AN03: Guide to Image Quality and Pixel Correction Methods

Introduction

Image quality and pixel correction are two related topics that are central to understanding and optimizing the performance of RadEye x-ray sensors and Shad-o-Box cameras. These devices are based on the RadEye1 imager, a large-area CMOS sensor specifically designed for x-ray imaging applications. The image quality specifications and pixel correction methods outlined in this guide are designed to help you optimize the RadEye1 for your application.

The first part of this guide gives an overview of important concepts and definitions in determining the image quality of an x-ray image sensor. The second part addresses the topic of pixel corrections and describes several methods that are commonly used to replace defective pixels in an image.

Image Quality

Why image quality definitions? In an ideal world, every pixel on every imager would behave exactly the same. Although it would be possible to screen imagers and accept only those that come close to that goal, this would make them prohibitively expensive. The reality is that the RadEye1 imager, with a die area of 12.34 cm^2 and more than 1.6 million transistors, is a very complex IC that no semiconductor fab in the world would be able to make without introducing some amount of variations. In order to make the best use of current state-of-the-art process technology, Rad-icon offers several image quality grades that are defined below.

Image Quality Grade

Rad-icon image sensors are available in two image quality grades. **Premium Grade** RadEye1 sensors do not contain any defective rows or columns (lines). **Standard Grade** sensors may contain several line defects – up to three lines for the smaller devices (RadEye1 and RadEye2), up to five for the RadEye3, and up to seven for the RadEye4 sensor. A row or column (line) defect is defined as any line in which 40% or more of the pixels are defective. Two adjacent defective lines count as a single defect. A limited number of **Engineering Grade** devices with up to 10% defective pixels may also be available for evaluation purposes.

Both Premium and Standard quality grade devices may contain individual defective pixels numbering up to 0.1% of the total number of pixels. For example, a RadEye1 sensor with 524288 pixels may contain up to 524 individual pixel defects. A typical sensor contains less than ten individual pixel defects. However, a partial line defect that does not meet the 40% condition may count as a few hundred individual pixel defects.

Temperature Response

A defective pixel is defined as a pixel whose dark signal exceeds 10% of the saturation signal, or whose light response is less than 50% of the average light response of all functional pixels in the imager. The saturation signal is defined in the device data sheet (e.g. 3,000,000 electrons for the RadEye1). These characteristics are typically measured at room temperature using an integration time (exposure) of one second.

The dark signal of the device is made up mostly of leakage current that is collected in the photodiodes over the course of one exposure. This dark current is temperature-dependent and approximately doubles for every 10°C increase in temperature. Therefore, if the dark current of a pixel is 1000 electrons per second at room temperature, it will increase to approximately 10,000 electrons/sec at 50°C. Since every pixel sees the same increase in temperature, the **dark signal non-uniformity** or fixed-pattern noise will scale as well. This is shown in the two images in Figure 1 that were taken at room temperature and at 55°C. Since x-ray cameras typically incorporate pixel-by-pixel offset correction, the dark non-uniformity can be subtracted out as long as the sensor temperature is stable.

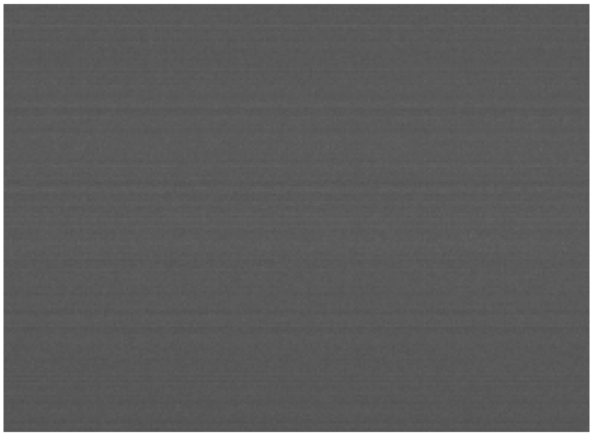

Fig. 1a – Dark image at 25°C

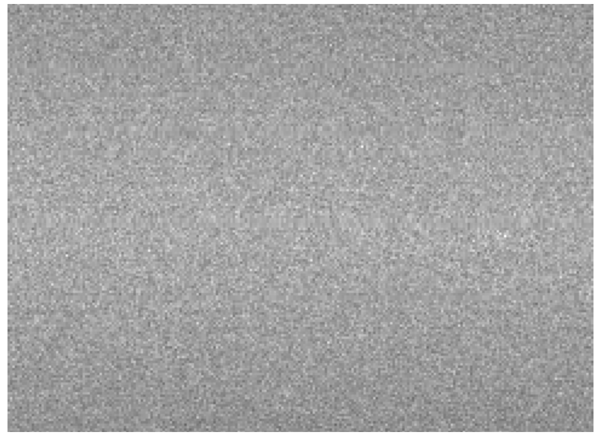

Fig. 1b – Dark image at 55°C

Usable Imaging Area

The **Usable Imaging Area** of a RadEye sensor may be slightly smaller than the total number of rows and columns. The first revision of the RadEye1 sensor featured a usable imaging area of 511 columns by 1022 rows. In the newer revisions the imaging area has been expanded to the full 512 columns by 1024 rows.

The larger RadEye sensors and Shad-o-Box cameras are assembled from two or more image sensors and contain small gaps between the individual image sections. The width of these gaps is typically about 100 µm. Rad-icon's ShadoCam software can compensate for these gaps by inserting two extra columns into the image and filling in the missing pixels with its pixel correction algorithm (see below).

The imaging area of the RadEye1 sensor also contains a small amount of digital circuitry that has been placed between the two central columns on the device. The pixels in each of these columns consequently are about 25% smaller than the pixels in the rest of the device. The signal gain from these columns is compensated to match the surrounding pixels. However, due to the presence of the digital circuitry, the pixels in these two columns have higher dark current than the surrounding pixels. The standard offset and/or pixel correction techniques can be used to compensate for the difference in dark signal.

Rows and columns that are outside of the usable imaging area, part of the gap between imagers, or part of the central two columns are not included in the image quality grade definition. Only random manufacturing defects are counted in order to grade a device. Of course, the image quality grade and usable imaging area definitions are subject to change. Rad-icon is continually working to improve the performance of the RadEye and Shad-o-Box product lines based on inputs and feedback from our customers.

Pixel Correction

A pixel that responds differently from its neighbors can be distracting and is often unacceptable. Digital x-ray imaging systems use **offset and gain correction** in order to present a more uniform image. This correction scheme (also sometimes referred to as two-point correction) adjusts the signal response of every pixel in the image based on two calibration points – one with zero signal (the offset) and one that's typically around 50% of saturation (to calculate the gain). Besides correcting non-uniform response in the imager, this scheme also corrects variations in the x-ray beam (i.e. the heel effect) as well as non-uniformity in the signal path (for example scratches on the protective cover or variations in the electronics).

But what about pixels that are too dark or too saturated to respond to offset or gain correction? If the pixel response is too low or the pixel is permanently saturated then there isn't enough information in its signal to faithfully reconstruct the image. In this case the true signal from the defective pixel has to be estimated based on the signal information from its nearest neighbors. There are several techniques that can be used to accomplish this, with various tradeoffs in terms of effectiveness and complexity of the calculations.

Individual Pixels

The simplest method to correct an individual pixel is to apply a **median filter**. This technique simply replaces the pixel with the median of the surrounding pixels' values. It is quite robust in terms of screening out other questionable pixels (those having either very high or very low values), but uses only a small amount of the information available by simply duplicating one of the neighboring pixels.

A similar method that is slightly more complex is the **mean filter**. This technique replaces the defective pixel with the average value of the surrounding pixels. In order for this to work, the surrounding pixels must either be "known good pixels", or the algorithm must contain a provision for ignoring neighboring pixels that are known to be defective. Since this technique uses information from more than just one of the surrounding pixels, the result is slightly more pleasing than the median filter. Individual pixels that have been corrected with a mean filter are very hard to identify in the corrected image.

Rows and Columns

Defective rows and columns are more difficult to correct than individual pixels, since there are fewer surrounding "known good pixels", and also because it is much easier to notice a linear discontinuity in an image rather than an individual point. Nevertheless, they are often treated simply as a collection of individual pixel defects and corrected using either the median or the mean filter described above. An even simpler technique is to use **interpolation** along the direction perpendicular to the defective row or column. This method is essentially the same as the mean filter, but uses only the two nearest neighbors to the left and right (or top and bottom) of each defective pixel in the column (or row).

Unfortunately, a linear image defect corrected via the mean filter or interpolation is easily noticeable in an image where a sharp edge crosses the defective column or row. Both of these techniques effectively blur the image in the vicinity of the defect, and any high-frequency information is lost. If the defect consists of two adjacent rows or columns, the blur becomes even more noticeable. One way to avoid this situation is to use an **image gradient** technique. This method, instead of indiscriminately averaging all or just two of the surrounding pixels, looks at the image gradient along several directions in the vicinity of the defective pixel, and then interpolates the missing value along the direction of the minimum gradient. For example, if a step in the image crosses a defective column at a 45° angle, the minimum image gradient lies along the direction of the step (or edge). Interpolating between two pixels along this direction produces a better estimate of the value of the missing pixel than interpolating horizontally across the defective column. The improvement in image quality can be quite dramatic, even if two or more defective rows and columns are bridged. Figure 2 illustrates the difference on a "worst case" test image that features many high-contrast edges running across a two-column defect in the center of the image. Whereas the location of the defect is quite obvious in the interpolated image, the image gradient method reconstructs the missing information almost perfectly.

The image gradient method has two disadvantages. One is the increased complexity in the calculations, which is important in a real-time or near real-time imaging system. The other disadvantage is that the image gradient

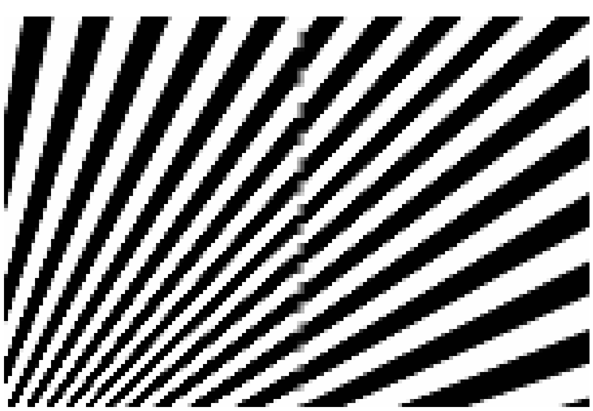

Fig. 2a – Two-column defect with interpolation

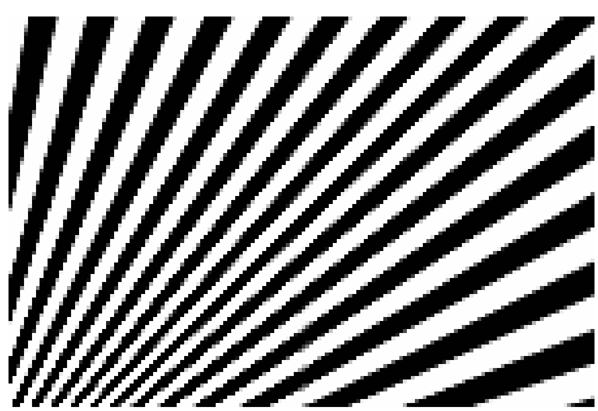

Fig. 2b – Two-column defect with gradient method technique can produce artificial image artifacts if the image contains high-contrast information at or near the Nyquist limit of the detector. However, this is a special case that rarely occurs in an x-ray imaging system where the MTF is typically very low at high spatial frequencies.

For a more detailed analysis of the image gradient technique, see the paper titled "Comparison of adaptive linear interpolation and conventional linear interpolation for digital radiography systems" by F. Xu, H. Liu, G. Wang and B. A. Alford, *Journal of Electronic Imaging*, Jan. 2000, Vol. 9(1), pp. 22-31.

ShadoCam Pixel Map

Rad-icon's ShadoCam software provides built-in offset, gain and pixel correction to automatically provide the best possible image quality to the user. For pixel correction, ShadoCam uses the mean filter technique to correct individual pixels. Rows and columns can be corrected either by straight interpolation or by using the image gradient method. The correction method can be selected from the *Preferences* dialog in the *Acquisition* menu.

ShadoCam keeps a master list of defective pixels, rows and columns called the **Pixel Map**. This is a text-based list that identifies defective pixels by their row and column coordinates, and defective rows and columns by their respective y- and x-coordinates. Each Shad-o-Box camera is shipped with a factory-calibrated pixel map. However, ShadoCam also allows manual editing of the pixel map, and it can calculate a new pixel map based on thresholds selected for a given image.

Summary

CMOS image sensors are complicated, highly integrated analog circuits that always exhibit some degree of variation from one device to the next. Image quality definitions are used to quantify these variations and allow us to categorize the performance of these devices. Rad-icon's image quality definitions include Premium Grade sensors that are free of row and column defects, as well as Standard Grade sensors that may contain a small number of defective lines. The usable imaging area of a device may be slightly smaller than the total number of pixels.

Pixel correction is a software technique that is used to replace defective pixels in the image with an estimated value. Most pixel correction techniques use the neighboring pixels to estimate the correct value for the missing pixel. Using a larger number of pixels often improves the accuracy of the repair, at the expense of increased computational requirements. Simple pixel correction techniques include the median filter and linear interpolation. The more complicated gradient technique uses image gradient information to better predict the missing image values.