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Expanding the Dynamic Range of Focal Plane Arrays Using an Orthogonal Code Readout

Audience

This paper will be of interest to CMOS image array designers and business managers because it explains how to digitally expand the dynamic range of existing machine vision pixel architectures.

Abstract

An Orthogonal Code Readout (OCR) electronically expands the dynamic range of CMOS active pixels. When OCR is implemented, the dynamic range of a pixel is not limited by per-pixel capacitance. When employed as a thermal array readout, OCR simplifies thermal detector array fabrication by eliminating the need for large electron well capacitors.

1. Introduction:

Combining an Orthogonal Code Readout (OCR) with an active CMOS pixel retains the noise characteristics of the pixel while eliminating pixel saturation. OCR-enabled cameras image through glare and capture the details of both bright and dark areas in a partially-shaded, daytime scene.

OCR works by continually and rapidly sampling the intensities of all of the pixels in a focal plane array (FPA). The continual samples sense the current generated by each pixel, and signal integration occurs in a digital processor. When OCR is implemented, the dynamic range of a pixel is not limited by per-pixel capacitance.

Orthogonal codes make the rapid sampling of all pixel signals possible. Many pixels are sampled simultaneously by basing the sums on orthogonal codes. An image is formed in the digital processor by retrieving the time sequences representing individual pixel sample-streams.

OCR can also be used as a thermal FPA read out integrated circuit (ROIC), but the advantage for thermal imagers is simplification of FPA fabrication and not performance enhancement. For example, since large electron storage capacitors are not needed, direct deposit of the infrared photo detectors onto the ROIC might be possible. If bump bonding or press-fitting the detector array and ROIC is necessary, OCR still provides an unlimited digital electron well and makes room for additional image processing circuitry by eliminating the large electron well capacitors.

A further advantage of OCR is that it improves image quantization. Each pixel intensity is sampled multiple times, each time in combination with different signals. If the same ADC is used to digitize image data and OCR data, the OCR image will be better quantized.

The following list describes the benefits of implementing OCR.

- OCR widens the dynamic range of any CMOS pixel architecture.
- OCR simplifies the fabrication of infrared focal planes
- OCR implements a global shutter.
- Exposure time is not limited by scene illumination.
- OCR processing decreases quantization error.
- OCR shares the same motion-blur characteristics as non-OCR imagers.

Section 2 explains OCR implementation and operation. Section 3 discusses the ramifications of various image array design choices. Section 4 uses examples to illustrate that, with proper choice of orthogonal code set, motion has the same effect on OCR imaging as on traditional imaging. Conclusions are in Section 5.

2. Orthogonal Code Readout Operation

OCR is compatible with almost all CMOS pixel architectures. The example presented in this section uses the two FET passive pixel shown in Fig. 1 because it simplifies the explanation of OCR operating theory. The photo charge generated by each photo detector is stored on the detector capacitance. The photo electrons are discharged at some regular interval by selecting either the Add or Subtract FET in each pixel.

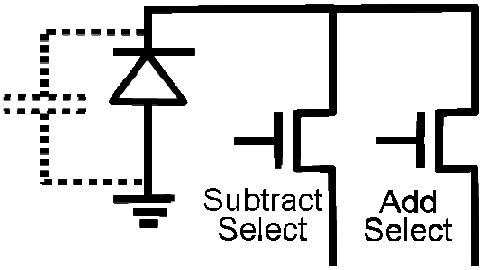

Fig. 1. The passive pixel shown in this figure incorporates two FET, one to add and one to subtract pixel photo charge from an OCR sum.

Fig. 2 shows twelve of the Fig. 1 pixels arranged in a four by three image array. The two FET in each pixel connect the photo diode signal to either the plus or minus input of a differential sample and hold and digitizer circuit. In this example, all three pixels in each of the four columns are treated alike, so only the processing for a single row of four pixels is described in detail.

The FET control lines in Fig. 2 select add or subtract for each sample of the combined pixel signals. The plots at lower right in Fig. 2 show the on/off (high/low) states applied to the eight FET gates. The abscissa axis of each of the eight plots is time. Plots A_+, B_+, C_+. and D_+ show control signals applied to the four Add FET in each row. Plots A_-, B_-, C_-, and D_- show the on/off control of each Subtract FET.

Walsh-Hadamard Codes are used in the examples presented in this paper. One benefit of Hadamard Codes (HC) is that they are a series of positive and negative ones, and that means that image correlations are pixel sums and differences. Although HC only exist for specific code lengths, there are a number of options. HC sets are available for lengths n, where n, n/12, or n/20 is a power of 2. Integer multiples of n also work for OCR.

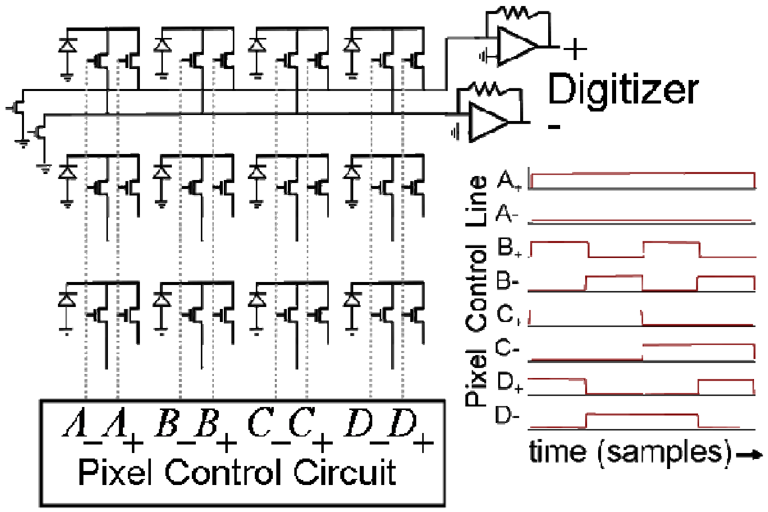

Fig. 2. The pixels illustrated in Fig. 1 form a 4 by 3 pixel array. Control signal state for A_- through D_+ are shown at lower right.

The encoding process works as follows. Four signals P_A, P_B, P_C, and P_D from pixels A, B, C, and D are encoded using a four element HC to yield four sample values S_A, S_B, S_C, and S_D.

$$[S_A\ S_B\ S_C\ S_D] = [P_A\ P_B\ P_C\ P_D] * \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \qquad 1$$

$$[S_A\ S_B\ S_C\ S_D] = [(P_A+P_B+P_C+P_D)\ (P_A-P_B+P_C-P_D)\ (P_A+P_B-P_C-P_D)\ (P_A-P_B-P_C+P_D)]$$

where (*) indicates matrix multiply. To retrieve pixel intensity values P_A, P_B, P_C, and P_D

$$[P_A\ P_B\ P_C\ P_D] = [S_A\ S_B\ S_C\ S_D] * \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}. \qquad 2$$

If the number of pixels in a row is NN, then NN pixels are summed for each sample and NN samples are taken over the exposure period. Pixel values Pixel(1:NN) are retrieved by the summation shown in Eq. 3.

$$Pixel(1:NN) = \sum_m Sample(m)\, H(m,1:NN) \qquad 3$$

where H(m,1:NN) represents the m^{th} row of the Hadamard matrix.

The intent of this section is to explain OCR operation; a practical implementation would certainly multiplex more than four pixels per row. Further, the image array designer might choose to multiplex columns or areas rather than rows.

3. Orthogonal Code Readout Design Options

The purpose of this section is to clarify OCR application by describing some of the implementation problems and possible solutions.

One problem is that a many-pixel version of the Fig. 2 image array would not be shot noise limited at low illumination levels. With less than a thousand photo electrons per pixel per image frame, variation of pixel amplitudes between samples disrupts the OCR decode process. The one thousand electrons is total per frame, and the number of electrons per sample will be quite small if the Hadamard Code is a practical length. Pixel amplitudes therefore vary excessively between samples, and the digital processor cannot properly decode and integrate the pixel signals.

However, shot noise limited performance at low light levels can be recovered by incorporating some form of temporal filtering in the pixel. Some implementation options are discussed in this section.

When it comes to implementing the digitizer circuitry, OCR provides both a benefit and a problem. The benefit is that OCR improves image quantization beyond that provided by the hardware digital converter. The reason quantization improves and the amount of improvement are explained in this section. The OCR implementation problem is that, for the architecture shown in Fig. 2, all the OCR samples must be digitized in an exposure time and not frame time. The nature of the problem and practical solutions are also described in this section.

3.1 Improving Passive Pixel Noise Performance

In Section 2, a simple pixel architecture was used to illustrate the theory. If actually implemented, however, the Fig. 1 architecture would function poorly. That is because OCR processing works best if each pixel presents a constant signal amplitude. If the Fig. 1 pixel is sampled often, little photo charge has accumulated before sampling, and each sample is noisy. If the samples are excessively noisy, the orthogonal decode is disrupted, and OCR does not correctly integrate the signal from each pixel.

Combining OCR with an active pixel array is likely the best solution to the low illumination noise problem, However, the Fig. 1 pixel has a larger fill factor and better producibility than active pixels, and those factors weigh in favor of a passive pixel solution.

When used in conjunction with OCR, it is theoretically possible to improve the noise performance of the Fig. 1 pixel by using the FET as variable resistors instead of switches. A low pass filter is created by the detector capacitance and FET resistance. Since the detector capacitance is small, gate duty cycle (that is, briefly toggling the FET to produce a high source to drain average resistance) can be used in combination with variable gate voltage to effectively control average FET resistance.

The drain current from a low pass is proportional to the radiation incident on the photo detector. As incident radiation increases, voltage across the detector increases, and that increases current from the pixel. The increase in pixel current is sensed to create an image. As voltage increases, the drain current also increases, thereby preventing pixel saturation.

Creating a low pass filter in each pixel does not increase signal current but does reduce sample-to-sample variations to the point that shot-noise-limited performance is re-established. A low pass filter can substitute for a charge integrator because of the rapid pixel sampling provided by OCR processing.

3.2 Using an Active Pixel to Improve Noise Performance

Substituting the active pixel in Fig. 3 for the passive pixel in Fig. 1 adds complexity and also reduces detector fill factor. However, noise behavior improves markedly, and the large dynamic range benefit of OCR is enabled. Further, very long exposure times are possible, because exposure time is not limited by the active pixel characteristics. The only limit on exposure time is avoidance of motion blur.

Fig. 3 shows a simple active pixel circuit, but any active pixel architecture can be used with OCR. The OCR coding operation is the same as described in Section 2. However, the active pixel is reset after some number (N) of OCR samples. If (n) is the count from 1 to N, and if P sample trains are taken such that N multiplied by P equals the Hadamard Code length, then the sample amplitudes are normalized by dividing by the count from last reset (n). The normalization by (n) can be applied in the digital processor rather than in hardware.

Normalization of the code samples is necessary because active pixels integrate photo electrons whereas OCR expects a current measurement that is constant over time. Precise normalization is not critical, but un-normalized samples create lines offset from bright edges in the image. Other than normalizing the samples, OCR sampling and image processing remain the same as described in Section 2.

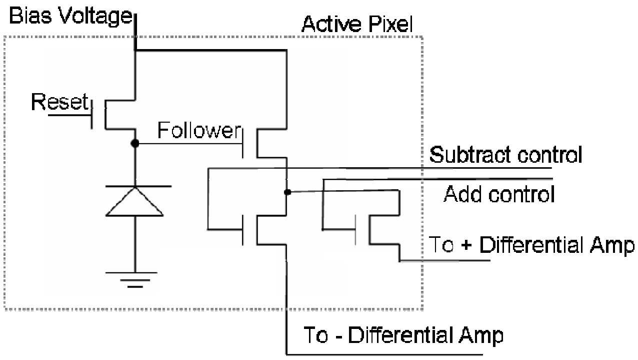

Fig. 3 illustrates a simple active pixel.

3.3 Analog to Digital Quantization Error

Each pixel intensity is sampled multiple times, each time in combination with different signals. If the same ADC is used to digitize image data and OCR data, the OCR data will be better quantized. Quantization improvement depends upon the characteristics of the data being digitized; that is, quantization error depends upon the scene.

At left in Fig. 4, the 256 by 256 pixel cameraman picture is degraded to six bits (64 gray levels). There is some degradation of the face and around the hair. Also, parts of the fingers of his gloved hand are not visible. However, the major quantization problems are very visible in the sky and buildings in the background. At right, the Hadamard samples are digitized with six bit quantization, and the whole picture is well-quantized.

If the OCR code length is N, then quantization improves by N for uniform areas like gray scales or the sky in the cameraman picture. If the picture consists of uniformly distributed random values, then quantization is improved by the $\sqrt{N}$. Table 1 provides image quantization for various combinations of hardware ADC, OCR code length, and image types.

Fig. 4. Both the cameraman picture at left and the OCR reconstruction at right are digitized using 6 bits. The OCR picture has fewer quantization artifacts.

Table 1. OCR Quantization Improvement

ADC bits	Code Length	Type of Scene	
		Random	Gray Scale
6	256	10	14
8	32	10	13
8	64	11	14
8	1024	13	18
8	4096	14	20
10	32	>12	15
10	64	13	16
10	1024	15	20
10	4096	16	22
12	32	>14	17
12	64	15	18
12	1024	17	22
12	4096	18	24

3.4 Analog to Digital Conversion Rate

The encoding process illustrated in Fig. 2 must be completed within an exposure time. In order to accomplish that, the pixels described by Figs. 1 and 3 require an analog to digital conversion (ADC) rate of

$$ADC_{rate} = {(H_{pix}\, V_{pix})}\Big/_{\text{exposure time}} \qquad 4$$

where Hpix and Vpix are the number of horizontal and vertical pixels, respectively. There are a number of ways to solve that OCR implementation problem.

One option is to add a sample and hold array as illustrated at upper right in Fig. 5. One storage area consisting of two FET and two capacitors is required for every pixel. The control logic diagramed at lower right does not change, but instead of immediate digitization, each OCR sample is stored on a capacitor pair.

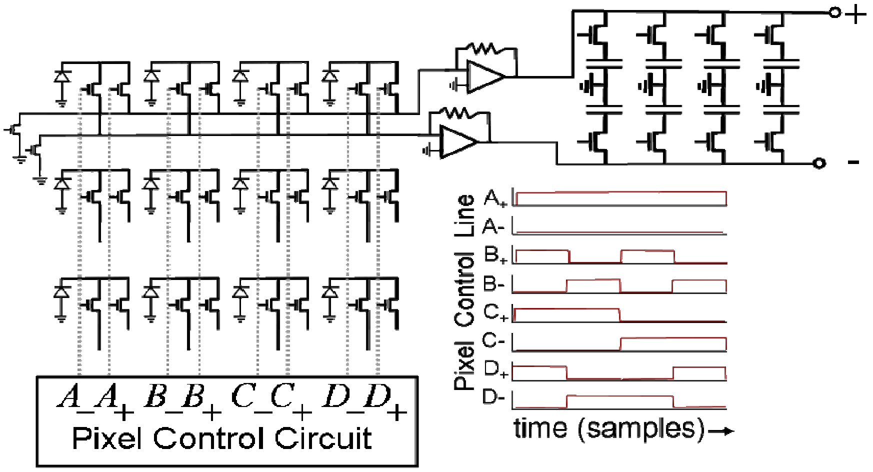

Fig. 5. A sample and hold array is added to the OCR configuration of Fig. 2 in order to reduce the required analog to digital conversation rate.

A second option is to add an in-pixel sample and hold as shown in Fig. 6. This option reduces detector fill factor, but it also enables much faster exposure times. OCR samples are taken during exposure. Once exposure time has elapsed, the transfer gate is opened, but OCR sampling continues until code completion. Once the transfer gate is opened, the divide by (n) normalization stops, but the relative contribution of samples taken with the transfer gate in a different state must be assessed and the code correctly normalized. Again, however, the sample normalization requires attention but not great precision. Also, the sample normalization is done digitally.

When selecting code length and layout, it is important to keep in mind that a different inter-pixel time relationship between acquisition and display can lead to image artifacts with non-static scenes. The next section explains how to avoid the motion problems associated with orthogonal encoding.

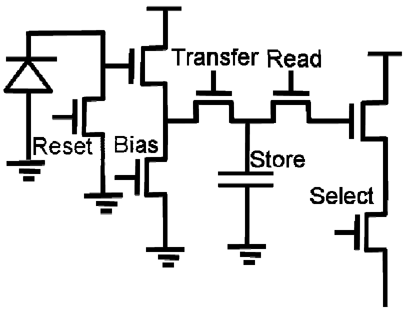

Fig. 6 illustrates an active pixel with in-pixel storage.

4. Avoiding Hadamard Code Related Motion Artifacts

The theory in the previous sections assumes a static scene, and that assumption is seldom completely valid. Like other cameras, a camera that implements OCR is subject to motion blur. Since motion blur limits exposure time, it is important that implementing OCR not make the motion blur worse than occurs with existing camera technology. That standard can be achieved by proper selection of orthogonal codes.

Fig. 7 illustrates the type of motion simulated. The camera is panned diagonally up such that the scene moves down in the image. Each simulation moves the scene a specified number of pixels both horizontally and vertically. The simulation uses image bi-linear interpolation to position the scene correctly for each sample.

Fig. 7 showing how the image moves when simulating motion. The camera is panned diagonally up.

The first example implements OCR using the 32 element Hadamard Code shown in Fig. 8. The Hadamard matrix is displayed twice with the rows in different orders. The matrices are represented by pictures where ones are white squares and minus ones are black squares. Note that the orthogonality of the HC does not depend on row order. Each row is orthogonal to the other rows, and that does not change when rows are moved up or down.

However, when applying the codes for imaging, each row in order from top to bottom is used to establish which pixels in the detector array row are added and which are subtracted. The time order of how the imagery is sampled will affect the resulting picture if there is motion in the scene.

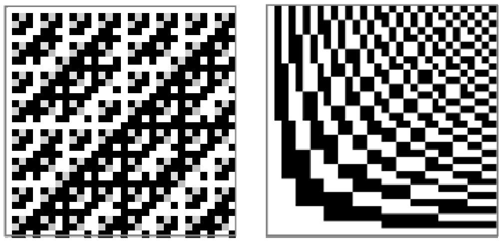

Fig. 8. In the matrix at left, the rows are in normal order, whereas the rows in the matrix at right are in sequence order. The same rows are found in both matrices, but the vertical position of rows is different.

The matrix illustrated at left is in normal order; that is, the left-hand picture is what is typically called a Hadamard matrix. The row arrangement shown at right in Fig. 8 is in descending sequency order. Sequency is the number of times the amplitude changes from minus one to one or from one to minus one in a row. The right-hand matrix is derived from the left-hand matrix by placing the rows in descending sequency order. The following discussion also holds for ascending sequency order; that is, the right-hand matrix can be flipped vertically.

Fig. 9 shows pictures of Goldhill blurred by motion. The pictures in Fig. 9 are all 1024 pixels horizontally by 200 pixels vertically. Picture A is the original blurred by 8 pixel motion both horizontally and vertically. Pictures B and C are constructed using 32 element Hadamard encoding. Picture B used sequenced Hadamard, and C used non-sequenced Hadamard. The 1024 horizontal pixels were encoded in groups of 32 pixels. The first Hadamard row was applied to all groups, then the image moved, and then the second Hadamard row applied, etcetera.

All of the pictures in Fig. 9 appear to be equivalent, with no apparent effect from Hadamard encoding, sequenced or not. In this example, the motion blur for OCR image arrays and normal staring integration are the same.

Fig. 9. Pictures of Goldhill showing 8 pixel standard motion blur in A, motion blur using a non-sequenced 32 element HC in B, and a sequenced encode in C.

The next example illustrates a different situation. The imagery in Fig. 10 is 512 pixels wide by 385 pixels high. In these pictures, the scene moves 16 pixels horizontally and 16 pixels vertically during image capture. Each row is encoded using a 512 element HC.

Picture A in Fig. 10 uses non-sequenced Hadamard coding, picture B uses sequenced coding, and C shows the result of typical motion blur. The problem with non-sequenced Hadamard coding is quite obvious. However, the sequenced Hadamard picture is visibly identical to the typical motion blur. Sequencing the Hadamard matrix eliminated the motion artifacts associated with Hadamard encoding.

Fig. 11 compares traditional motion blur with that created by sequenced Hadamard when using 512 element Hadamard codes. In Fig. 11, A and C employ sequenced Hadamard coding, and B and D represent traditional motion blur. The scene moved 8 pixels in both directions during A and B image capture. The scene moved 32 pixels both horizontally and vertically when capturing C and D imagery. Again, sequencing eliminates motion artifacts and makes OCR motion blur the same as the blur associated with traditional imaging.

As illustrated by Figs. 9 through 11, Hadamard coding can result in corrupted imagery if the Hadamard control matrix is not sequenced. However, when the Hadamard control matrix is properly sequenced, Hadamard coding does not degrade image quality beyond the blur traditionally associated with photographing moving objects.

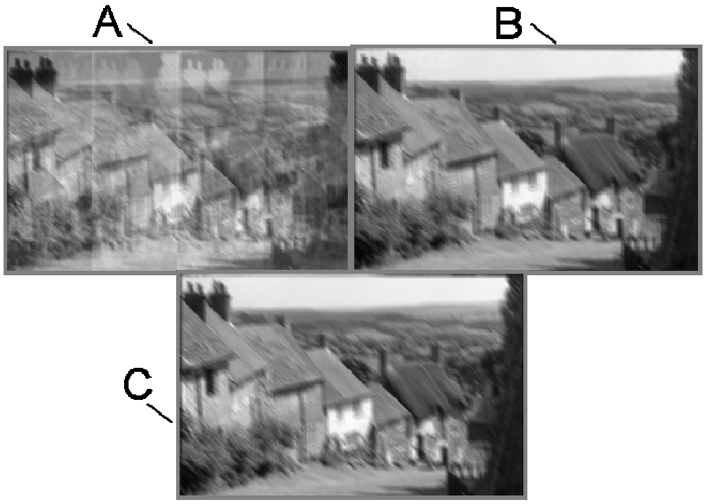

Fig. 10. Picture A was encoded using a non-sequenced 512 element Hadamard. In that case, the non-sequenced code resulted in serious degradation of the image. Picture B used a sequenced Hadamard, and C is the result of standard integration. Pictures B and C are nearly identical.

Fig. 11. Pictures A and C were encoded using a 512 element sequenced HC, and picture B and D represent typical staring array motion blur. Scene movement during image capture was 8 pixels for A and B and 32 pixels for C and D. There is no visible difference between typical motion blur and that obtained using sequenced Hadamard encoding.

5. Conclusions

The Orthogonal Code Readout (OCR) expands the dynamic range of CMOS pixels by electronically adding deep, digital electron wells. The exposure time is divided into short, contiguous intervals. During each interval, the CMOS pixel integrates photo electrons in the traditional fashion. Simultaneously, OCR samples and stores pixel intensities. The pixels are reset before saturation occurs, and the in-pixel signal integration is re-started. The OCR samples are digitally processed to recover pixel intensities integrated over the complete exposure time. OCR retains the sensitivity behavior of the active pixel while also enhancing dynamic range.

The sensitivity of the active pixel is retained because photo electrons are integrated in-pixel, but the continual reads allow pixel reset before saturation occurs. The signal integration for each pixel occurs first in the pixel and then in the digital processor.

Combining OCR with an active CMOS pixel eliminates saturation regardless of optics F/stop and exposure time. The only limit on exposure time is avoidance of motion blur. OCR makes it possible to view through glare, to enhance very low contrast imagery, and to capture the details of both bright and dark areas in a partially-shaded, daytime scene.

OCR can also be used as a thermal FPA ROIC, but the advantage for thermal imagers is simplification of FPA fabrication. For example, since large electron storage capacitors are not needed, direct deposit of the infrared photo detectors onto the ROIC might be possible. If bump bonding or press-fitting the detector array and ROIC is necessary, OCR still provides an unlimited digital electron well while freeing ROIC space for new image processing circuitry.

When implementing OCR, motion artifacts are avoided by using short Hadamard Codes or by using sequenced codes of any length.

The primary engineering challenge when implementing OCR is that orthogonal coding requires code completion. That is, all of the sequences (the rows) in the Hadamard Matrix must be applied and the samples taken. OCR implementation requires either a capacitor array to store OCR samples or fast digitization.

For further information about Orthogonal Code Readout or to discuss implementing OCR in your camera or focal plane array designs, please contact Richard Vollmerhausen at 407 807 9731 or email richard@nextgenimagers.com.