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Improving Color Accuracy When Imaging Cultural Heritage Using a Bi-Color LED Source

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Abstract
Cultural-heritage imaging is critical to preserving the world's treasures. This field is so demanding of color accuracy that the inherent limitations of RGB imaging can often be an issue. Various imaging systems of increasing complexity have been proposed, up to and including those that report full spectral reflectance for each pixel. These systems can improve color accuracy, but their complexity and slow operational speed hamper their widespread use in this field. A simpler and faster bi-color lighting and dual-RGB processing system is proposed that improves the color accuracy of verification targets. The system can be used with any off-the-shelf RGB camera, including prosumer models.

Introduction
Cultural-heritage imaging is a critical aspect of the efforts to preserve world treasures. This field is so demanding of color accuracy that the inherent limitations of RGB imaging can often be an issue. There are three general approaches to overcome these limitations: improving sensor design, multispectral capture, and full-spectrum capture.

An early commercial system was the IBM Pro/3000. The usual RGB scanback was replaced with a monochrome scanback and custom RGB filters that approximated the human visual system, and tungsten lighting. This system was used at the National Gallery of Art in Washington DC and the Vatican [1]. Nonetheless, it was not widely adopted despite its superior color compared with contemporary RGB scanbacks. Cost and proprietary encoding were limiting factors.

An approach that can achieve accurate color for all materials is visible spectrum imaging. The spectra are used to calculate CIE tristimulus values that are encoded in a known color space such as Adobe RGB or ProPhoto RGB. There is a tradeoff between spectral and spatial resolution. The Surface Optics SOC760 hyperspectral imaging system captures 650 spectral images (bands), each with spatial resolution of 640 x 2048 pixels (1.3 MP). Using this system for archiving requires a motorized easel and considerable time per object. The Phase One Rainbow multispectral system captures 16 spectral images, each with a spatial resolution to 14204 x 10652 pixels (150 MP monochrome sensor). These types of systems also have not seen wide acceptance, limited by cost, complexity, and poor productivity.

Imai and Berns pioneered an intermediate approach where two different light sources were combined with an RGB system producing six channels (from two captures), known as dual-RGB imaging [2–4]. Profiling combined the image pair into a single color-accurate image. The specific camera defined spatial resolution. Their first experiments used the IBM Pro/3000 and a blue Wratten filter for the second capture. The two sources were tungsten and daylight.

The system evolved to the use of a single white light, an RGB area-array sensor with extended sensitivity (by removing the IR cut filter), and cyan and yellow absorption filters, each glued to a visible bandpass filter. Prototype systems were built using Phase One and Canon cameras with a filter wheel attached to the front of the lens. These were used in the conservation departments at the Museum of Modern Art, New York, and the Getty Conservation Institute. Several limitations emerged. First, image registration was required because the filters did not have identical thickness and the wheel did not maintain alignment. Second, the profile resulted in a loss of spatial image quality.

This approach was commercialized by Sinar in their CTM (color-to-match) system once these limitations were addressed. First, a filter slider with high precision replaced the filter wheel. Second the pair of filters were manufactured with identical thickness. Third, an apochromatic lens was used. These three changes eliminated the need for registration. Fourth, a new profiling approach was used that improved spatial image quality [5]. Despite its high color accuracy [6], this system also was not widely adopted, limited by cost, poor productivity, and complexity.

Each of these systems include a specialized camera and lens. It is not possible to use a studio's existing cameras. We recognized an opportunity if the dual-RGB approach was lighting-centric rather than camera-centric. In this manner, the technique could be used with whatever camera fits an institution's budgets and technical needs, including cameras it already owns. During the last decade, LED lighting has exploded with many choices of white and colored lights. The purpose of this paper is to describe our efforts in developing a bi-color LED lighting system compatible with the dual-RGB approach.

Design Criteria
The following criteria were used to design the bi-color LED source:

1. Compatible with any RGB camera: Our goal was to enable this approach to be used with any digital color camera and not limited to a single manufacturer.

2. Camera modification not required: The first-listed author's previous dual-RGB research [2–4] required replacing the cyan IR filter with clear optical glass, which in many cases, invalidated the manufacturer's warranty, and rendered the system less readily usable for standard RGB imaging.

3. Colorimetric accuracy improved compared with single-capture RGB: The improvement was evaluated using targets different from the profiling target, that is, independent data, referred to as validation data in this paper. The mean, minimum, maximum, and 90th percentile CIEDE2000 were analyzed.

4. Spatial image quality similar to RGB: Combining images may lead to an increase in noise and noticeable color fringing caused by lens chromatic aberration. The color of the second LED and how the images are combined determine the extent of that increase.

5. Image registration not required: Previous dual-RGB systems used filters. If they are not identical in thickness, planarity, and angle relative to the normal angle, image registration is required. Using two sources eliminates this problem for lenses with well controlled chromatic aberration

6. Single-capture RGB or dual-RGB imaging can be performed: Many use cases do not require color accuracy beyond what can be achieved in a standard RGB workflow. Accordingly, one of the lights was a high color-rendering white light. In this manner, we are taking advantage of the manufacturer's sensor design.

LED Selection

Camera signals were simulated using the spectral power distributions of a pair of sources, the spectral sensitivities of three commercial RGB sensors described in reference [7], and spectral reflectance data for an extensive set of materials [7].

The first source was selected to have a high color-rendering index (CRI), high color quality score (CQS), and a correlated color temperature (CCT) resulting in the best colorimetric performance for D50. In this manner, the highest quality single-capture RGB workflow is achieved. The second source was a combination of unity-normalized one, two, three, and four LEDs. These were chosen from an extensive library of colored LEDs, plotted in Figure 1.

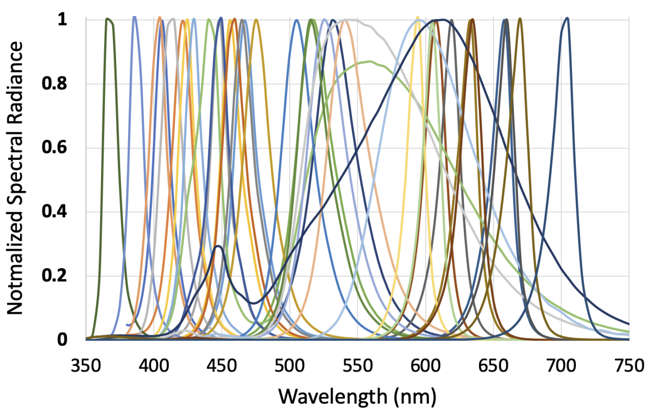

***Figure 1**. Normalized spectral radiance of the library of LEDs evaluated.*

Shaper-matrix profiles (SMAT) were calculated for the white plus each colored LED using a pseudo-inverse between the six signals and XYZ. The mean, 90th percentile, and maximum CIEDE2000 were recorded for the reflectance data. Also recorded was total matrix transformation noise [5], mu-factor [8], and throughput. A single metric, mean(ΔE_{00}) + 0.4(90th percentile ΔE_{00}) + total noise was used for an initial sort, where the best colored LED combination had the smallest metric. These calculations were repeated for each sensor.

Three-LED combinations were the optimal number of LEDs; one and two were too few while the results from four were not better than three.

The top 10 combinations from each sensor were analyzed using all the metrics. The optimal light was a combination of violet, blue, and bluish-green LEDs with peaks at approximately 410nm, 450nm, and 520nm, respectively. The ratio of the three LEDs was determined using the same approach as the LED selection. The color of this LED combination is sapphire. The white and sapphire lights are plotted in Figure 2. Interestingly, these results were similar to a fourth layer in color film [9] commercialized in Fuji Reala and the Sony RGBE (Emerald) sensor.

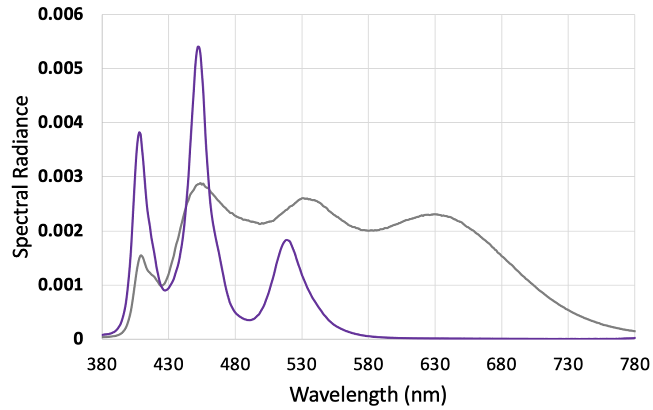

***Figure 2**. Relative spectral output of the white and sapphire channels.*

Prototype Experiment

Prototype panels with prismatic diffusers were built that were manually controlled by individual power supplies for each LED channel (four in all), shown in Figure 3. An experiment was performed to test the panels using a Phase One iXG 100mp. The positions of the lights and camera were set to minimize specular reflections, determined using a black semi-glossy panel. The camera was controlled by Capture One 22 CH and configured to output in Linear Scientific mode with no color correction. Matlab software was used to flat field relative to white foam core and optimize shaper-matrices for white light and both white and sapphire lights. The optimization minimized the average CIEDE2000 for the profiling target. There was a marked improvement using the dual-RGB approach, particularly evaluating verification targets and analyzing the mean and 90th percentile CIEDE2000.

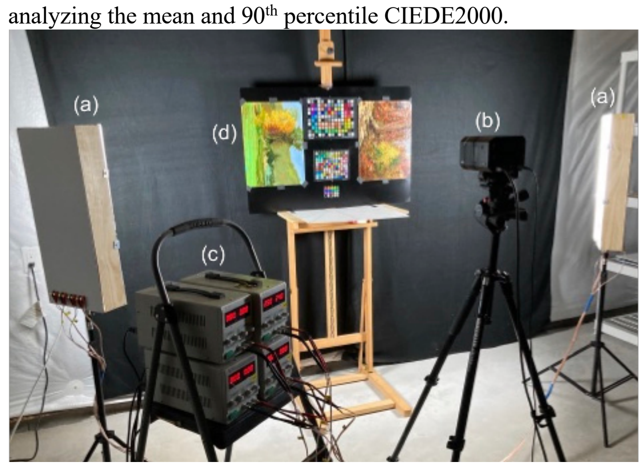

***Figure 3**. System for initial testing, showing lighting panels (a), Phase One iXG100MP camera (b), power supplies (c) and targets (d).*

Experimental

Lighting and Setup

The prototype light was used as a template for a commercial product, the DT Stellar, which was then used for further experiments. These lights are diffuse illuminators. A pair with barn doors were attached to a DT Atom digitization station. The arms are 45° from the normal angle (where the camera is located). The center of each light is aimed such that the average of the angles of illumination is approximately 55° from the normal angle. The barn doors and the aiming were set to minimize specular reflections in the images. The camera was at a distance so that the Stellar did not illuminate the camera.

Cameras

Four cameras were evaluated, controlled by Capture One 23 Pro: Canon EOS R5, Fuji GFX100, Phase One iXH 150mp, and Sony A7R IV. The tone curve was set to Linear Scientific. Capture One was used for flat fielding (called "LCC" in that program). For all the cameras, the aperture was set to f/8 and ISO 100.

Profiling Target

A DT NGT2 target was used to build profiles [10]. The target white was used for color balancing. Exposure time and light intensity were adjusted so the target white had 8-bit counts of around 245.

Verification Targets

Predicting real-world performance must be done by evaluating a target (or several) with spectral characteristics and CIELAB coordinates different from the profiling target. Ideally, the profiling and validating targets have the same surface characteristics such as gloss and texture. Such a target is yet to be produced. In the interim, we used the FADGI/ISO 19264 [11], the ColorChecker SG [12], and the Artist Paint [13] targets for validation.

Spectrophotometry and Colorimetry

The spectral reflectance factor of all four targets was measured using a Konica-Minolta FD7 bidirectional spectrophotometer. CIE D50 and the 1931 standard observer were used to calculate CIELAB. Images were encoded using ProPhotoRGB, resulting in a D50 workflow. The white and sapphire raw images for the APT are shown in Figure 4. A dual-RGB rendered image is shown in Figure 5.

Profiles

Four profiles were tested: the generic commercial profile provided by Capture One, BasICColor multi-dimensional look-up table (MLUT), Argyll MLUT, and dual-RGB SMAT.

Results and Discussion

The DT-NGT target was used for profiling. We have not included this target's color-difference statistics because profiling and evaluating the same data is "teaching to the test" [14]. Such data can only tell us if there is a problem in processing; for example, an average of 20ΔE00 would strongly indicate a problem with that workflow of creating the profile. In our case the data did not indicate a problem in processing. Otherwise, the profiling data should not be used as the basis for any conclusions about performance.

The color difference statistics for these targets are listed in Table 1 corresponding to the four tested cameras and the four profiles. The sum of the mean, 90th percentile, minimum, and maximum ΔE_{00} was used as a ranking metric. Previously, we relied on the 90th percentile. We have included the maximum because it represents challenging materials. The minimum was included because of the range of values depending on the profiling method. (Visual experimentation is required to define a metric, likely a weighted sum of these statistics, that well predicts real-world image archiving and can be used to produce an interval scale. This is why we use "ranking".) The average sum for each camera and profiling method is listed in Table 2; the grand average of each profile method is listed in the bottom row.

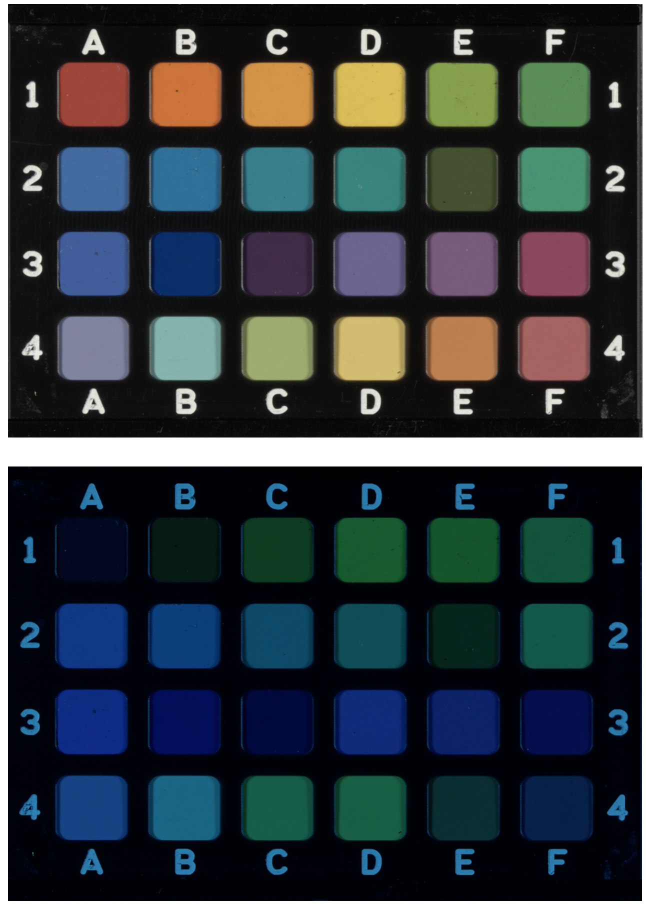

***Figure 4**. Capture One screenshots of the white and sapphire APT images.*

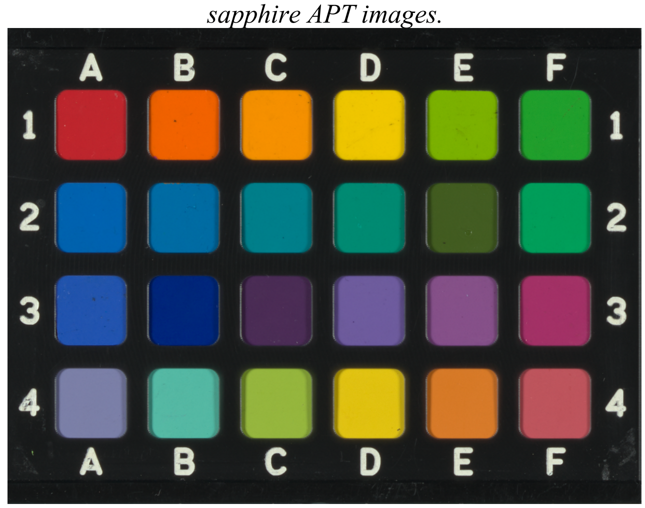

***Figure 5.** Dual-RGB rendered APT target.*

Table 1. CIEDE2000 statistics for each listed camera, evaluation target, and profiling method.

Canon EOS R5		Capture One	Dual-RGB	BasICColor	Argyll MLUT
ISO 19264	Mean	3.6	1.2	1.4	1.5
	90th perc	5.2	1.6	2.2	2.3
	Minimum	0.4	0.3	0.3	0.4
	Maximum	8.3	3.3	6.3	5.0
	Sum	**17.4**	**6.4**	**10.2**	**9.2**
CCSG	Mean	3.3	1.4	2.0	1.8
	90th perc	3.9	1.7	3.9	1.6
	Minimum	0.5	0.3	0.3	0.2
	Maximum	8.7	6.0	8.0	12.8
	Sum	**16.4**	**9.5**	**14.3**	**16.4**
APT	Mean	3.8	1.3	2.0	2.5
	90th perc	6.6	2.1	3.0	3.9
	Minimum	1.0	0.4	0.6	0.8
	Maximum	8.0	2.9	4.4	11.5
	Sum	**19.4**	**6.7**	**10.1**	**18.7**
Fuji GFX100		Capture One	Dual-RGB	BasICColor	Argyll MLUT
ISO 19264	Mean	3.0	1.0	1.5	1.4
	90th perc	5.4	1.5	2.5	2.3
	Minimum	0.4	0.0	0.4	0.3
	Maximum	7.6	5.0	6.0	6.5
	Sum	**16.4**	**7.5**	**10.4**	**10.3**
CCSG	Mean	3.2	1.9	2.5	2.4
	90th perc	5.5	2.6	3.4	3.2
	Minimum	0.7	0.7	0.6	0.6
	Maximum	7.6	4.6	6.0	14.7
	Sum	**17.0**	**9.8**	**12.5**	**20.9**
APT	Mean	5.0	1.2	1.9	2.4
	90th perc	7.4	1.8	2.9	2.6
	Minimum	1.9	0.3	0.5	0.4
	Maximum	8.9	2.5	5.0	13.4
	Sum	**23.2**	**5.7**	**10.2**	**18.7**
Phase One iXH 150mp		Capture One	Dual-RGB	BasICColor	Argyll MLUT
ISO 19264	Mean	7.1	1.0	1.0	0.8
	90th perc	9.4	1.4	1.6	1.3
	Minimum	1.5	0.1	0.4	0.1
	Maximum	12.5	2.7	3.1	2.3
	Sum	**30.5**	**5.2**	**6.0**	**4.4**
CCSG	Mean	2.9	1.1	1.4	1.1
	90th perc	4.9	1.6	2.1	1.7
	Minimum	0.8	0.1	0.3	0.1
	Maximum	7.9	2.7	5.3	9.2
	Sum	**16.4**	**5.5**	**9.1**	**12.1**
APT	Mean	4.0	2.2	2.6	3.4
	90th perc	6.3	2.9	3.6	4.0
	Minimum	0.8	0.6	1.5	2.3
	Maximum	7.7	3.7	4.2	8.1
	Sum	**18.7**	**9.4**	**12.0**	**17.8**
Sony A7R IV		Capture One	Dual-RGB	BasICColor	Argyll MLUT
ISO 19264	Mean	3.3	1.1	1.3	1.0
	90th perc	5.7	1.4	2.0	1.8
	Minimum	0.5	0.2	0.3	0.1
	Maximum	7.6	3.4	3.5	5.8
	Sum	**17.2**	**6.1**	**7.1**	**8.7**
CCSG	Mean	4.1	2.11	2.4	1.8
	90th perc	6.7	2.77	3.3	3.0
	Minimum	0.5	0.94	1.0	0.1
	Maximum	8.7	4.15	5.1	13.1
	Sum	**20.1**	**10.0**	**11.8**	**17.9**
APT	Mean	4.4	1.4	1.8	2.0
	90th perc	7.5	2.1	2.3	3.2
	Minimum	1.0	0.6	0.8	0.3
	Maximum	8.0	2.4	4.1	11.7
	Sum	**20.9**	**6.4**	**9.0**	**17.2**

The salient results are listed in Table 2. The generic commercial profiles provided by Capture One had the bottom ranking. There were hue errors and an increase in contrast. Boosting contrast is not appropriate for image archiving. The highest ranking was the dual-RGB method. This occurred for all cameras. The second ranking was BasICColor while the third ranking was Argyll. We were surprised by the poor performance of Argyll. We expected this method to have similar performance to BasICColor, both being MLUTs. Looking at the profiles revealed that the BasICColor MLUT was over five times the size of Argyll. A larger MLUT reduces interpolation error.

Table 2. Average Sum (from Table 1) for each listed camera and profiling method.

Camera	Capture One	Dual-RGB	BasICColor	Argyll MLUT
Canon EOS R5	17.7	7.5	11.5	14.8
Fuji GFX100	18.9	7.7	11.0	16.6
Phase One iXH 150mp	21.8	6.7	9.0	11.4
Sony A7R IV	19.4	7.5	9.3	14.6
Grand Average	19.5	7.4	10.2	14.4

Conclusions and Future Work

Dual-RGB imaging using a bi-color LED source resulted in higher-ranked performance compared with RGB imaging and a multi-dimensional look-up table (MLUT) profile. This occurred for all the cameras and targets. A reasonable question is why? Simply, the six channels of data provided by dual-RGB imaging result in a closer approximation of the human visual system's spectral sensitivities, specifically, approximating the CIE 1931 standard observer. A MLUT of three-channel data cannot overcome a poorer approximation of the human visual system, particularly when evaluating verification data.

This research has not addressed spatial image quality beyond its inclusion when designing the sapphire light. We anticipate the usual advantages of a SMAT compared with MLUT profiles, for example, minimal banding artifacts and greater resilience to small changes in capture conditions. One of the design criteria was to achieve similar spatial image quality to RGB imaging. This will be tested in the future.

Independent testing of this approach is now under way at the Library of Congress and will provide additional insight as to the performance of dual-RGB imaging in real-world high-volume production.

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