Optimizing Spectral Color Reproduction in Multiprimary Digital Projection

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Abstract

Multispectral display technology employing more than 3 primaries and utilizing spectral color reproduction image processing rather than traditional trichromatic models is key to expanding color gamut, rendering fully accurate color reproduction and minimizing observer metamerism. In the presented work, two LCD HDTV projectors are modified by optical filtration to generate 6 unique and controllable primary spectra. A full spectral reconstruction model is then proposed and executed for reproducing target color patches under specified illumination. This system is built in an effort to assess the feasibility of simple retrofit strategies for abridged multispectral display from native P3 and sRGB-optimized devices. Due to narrow spectral signatures in each of the LCD-modulated RGB primaries, spectral reconstruction and observer metamerism improvements over a simple 3-primary system are negligible. Significant improvements, however, are simulated by optimization of ideal primary spectra for specific target sets, providing basis for future system refinement. Also concerning in the constructed system are inherent spatial non-uniformities, scene-dependent flare characteristics and long-term colorimetric drift that pose several engineering challenges for a fully functional system.

Introduction

Traditional image display paradigms for both still and motion picture applications are rooted in a 3-primary metameric match model relying exclusively on Grassmann's laws of additivity and the fundamental quantal catch treatment of the human visual system. Color-matching functions are employed to spectrally integrate visual stimuli, simplifying the higher order complexity of real radiometric distributions from scene colors and enabling accurate reproduction via finite scaled outputs in just a small number of primary channels. Problems in this model, though, may be encountered with restrictions to color gamut and spectral accuracy and with limitations from observer metamerism. In the former, fully characterized scene content may constitute a reproduction stimuli outside the capabilities of the traditional limited primary display device. In the latter, controlled metameric matches of color within the display for a single observer may prove to not be matches for another observer with slightly different color-matching functions.

The solution to these problems lies, in part, in generating a full spectrum-based reproduction environment. In the ideal case, narrow bandpass, high spectral resolution primary sets would be conceived to accomplish the goals of controllable spectral reproduction of target stimuli. By combining near monochromatic primaries at a high sample rate across the visible electromagnetic spectrum, many sufficiently complex stimuli could be rigorously rendered. In a practical sense, however, an abridged spectral reproduction model makes more sense in both hardware design and image processing complexity, employing superimposed images from two or more traditional 3-primary projection devices whose individual primary spectra are purposefully optimized.

For this work, two LCD digital projectors are used to prove the feasibility of constructing an abridged spectral reproduction display environment from P3 digital cinema-based displays. Native primary spectra from each device are modified by way of optical filtration to generate as many as 6 unique and controllable projection primaries. By careful characterization of the projectors and optimization of primary drive amounts, spectral reconstruction of simple color patch targets is achievable with the proposed system.

Background and Theory

Traditionally, additive electronic displays are well represented by a gain-offset-gamma (GOG) or gain-offset-gamma-offset (GOGO) model as summarized by Day, et al., to relate device drive value in each channel (analog voltage or digital drive value for example) to a radiometric scalar of the maximum channel output spectrum [1]. Via primary rotation to CIE tristimulus amounts, these scalars can further predict reproduced colorimetry in a metameric reproduction model.

Owing to natural variations in ocular media transmission, photoreceptor spectral sensitivities and post-retinal mechanisms, any population of human observers will comprise a disparate set of color matching functions. Further, even single observers experience an alteration of their color matching functions with age and field of view [2]. As such, a metameric reproduction for the 1931 2° standard observer does not guarantee a similar match for any real observer [3]. For emissive displays, the only sure way to avoid all observer metamerism failure is to produce a multiprimary spectral reconstruction of the target object stimuli [4,5]. Much of the historical work progressing multiprimary display development has been promoted in the context of general gamut expansion beyond traditional 3-primary limitations with ancillary benefit to the observer metamerism problem [6,7,8]. However, Hill has specifically shown how multispectral display signal mapping may be algorithmically optimized to limit observer metamerism when there are limitations on fully accurate spectral reconstruction [9].

A rigorous multispectral reproduction system would require a narrow band primary for each level of granularity within the desired visible spectrum. This type of system is largely impractical for typical image capture, processing and reproduction workflows and so an alternative abridged spectral reproduction system will be investigated instead. Analogous abridged multispectral reproduction systems have proven successful in generating reasonable spectrum reconstruction in the fields of digital image capture and multi-ink inkjet printing [10,11,12]. In these applications a co-optimization of spectral accuracy and reduced illuminant and/or observer metamerism performance is often employed. Abridged filter-based approaches have also been used extensively in low-end spectrometers and colorimeters. Yamaguchi, et al. have demonstrated an end-to-end multispectral capture and display system employing a 16-channel digital camera and 6-channel projection display, complete with models for data management and transmission in an ICC-analogous workflow [13]. Several attempts have also been made to adapt the techniques to real-time video workflows for motion imaging applications [14].

The current work serves to explore primary spectra optimization for a 6-band display system employing available consumer LCD HDTV projectors having native primary spectra consistent with a P3 or sRGB gamut. Two projectors will be characterized and their primary spectra modified by the addition of ancillary color filters. With the proper filters, the spectral peaks of the projectors should prove separable enough to yield 6 independent color channels, appropriate for generating spectral matches to reasonably well-behaved aim spectra.

Once the projectors are appropriately characterized, a basic spectral reconstruction model can be built for the 6-channel system via equation 1 (which includes baseline black signatures for each device as well). Taking advantage of presumed primary stability in a well-behaved additive system, equation 1 can be further expanded to equation 2 where the characteristic primary spectra, $SPD(\lambda)_{i\_max}$, are the absolute radiometric measures of the maximally driven primary in each projector and for each channel. Relative radiometric primary amounts in the full summation are generalized by the scaling constants, **k** (1x6 vector for the proposed system), which are analogous quantities to *RGB* radiometric scalars in the Day et al. model but defined more generically for multi-channel systems with more than 3 controllable primaries.

$$\begin{aligned} SPD(\lambda)_{mix} &= SPD(\lambda)_{r,A} + SPD(\lambda)_{r,B} + SPD(\lambda)_{g,A} + SPD(\lambda)_{g,B} \\ &+ SPD(\lambda)_{b,A} + SPD(\lambda)_{b,B} + SPD(\lambda)_{k,A} + SPD(\lambda)_{k,B} \end{aligned} \tag{1}$$

$$SPD(\lambda)_{mix} = \begin{bmatrix} \mathbf{k} & 1 & 1 \end{bmatrix} \begin{bmatrix} SPD(\lambda)_{r\_\max,A} \\ SPD(\lambda)_{r\_\max,B} \\ SPD(\lambda)_{g\_\max,A} \\ SPD(\lambda)_{g\_\max,B} \\ SPD(\lambda)_{b\_\max,A} \\ SPD(\lambda)_{b\_\max,B} \\ SPD(\lambda)_{k,A} \\ SPD(\lambda)_{k,B} \end{bmatrix} \tag{2}$$

Typically, aim spectra will be presented as an objective goal for the multiprimary display system and as such, an optimization approach can be used to determine theoretical scalars, **k**, needed to reproduce any target (recognizing that there are limitations on the amplitude of each term within **k**). Unlike typical reflectance space spectral reconstruction modeling performed by Wyble, et al. on inkjet systems [11], emissive spectral reproduction demands consideration of absolute radiometric output, especially when accounting for the superposition of the two distinct projector optical paths. A relative shift in the absolute white luminance of one projector versus the other can lead to degraded spectral output quality through the full model. Further, a spectral aim set that demands more flux than the total system is capable of from any single channel likewise limits the optimized performance.

k scalars from equation 2 may be derived for any aim spectra set utilizing appropriate constrained nonlinear optimization. For best results, a spectral/colorimetric co-optimization is desirable. The spectral reconstruction system proposed in this work offers 6 distinct primary spectra and is thus capable of infinite combinations of output for achieving standard colorimetric matches to the aim spectra. Several potential techniques are available for this task including 2-stage co-optimization wherein an initial spectral optimization provides **k** inputs to a colorimetric refinement or matrix-switching approaches focused on optimizing colorimetric processing efficiency for real-time video sequences at the expense of spectral accuracy [15]. Further, full Lagrange multiplier-based spectral/colorimetric co-optimizations that potentially bypass the computational overhead of nonlinear optimization are also proposed in previous work [16].

Experimental

To generate 6 superimposed channels of color for spectral reconstruction, twin Panasonic PTAX200U LCD projectors capable of 1920x1080 resolution from a 3-chip RGB configuration were used (noted here forward as Projector A and Projector B). Each projector was driven natively in 8bits. Prior to use and measurement, the projectors were allowed a 30-minute warm-up time. For tests in which both projector outputs were superimposed, a vertical stack rig was used to overlap both images.

Spectra and colorimetry from projected patches on each device were obtained via a Photo Research PR655 spectroradiometer. Color patches were generated for neutral, red, green and blue ramps as well as for two series of 5x5x5 factorial color channel combinations, one across the full 8bit domain and one concentrated at lower drive values. The patches were sized to 400 pixels square and the remainder of the screen was set to black.

Results and Discussion

Display Characterization

Neutral scale additivity in luminance across the full display dynamic range of Projector A is provided in Figure 1. The device delivers excellent additivity for the sum of the individually measured primaries as compared to the neutral ramp. In fact, it appears it is only the fully driven white where differences are greater than 1.0%. Projector B shows similar results.

To evaluate display scalability, black-corrected chromaticity coordinates for each of the primary ramps for Projector A are shown in Figure 2. The overall gamut of Projector A is consistent with the digital cinema P3 standard and Projector B is, again, similar.

Using the full collection of patch measurements and the Day et al. optimization scheme, the primary colorimetric rotation matrix for each projector and display radiometric scalar LUTs were computed for inclusion in the rigorous spectral models.

Spatial uniformity in the projectors was determined by driving white patches against a black background in symmetrical positions throughout the full screen area. Maximum luminance fall-off from screen center to corner was 20.6%. For higher end theatrical

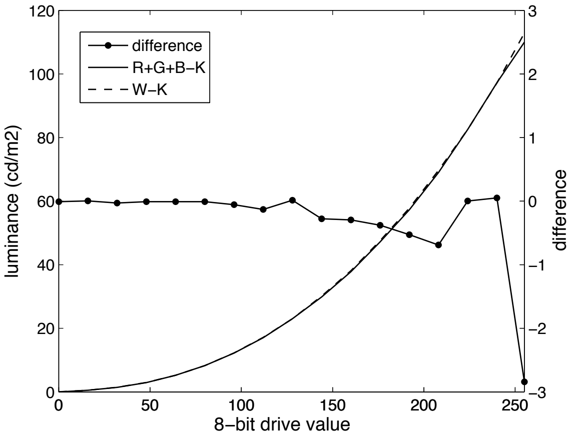

***Figure 1.** Full grayscale additivity test results for Projector A, showing summed luminance of RGB primary ramps versus luminance of neutral scale ramp (offset black luminance subtracted out)*

projection, the Society of Motion Picture and Television Engineers (SMPTE) demands screen luminances fall to no more than 75% of the center luminance in any portion of the image area. Further, white point chromaticity is permitted to drift from the center reading by as much as 0.015. Thus while presenting some level of concern for more serious color simulation, the projectors lie within acceptable tolerances for even high-end theatrical viewing. For a superimposed multispectral projection system, these variations must be compensated as luminance and chromaticity non-uniformities will render localized variation in the mixing model needed to produce aim spectral color reproduction.

Spatial independence was analyzed for the projectors to assess how color patches generated in the middle of the image area might vary in measurement when presented against differently colored backgrounds. Darker patches proved most influenced by the variation in background color, suggesting the majority of the differences can be attributed to optical flare. The overall magnitude of these errors is visually significant, further complicating the utility of the projectors for serious color simulation work. Overall, results of these tests are far inferior to those measured on high-end emissive LCD panels by Day et al. [1], not surprising considering the increased optical complexity and raised light management challenges of a 3-chip projection architecture.

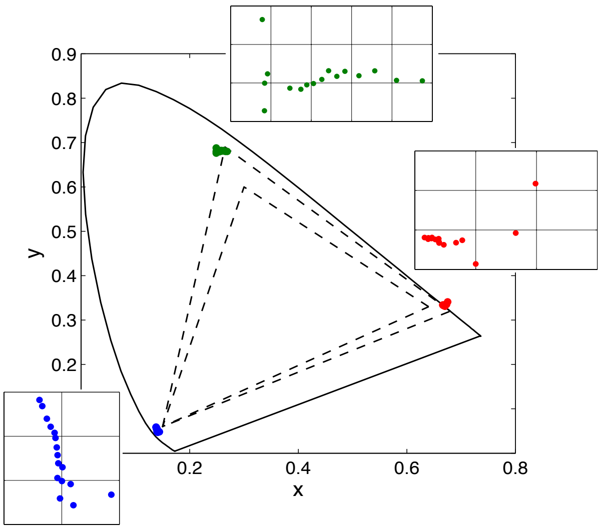

***Figure 2.** Primary ramp scalability test results for Projector A in 1931 x,y chromaticity, offset black level subtracted out; smaller triangle shown is ITU Rec. 709 (sRGB) primary gamut; larger is digital cinema P3 gamut; grid division in call-out figures is 0.005 chromaticity units*

Verification and Long-term Stability

Characterizing the radiometric performance of the LCD projectors in a single stable experimental exercise is only useful for interpreting color reproduction models for the devices in a finite window of time beyond the characterization. Extending the utility of models over longer operational periods is only possible if the projectors themselves are consistent in performance. An extensive verification experiment was executed for each projector over a 4-month period. The maximum output luminance and white chromaticity of the projectors were measured periodically over a span encompassing 211 lamp hours for Projector A and 82 lamp hours for Projector B. Figures 3 and 4 summarize the results gathered. Projector A loses 18% of its peak output after 50 hours and 38% after 200 hours. Projector B shows similar trending though results were not collected over as long a lamp life. In terms of white point chromaticity stability, both projectors likewise exhibited a drift with Projector A trending slightly green-cyan and Projector B trending yellow.

To assess the consistency of the optimized color reproduction models derived for each projector at each point in the 4-month study, a set of 11 color patches were driven to each device and measured during the sampling sessions. Mean and maximum ΔE_{00} values for the actual measurements versus the radiometric model predictions were tallied for each trial. Figure 5 shows the trend of mean ΔE_{00} for each projector over time. Versus the baseline starting error of approximately 0.6, projector A drifted to greater than 2.0 average color difference by 200 hours.

Primary Characterization

Principal components analysis was employed to determine the major eigenvectors in the primary spectra for each color channel and for each projector independently. The first eigenvectors in each channel, normalized to a peak of 1.0, are shown in Figure 6. For Projector A, these eigenvectors account for 99.96%, 99.93% and 99.90% of the total spectral variability in red, green and blue. For Projector B, the eigenvalues are 99.97%, 99.94% and 99.93%. Though primaries found in many LCD-based displays can be quite variable across the full system dynamic range, the stability of the Panasonic primaries here is excellent.

Filter Selection Models

Ideal filters for modifying native spectra in this application will employ a narrow notch characteristic in at least one strategic spectral location that would impact the normalized peak position of 1 or 2 of the original primary spectra without distorting the other channel(s). Candidate filters for the proposed system were evaluated through a full spectral reconstruction model. The first

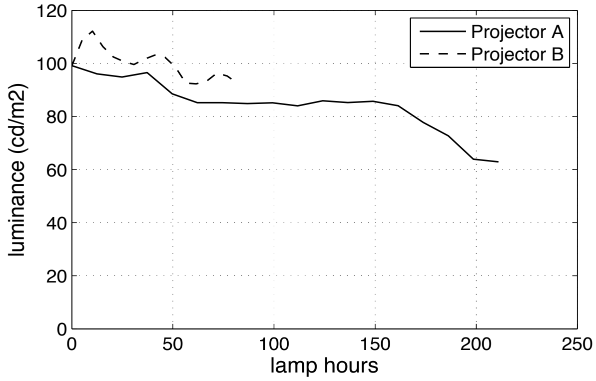

Figure 3. *Full-on white luminance stability*

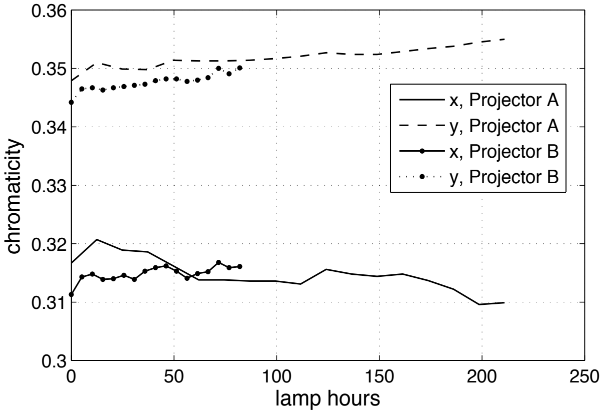

Figure 4. *Full-on white chromaticity stability*

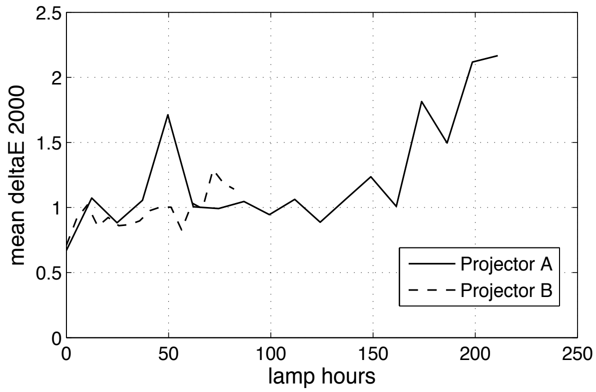

Figure 5. *Optimized model prediction stability*

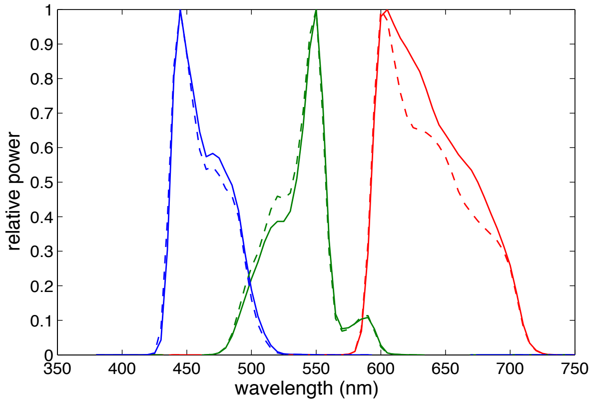

Figure 6. *First eigenvectors from RGB primary series for Projectors A (solid) and B (dashed), normalized to 1.0 peak*

criterion assessed was total luminance loss expected by inclusion of the filters. In Figure 7, the absolute radiometric summation of the maximum driven primaries are shown for the native system. Also summarized are the predicted absolute spectra and individual attenuated spectra for a system comprising Schott UG5 1mm glass over Projector A and Schott GG455 1mm glass over Projector B. Finally shown are the aim white spectra representing the white MacBeth color checker target patch illuminated by a CIE D65 illuminant and the spectral reconstruction match for this system, achieved following a minimization of spectral rms error using equation 2. **k** scalar amounts derived from the reconstruction optimization are shown in the legend of this subplot. For this combination the relative spectral rms error is 0.36 and the ΔE_{00} (D65-illuminated MacBeth white patch, 1931 2° observer) is 8.5.

Figure 8 summarizes the results of matching the D65-illuminated MacBeth Color Checker white patch with a goal of minimizing ΔE_{00} and using the previously determined **k** scalars from the spectral rms minimization as starting guess in a constrained optimization. Radiometric scalars were restricted to a physically realizable maximum value of 1.0 but allowed to vary as much as needed from the spectrally optimized starting point to achieve the colorimetric match. As expected, the color difference error is easily nulled altogether with superfluous degrees of freedom but at the expense of the relative spectral rms error which has risen from 0.36 to 0.40. The visual match of the two spectra remains poor for not only the white but all 24 MacBeth patches (not shown). Table 1 summarizes the quality of spectral reconstruction for the MacBeth patches for this modeled system as well as a number of other notable projector filter combinations investigated. As evidence of the limitations in effective manipulation of the original projector spectra, many of the combinations perform only marginally better than the native system without any added filtration (first row, Table 1).

Actual Filter Characterizations

A real system incorporating a Schott GG455 glass filter over Projector A and a UG5 filter over Projector B was constructed to assess actual system performance. Expected results for the dual projection system were simulated from real device primary measurements and are shown in Table 2. Variations here summarize expected spectral and colorimetric matches for 4 different spectra/colorimetry co-optimization constraints – specifically, the original spectrally-optimized **k** scalars are held to within 10%, 20%, 30% or no constraint for predicting the optimal co-optimization **k** values. As the constraint is tightened, perfect colorimetric matches for all patches are not possible and the mean and maximum color difference predictions versus aim increase from 0. Results for the actual filter model with no constraints compare favorably with the results of Table 1. For the 10% constraint, however, the rms advantage gained (12% improvement in mean rms error) comes at the cost of an average ΔE_{00} of 2.4.

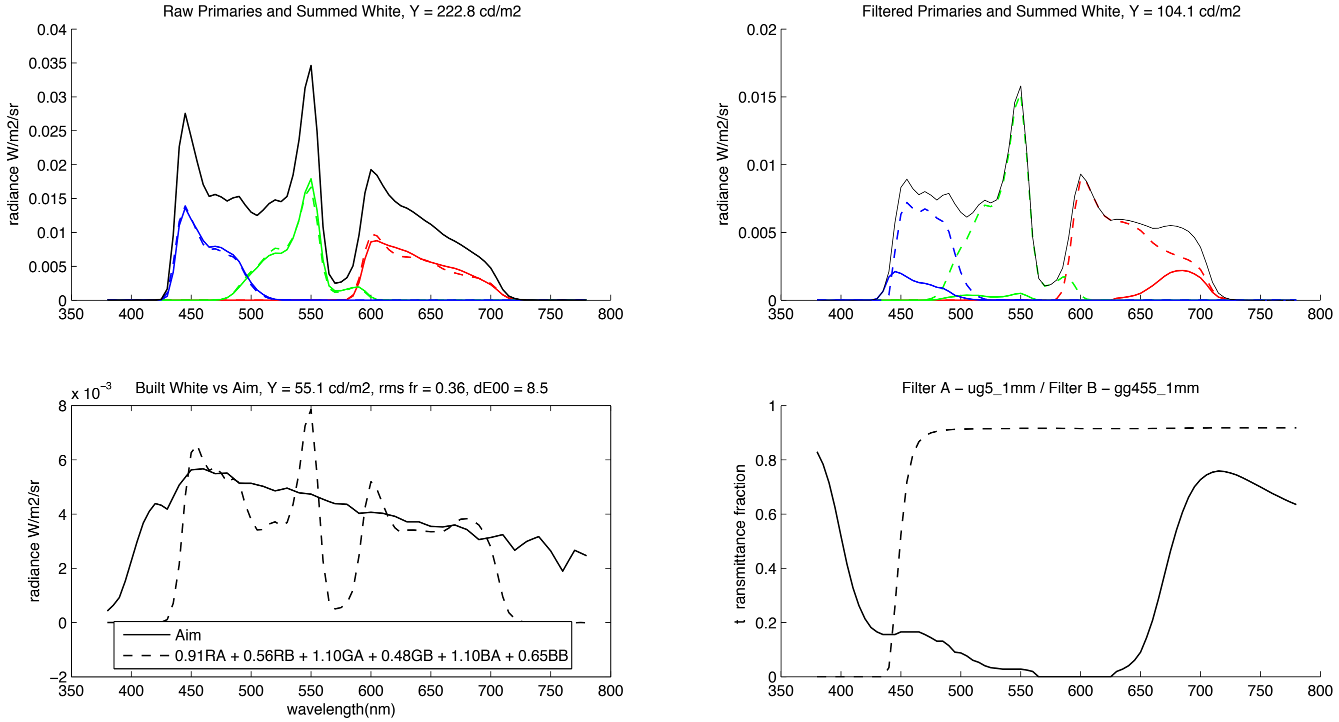

Figure 7. *Model of Schott UG5, 1mm and GG455, 1mm glass in spectral projection system – (upper left) PCA modeled maximum spectra for each projector; (upper right) predicted primary spectra attenuated by inclusion of filters; (lower left) modeled spectral reconstruction of MacBeth white under D65; (lower right) Schott filter transmission spectra*

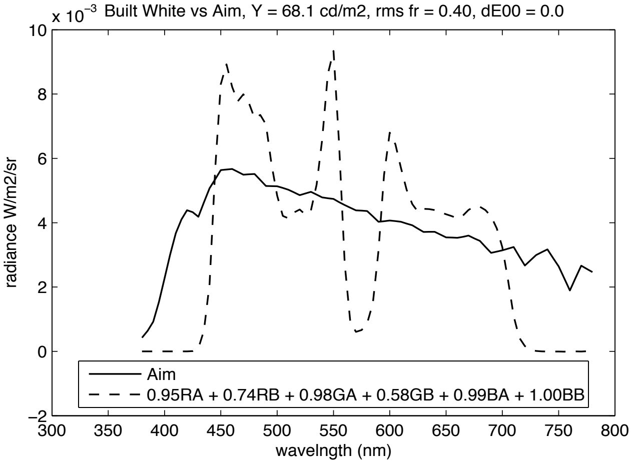

Figure 8. *Model of Schott UG5, 1mm and GG455, 1mm glass in spectral projection system – predicted reproduction of MacBeth white patch under D65 from colorimetric optimization*

Observer Metamerism

Ultimately, success in generating spectral matches of target stimuli using the dual projection system would be best judged by characterizing observer metamerism. Failures to achieve a precise spectral match in the abridged system studied are clearly evident in Figures 7 and 8. And so progress in the design approach and in the system model towards the ultimate goal of this work may be illustrated through improvement in observer metamerism.

Fairchild, et al. have documented a methodology used to evaluate observer metamerism in additive electronic displays employing the CIE 2006 color-matching function models for observers of varying ages and subtending various angular fields of view [17]. Primary drive amounts needed to enforce a metameric match between aim spectra and the multiprimary reproduction are calculated using a chosen CIE 2006 color-matching function. Once matched for that particular observer, the resultant modeled spectra of each system are assessed for subsequent colorimetric match assuming the 1931 2° standard observer and resulting color difference values are tallied.

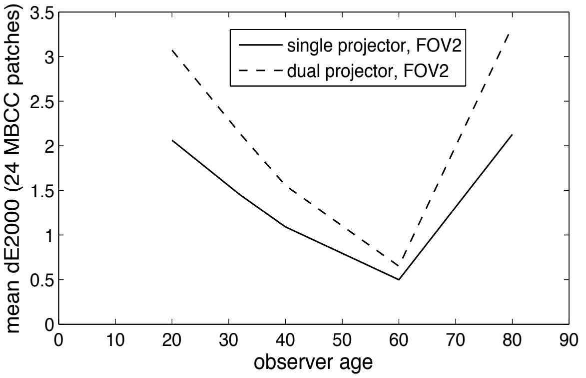

Figure 9. *Color difference summary for 1931 2° observer after generating metameric matches in projection to D65-illuminated MacBeth color checker patches for CIE2006 observers of ages 20, 32, 40, 60 and 80 at 2° fov, single projector vs GG455/UG5 system*

Table 1. D65-illuminated MacBeth CC spectral reconstruction for various filter combinations from Schott and Semrock on native projectors, derived from manufacturer's filter data and PCA-characterized projector primaries

		Spectral RMS optimization only (24 patches)				RMS/DE2000 co-optimization	
Filter A	Filter B	mean rms	max rms	mean dE00	max dE00	mean rms	max rms
none	none	0.14	0.34	6.0	10.0	0.15	0.36
BG1(1mm)	GG10(1mm)	0.12	0.31	4.6	7.1	0.14	0.35
BG24(1mm)	GG10(1mm)	0.11	0.31	5.0	8.2	0.13	0.35
BG28(1mm)	OG570(1mm)	0.13	0.32	4.9	9.8	0.14	0.34
BG7(1mm)	BG36(1mm)	0.14	0.34	5.9	12.3	0.18	0.51
BG7(1mm)	OG570(1mm)	0.13	0.32	5.0	8.8	0.14	0.33
DI01_488_532_638	none	0.14	0.33	4.9	8.2	0.17	0.38
FF01_510_42	none	0.13	0.32	4.5	7.4	0.15	0.35
UG5(1mm)	GG455(1mm)	0.12	0.32	5.0	8.8	0.14	0.38
GG475(1mm)	FF660	0.12	0.33	5.1	7.3	0.15	0.36

Table 2. Predicted spectral reconstruction model performance for GG455/UG5 projection system implementing spectral rms and ΔE_{00} co-optimization

mean rms	max rms	mean dE00	max dE00	k constraint
0.135	0.372	0.0	0.0	none
0.131	0.350	0.2	1.8	30%
0.126	0.333	0.7	2.6	20%
0.119	0.324	2.4	4.9	10%

Table 3. Optimized Gaussian Primary Parameters

	B 1	B 2	G 1	G 2	R 1	R 2
μ	425	473	524	576	624	687
σ	23.1	26.4	24.2	27.7	20.6	43.2

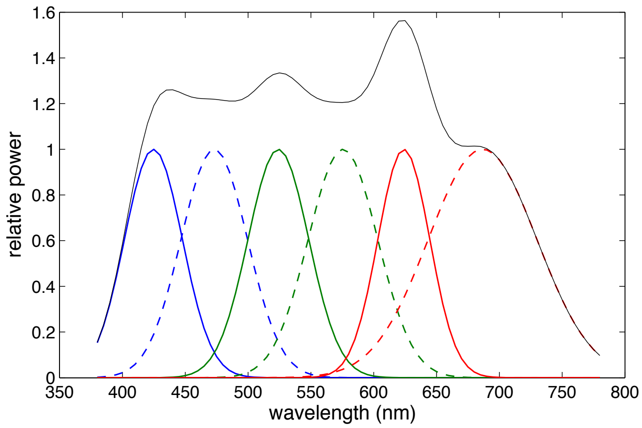

***Figure 10**. Optimized Gaussian primaries*

For the present work, spectral/colorimetric co-optimization is performed based on CIE 2006 color-matching function sets incorporating observer ages of 20, 32, 40, 60 and 80 all at a 2° field of view. Results reported here are for the "no constraint" co-optimization method to provide the best possible observer metamerism results for each scenario.

The GG455/UG5 dual projector system described thus far is compared for observer metamerism performance versus a model incorporating only a single projector. Mean ΔE_{00} (1931 2°) for the 24 patches as a function of metameric-match age for each system are compared in Figure 9. Clearly, the 6-channel dual projection system fails to deliver any benefit for observer metamerism versus the native performance of projector A alone. This likely stems from the fact that though 6 channels are provided in the dual projection system, each primary spectral peak is notably narrower than that found in the native single projector and thus large first derivative variations in spectral reconstruction plague the colorimetric sensitivity of the observer metamerism approach.

With the less than ideal results determined for the actual GG455/UG5 projection system, attention is turned to alternate primary spectra that may perform better. A candidate set of Gaussian primaries was investigated to see if mathematically simplified spectra could yield improved matches in 6 channels versus the narrow native primary reconstruction of the Panasonic projectors. The spectral rms error optimization model was invoked to generate ideal spectral matches to a subset of the MacBeth patches: light skin, red, green, blue, cyan, magenta, yellow and white. Independent variables in the optimization were the 6 Gaussian peak wavelengths, μ_i, and the 6 standard deviations (peak widths), σ_i. Table 3 summarizes parameters for the optimized primaries and Figure 10 shows the individual and summed spectra. Generating a full spectral/colorimetric co-optimization of the D65-illuminated MacBeth patches via these primaries, the mean and maximum rms spectral fraction values were lowered significantly to 0.02 and 0.05 respectively. The maximum co-optimized ΔE_{00} value was 0.02. Further, colorimetric optimization alterations to **k** were restricted to 10% deviation from original spectral optimizations with no issue in achieving near 0 metameric matches across all the patches. Spectral matches for all 24 patches are shown in Figure 11. For the observer metamerism models, the results are similarly impressive. Figure 12 shows benefits gained in various observer ages versus the single 3-primary projector.

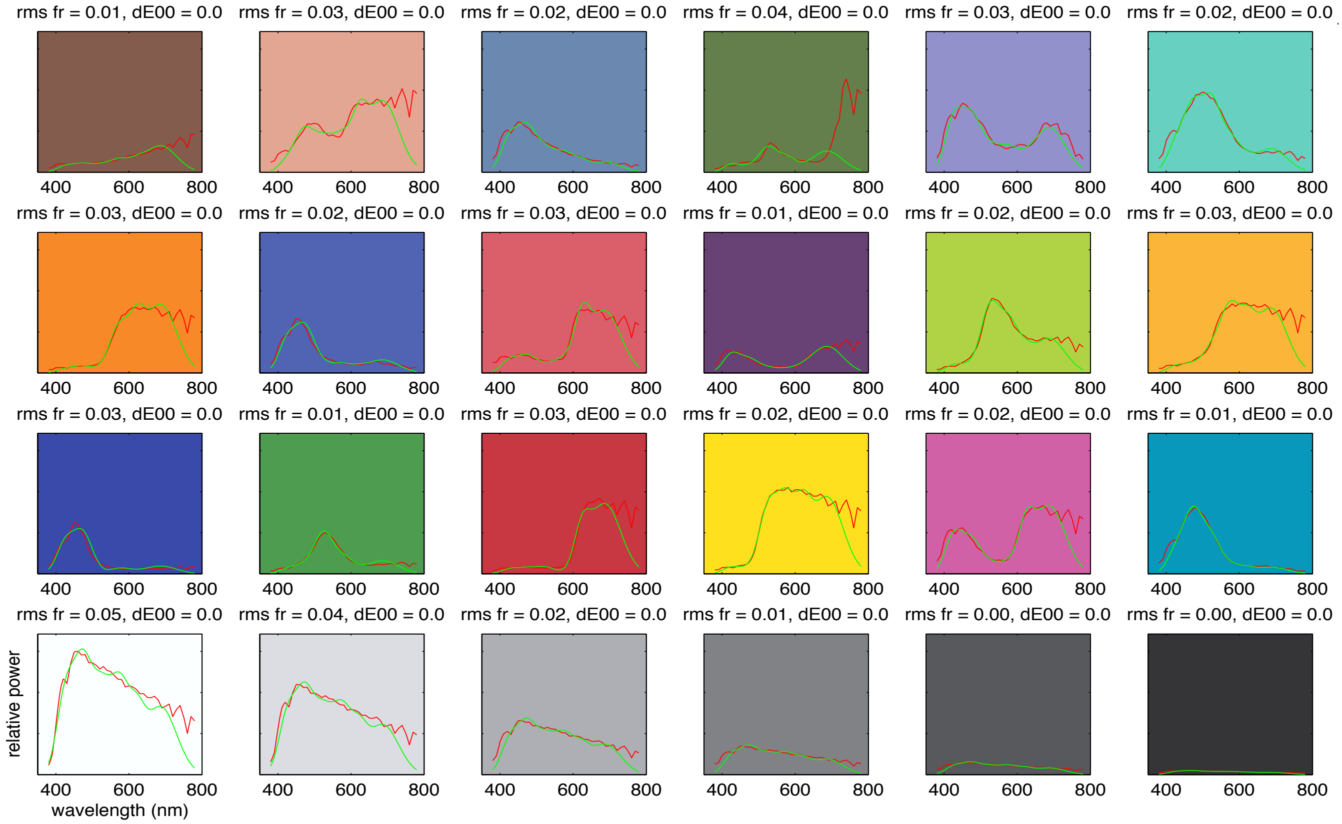

Figure 11. *Ideal Gaussian primary 6-channel spectral reconstructions after spectral and colorimetric co-optimization*

Conclusions

Abridged multispectral projection shows promise for reducing observer metamerism and expanding spectral gamut reproduction; however, the current generation of native wide-gamut LCD, DLP and laser projection technologies provides limited flexibility based on techniques utilizing external optical filtration. Improved performance is realized when narrow band native primary spectra can be removed and idealized primary spectra inserted instead.

Beyond primary spectra optimization, additional engineering concerns around display uniformity, spatial independence and long-term colorimetric drift must be addressed to make these techniques viable.

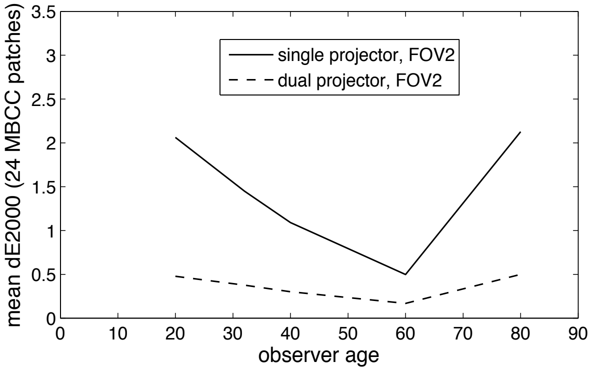

Figure 12. *Observer metamerism summary; single projection model vs ideal Gaussian dual projection model*

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Biography

David Long joined the faculty of the School of Film and Animation at Rochester Institute of Technology in 2007, where he is currently Program Chair and Assistant Professor for the BS Motion Picture Science program.

Previous to RIT, Long worked as a Development Engineer and Imaging Scientist with Kodak's Entertainment Imaging Division. At Kodak, his primary responsibilities included new product development, image science and systems integration for the motion picture group, focusing on film and hybrid imaging products.

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