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Digital Camera Sensors: A Simulation Study

Background:

This study involves a simulation that examines the influence of various parameters on the performance of digital camera sensors, including a monochrome sensor and a Bayer RGB sensor. The simulation begins with a scene featuring a slanted bar with sharp contrast. An optical system with a fixed f-number and auto exposure is enabled for both sensors. To evaluate the performance of the monochrome sensor, the ISO12233 metric was used, which involved calculating and plotting the modulation transfer function (MTF). The MTF is a measure of the spatial resolution of an imaging system and describes its ability to reproduce high spatial frequency details. The MTF and line spread function (LSF) are computed and plotted for different pixel sizes, fill factors, and voltage swings.

For the RGB sensor simulation, a Macbeth chart was used and CIELAB ΔE values were calculated and plotted for each patch to investigate the effect of different parameters on the performance of the sensor. The three dimensions of the CIELAB space are L*, a*, and b*, which represent lightness, red-green chromaticity, and yellow-blue chromaticity, respectively. It is useful because it takes into account the fact that the human visual system is more sensitive to some colors than others, so a small difference in color may be more noticeable for some colors than for others. The ΔE value is a measure of the difference in color between two points in the CIELAB color space. These values were also plotted for different pixel sizes, fill factors, and voltage swings. The resulting plots can be used to evaluate the performance of the sensors under different conditions and optimize the design of a digital camera sensor. The simulation employs functions from the ISET (Imaging Science and Engineering Toolbox) library to create and manipulate the scene, optical system, and sensors.

Results:

The first parameter that was investigated in the simulation of the monochrome sensor was the pixel size. The results showed that as the pixel size decreased, the resolution of the sensor improved. This can be seen in the wider modulation transfer function (MTF) and narrower line spread function (LSF) at smaller pixel sizes. The improvement in resolution is expected, as smaller pixels can capture finer details.

The second parameter that was studied was the fill factor of the sensor. When the fill factor was varied from 0.1 to 1.0, there were no noticeable trends in the MTFs or LSFs with auto exposure enabled. This is expected, as the auto exposure feature increases the exposure time to compensate for poor lighting conditions. However, when the exposure time was fixed, noise increased significantly at low fill factors. This can be attributed to the poor lighting conditions, which result in small signal-to-noise ratios.

The third parameter that was examined was the voltage swing of the sensor. The results showed that there were no noticeable trends in the MTFs or LSFs as the voltage swing was varied from 0.1 V to 5 V. However, noise became apparent at very low voltage swings. This is expected, as small voltage swings result in a low signal-to-noise ratio despite the strength of the signal.

The first parameter that was investigated in the simulation of the RGB Bayer sensor was the pixel size. The results showed that there were no noticeable trends in the mean CIELAB ΔE values as the pixel size was varied from 0.75 μm to 6 μm. This suggests that the color accuracy of the sensor is not significantly affected by the pixel size within this range. The lack of significant trends at low frequencies, where there is not much detail to display, can likely be attributed to the fact that only color is being displayed.

The second parameter that was studied was the fill factor of the sensor. The results showed that there were no noticeable trends in the mean ΔE values with auto exposure enabled. This is expected, as the auto exposure feature increases the exposure time to compensate for poor lighting conditions. However, when the exposure time was fixed, the mean ΔE values did not change significantly even at low fill factors. The luminance series did begin to underperform, but this and the increase in mean ΔE values was not as significant as expected due to the increase in noise seen in the monochrome sensor.

The third parameter that was examined was the voltage swing of the sensor. The results showed that there were no noticeable trends in the mean ΔE values for voltage swings of 1 V or higher. However, for voltage swings below 1 V, the mean ΔE values began to increase. At very low voltage swings, the ΔE values became very high. This can be attributed to the poor signal-to-noise ratios, which lead to poor color estimates.

The results of the simulation show that the pixel size has a significant effect on the quality of the final image. As the pixel size decreases, the images become more detailed and have less pixelation. However, at very small pixel sizes, the image may become hued and affect color accuracy. The fill factor had a relatively minor effect on the system, as auto exposure can compensate for poor fill factors. Even with auto exposure disabled, there was a minimal effect on the system. The voltage swing had little effect on the MTFs or LSFs, but very small voltage swings did worsen the color accuracy of the system.

Conclusions:

The results of the simulation suggest that varying the pixel size within a certain range (0.75um-8.0um) does not significantly affect the color accuracy of the generated images. Though, it should be noted that this only holds for very low spatial frequencies; the color resolution still depends on the MTF of the system. Decreasing the pixel size within this range increases the bandwidth of the MTFs and decreases the width of the LSFs, improving the visual acuity of the system. However, decreasing the pixel size below 0.5um significantly worsens the color accuracy of the system, resulting in images with a noticeable blue tint. Although the exact cause of this hue effect is unknown (Professor Wandell mentioned it may be a fault it his code), it is likely inconsequential. The wavelengths of light we can see range from 0.4 um to 0.7 um which is usually expressed in nanometers. Thus, it does not make much sense to push pixel sizes into this region because they will under sample the very wavelengths we want to capture.

Very low voltage swings can lead to poor color accuracy, as they result in poor luminance estimates and larger average ΔE values. However, voltage swings do not affect the sharpness of the system and voltages above 1 V had almost no effect. Lastly, the fill factor of the sensor had a negligible effect on the results when auto exposure was enabled in the simulation. When auto exposure was disabled, the noise became more apparent, but system performance remained the same. Overall, these results are reassuring yet insightful and can be used to aid in the design of a digital camera sensor.

Appendix:

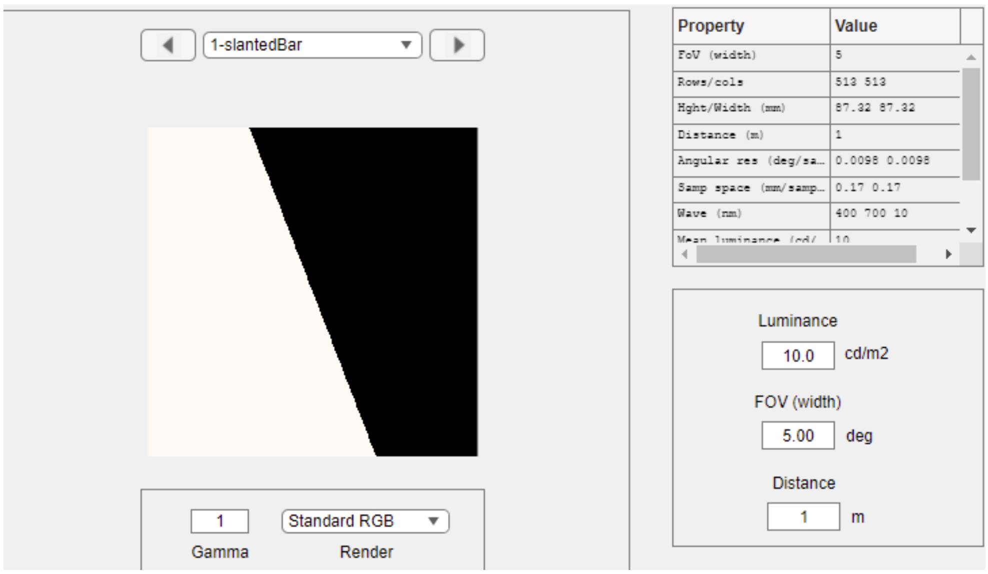

Figure 1: *Slanted bar scene setup.*

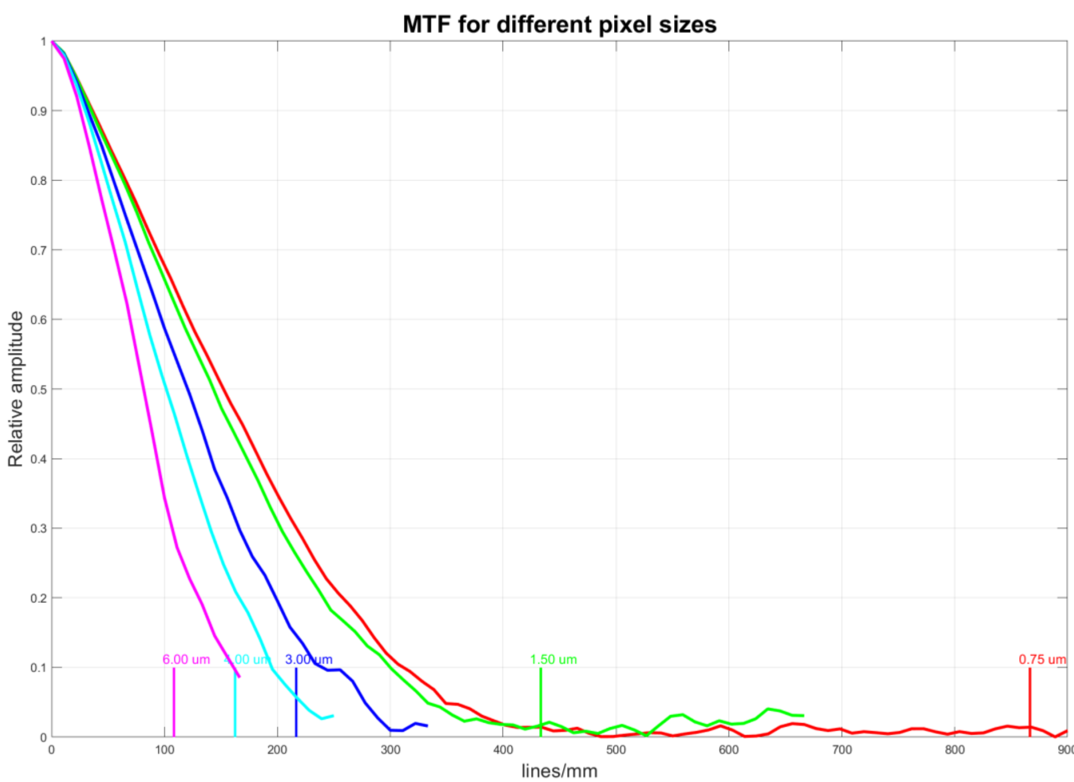

Figure 2: *Monochrome sensor MTFs for different pixel sizes.*

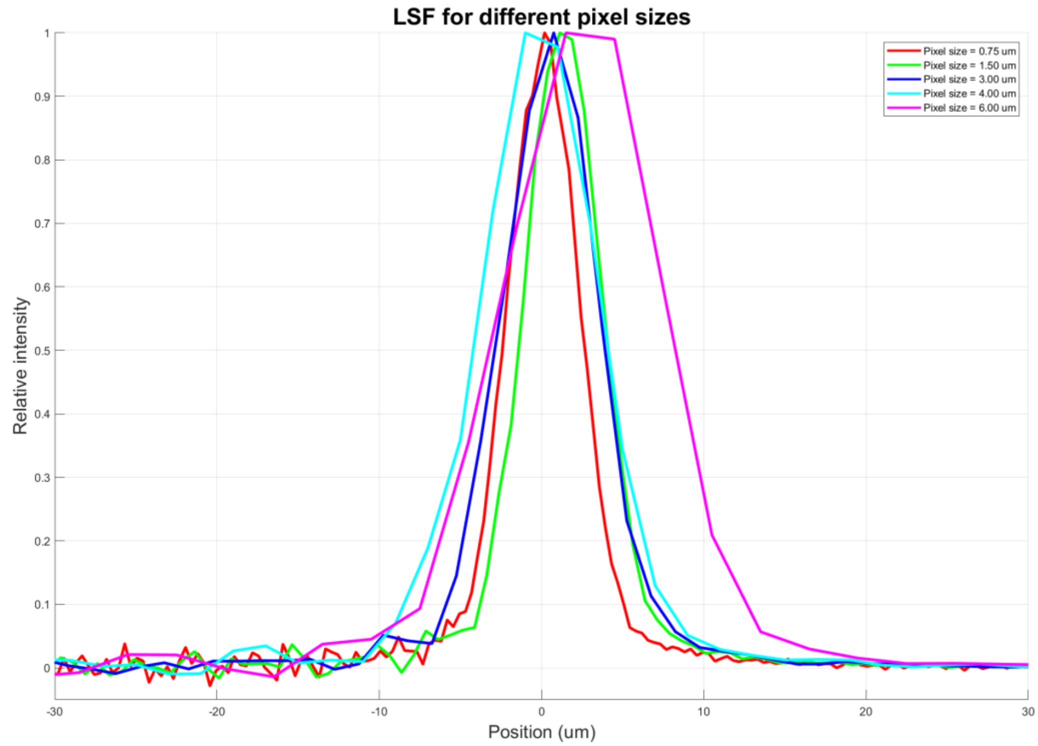

Figure 3: *Monochrome sensor LSFs for different pixel sizes.*

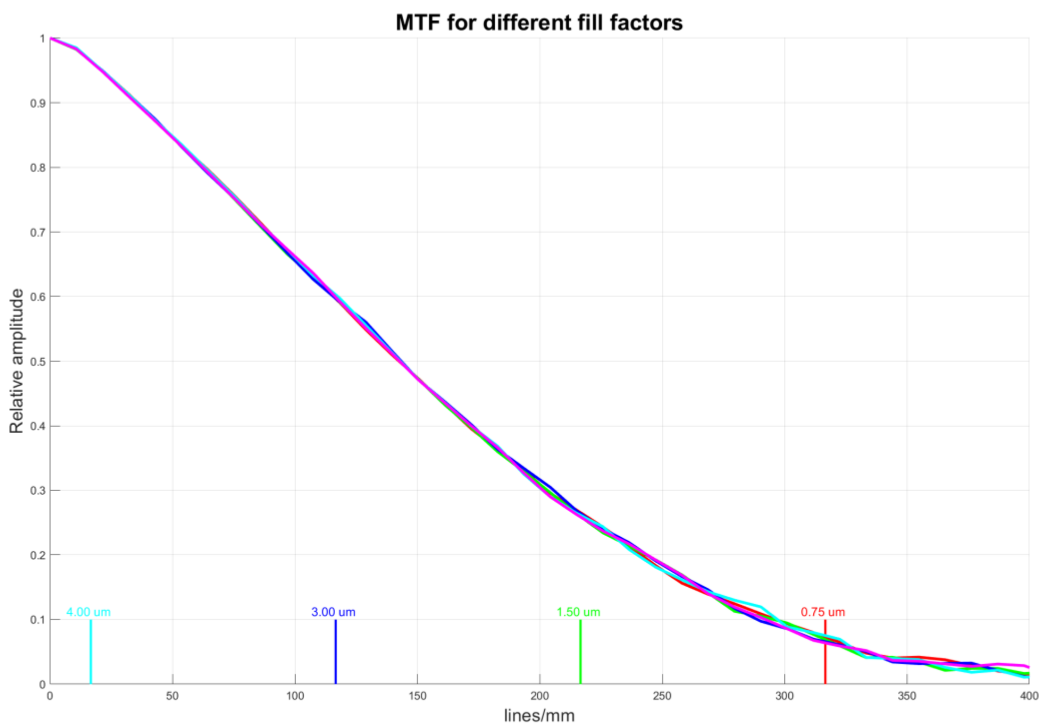

Figure 4: *Monochrome sensor MTFs for different fill factors.*

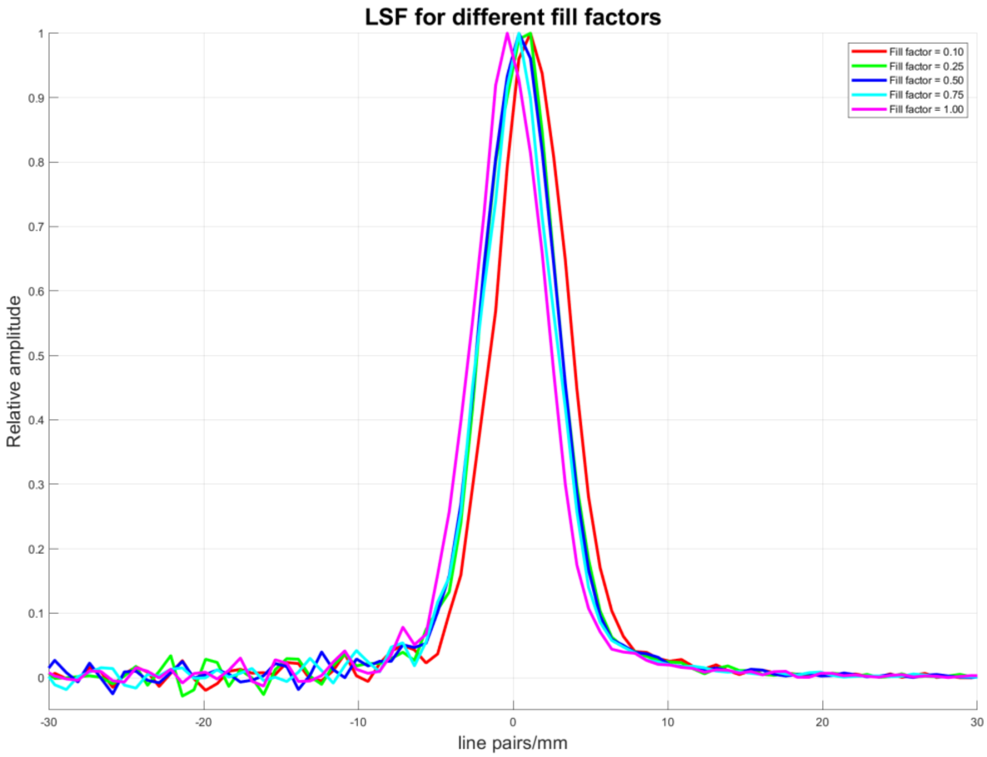

Figure 5: *Monochrome sensor LSFs for different fill factors.*

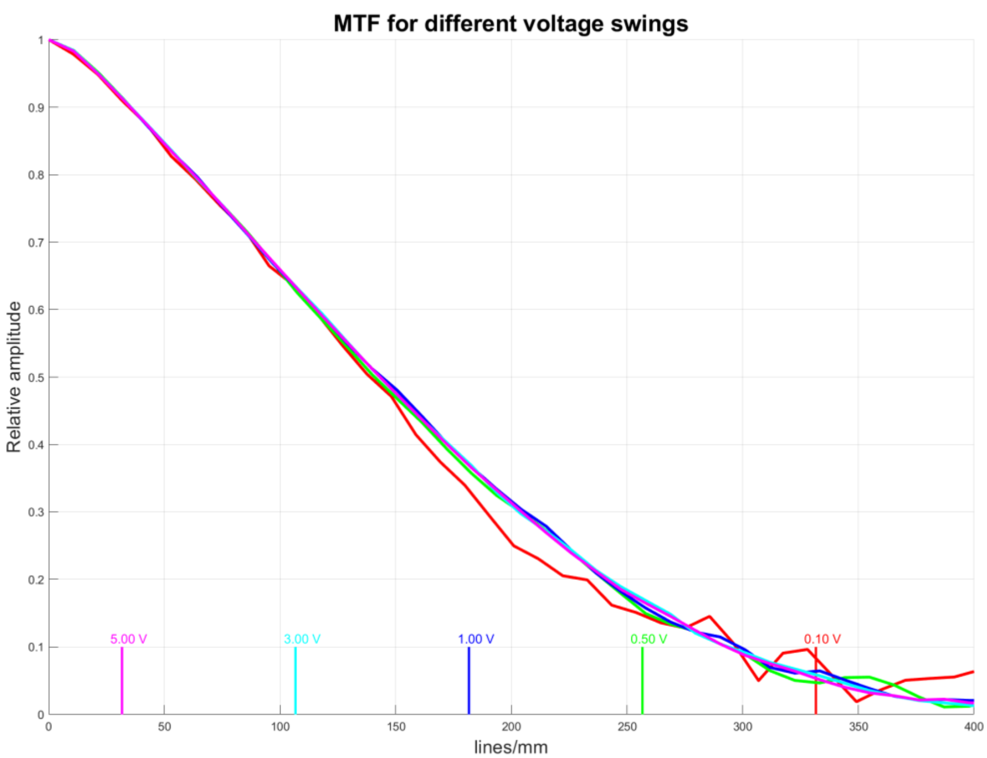

Figure 6: *Monochrome sensor MTFs for different voltage swings.*

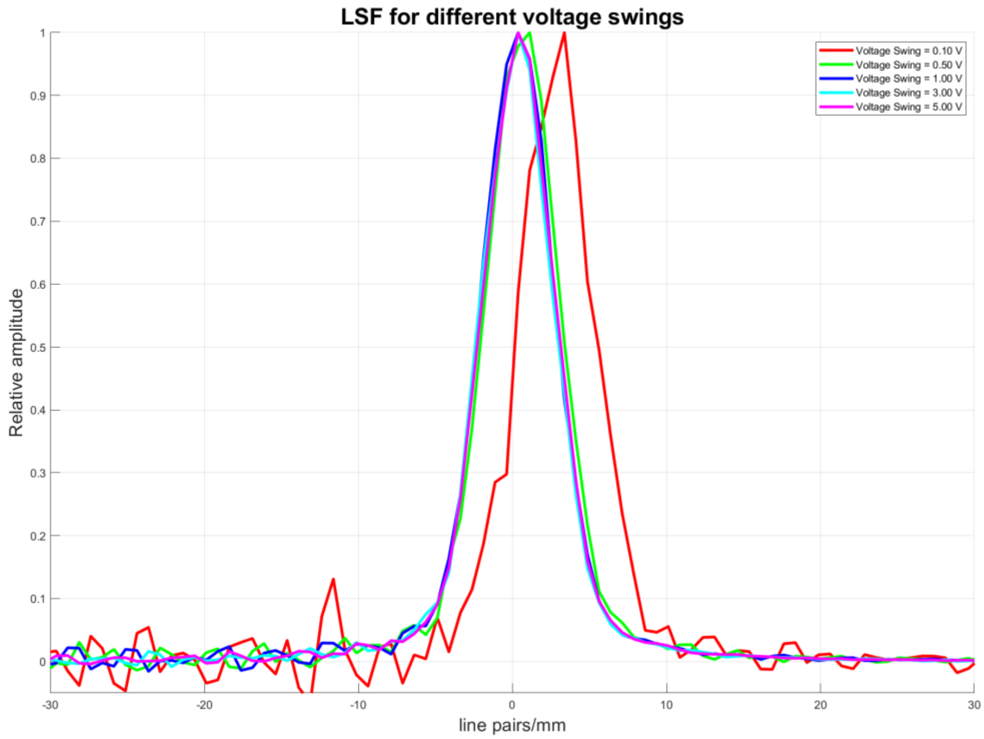

Figure 7: *Monochrome sensor LSFs for different voltage swings.*

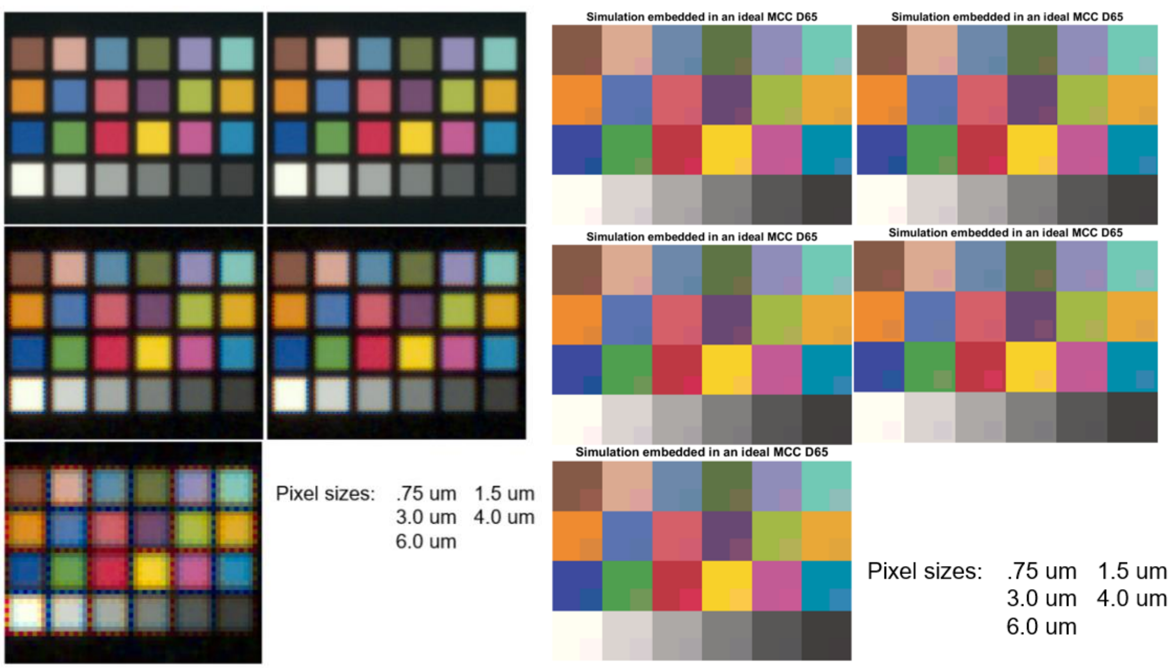

Figure 8: *RGB Bayer sensor Macbeth color chart simulation for different pixel sizes.* *<u>LEFT</u>: Macbeth color chart with black borders. <u>RIGHT</u>: Macbeth simulation embedded within an ideal Macbeth chart.*

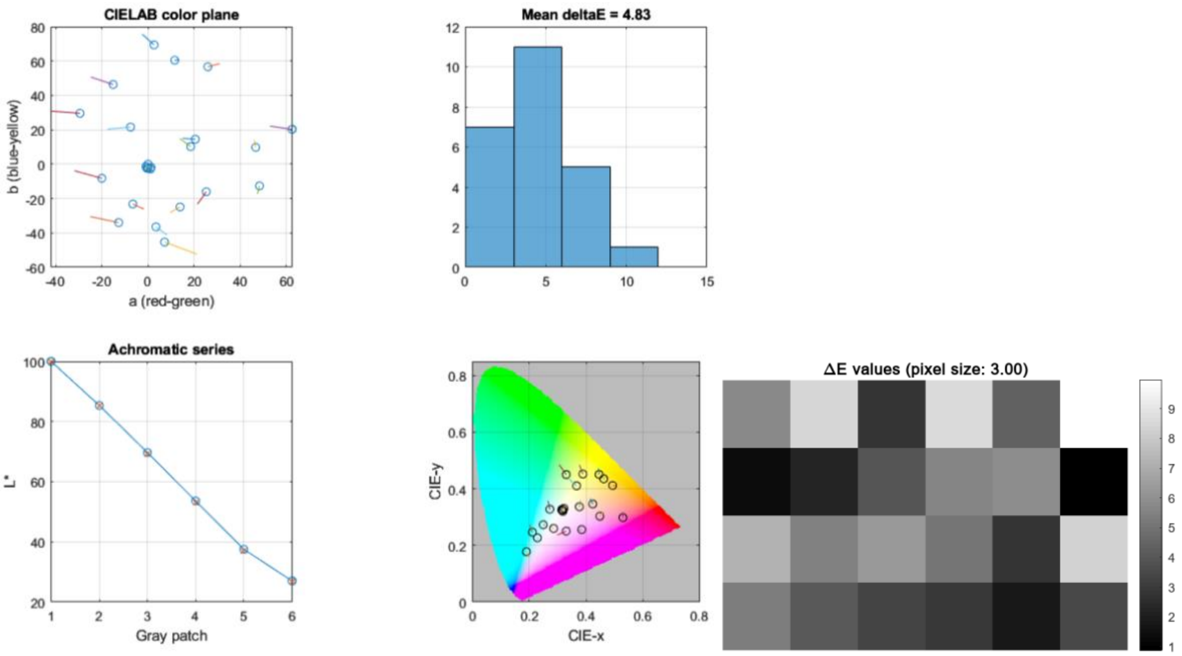

Figure 9: *RGB Bayer sensor ΔE values for each Macbeth color patch. These results are for a 3.0um pixel but the other pixel sizes yield nearly identical results.*

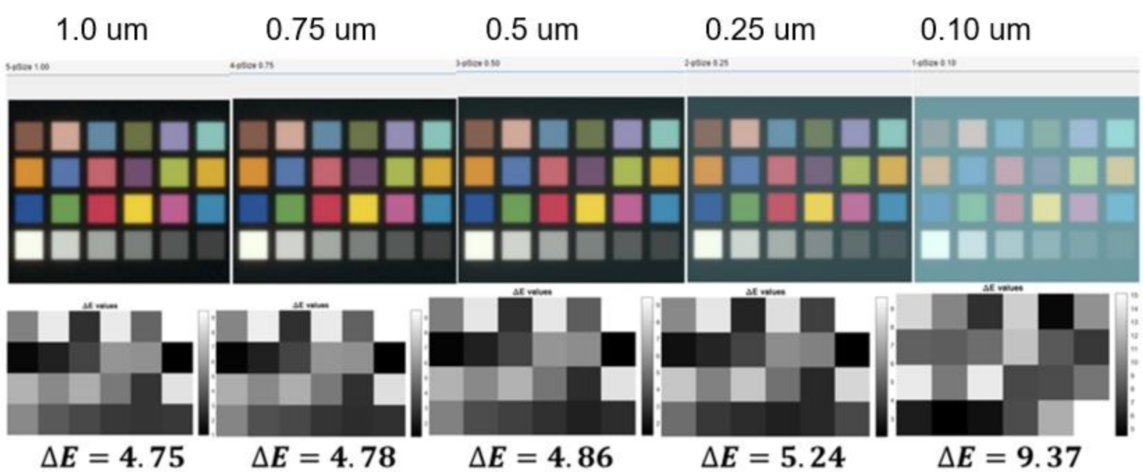

Figure 10: *RGB Bayer sensor for very small pixel sizes.*

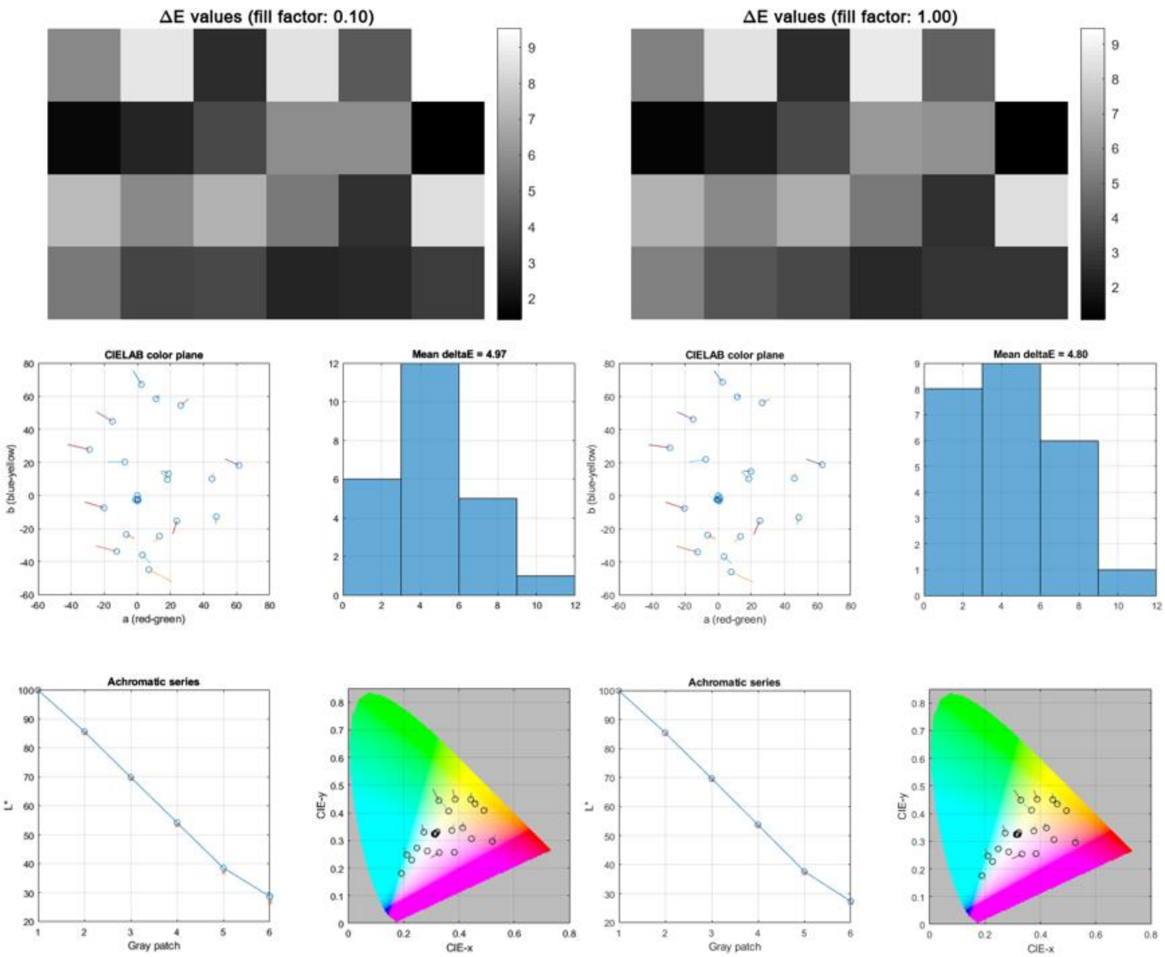

Figure 11: *RGB Bayer sensor color results for two extreme fill factors.*

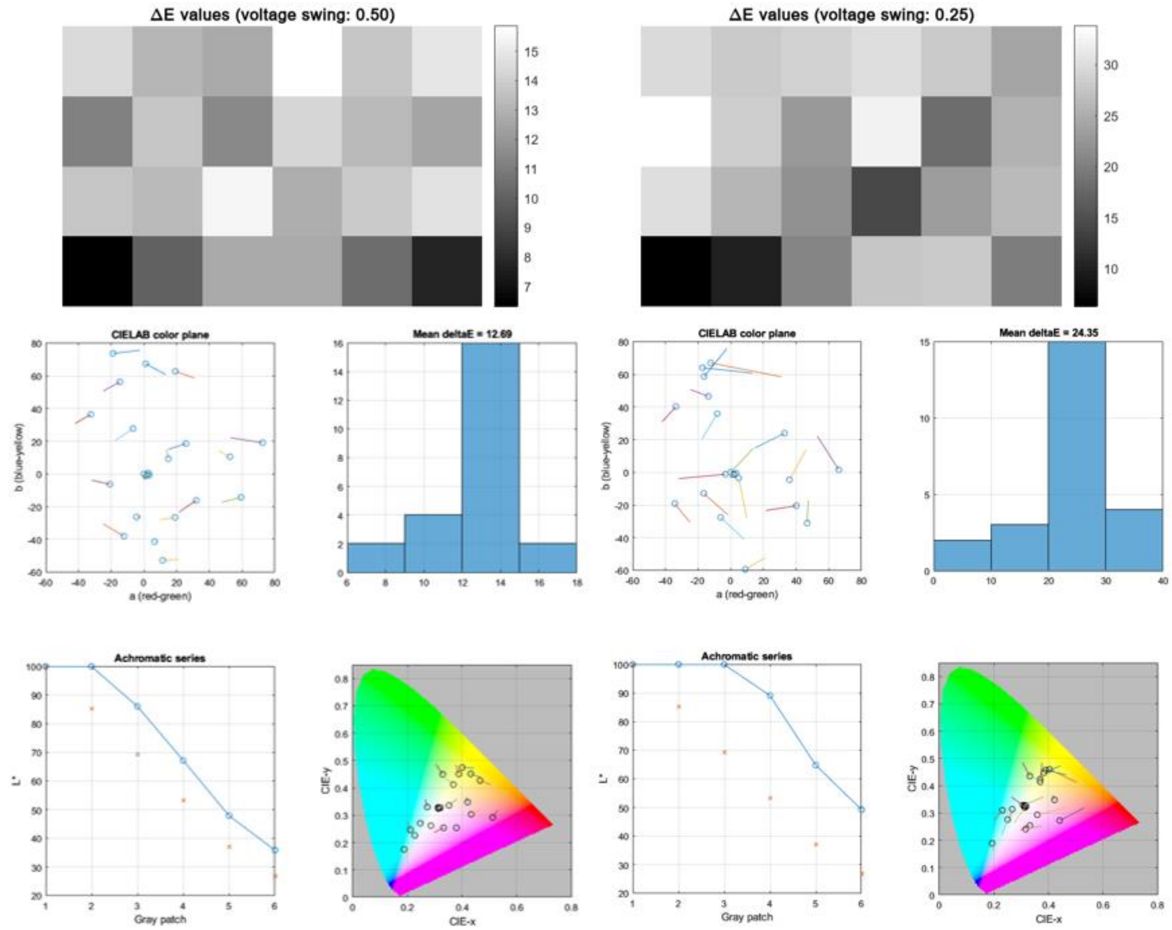

Figure 12: *RGB Bayer sensor color results for small voltage swings.*

References:

ISETCam - https://github.com/ISET/isetcam
PSYCH221 - https://github.com/ISET/psych221
Wandell, Brian. *Foundations of Vision. Sinauer Associates*, http://foundationsofvision.stanford.edu/ (December 4, 2022).