# Rigging a Multiprimary LED Panel for Reducing Sensor Metamerism

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***Abstract*— Multiprimary display technology is revisited in the context of LED volumes, where the cinema camera is the observer instead of the human visual system. The act of introducing one or more non-RGB primaries to an LED volume - even if the source material doesn't have corresponding native non-RGB channels - can reduce inconsistencies between color reproduction of displayed material on different cameras deployed on a set, i.e. sensor metamerism. However, as is inherent with the color physics of any display, this comes at the cost of reduced gamut area overall which the extra primary only slightly counteracts.**

***Keywords*— Multiprimary, LED, virtual production, color matching functions, sensor metamerism, Pointer's gamut**

## I. Introduction

LED panels manufactured by the likes of Roe, Absen and Everbrighten which were previously used mainly for live shows and outdoor signage have found a new home on-set in the fields of cinema and TV production as an alternative to green screen-based compositing workflows. Imagery is provided either via plates played back on a media server or rendered live through software like Unreal Engine and allows for cast and crew to see a live representation of the background on set. These panels, like nearly all other display hardware available across industries, rely on trichromatic color reproduction via the three additive primaries - red, green, and blue. Each pixel is made up of three LEDs, one for each color. This scheme has been the standard since the beginning of the color display and is based on the three cone types found in the human retina. However, in cinema and TV production the intended observer on set isn't the human, but rather the camera. Depending on the spectral sensitivity of a given cinema camera and the peak wavelengths of the three channels of a given LED panel, not all real surface colors one might wish to depict on the panel may reproduce faithfully in the captured footage. Adding LEDs with additional color channels to a panel could potentially expand the displayable color gamut to be more inclusive of these surface colors, making color depictions from the LED panel match closer to images captured of real objects – additionally, the inclusion of additional primaries can reduce the variance between reproduced colors between multiple cameras, referred to here as sensor metamerism.

A separate but related problem this addition of multiprimary LEDs could help solve is the insufficiencies RGB walls face when being used for lighting instead of background simulation [1]. This was not their intended use originally but they prove to be a very flexible option when it comes to creating detailed simulations of light sources in a scene, particularly with glossy or reflective objects. LEDs have narrow wavelength peaks and producing light relatively evenly across the whole spectrum is important for emulating natural or incandescent light sources. Having only three narrow peaks in the red, green, and blue bands leads to deficiencies in the regions in-between like cyan and yellow. In this realm, the introduction of multiprimary LEDs is not a new revelation. Manufacturers of LED-based stage lighting have been adding amber and lime emitters to fill in these gaps, and some lighting-focused LED wall products have introduced white LEDs to fill the spectrum out in-between.

## II. Background

### A. Gamut Expansion

First, it must be affirmed that additional primaries will indeed expand upon what is already displayable with just red, green, and blue pixels. This can be accomplished by measuring the spectrum of each LED using a Photo Research

PR655 spectroradiometer. The device will automatically give the chromaticity coordinate values which will be used to construct gamuts to be compared, however the methodology in obtaining these values will be reviewed. Light is measured at a certain number of wavelength steps across the visible spectrum in terms of luminance. Due to the nature of LEDs, in this circumstance this will produce a fairly parabolic function centered around a certain wavelength peak value. The resulting spectra for each LED will then be multiplied, step-by-step across the wavelength range, by a corresponding color matching function (CMF) - specifically the functions defined in CIE 1931 [2], which are based on experiments that defined the RGB combinations needed to produce a perceptually identical light at that wavelength. CIE 1931 defines three functions that are a linear transformation of the color combination functions found from that experiment: X, Y, and Z. The sum of all of these products for each function will provide individual X, Y, and Z values. This three-dimensional system can be reduced to two dimensions by turning the values into ratios, which effectively removes the dimension that represents intensity:

$$x = \frac{X}{X+Y+Z} \quad (1)$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

x and y represent the resulting chromaticity coordinates that can then be plotted two-dimensionally, where z can be excluded since it's always derivable from x and y. A color gamut in this context is simply the area of a shape defined by vertices whose coordinates are the x and y values obtained from each pixel's diode. All colors represented by chromaticity coordinates inside of this shape can be accurately reproduced by a display with that gamut. The first goal is for new multiprimary pixels to have chromaticity coordinates that fall outside the original gamut, as to increase the total area.

### *B. Pointer's Gamut*

It's not enough to blindly expand the display gamut in any direction. The choice of additional primary needs to be motivated by what the display may actually be tasked with reproducing. There's only a certain set of colors that are encountered in the real world, whether they be produced by natural or biological means or through dyes and paints. While it is true that, in virtual production, LED panels sometimes render scenes that are computer-generated and as such may exhibit colors that aren't typically reproducible by real-world materials, the general intent of in-camera VFX is often to fool the viewer into thinking the background is real and not a display. Therefore, real surface colors are a large focus when it comes to improving display performance. This is where Pointer's Gamut comes in [3].

Pointer's Gamut defines an area inclusive of as many subtractive-based surface colors as possible. Developed by M. R. Pointer, it sources data points from a number of standardized works, including the Munsell Limit Color Cascade, Matte Munsell Atlas, and Royal Horticultural Society Colour Charts. The result is an irregularly-shaped gamut which can be overlaid on display gamuts to check for deficiencies in color reproduction. Regions where Pointer's Gamut is present but the measured LED panel's gamut isn't are of most interest when selecting an additional primary, as ideally an additional primary can expand the LED panel's gamut to encapsulate previously uncovered regions of Pointer's Gamut along one of the three main axes - cyan, yellow, or magenta.

### *C. Delta E Minimization*

With additional primaries outfitted on a panel, even if it's known that once out-of-gamut colors are now reproducible, the color combinations required to produce those colors must still be derived. This will be done through brute-force optimization of color difference with respect to multiple different cinema camera CMFs [4] - namely the Arri Alexa and BMD Ursa Mini Pro G2. By using multiple different "observers" for optimization, and involving observers based off of camera spectral sensitivity, metamerism can be minimized. Metamerism in its typical sense refers to variance in perception of color across multiple human observers. As mentioned in the introduction, the problem in this case is unique in that the "observer" being optimized for is not a human, but rather a cinema camera, whose spectral sensitivity functions are unique compared to those of the human visual system.

The most widely supported way to measure color difference is through CIE's delta E (ΔE*) metric. This requires conversion of measured values into the CIELAB color space which is more perceptually uniform than XYZ. There have been multiple revisions to the ΔE* formula, but the original one from 1976 follows:

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2} \quad (2)$$

Above, $(L^*_1, a^*_1, b^*_1)$ are the color values derived from the sum of the emission spectra of both the original and multiprimary LEDs displaying one of a number of test colors corresponding to those printed on a Macbeth color checker chart, and $(L^*_2, a^*_2, b^*_2)$ are the direct spectral measurements of the patches of those same test colors. Different LED emission spectra are procedurally generated and tested until the ΔE* value reaches a minimum value across all tested CMFs. To be clear, this will be simulated radiometric scalar values (colloquially known as LED brightness or pixel values) being used to produced simulated L*a*b* values that represent real potential brightness values, and every potential combination of scalar values will be checked against a  single computed value obtained from the integral of spectral measurements of the Macbeth chart, the 6500K light source, and multiple different CMFs. Each CMF will produce its own final ΔE* comparison value, and the optimal result is where the maximum of each CMF's ΔE* value is the lowest possible.

## III. Methods

### *A. Hardware*

Four standard RGB LED panels were provided for research by PRG. These were all Everbrighten BR15mm panels, named for their 15.63mm pixel pitch. A pixel pitch this low is atypical for cinema work and generally used for outdoor signage or live event display, and as such the individual pixels were brighter to compensate for the intended surround environment of the outdoors, capable of 5500 nits peak output. However, the large size of each individual pixel would prove to be useful when performing hardware modifications in the future. These panels were outfitted with Nichia NSSM032T LED modules, which are 4.5mm long, 4mm wide, and 2.7mm tall. The modules are 6PLCC, meaning they have six contacts with the board - an anode and a cathode for each diode, with there being one red, one green, and one blue diode. Each panel had a resolution of 64 by 32 pixels, and was composed of 16 submodules each with a resolution of 32 by 4 pixels. Plastic shielding could be removed from the front of each submodule to reveal the PCB underneath, which itself was dipped in a weatherproof coating which could be peeled away for access.

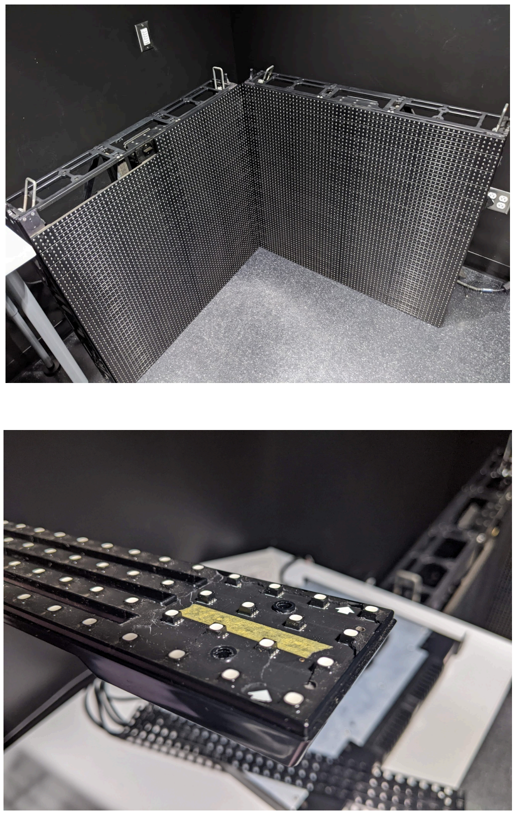


Fig. 1-2 Everbrighten BR15mm panels pictured with one submodule removed in the top left above. Below, The right side of the removed submodule is pictured with its shielding and potting peeled away, revealing the Nichia NSSM032T LED modules and their soldered connection to the PCB.

In order to introduce new multiprimary LEDs to an existing board, a certain number of the original pixels would need to be removed and replaced. It would be ideal to use an LED module with both RGB and multiprimary diodes to allow for all channels to be distributed evenly at all pixel locations, however parts like this aren't typically available for individual purchase and would require extra contacts that the PCB wouldn't have corresponding outputs for. Instead, pixels were replaced in an alternating fashion such that a certain percentage of pixel locations housed multiprimary-only LEDs while the remainder kept the original Nichia RGB modules. When searching for potential candidates to supply the multiprimary light, it had to be made certain that the new pixels would be physically and electrically similar enough to the old ones to be compatible with the PCB. This meant being approximately the same size, having contacts that were spaced out enough horizontally and not too spaced out vertically as to cause a short between diode contacts, and having a similar current draw.

### *B. Primary Selection*

After having already eliminated a large number of LED products to serve as an additional primary based on physical characteristics alone, the colorimetric properties must also be looked at, namely the wavelength peak, width, and luminous intensity. Chromaticity coordinates in XYZ space can be derived by integration with the CIE 1931 CMFs as previously described, as long as the LED product in question provides either a wavelength plot or values for peak wavelength and full width at half maximum, which is the distance across the parabola in terms of wavelength at 50% intensity on both sides.

The actual color of the additional multiprimary pixels were chosen indiscriminately and based solely on percentage expansion of Pointer's Gamut. Some colors were more widely produced and available than others; for example a number of potential candidates in the deep blue or yellow ranges were discovered but cyan and yellow-green options were far more elusive. This could be attributed to manufacturing processes or user needs: almost all green LEDs available had a peak wavelength of 555nm which is also the peak sensitivity of the human eye; additionally due to unknown physical origin there is a gap in efficiency around that wavelength range known as the "green gap," [5] so choosing to manufacture at the perceptually brightest wavelength in the range can help with efficiency. Unfortunately, to actually aid in gamut expansion a wavelength around 20nm higher would be needed, but this niche use case is not well-represented enough to allow for off-the-shelf LED products at the ideal green wavelength to be readily available.

It was decided fairly early on that, because this is merely a proof of concept with limited manpower to carry out hardware modifications, only one additional primary would need to be incorporated. The LED module that most suited both physical and colorimetric needs was decided to be QT-Brightek's QBLP679-YK. This module was similar in size - 5mm by 5mm in area - had the same contact layout as the original Nichia modules, had a similar luminous intensity, and stood outside the gamut of Nichia's RGB diodes. This module had three diodes, like Nichia's, but instead of RGB it was three yellow diodes with two contacts each. The diodes behaved in exactly the same way as they did for the original module; if a solely red signal was passed to it, only the top yellow diode lit up, where the original red diode was. It should be noted that the expected amount of gamut area expansion from this new primary based on wavelength peaks provided in the Nichia and QT-Brightek datasheets was greater than what was actually exhibited based on measurements taken of the pixels installed.

### *C. Fabrication*

It was originally planned to outfit new LED modules over the area of an entire 64 by 32 pixel panel, however the labor needed to do this versus what was available made this infeasible so instead only a single 32 by 4 pixel submodule was fully outfitted and measured. The replacement pattern chosen was every other pixel on every other row, so a quarter of all pixels or 32 total new yellow pixels. Doing it this way provided for an equal number of yellow diodes to red, grene, or blue diodes overall.

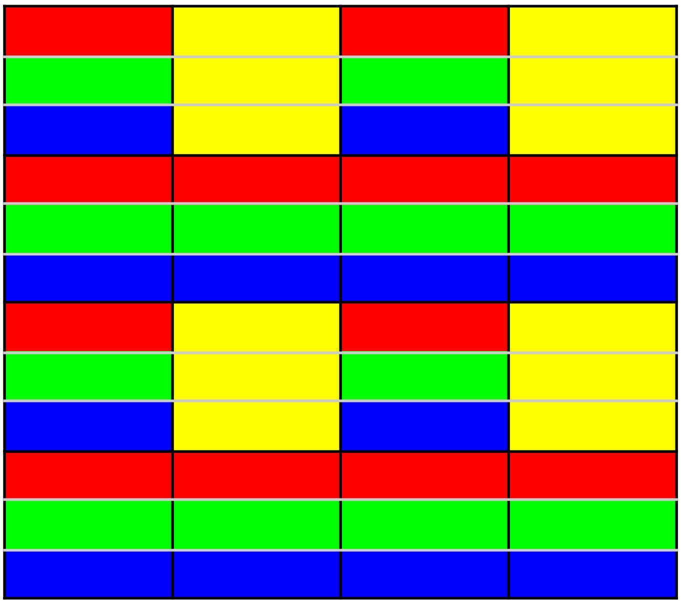
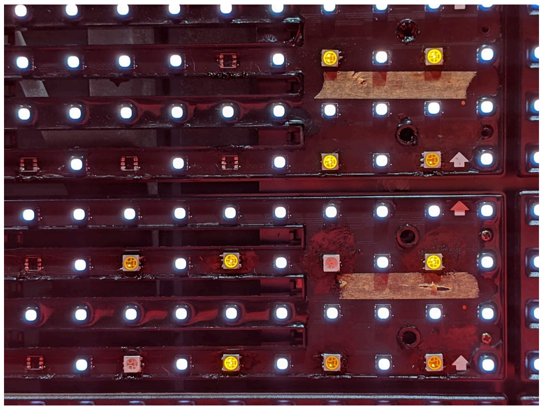


Fig. 3 Diagram of diode layout of a 4 by 4 pixel area of the experimental submodule.

The fabrication process started with unscrewing the submodule from the panel and stripping it from its plastic shielding and silicone potting; the former could just be pried off by hand while the latter could be picked off with a tool like needle nose pliers. This would reveal the pixels' bodies themselves and their connection to the PCB underneath. It was later discovered that the PCB could further be removed from its plastic housing with tweezers which allowed for easier access. From there, the solder connection to each pixel was melted with a heat gun at 400°C for about 30 seconds. A heat gun was used that directed air away from the top of the part to the sides where the actual solder connection was, which prevented the original pixel from melting. Once the original pixel was removed, a flat tipped soldering iron was then used to wipe away excess solder still on the pads of the PCB. Isopropyl alcohol was also used to clean remaining flux. With a clean surface, solder paste was applied to the board contacts in three stages across the submodule and pixels were placed to be reflowed. Because of the slightly larger size of the new pixels compared to the old pixels, special care had to be taken with alignment as the PCB contacts were obscured by the pixel body. After reflow with hot air was performed, a multimeter was used to probe the two contacts for each diode for continuity. If a second diode lit while one was being probed, this would indicate a short which required refitting of that LED. After refitting, the board was reinserted into its plastic housing and reattached to the panel for testing. The shielding and potting were not restored as this panel was no longer expected to be used in an outdoor environment. One of the 32 pixel locations had a torn PCB pad so it remained unpopulated with a yellow pixel.



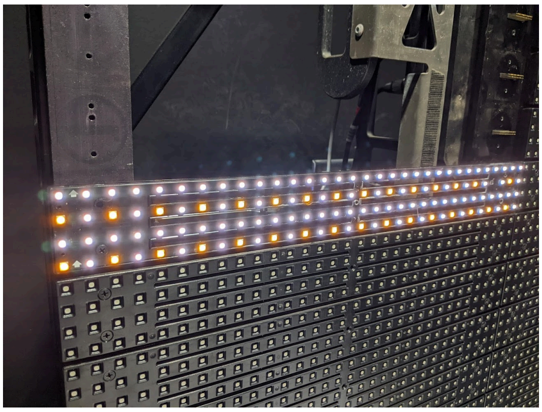


Fig. 4-5 Above, an early attempt at replacing pixels via hand soldering is pictured, which resulted in weak connections and only partial illumination of diodes. Below, the fully outfitted module is pictured displaying a (255,255,255) RGB signal on all pixels.

*D. Measurement*

To obtain the output spectrum of the experimental submodule which would be needed for ΔE* minimization, bitmap images were created to illuminate the red, green, blue, and yellow diodes at full output. Drafting vellum paper was draped in front of the panel for diffusion, and all exterior room lights were turned off for measurement with the PR655. Two measurements of each LED color were taken from around 5 meters away.

## IV. Results

### A. Gamut Coverage

As mentioned previously, the expected increase in coverage from data provided on LED datasheets was greater than what was actually measured, in particular due to a shift upwards on the x axis from the green diode in real life versus what was expected. Expected Pointer's Gamut coverage increased from 92.35% to 96.10%, while measured coverage increased from 96.40% to 96.58%

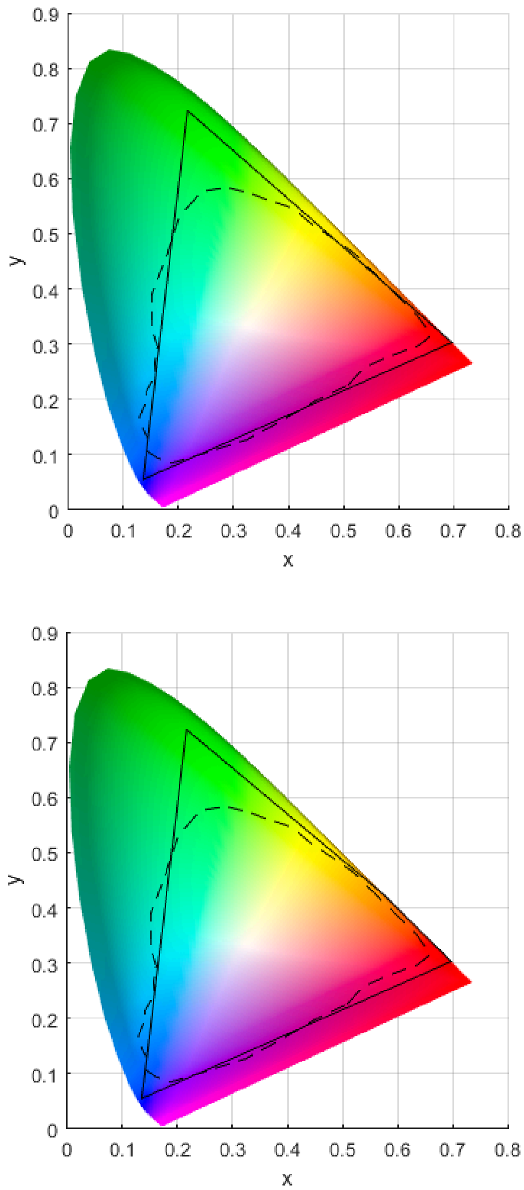



Fig. 6-7 CIE1931 Pointer's Gamut coverage diagrams using measured data. RGB top, RGBY bottom. Dashed line is Pointer's Gamut; solid is the panel display gamut. Notice how the red-green axis intersects Pointer's Gamut in RGB but completely engulfs it in RGBY.

This produces an overall CIE 1931 coverage increase of 0.18% - from 96.40% to 96.58%.

### B. Sensor Metamerism

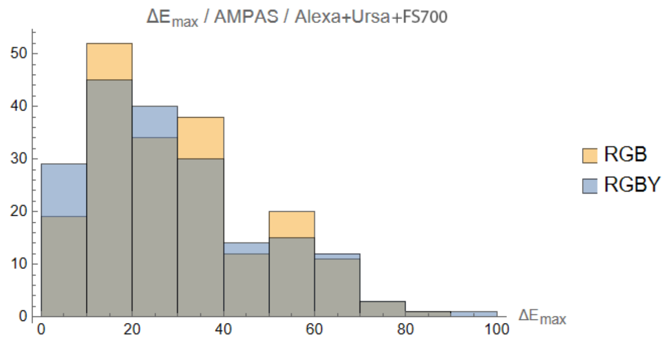



Fig. 8 Histogram comparison of distribution of $\Delta E_{max}$ values with both the RGB and RGBY gamuts of the experimental display.

In the above figure, as previously described, lower $\Delta E_{max}$ values are better. This figure displays the distribution of $\Delta E_{max}$ values optimized for the AMPAS 190-patch set of important surface colors originally derived by Kodak. Color distances are determined between spectral sensitivities for the Arri Alexa, Ursa Mini Pro G2, and Sony FS700 cameras.

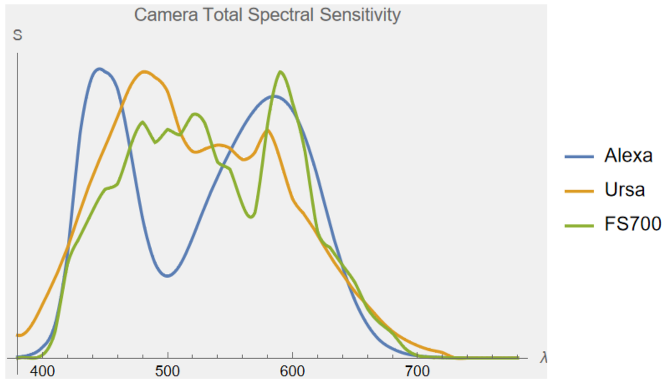



Fig. 9 Spectral sensitivities of the three cinema cameras being optimized to. Note that the provided Alexa spectral sensitivity was pre-calibrated to closely match human color matching functions while the Ursa and FS700 curves are directly from the sensor.

A median value of 26.9094 with 95% confidence intervals of 6.2526 and 60.3514 was calculated with RGB primaries, while a median value of 25.4442 with 95% confidence intervals of 5.2839 and 60.9309 was calculated with RGBY primaries. This is an overall $\Delta E_{max}$ decrease of 5.4%, and provides a P-value of 0.367 which indicates statistically insignificant data.

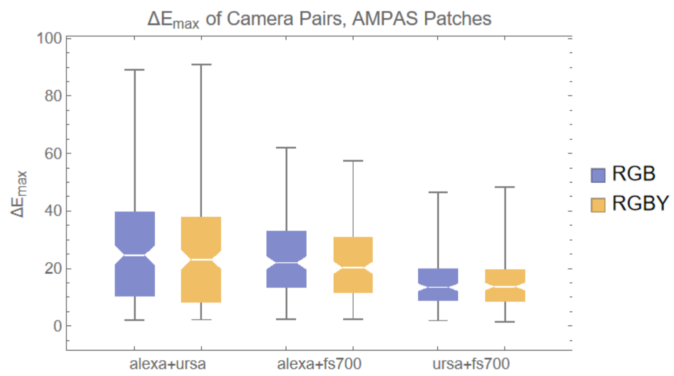
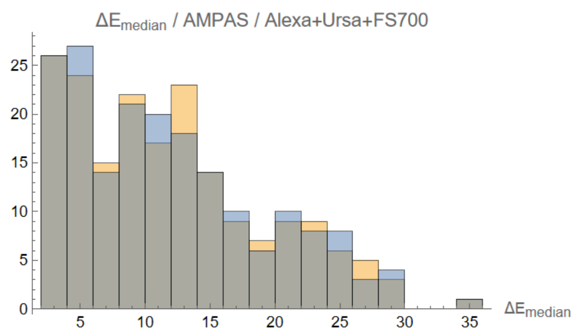
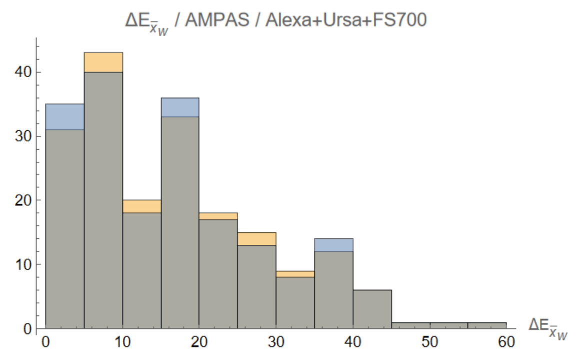



Fig. 10 Box and whiskers plots showing $\Delta E_{max}$ differences between each pair of cinema cameras.

$\Delta E_{max}$ comparisons between each pair of the three cinema cameras indicate the biggest improvement being between the Alexa and FS700 with a 7.79% decrease from 22.0056 to 20.2895, closely followed by the Alexa and Ursa pairing with a 7.52% decrease from 24.9505 to 23.0746. With the Ursa and FS700 there was a 1.96% increase in $\Delta E_{max}$ from 13.4954 to 13.7598, however the P-values for all of these relationships weren't statistically significant with values of 0.33, 0.53, and 0.67 respectively.



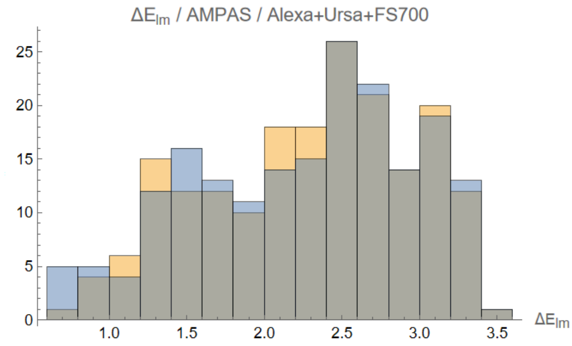




Fig. 11-13 Histogram comparison of distributions of multiple ΔE optimization methods. Fig. 11 is based on median, Fig. 12 is based on winsorized mean, and Fig. 13 is based on log of median.

ΔE optimization methods besides max were also evaluated for thoroughness. Using $\Delta E_{median}$, a 1.5% increase in median from 10.9625 to 11.1285 was observed and was statistically insignificant with a P-value of 0.82. Using $\Delta E_{\bar{x}w}$ or winsorized mean (where outliers are replaced with their next closest data point), a 0.007% increase in median from 15.2145 to 15.2156 was observed which was also statistically insignificant (P-value 0.89). Finally, $\Delta E_{lm}$ or log of median produced a 0.625% increase from 2.394 to 2.409, which was also statistically insignificant with a P-value of 0.82.

### *C. Chromaticity Shift*

The AMPAS patches as they're directly viewed by a human observer as characterized by CIE 1931 under D65 light follows:

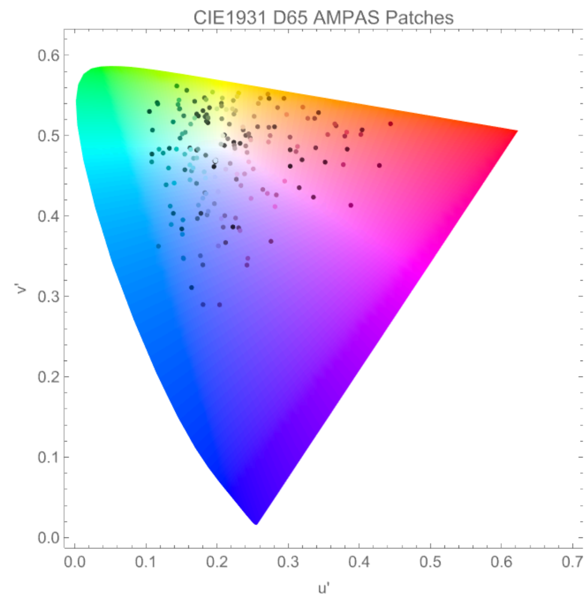



Fig. 14 Graphed in the CIE 1964 color space due to its perceptual uniformity.

These same patches when displayed on the panels being viewed by a human observer characterized by CIE 1931 after $\Delta E_{max}$ three-camera optimization shifts in the following way:

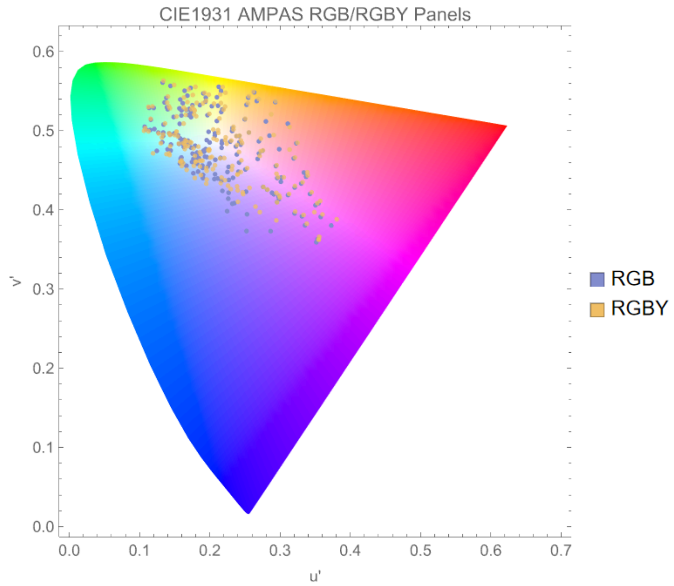
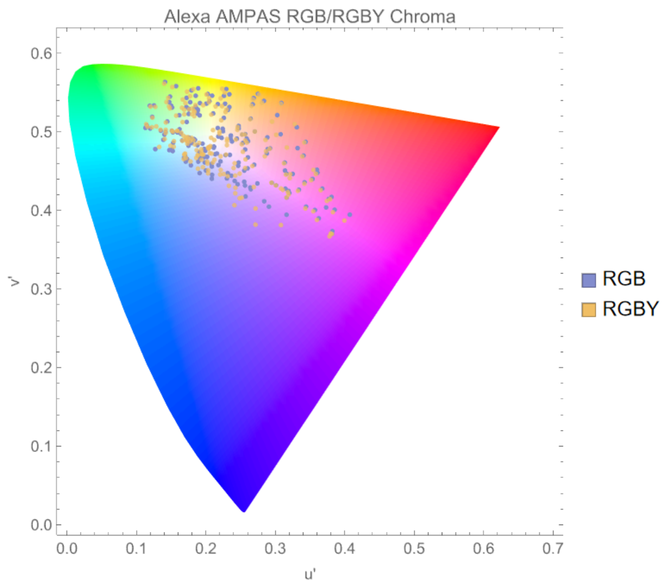
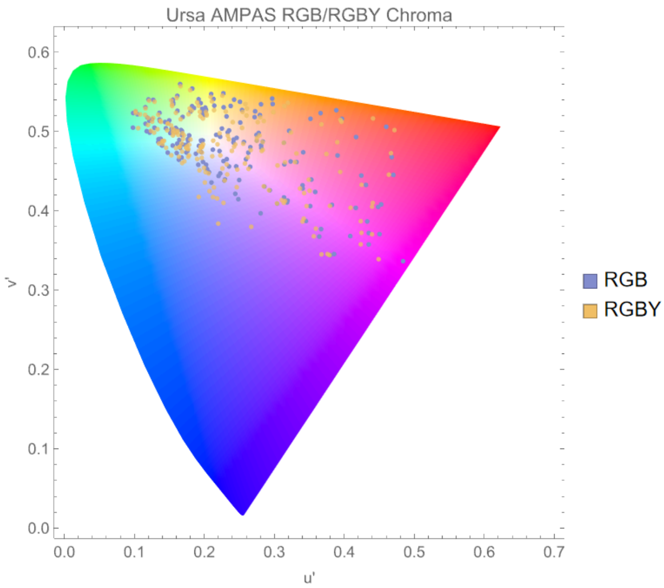



Fig. 14 Chromaticity coordinate shift after camera optimization as a result of incorporating the fourth yellow primary when viewed by a human observer.

If being observed by the three cameras being optimized for instead of a human, the patches then shift in the following three ways:



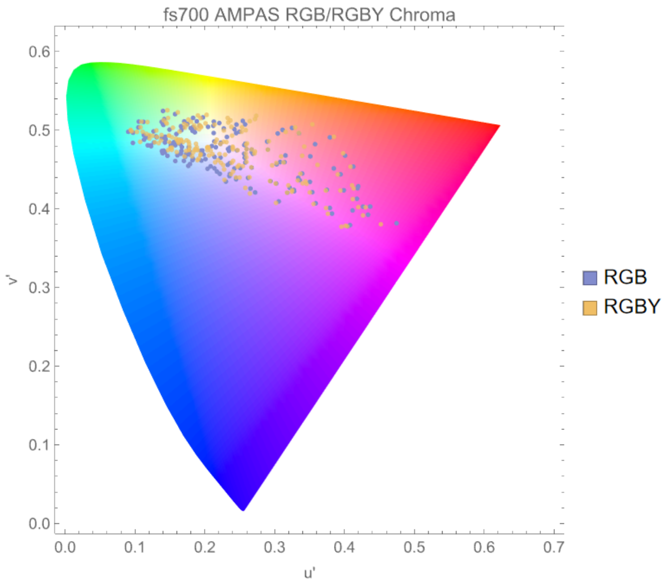




Fig. 15-17 Chromaticity coordinate shift after camera optimization as a result of incorporating the fourth yellow primary when viewed by an Arri Alexa (Fig. 15), an Ursa Mini (Fig. 16), and a Sony FS700 (Fig. 17). Again note that the Alexa spectral sensitivity data used was pre-calibrated to closely fit that of a human observer so the resulting data highly resembles shifts based off of the CIE 1931 standard observer.

Overall, based on the CIE 1931 observer viewing the optimized patchset on the panels, there is a 50.76% loss in gamut area. Adding the yellow primary reduces that loss to 47.21%. Post-optimization, there is a 7.2% increase in reproducible gamut area brought upon by the fourth primary, although the impact taken by the optimization before introduction of this additional primary is already considerable.

## V. Conclusion

### *A. Discussion & Future Work*

The limitations of the experimental setup employed and the duality of the issues addressed here must both be reviewed. Utilizing separate pixel locations for multiprimary colors instead of fabricating a full set of pixels with multiprimary subpixels included was purely a result of hardware availability limitations. For display purposes, this would not be acceptable. For lighting purposes, it could be more feasible, however the benefits of using this type of display for lighting were not quantitatively explored here. Additionally, the method used for sensor metamerism reduction worked based on individually optimizing surface colors and as such only allows for display of certain pre-trained solid color patches. Displaying images with multiple pixel values that span the full range of colors was not an issue addressed here and is also the primary reason LED panels are used instead of traditional lighting methods. In order to do that, an algorithmic approach would need to be taken which has yet to be developed with the same goal in mind of reducing sensor metamerism. The secondary goal of increasing gamut coverage was also only technically achieved, but didn't amount to much quantitatively. This is something that's based purely on what can be physically accomplished by LED manufacturers. As is visible in figures 6 and 7, much of the Pointer's Gamut that isn't reproducible is along the cyan axis. Should a viable cyan primary be introduced to market in the ideal range of chromaticity coordinates, the steps outlined here with a yellow primary could be exactly repeated with cyan or with both cyan and yellow.

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