Spatial Frequency Response of Color Image Sensors: Bayer Color Filters and Foveon X3

Paul M. Hubel, John Liu and Rudolph J. Guttosch
Foveon, Inc.
Santa Clara, California

Abstract

We compared the Spatial Frequency Response (SFR) of image sensors that use the Bayer color filter pattern and Foveon X3 technology for color image capture. Sensors for both consumer and professional cameras were tested. The results show that the SFR for Foveon X3 sensors is up to 2.4x better. In addition to the standard SFR method, we also applied the SFR method using a red/blue edge. In this case, the X3 SFR was 3–5x higher than that for Bayer filter pattern devices.

Introduction

In their native state, the image sensors used in digital image capture devices are black-and-white. To enable color capture, small color filters are placed on top of each photodiode. The filter pattern most often used is derived in some way from the Bayer pattern[1], a repeating array of red, green, and blue pixels that lie next to each other in the image plane.

A required image-processing step for Bayer pattern sensors is interpolation, during which the missing data is estimated from neighboring pixel data. For a red pixel location, for example, the green and blue data must be interpolated from green and blue neighbors since these values are not directly recorded. Bayer pattern images are less sharp than they otherwise could be due to under sampling, and, unless optical blurring is introduced, exhibit color aliasing artifacts due to the lateral displacement of the color filters.

Recently a new image sensor technology was developed[2,3] which does away with the drawbacks of the traditional Bayer color filter pattern. The new technology, found in Foveon X3 image sensors, directly measures red, green and blue at each location by stacking color pixels on top of one another, increasing the sampling density in the image plane.

The benefits include improved sharpness in luminance and chrominance, as well as freedom from color aliasing artifacts. The sharpness improvement can be seen in comparison images and also measured quantitatively using standard methods available to the digital camera industry.

Bayer Background

The Bayer pattern, also known as a Color Filter Array (CFA) or a mosaic pattern, is made up of a repeating array of red, green, and blue filter material deposited on top of each spatial location in the array (figure 1). These tiny filters enable what is normally a black-and-white sensor to create color images.

R	G	R	G
G	B	G	B
R	G	R	G
G	B	G	B

Figure 1 Typical Bayer filter pattern showing the alternate sampling of red, green and blue pixels.

By using 2 green filtered pixels for every red or blue, the Bayer pattern is designed to maximize perceived sharpness in the luminance channel, composed mostly of green information. However, since the image plane is under sampled, the full detail available is not attained. In addition, color detail is lost due to the even lower sampling density of the red and blue channels in the sensor. Figure 2 shows a Bayer filter pattern decomposed into its constituent colors, showing the sparseness of the sampling.

R		R	
R		R	

	G		G
G		G	
	G		G
G		G	

	B		B
	B		B

Figure 2 Decomposition of a typical Bayer color filter pattern into its components. Under sampling in the image plane results in lower sharpness than could otherwise be achieved. Further, gaps in the image plane lead to color moiré artifacts.

Introduced in the 1970's, the Bayer pattern improved the state-of-the-art, but imposes constraints on the digital camera designer. The camera design must perform the following:

- interpolate the missing color data to create three complete color image planes (R, G, & B)
- account for the inherent reduction in the sharpness of the luminance and chrominance channels
- suppress the color aliasing artifacts resulting from the incomplete sampling of the image data.

Besides the loss in sharpness due to under sampling, there is another factor contributing to image degradation: the blur filters. Blur filters reduce the color aliasing artifacts caused by spatial phase differences among the color channels (i.e. the red, green and blue filters are placed next to each other). Two blur filters are typically placed in the optical path: one to blur in the horizontal direction, the other in the vertical. The blur filters reduce color aliasing at the expense of image sharpness.

Foveon X3 Technology

An alternative method for obtaining color images from a solid-state imaging array is now available. Foveon X3 image sensors take advantage of the ability of silicon to absorb different wavelengths of light at different depths in silicon. In contrast to the lateral color sensing method in the Bayer filter pattern, X3 image sensors enable red, green and blue pixels to be stacked vertically. A schematic representation of this vertical arrangement is shown in Figure 3.

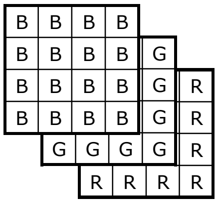

Figure 3 Schematic depiction of Foveon X3 image sensor showing stacks of color pixels, which record color depth wise in silicon.

Figure 4 shows the color planes that result directly from image capture, without interpolation.

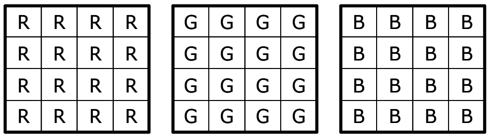

Figure 4 Fully populated image sampling found in film scanners, color-separation prism cameras, and also in Foveon X3 image sensors.

Vertical stacking increases pixel density, thereby improving sharpness per unit are of the image sensor. The stacks of red, green and blue pixels also eliminate the phase differences among the samples in color planes. Blur filters are not necessary to combat color moiré patterns. The sharpness improvement using an X3 image sensor in both the luminance and chrominance can be measured using standard techniques.

Spatial Frequency Response Method

The standard, ISO12233[4], provides the capability to compare spatial frequency responses among digital cameras and digital image sensors. This ISO standard specifies a method for testing the spatial frequency response (SFR) of digital cameras. This standard provided the methods used in this comparison.

The method specifies photographing an IT10 resolution chart with a digital camera and linearizing the data by inverting the OECF (Opto-Electronic Conversion Function[5]). The chart was framed in the camera's viewfinder according to the ISO specification. Within the target is slanted edge that is used for SFR analysis. Software written in Matlab is available to produce plots of the SFR as a function of frequency as part of the ISO standard.

Comparisons were obtained using image sensors matched as closely as possible to each other in terms of the size of pixel pitch. Special emphasis was placed on reducing effects of lens variations by using either the same lens (in the C-mount case), or the same model of lens (in the 35mm digital SLR case).

The image sensors, cameras, and lenses tested are listed in Table 1. Tests were run on 2 different device classes: devices with small pixel pitches that are typical of consumer digital still cameras and devices with large pixel pitches typically found in digital Single Lens Reflex (SLR) cameras.

Sensor	**Pixel Cell Size (µm)**	**Lens**
Sony ICX205	4.65	C-mount
Foveon F19	5.0	C-Mount
Canon 10D SLR w/ proprietary Canon sensor	7.4	Sigma 50mm macro
Sigma SD10 SLR w/ Foveon X3 Sensor	9.1	Sigma 50mm macro

Table 1 Image Sensors, cameras and Lenses Tested

The IT10 chart is produced only in black-and-white. Since the goal of creating a color image sensor is to capture color images, an investigation into the performance of the two image sensor types using a color target was also appropriate. Additional tests were performed using a modified slanted edge to examine the performance of the two types of sensors for color detail. A red/blue slanted edge target was created and images of it were recorded. From those pictures, a luminance SFR was derived which illustrates the differences in color sampling.

SFR Results – Black/White Edge

Figures 5 and 6 present the SFR results for consumer and digital SLR data. Large differences can be seen when comparing the SFR of the Bayer pattern image sensor versus the X3 image sensor.

Regardless of pixel size, the results are similar. The difference in SFR for a black-and-white target measured in this investigation was a factor of 2 or greater.

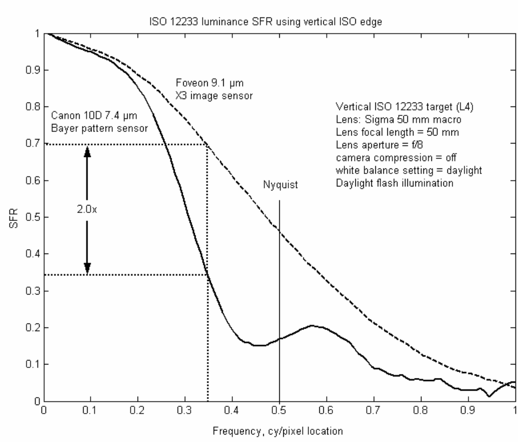

Figure 5 SFR for Canon10D camera with Bayer pattern image sensor (solid line) and Sigma SD10 camera with Foveon X3 image sensor (dashed line). The frequency response of the Foveon X3 pixel location is 2x at 0.35 cycles per pixel location.

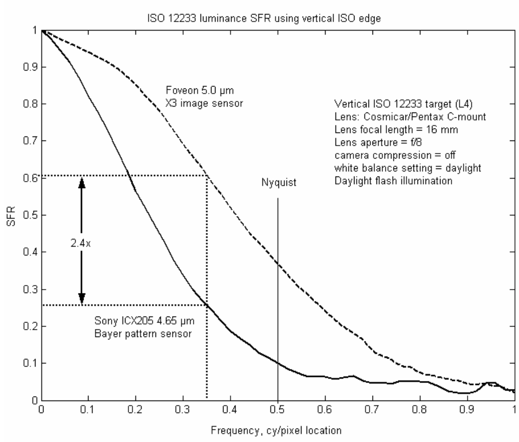

Figure 6 SFR for Sony ICX205 (solid line) and Foveon F19 (dashed line). The frequency response of the Foveon X3 pixel location is 2.4x at 0.35 cycles per pixel location.

The difference in edge response is also apparent when examining images of the IT10 target (Figure 7). Due to the lower sampling density and the blur filter, it takes more pixels to make a black-to-white transition for a Bayer pattern sensor. The higher slope of the transition from black to white in object space in the Foveon X3 case translates directly into superior SFR.

Figure 7 Images of slant edge used in computing the luminance SFR for Canon 10D (left) and Sigma SD10 with Foveon X3 image sensor (right). The sharper edges in the Foveon X3 image are evident.

SFR Results – Red/Blue Edge

The Bayer pattern samples the blue and red channels at half the rate of the green. Since the sampling rate for X3 technology is the same for red, green, and blue, sharper edges and greater detail were predicted. The X3 image sensor provided from 3x to 5x higher response for a red/blue edge. Both plots also show significant reduction in response as the Nyquist frequency is approached compared to the black/white edge.

In Figure 8 the SFR of the professional-grade arrays is plotted for a red/blue edge. The X3 image sensor records this edge nearly identically to the black-and-white case, while the Bayer pattern response is significantly reduced at frequencies above 0.2 cy/pixel.

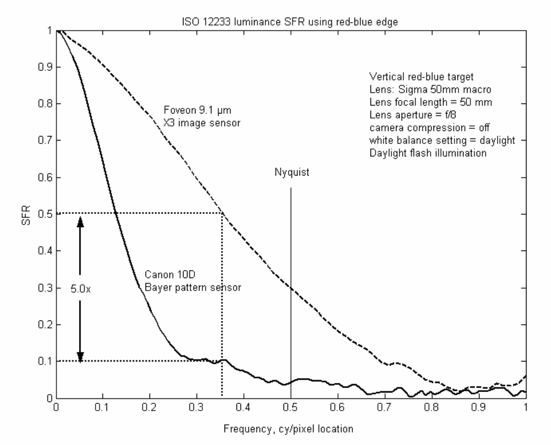

Figure 8 Chrominance SFR for Canon10D camera with Bayer pattern image sensor (solid line) and Sigma SD10 camera with Foveon X3 image sensor (dashed line).

Figure 9 displays the results from the consumer-grade image sensors. Response for the Bayer pattern imager is significantly degraded compared to the black/white edge.

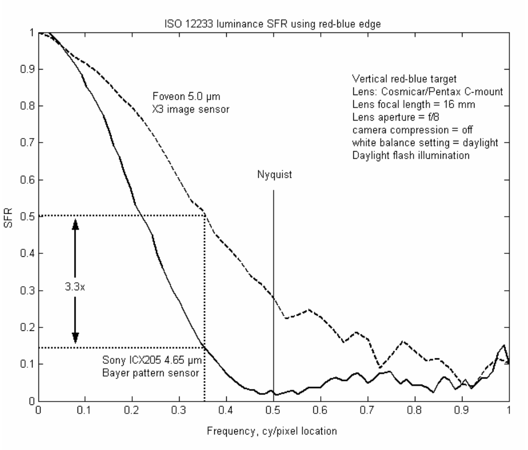

Figure 9 Chrominance SFR for Sony ICX205 (solid line) and Foveon F19 (dashed line).

Figure 10 Image of red/blue slant edge used in computing the chrominance SFR for Canon 10 (left) and Sigma SD10 with Foveon X3 image sensor (right). The sharper edges in the Foveon X3 image are evident.

The difference in sharpness can be readily seen in the comparison in Figure 10.

Conclusion

Using the standard measurement techniques found in ISO 12233, it was shown that the SFR of Foveon X3 sensor technology is superior to that of a Bayer pattern CFA. The improvement in SFR is apparent regardless of size of the photodiode location. The X3 pixel performance is overwhelming whether black-and-white or color edges are examined.

The performance improvement with Foveon X3 image sensors has an important impact on the cost of products using digital image sensors. For a given pixel location size, a sensor of 2-3 times the image area is necessary to attain the image quality produced by a sensor with X3 technology. When color detail is considered, the performance difference can be even greater.

---

[1] B. Bayer, U. S. Patent No. 3,971,065.

[2] R. B. Merrill, “Color Separation in an Active Pixel Cell Imaging Array Using a Triple-Well Structure, ” US Patent 5,965,875; 1999.

[3] R. Lyon, P. Hubel, “Eyeing the Camera: Into the Next Century”, *IS&T/TSID 10th Color Imaging Conference Proceedings*, Scottsdale, AZ, USA; 2002 pp. 349-355.

[4] ISO 12233:2000 Photography-Electronic still picture cameras-Resolution measurements.

[5] ISO 14524 Photography – Electronic Still Picture Cameras – Methods for measuring opto-electronic conversion functions (OECFs).