Eyeing the Camera: Into the Next Century

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Abstract

In the two centuries of photography, there has been a wealth of invention and innovation aimed at capturing a realistic and pleasing full-color two-dimensional representation of a scene. In this paper, we look back at the historical milestones of color photography and bring into focus a fascinating parallelism between the evolution of chemical based color imaging starting over a century ago, and the evolution of electronic photography which continues today. The second part of our paper is dedicated to a technical discussion of the new Foveon X3 multi-layer color image sensor; what could be descried as a new more advanced species of camera sensor technology. The X3 technology is compared to other competing sensor technologies; we compare spectral sensitivities using one of many possible figures of merit. Finally we show and describe how, like the human visual system, the Foveon X3 sensor has an inherent luminance-chrominance behavior which results in higher image quality using fewer image pixels.

The Past Two Centuries

Color Sensing in Film and Digital Photography

The history of color photography is rich with exciting progress in technologies for color capture and color reproduction. Examining this history, we find that in many ways the development of digital photography is following a path parallel to that of film photography, offset by about a century. The parallels extend back to black-and-white photography as well, but that takes us a bit off topic.

Inspired by Hermann Helmholtz's recent revival of Thomas Young's tri-chromatic theory of human color perception, in 1860 James Clerk Maxwell clarified the details of primaries and the idea of a color triangle covering only a portion of all possible colors. In 1861, he applied these ideas in the first demonstration of three-shot color photography, shot through three color filters, and demonstrated additive color reproduction using three projectors. Similarly, initial efforts toward color electronic photography used separate exposures for each color, and additive reproduction, by adapting television systems to frame-sequential color. An early three-shot-color electronic-still-photography example was the 1966 Surveyor 1 spacecraft, which used a vidicon with RGB filter wheel to electronically capture color images from the surface of the moon.

Three-shot cameras with glass plates were used around the turn of the century, for example by Sergei Prokudin-Gorskii, photographer to the Czar of Russia. Reproduction was done by additive projection, as Maxwell did, as well as by subtractive sandwiches, as demonstrated in 1869 by Louis Ducos du Hauron and Charles Cros. In the late twentieth century, we saw the development of three-shot digital cameras with solid-state sensors, which are still used for professional still-life work; both additive reproduction (on screen) and subtractive (on print) became common for digital work.

Dr. Hermann Vogel's accidental discovery of dye sensitization of emulsions in 1873 led to a great increase in the practical applicability of photography—originally impractical with only blue-sensitive films. Corresponding improvements in digital sensors were needed a hundred years later to extend mostly-red-sensitive CCD sensors into the blue end of the spectrum before they would be suitable for color photography, around 1973.

Gabriel Lippmann's 1891 color photography method using interference fringes in an emulsion has no known analog in digital sensors, and never became very practical.

Ducos du Hauron helped move the three-shot camera concept toward a one-shot camera, by working on optical beamsplitters to expose three plates at once. Frederic Ives developed the concept further, and made practical color cameras in 1892. Three-plate film cameras, such as the Devin Tri-Color, were used through the first half of the twentieth century, overlapping with other technologies. The Technicolor movie camera is a famous success story of that class. Though collapsing the color sensing into a single shot solved motion problems, it left the difficult alignment problem in the reproduction stage. Decades later, on the parallel digital path, prism-based digital color separation cameras, such as the Foveon, suffered a corresponding alignment difficulty in their manufacture, making them rather expensive.

Ducos du Hauron also started another important technology track, of what has been called screen plates or mosaics, but it was John Joly who first made it work via his carefully ruled micro-strips of red, green, and blue ink. The striped color film was later modified into a random mosaic in the Autochrome process of the Lumiere brothers, around 1904, and further improved as Agfacolor film, with versions around 1912, 1916, and 1923. Correspondingly, color CCD imagers evolved from using striped filters to using improved mosaic patterns of filters, mostly converging in the 1990s on the Bayer pattern, introduced by Bryce Bayer in 1976.

The integrated color filter array enabled single-plate and single-sensor color cameras, which led to a surge in popularity of color photography with these simplified devices. But the division of plate area or sensor area into tiny regions, each sensitive to only one-third of the visible spectrum, left a lot to be desired in sensitivity, clarity, color accuracy, and freedom from sampling artifacts.

Many saw that the key next step would be a layered arrangement of color-sensitive planes. Kodachrome in 1935, Agfacolor Neu in 1936, and Polacolor film in 1957 were the culminations of several intense efforts to implement such an approach in film. Correspondingly, many groups have worked to find a way to make multi-layer solid-state color sensors, sometimes trying to use the "vertical color filter" inherent in a semi-transparent silicon substrate. The Foveon X3 three-layer silicon imager, announced in 2002, is the culmination of one such effort.

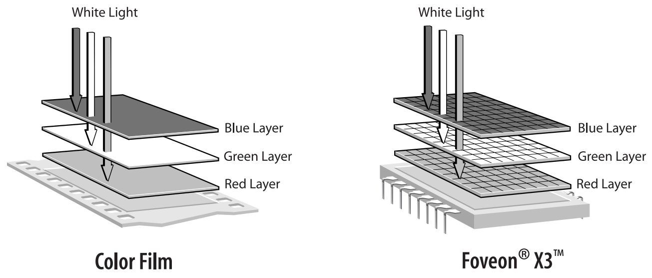


Figure 1. The introduction this year of Foveon X3 technology achieves for solid-state sensors what Kodachrome did for color film in 1935.

Of course, once such a breakthrough has been introduced and proven viable, a rapid development of improvements does inevitably follow. In each of seven decades of color film development, progress has been amazing. It is reasonable to expect similar progress for silicon sensors, though on a modern accelerated schedule.

Just as the development of Kodachrome and other multi-layered films left some room for continuation of older technologies, such as the striped filter array of instant Polacolor2 transparency film, the introduction of multi-layer silicon sensors, such as Foveon X3, will leave room for other approaches for many years to come.

Foveon X3 Technology

As we start the 21st century, several groups[1,2,3,4,5] are striving to do for digital photography what Kodachrome and AgfaColor did for film photography in the first part of the 20th century: produce a multi-layer silicon sensor. The first commercial product to use the Foveon X3 technology, the Sigma SD9 (figure 2), uses just such a layered silicon sensor fabricated on a standard CMOS (complementary metal-oxide semiconductor) processing line.

Figure 2. The Sigma SD9 is the first digital camera to use a full-color multi-layer sensor technology: The Foveon X3 sensor.

Wavelength-Dependent Absorption Depth

Figure 3 shows a schematic drawing of a sensor that absorbs first the blue wavelength photons as the incident light enters the device, then the green photons, and finally the red photons at the deepest layer.[6] Three separate PN junctions are buried at different depths inside the silicon surface and used to separate the electron-hole pairs that are formed by this naturally occurring property of silicon. As expected, the depths of the electrodes are the key variables that determine the spectral sensitivities of such a device.

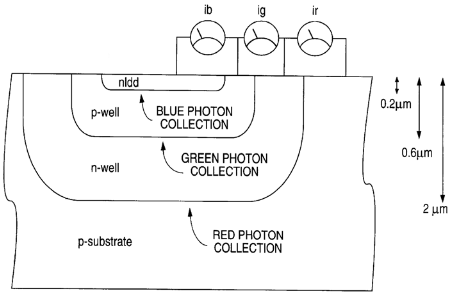


Figure 3. A schematic drawing of a sensor stack that captures all of the incident photons, filtering the color components by the wavelength-dependent absorption of silicon.

The wavelength-dependent absorption coefficient of silicon, and corresponding mean penetration depth, are plotted in Figure 4.[7] Silicon's indirect band-gap makes the material semi-transparent. As light enters the sensor, it is absorbed to produce electron-hole pairs in proportion to the absorption coefficient, yielding many more charge carriers for short wavelengths than for long wavelengths near the silicon surface; both the rate of absorption and the remaining photon density decrease exponentially as the light penetrates the silicon, leaving only red and IR light to penetrate beyond a few microns. Figure 5 plots the absorption as a function of depth, which is an exponential function of depth for any wavelength. The higher-energy photons interact more strongly, have a smaller space constant, and thus the exponential fall-off with depth is more rapid, as shown.

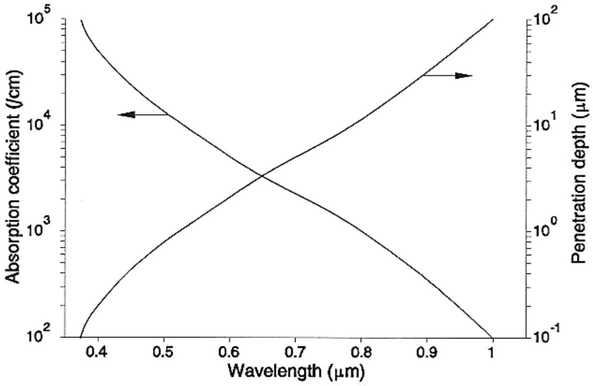


Figure 4. Absorption coefficient and penetration depth in Silicon, vs. wavelength.

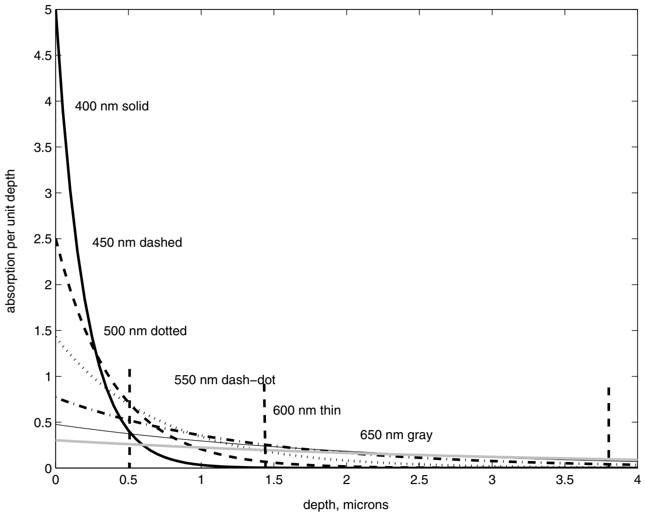


Figure 5. Light absorption in silicon as a function of depth and wavelength.

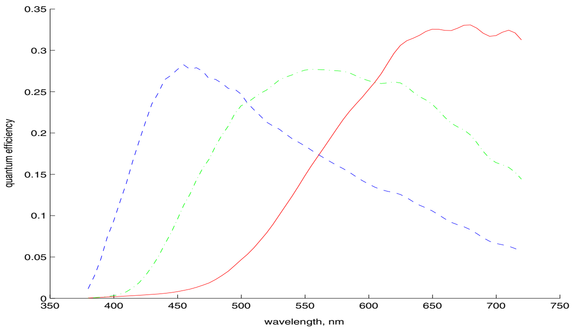


Figure 6. Wavelength vs. quantum efficiency.

Spectral Characteristics of X3 Sensors

In figure 6 we have plotted quantum efficiency for a Foveon X3 sensor as a function of wavelength generated using photocurrent detection at approximately the depths marked by the dashed lines in figure 5; these are actual sensitivities measured using a monochrometer. When spectral sensitivity is calculated and an IR filter such as a 2mm thick CM500 is applied to the data, we get the more familiar looking spectral sensitivities of figure 7. These curves, even though they use no pigment or dye filtration, are remarkably similar to curves found on today's digital camera sensors and to the human cone sensitivities.

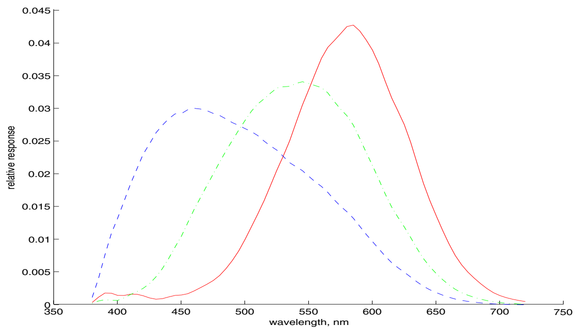


Figure 7. Wavelength vs. spectral sensitivity with a 2 mm cm500 IR filter.

Comparison with Other Popular Sensors

Figure 8A shows an estimation of spectral sensitivities measured from a professional charged-coupled device (CCD) digital camera from Kodak, made using several exposures of reference surfaces through interference filters and a Weiner estimation technique.[8] In figure 8B we show curves from an HP digital camera using a Sony CCD, and in figure 8C a Concord EyeQ digital camera using an Agilent CMOS sensor both made using another published estimation technique.[9] There are many methods we could use to compare these curves to the Foveon X3 sensor curves from figure 7.

Metamerism Index

One figure of merit, proposed in an early draft of an ISO standard (17321 WD4—used here because a better alternative has not yet been agreed upon) is the so-called Digital Camera Metamerism Index[10]. This quantity was designed to show how colorimetrically accurate a digital camera can analyze a scene. The metamerism index corresponds to the error between the ISORGB color matching functions and the spectral sensitivities of the camera transformed by a color correction matrix derived using a standard method (also described in the same standard). Table 1 shows how the Foveon X3 technology compares to the sensors used in the Kodak frame-transfer ccd, the Agilent CMOS sensor, and the Sony inter-line ccd (lower numbers show greater color accuracy).

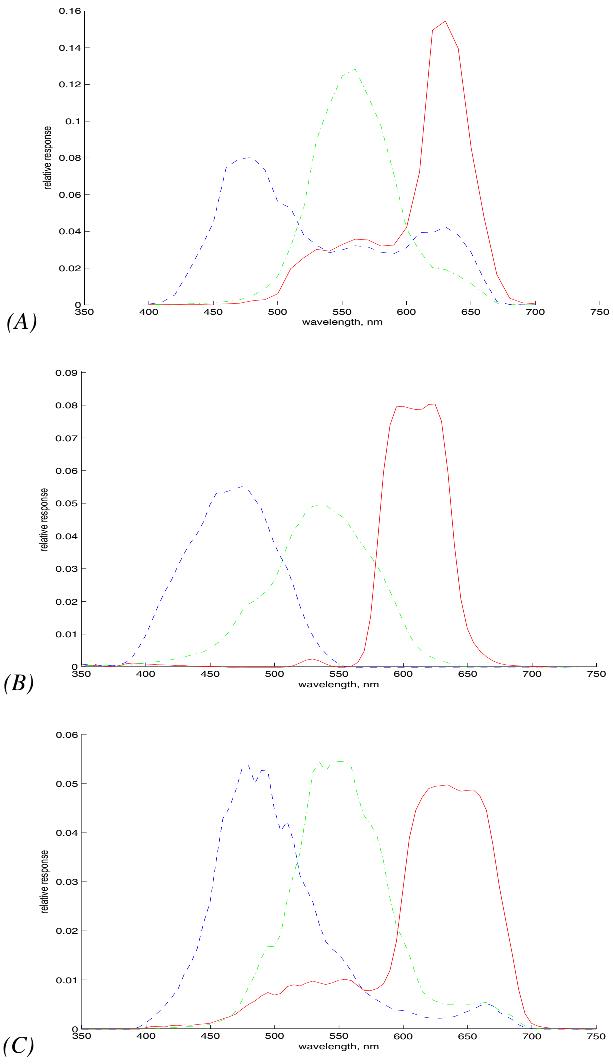


Figure 8. Spectral sensitivities of three digital camers using (A) a Kodak Frame-transfer ccd array, (B) a Sony interline ccd array, and (C) an Agilent CMOS array.

Table 1. The Metamerism Index a Kodak frame-transfer ccds, an Agilent CMOS sensor, a Sony interline ccd, and the Foveon X3 sensor. Lower values correlate with the camera having better ability to colorimetrically capture a scene

Camera	Sensor	Metamerism index
Kodak DCS-460	Kodak	0.2974
Concord EyeQ	Agilent	0.2873
Sigma SD9	Foveon X3 – F7	0.1999
HP 618	Sony ICX-284	0.1802

Additional Filters to Shape Overall Response

Color accuracy and noise performance can be optimized by the addition of filters into the optical path of the device. (Unlike the filters used in mosaic color filter arrays, these filters are the same for each pixel.) The importance of the extinction and the spectral shape of the UV and violet response has been investigated in the photographic literature[11] and the importance of the design of the IR filter has been analyzed and discussed[12]. (In the case of the HP/Sony ccd camera, the IR filter was optimized for color accuracy using the Metamerism Index).

In order to see how well the spectral sensitivity curves of the stacked detectors can be used to estimate the colorimetry of a scene, we need to add a pre-filter to reduce UV and IR and optionally to further shape the total sensitivity; then we can compare the "net" spectral sensitivity curves to the closest corresponding set of color-matching functions (linear combinations of the sensitivities of the three types of human cones). Figure 9 shows such a comparison.

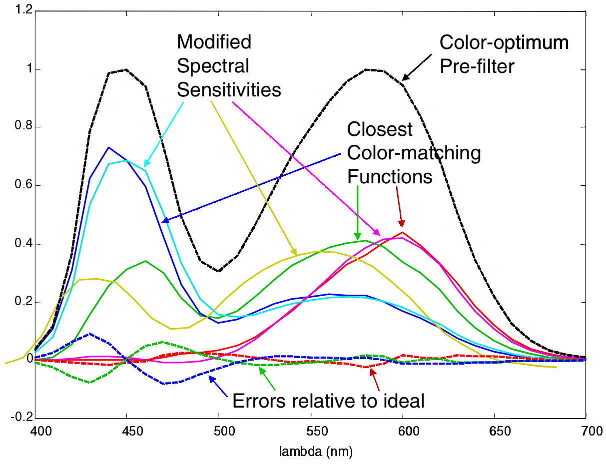


Figure 9. Comparison of the closest linear combination of cone sensitivities with the spectral sensitivities of the Foveon X3 sensor with optimized pre-filtering.

We computed an approximately color-optimum prefilter by including a UV cutoff matched to the short-wavelength cones, an IR cutoff roughly matched to the long-wavelength cones, and an intermediate region designed to come as close as possible to unity transmission at several wavelengths while staying close to a weighted sum of cone curves (or equivalently, to a weighted sum of the XYZ standard observer curves). Multiplying the original spectral curves by this prefilter yields the net sensitivities shown; it is a simple matter to then find a "closest" set of color-matching functions. The ones shown in the figure are closest in the camera-RGB space, but typically better photographic color will be achieved by optimizing the error in some other space, such as RGB or Lab (such as described in working drafts of ISO 17321 and another references[13]).

This early graphical analysis is what led us to conclude that the response curves that we could get from silicon color filtering would yield relatively small color errors, with suitable matrixing. In practice, we do not attempt to design or use a color-optimum prefilter; rather, we select the prefilter to allow somewhat more light through than the illustrated filter does, to improve sensitivity, and we use sharper UV and IR cutoffs, to improve rejection of chromatic aberration at extreme wavelengths. The color accuracy is still excellent with such a simplified prefilter.

Examples

Several images taken using a Foveon X3 sensor will be shown during the presentation and included on the supplemental media CD supplied with these proceedings. The sensor array used for these photographs is the 1536 x 2304 x 3 pixel array in the Sigma SD9 camera. The sensor contains 10.5 million active pixel sensors, or 3.5 million full-color pixels. All digital cameras to date (except a few professional models that use three-shot or beamsplitters) use a mosaic of single-color filters superimposed over a panchromatic array. These filters are usually arranged in the 2-by-2 Bayer pattern mentioned earlier where each pixel will see the world through one of either red, blue, or green filters [or through cyan, magenta, yellow, or green filters; although this arrangement has been shown to give poorer signal-to-noise performance[14] and fallen out of favor, it has recently been re-discovered and exploited as a *feature*[15]]. In either case, the quoted resolution of digital cameras has converged on a 'pixel' being an area of the sensor that receives light from only 1/3 of the spectrum. This is contrary to the display industry or computer graphics industry where pixel count refers to full-color superimposed triplets. This discrepancy and confusion of a 'pixel' makes the marketing interesting.

Luminance

Images are composed of both chromaticity (color) and luminance (brightness) components. Generally speaking, the human visual system is more sensitive to luminance for image detail and sharpness.

While all colors (RGB) carry luminance information, based on the human visual system, green light contains the highest amount of luminance information. Manufacturers of mosaic sensors have known for years that critical luminance information is found in green light, and almost always dedicate the majority of pixels to gather green light. A typical mosaic sensor, using the Bayer pattern[16], dedicates 50% of the pixels to green and only 25% each for red and blue.

The relative weighting of luminance per color can be expressed as:

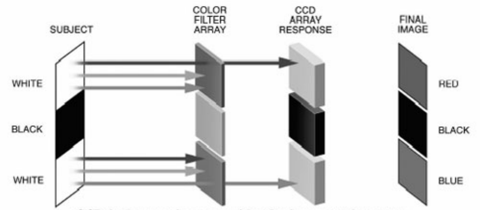
$$Y = R/3 + G + B/10 \tag{1}$$

where Y represents the luminance signal and R, G, and B are values in a standard color space (such as sRGB). This equation demonstrates how the luminance signal is dominated by the green part of the spectrum

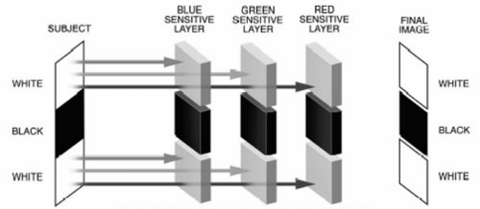
Since Foveon X3 technology measures every color at every location—including the all-important green—approximately twice as much luminance information is captured compared to a mosaic sensor. The results are images that, pixel-for-pixel, contain noticeably greater sharpness than images captured using a mosaic sensor.

Because of the fact that Mosaic-based sensors don't capture complete luminance or color information for every pixel location, interpolation routines ('demosaicing') are needed to fill-in the missing information.

In fact, misinterpreting luminance information will typically lead to greater interpolation artifacts than the artifacts caused by missing color. Figure 10 shows how a thin black line is seen through a filter mosaic compared to a layered structure. Although demosaic algorithms have improved substantially over the years they are still prone to visible errors degrading image quality and using substantial computational power.



CCD / color mosaic sensor with color interpretation errors



x3 sensor with no color interpretation errors

Figure 10. In the case of a thin black line incident on a mosaic sensor, interpolation errors are unavoidable (top). Using a multi-layer technology, such as Foveon X3, interpolation errors are avoided.

Blur Filters

Because of the inevitable image quality errors that remain after demosaicing routines, most digital cameras include a blurring filter in the optical path to reduce the artifacts caused by the under-sampling of the luminance and chrominance signals. While blurring filters will reduce unwanted artifacts, they result in an overall softening of the image, thus further reducing sharpness and resolution of the camera. The blur filter is another deviation of a digital camera's MegaPixel rating number from its real resolution.

Luminance-Chrominance Camera

Although green is the dominant wavelength (or color) of the luminance signal, there is still some significant luminance information in the red channel and a small amount in the blue. This distribution of luminance information across the spectrum underlies another advantage of the layered system: the three layers can be linearly combined to form a clean, sharp, virtually artifact-free luminance signal. As articulated so well by Dr. R.W.G. Hunt in his keynote lecture from the fourth Color Imaging Conference: an accurate and sharp luminance signal is just as important for color photography as it is for black and white photography.[17] Figure 11 shows a 200-by-300-pixel segment of an image taken using a mosaic filter camera—with and without a blur filter—and taken with the Foveon X3 sensor. Care was taken to ensure the optics were identical, the pixel size of the sensors were the same, and the camera's exposure parameters were the same (ISO speed, f-number, and shutter speed). Color versions of figure 11 (in addition to the components printed here) will be shown during the presentation and included in the supplementary CD. Because the luminance signal from the Foveon X3 sensor is formed by a combination of real measurements of light at all three components in perfect registration, the luminance channel is far superior to the interpolated and transformed data from the mosaic sensor. Although artifacts diminish with the introduction of an optical blur filter to the mosaic sensor, this blur also gives a noticeable reduction in the real resolution of such cameras.

Figure 12 shows the chrominance components of the same image used for the comparison in figure 11. In this figure, a* and b* are mapped into 8-bit grayscale images where middle grey at 128 is neutral, and color saturation increases at lighter and darker positions on the image. In the image taken with the color mosaic, the unnaturally saturated color artifacts show clearly as high contrast fringing in the text, cloth, and candy box (upper right); this fringing is suppressed but still visible in the image with blur filter, but non-existent in the components from the X3 sensor. It is interesting to note how these artifacts do not correspond to any information in the luminance channel nor any detail in the full color images.

Conclusion

Color photography has evolved through many technological changes, always needing to respect and incorporate knowledge of human color vision. Advances in our ability to separate and sample color have led to improved accuracy of image structure, ultimately by sampling three primary color bands in each of three layers, to capture high-resolution image structure without sampling artifacts. The human eye still uses a mosaic pattern of cones in the fovea centralis to detect moving color imagery; can we imagine that the eye might evolve to follow the layered concept, as film and solid-state sensors have?

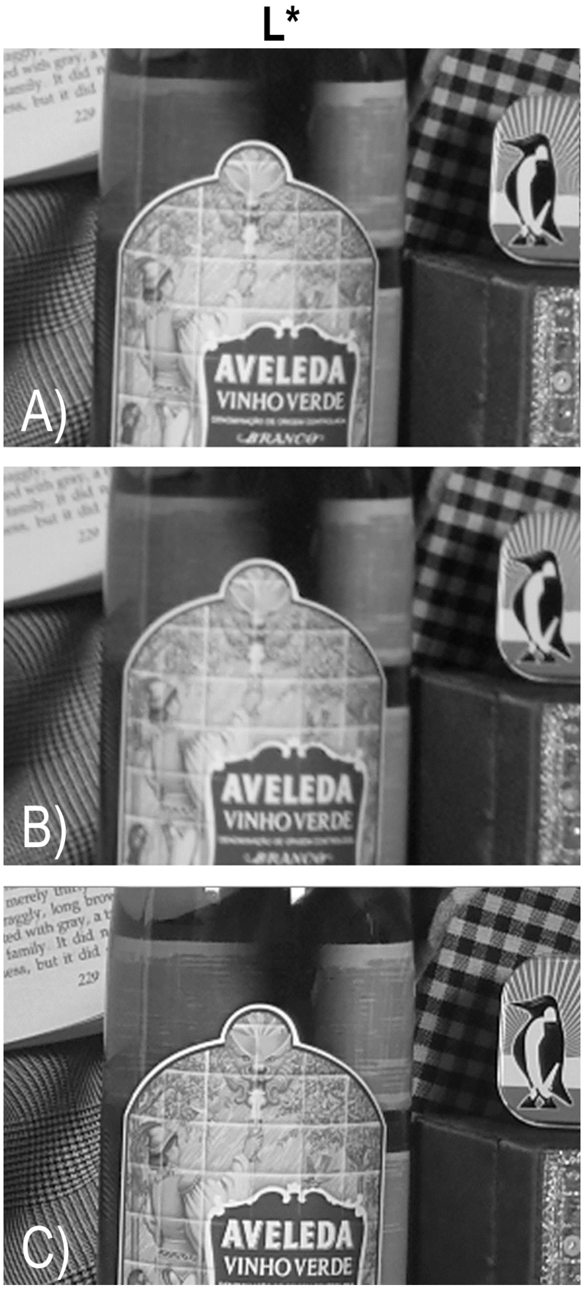


Figure 11. The luminance channel of images captured with a digital camera using A) a Bayer mosaic sensor, B) a Bayer mosaic sensor and a blur filter, and C) a Foveon X3 sensor that fully captures luminance information at every pixel location. Notice the artifacts caused by interpolation errors in A, softer lower resolution in B, and a clean sharp luminance record in C.

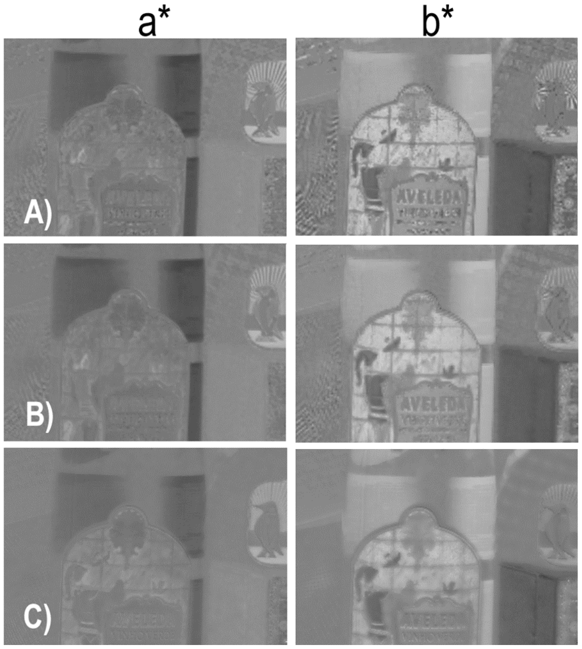


Figure 12. The corresponding a and b* components of the images shown in figure 11. Notice the fringing in the fabric, text and other areas that do not correspond to the luminance image. These artifacts are suppressed in the image taken using a blur filter, and nonexistent in the Foveon X3 image.*

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