voltage corresponding to the signal charge directly at the pixel by employing a source-follower FET. This approach has many advantages, but one disadvantage is that any non-linearities in the transfer curve of this amplifier will be superimposed onto the overall gain response of the detector.

The RadEye1 sensor is no exception to this rule. The response curve of the RadEye1 detector has a characteristic "S" shape, marked by a quasi-quadratic response near the low-signal end, a reasonably linear central section, and the standard roll-off at the high-signal end as the sensor approaches saturation (see Figure 1). The large-signal roll-off actually represents a form of gain compression, since the pixel capacitance (the reverse-biased photodiode) does not remain constant but instead increases as the bias voltage is depleted.

Standard Gain Correction

The standard correction methods for most image sensors include a dark offset calibration and gain correction. Because there are two calibration points – one with zero input signal and one at some arbitrary input signal level – this method is also referred to as *two-point correction*. For this analysis it is assumed that all input data (i.e. images) have already been corrected for dark offset variations using a simple dark offset subtraction.

We'll also assume that we are interested in calibrating individual pixels as opposed to defining some global calibration coefficients. Global corrections (i.e. where one coefficient is applied to the entire image) are not accurate enough to remove image variations, and are advisable only where memory or computation power are limited. Since cameras using RadEye sensors are usually connected to PCs, this is rarely a concern.

The standard gain correction technique makes use of a *flat-field image* in which every pixel receives the same amount of input signal. The exact magnitude of this input signal is arbitrary, although for best results it should be similar to the signal levels expected in the final corrected image. If the detector response is linear, the flat-field image exactly characterizes the gain of every pixel in the image. The response of the *i*th pixel is given by

$$y_i = a_i \cdot x,$$

x being the input signal, and we just measured a_i as

$$a_i = y_i(FF) / x(FF).$$

Since we are not concerned with input signal units, we can define the flat-field input to be

$$x(FF) \equiv 1,$$

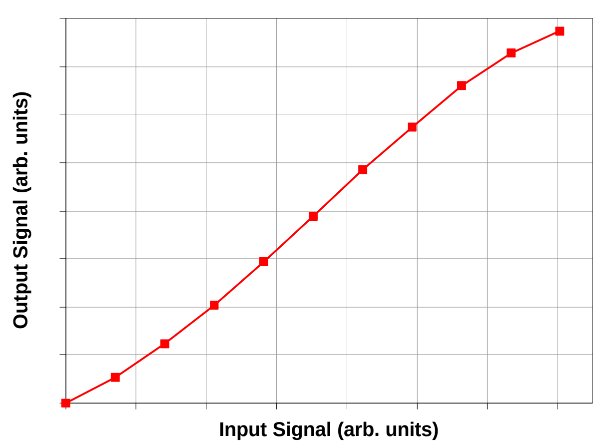

Figure 1: RadEye1 Response Curve

so that the pixel response simply becomes

$$y_i = y_i(FF) \cdot x.$$

The goal of the gain correction is to ensure that every pixel yields the same output signal *y* for a given input signal *x*. Thus, the desired pixel response is given by

$$y_i' = y_{avg}(FF) \cdot x.$$

Substituting for *x* (which is generally unknown), the final correction becomes

$$y_i' = [\ y_{avg}(FF) / y_i(FF)\ ] \cdot y_i.$$

In other words, each measured pixel value y_i is divided by its flat-field signal value y_i(FF) and then multiplied by the average flat-field signal in order to obtain the corrected pixel value. The actual input signal level for the flat-field image is completely arbitrary, and no prior knowledge about input signal levels is required for the correction.

Polynomial Gain Correction

Standard gain correction works well for detectors with linear response curves, since the pixel response moves along a straight line and only slope variations (i.e. the pixel gain) need to be corrected. If the detector response is non-linear, a more sophisticated correction method may be called for. One approach is to approximate the pixel response with a second- or higher-order polynomial. In the case of the RadEye1 sensor, a quadratic function serves very well to approximate the lower half of the response curve.

Characterizing a quadratic response for each pixel takes two sets of coefficients rather than the single correction coefficient for the standard gain correction. One way to obtain these coefficients is to acquire a large number of flat-field images at evenly spaced input signal levels, and then calculate a least-square optimized quadratic fit through the flat-field values for each pixel. Because of the number of calibration images that are required, this method may be suitable only if gain calibration is to be done infrequently and if the input signal can be easily controlled by software.

In the simplest case, the computation of the two calibration coefficients requires two input images. Furthermore, we can stipulate that the second calibration image is to be taken at exactly half the input signal level of the first image. This can be easily accomplished by simply cutting the x-ray mA in half, or by reducing the exposure time. The response of the *i*th pixel in the imager is now given by

$$y_i = a_i \cdot x^2 + b_i \cdot x.$$

This is shown as the solid red curve in Figure 2. As before, we measure a flat-field calibration point y_i(FF) at signal level x(FF) ≡ 1. We also measure a second "half-intensity" flat-field calibration point y_i(H) at signal level x(H) = ½.

The objective is to "linearize" the pixel response so that all pixels move along the same straight line shown as the dashed red curve in Figure 2. This ideal linearized response is the same as the one we assumed for the standard gain correction, and is given by

$$y_i' = y_{avg}(FF) \cdot x.$$

Again we need to substitute for the unknown input signal level *x*, which is a bit more complicated now due to the quadratic response, giving

$$y_i' = y_{avg}(FF) \cdot \{\ [\ (b_i/2a_i)^2 + y_i/a_i\ ]^{½} – b_i/2a_i\ \}.$$

Now all we need to do is calculate the coefficients a_i and b_i from the calibration images *y*(FF) and *y*(H) and we're done! For this we go back to the original quadratic pixel response and make use of the fact that

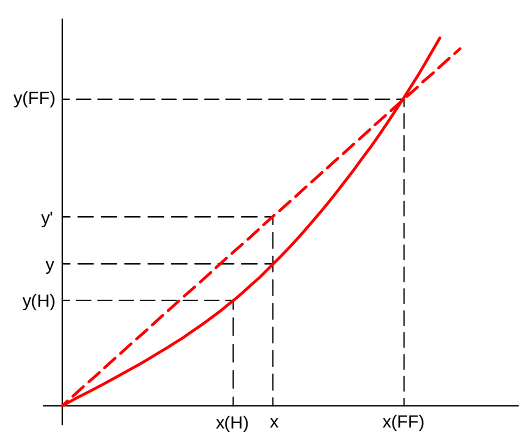

Figure 2: Non-linear response curve

we can define $x(\mathrm{FF}) \equiv 1$ and therefore $x(\mathrm{H}) = ½$. For the two calibration images we get

$$y_i(\mathrm{FF}) = a_i \cdot x(\mathrm{FF})^2 + b_i \cdot x(\mathrm{FF}) = a_i + b_i$$

and

$$y_i(\mathrm{H}) = a_i \cdot x(\mathrm{H})^2 + b_i \cdot x(\mathrm{H}) = a_i/4 + b_i/2.$$

Solving for a_i and b_i, we get

$$a_i = 2 \cdot y_i(\mathrm{FF}) - 4 \cdot y_i(\mathrm{H})$$

and

$$b_i = 4 \cdot y_i(\mathrm{H}) - y_i(\mathrm{FF}).$$

Although this method is computationally more difficult than the standard gain correction, this is rarely a problem given the computational power of a modern PC. The above correction algorithm can be easily incorporated into any correction code. It should be noted, however, that although the polynomial correction yields a much more accurate linear response than the standard gain correction, it is also more sensitive to errors. This is because the quadratic coefficients are calculated from only two correction images, instead of from a least-square fit over many images. Small errors in the offset correction (i.e. due to dark current drift with temperature) or inaccurate input signal control ($x(\mathrm{H}) \neq ½ \cdot x(\mathrm{FF})$) are amplified into larger variances if they affect the quadratic term of the correction. Perhaps somewhat surprisingly, the polynomially corrected images are not significantly more noisy than those obtained by standard gain correction, although averaging of the calibration images should nevertheless be employed.

Conclusion

We presented a relatively simple method to improve upon the standard two-point correction method for images from the RadEye family of sensors. The polynomial gain correction method takes advantage of the nearly perfectly quadratic response curve of the RadEye sensor for signal levels below one million electons. Only two flat-field calibration images are required to calculate the necessary correction coefficients, which means that instructions on how to perform the calibration can be easily incorporated into any x-ray imaging workflow. Although it would be preferable to acquire these images under software control, the method is simple enough that the calibration images can be obtained manually as well.

The RadEye sensor delivers performance advantages in the form of low noise, high sensitivity and extremely low image lag (among others). The active pixel architecture that makes this performance possible has one drawback in that the sensor response is not as linear as that of a CCD sensor. However, for applications where good linearity is important, it is possible to apply software corrections that compensate for this effect. Sensor calibrations are fundamental part of any high-performance x-ray imaging system, and the computing power available even in the most simple imaging system is more than adequate to perform these calibrations. The polynomial gain correction method lends itself well to software image correction, with minimal visibility and complications for the end user.