Spectral Implications for Camera Calibration Target

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Abstract

Accurate camera calibration is a critical step in the capture, processing, and archiving of object properties. To be most useful to the library/museum/archiving community, the patch colors in a camera color characterization target should facilitate accurate data capture from commercial RGB cameras. Target patches can be defined colorimetrically (i.e.: CIELAB) or spectrally (i.e.: reflectance). For some limited situations, colorimetric data is sufficient, but knowing and using the spectral reflectance of the patches affords increased flexibility and accuracy. In this work, the spectral reflectance of the patches are considered in light of the spectral detection properties of cameras. A spectral model will be developed to predict how well two commercial cameras perform when profiled against an available camera target.

Introduction

The development of a next generation camera characterization target ("NGT") has been described[1] including features that facilitate its use specifically for archiving library materials. Reference 1 includes details regarding the selection of colors for the target, as well as its characterization performance as compared to other targets in common use. The distribution of colors in the NGT were evaluated using existing color sets, in particular those described by Pointer[2] and Newhall, *et al*[3].

The NGT was designed from the outset as a colorimetric target, meaning that the definitions of the colors were only made in CIELAB color space. This decision was made consciously to keep the development and production tractable under the limited resources available. However, it was known that a better solution would be to define the patches by their spectral reflectance properties. This would allow the modeling of multiple light sources, as well as to connect the target to a complete spectral imaging workflow. The current work describes the effort made to connect the spectral properties of the target and those of commercial cameras, and an analysis of that effort.

The balance of this paper describes the effort to gather spectral data for aspects of the physical image capture system, including:

1. camera spectral sensitivities;
2. spectral reflectance of the patches;
3. a simple camera model incorporating 1, and 2; and
4. the evaluation of this model against actual camera profiling for a set of common color imaging targets.

Camera Spectral Sensitivities

The spectral sensitivities of an imaging system describe how the system responds to different wavelengths across the visible spectrum. To determine these properties, the imaging system is presented with a sequence of (near) monochromatic stimuli. The schematic of the experimental apparatus is shown in Figure 1.

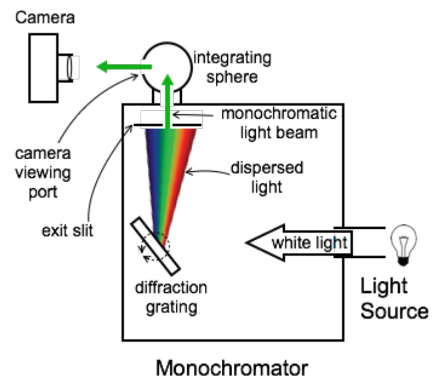

Figure 1*. Experimental apparatus to present near monochromatic stimuli to camera system. The diffraction grating is rotated, changing the wavelength of light incident on the exit slit. In this fashion the entire visible spectrum can be imaged in sequence, one wavelength band at a time.*

The procedure for capturing the monochromatic data and calculating the spectral sensitivities is well established. See reference 4 for a detailed procedure [4]. It is important that the camera be configured for a fixed exposure time, and it should be established that this exposure time does not cause any clipping (maximum image digital counts, often 255). Also, it is most useful if the bandwidth of the monochromator is the same as the wavelength steps. A common step interval is 10nm, therefore the bandwidth of the system should also be set at 10nm. Finally, the procedure must account for the level of the light source at each wavelength of interest. The camera digital counts at each wavelength are normalized to these levels. Figure 2 shows spectral sensitivity functions for the commercial camera evaluated here.

With the spectral sensitivities, the camera RGB output can be modeled. For any given image pixel, the spectral content of the scene is multiplied by each of the three sensitivity curves. This product is then integrated across all wavelengths to estimate the R, G, and B digital counts for this pixel. For brevity some of the mathematical details of these calculations are omitted. The techniques are well understood, and reference 4 should be consulted for mathematical specifics.

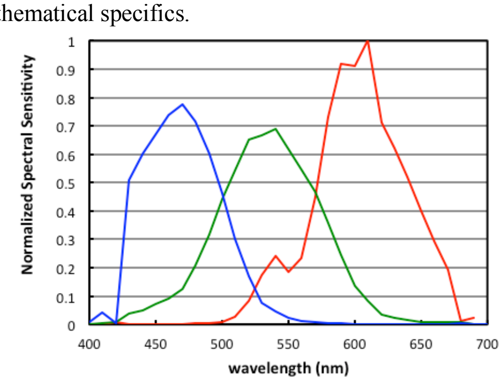

Figure 2a*. Normalized spectral sensitivity for Canon 1D Mark III.*

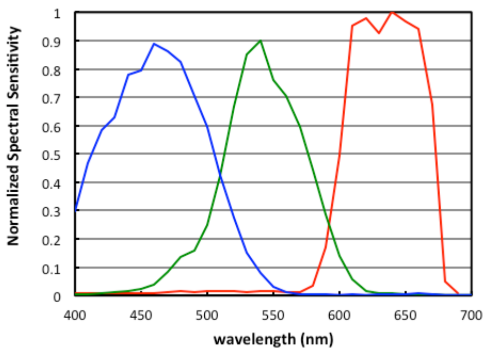

***Figure 2b**. Normalized spectral sensitivity for Metis flatbed scanner*

Evaluating Camera Spectral Sensitivities

The first thing to note of spectral sensitivities is spectral overlap between the channels. Without overlap, a system cannot determine which wavelength of light is stimulating the detector response. For example, consider the red curve in Figure 2b. At wavelengths greater than about 620nm, the only response is in the red channel. Therefore this system has no way to distinguish between wavelengths of light above 620nm. Figure 2a shows a slightly better situation; there is some green response up to 650nm. Even though the response is low, this small change will contribute to the colorimetric accuracy of this camera.

More practically, the fundamental question to consider is how accurately a camera can reproduce all colors. That is, how closely does the camera output match that of a human observer? A common method to evaluate general camera color reproduction quality is the μ-factor [4]. Essentially this is an analysis that predicts how close the camera spectral sensitivities are to the accepted human color matching functions. The mathematical details are in reference 4. Briefly, the metric is on a 0-1 scale, with higher values indicating an increased ability to match the behavior of a standard observer. Table 1 shows the μ-factor for the two cameras reported in this study. The calculation of μ-factor accounts for taking and viewing illuminant, both of which were CIE D50. The observer function was the CIE 1964 10° Standard observer.

Table 1. μ-factor Results for Test Cameras

Camera	μ-factor
Canon 1D Mark III	0.901
Metis flatbed scanner	0.735
Metis + BG40	0.791
Metis + BG60	0.814

The literature suggests that a μ-factor of at least 0.9 is desirable for cultural heritage imaging [5]. While we do not outright reject any capture system based solely on μ-factor, it does provide an indicator of which systems might be expected to perform better than others. Note the final two rows of Table 1 will be described below under *Spectral Tuning by Prefiltering*

Spectral Camera Model

To verify the utility of the spectral sensitivities, a simple camera model was developed incorporating the spectral properties of: a light source, a set of camera targets, and the spectral sensitivities from a series of commercial cameras. The same cameras were also used for actual capture of the set of camera targets in reference 1.

The spectral camera model assumes no internal processing (e.g.: white balance) other than the response of the detector given the light source, target, and color filter array. It also assumes the data are linearized; the cameras analyzed here reported 16 bit linear data. Note that the sensitivity of the detector necessarily also accounts for the transmittance of the filter above the detector. Mathematically, the model is described follows (red channel shown):

$$D_R = \frac{\sum_{\lambda} E_\lambda T_\lambda R_{norm,\lambda}}{D_{R,white}} D_{max}. \quad (1)$$

The variables used are:

- E_λ: spectral power distribution of the light source
- T_λ: spectral reflectance of the target patch
- $R_{norm,\lambda}$: normalized Red camera spectral sensitivity
- D_{max}: maximum digital count (here, always $2^{16} = 65536$)
- $D_{R,white}$: digital count for a theoretical white diffuse patch
- D_R: output digital count for the red channel

Analogous equations apply for the green and blue channels.

Camera Profiling

After the camera model is applied to any given target patch, the digital counts are processed through a camera profile, which predicts the color of that input target patch. The profile applied here includes offset terms for each channel, followed by a matrix transformation, yielding the predicted tristimulus values $\hat{X}$, $\hat{Y}$, $\hat{Z}$. Mathematically, the model is described as:

$$\begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix} = \begin{bmatrix} R_X & G_X & B_X \\ R_Y & G_Y & B_Y \\ R_Z & G_Z & B_Z \end{bmatrix} \begin{bmatrix} D_R/D_{R,max} - D_{R,offset} \\ D_G/D_{G,max} - D_{G,offset} \\ D_B/D_{B,max} - D_{B,offset} \end{bmatrix}. \quad (2)$$

In addition to the terms described for equation (1), there are 12 terms, all of which are optimized during the profile creation:

- The 3x3 matrix, the columns which are the fit tristimulus values of the R, G, and B camera primaries.
- The three offset terms: $D_{R,offset}$, $D_{G,offset}$, and $D_{B,offset}$.

The predicted tristimulus values are processed in the usual way through CIE equations [6] to yield CIELAB coordinates, which will be used to calculate model performance by color difference [7] to the reference measurements for each target patch.

In the results below, each camera is profiled using one target, and then evaluated using the reference measured data for several verification targets.

Spectral Model Analysis

For each of the imaging systems, the model shown in equation 1 was applied to a single camera calibration test chart: Next Generation Camera Target (NGT) [1]. Three commercially available targets were used as verification: X-Rite Colorchecker Classic (CC) [9]; X-Rite Colorchecker SG (CCSG) [9]; and IT8.7/2 (IT8) [10]. In addition to these three targets, four additional targets were applied. These four consisted of various artists paint colors. [11] The paint targets are referenced as #1-4; they were all designed as a part of a research program in spectral imaging, and represent a good sampling of artists' acrylic and oil paints. The workflow for the analysis is shown in Figure 3.

Figure 3a aligns with equation 1: the camera spectral sensitivities, target reflectance, and light source are combined to predict camera response in digital counts values $\hat{R}$, $\hat{G}$, $\hat{B}$. From there, the camera profile is applied, shown in equation 2. (The *R*, *G*, *B* digital counts are D_R, D_G, D_B in equation 2). Figure 3 shows the balance of the analysis as applied in this work

The upper portion of Figure 3b is identical to that of Figure 3a except that the targets are now test targets. Thereafter, the camera model predicts digital counts $\hat{R}$, $\hat{G}$, $\hat{B}$. The profile predicts tristimulus values , which are then processed to CIELAB using the traditional CIE equations. The evaluation is the ΔE_{00} color difference between the model CIELAB and the CIELAB calculated directly from the target reflectance, T_λ. This color difference includes some error in the forward profile model.

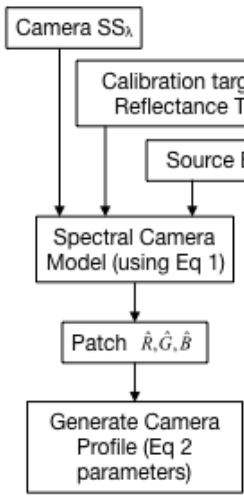

***Figure 3a**. Spectral workflow showing the use of the spectral sensitivities and the calibration target spectral reflectance in the derivation of the camera profile.*

Spectral Analysis Results

As shown in Fig 3b, for each verification target, the color difference between the measured target and the predicted CIELAB was calculated using ΔE_{00}. Results for the two cameras are shown in Table 2.

Table 2a. Spectral Model Performance
Mean Color Difference for Calibration Target

ID	Camera	ΔE_{00}
A	Canon 1D Mark III	0.56
B	Metis flatbed	1.26
C	Metis + BG40	1.03
D	Metis + BG60	0.86

Table 2b. Spectral Model Performance
Mean Color Difference for Paint Verification Targets

ID	ΔE_{00}			
	1	2	3	4
A	1.21	1.02	0.92	1.10
B	2.44	2.52	2.58	2.73
C	2.10	1.95	1.99	2.16
D	1.81	1.46	1.46	1.75

Table 2c. Spectral Model Performance
Mean Color Difference for Common Verification Targets

ID	ΔE_{00}		
	CC24	CCSG	IT8.7/2
A	1.77	1.66	1.23
B	4.91	4.24	2.36
C	3.67	3.38	2.03
D	2.81	2.59	2.02

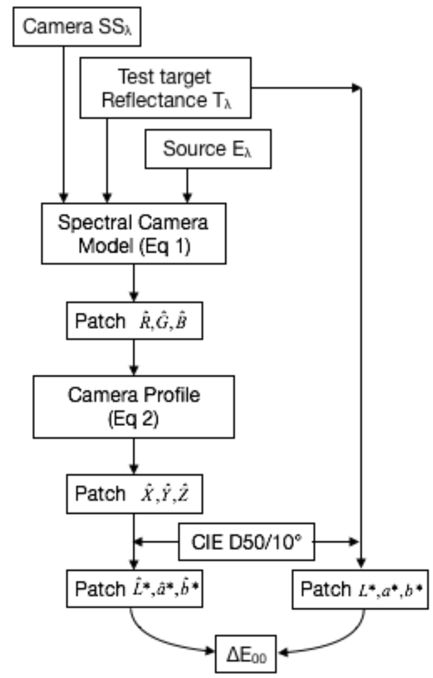

***Figure 3b**. Complete spectral workflow showing the use of the spectral sensitivities and target spectral reflectance for the prediction of $\hat{R}$, $\hat{G}$, $\hat{B}$ camera output. The forward profile predicts tristimulus values, which after conversion to CIELAB are compared to the measured target color.*

Considering the Spectral Nature of Targets

A good spectral target incorporates the maximum amount of spectral information in the fewest number of patches. The measurement of spectral reflectance relies on two scales: the wavelength scale and the reflectance scale. Ideally these two scales are treated independently. To establish the accuracy of the wavelength scale, an accepted method is to evaluate the locations of the inflection points of the spectral reflectance curves.[12] These are represented by the zero crossings of second derivative of reflectance with respect to wavelength. Ideally the location of the inflection points are spread across the wavelength scale. Figure 4 shows the distribution of these points for the four targets. A point is marked for each 10nm band in which an inflection point lies. What is most important is the wavelength coverage, not the absolute number of inflection points. Where present, gaps indicate a lack of wavelength information. That is, gaps show wavelength regions where the reflectance of all patches in a given target are relatively flat and unchanging.

To treat the reflectance scale independent of the wavelength scale, the reflectance of some patches, generally neutrals, should be invariant to wavelength shifts. The effect of shifting wavelength for two hypothetical neutral patches is shown in Figure 5. Figure 5 shows the baseline and ±5nm spectra. While ±5nm is an excessive estimate of the wavelength error in most modern instruments, a 1 or 2nm error is not uncommon, which result in errors as large as 0.6 ΔE_{00} for the example colors in Figure 4. Such a small color difference may seem inconsequential, but this should be considered with all the other sources of error in the imaging chain.

Spectral Tuning by Pre-filtering

Adjusting the fundamental spectral sensitivities of a camera is practically impossible short of completely replacing the detector, which essentially amounts to purchasing a new camera. However, relatively simple filtering techniques have been shown to improve colorimetric performance [13]. The technique addresses the lack of overlap discussed above, in particular between the red and green channels.

Figure 6 shows the modified spectral sensitivity curves of the Metis for two blue-green filters. The colorimetric results of the tuning are shown above in Tables 2a, 2b, and 2c. As the data show, this simple technique can significantly improve the colorimetric performance. To implement this modification, the selected filter need only be placed somewhere in the optical path (most easily in front of the lens). Thereafter, a new device profile must be created, capturing the profiling images with the filter in place. All future imaging would likewise be done with the filter remaining in place.

Conclusions and Future Work

Various features of a spectral camera characterization target have been identified and evaluated. Most important is the connection between the target properties and those of the camera system.

One goal of future work is to find alternative colors for patches that fill in the gaps in Figure 4, thus improving the wavelength information. Also, other methods will be considered to modify the digitization systems themselves (e.g.: pre-filtering), since it is likely that not all profiling improvements are able to be made by modifying the calibration target alone.

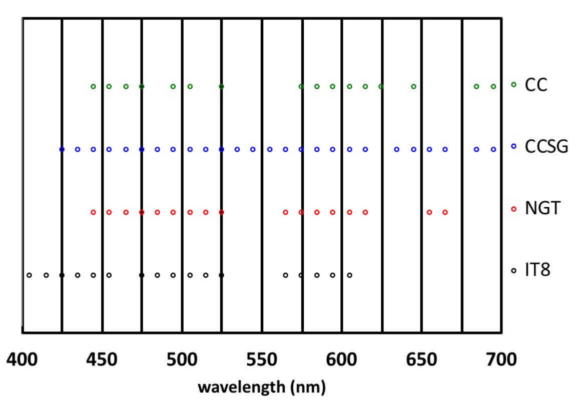

***Figure 4**. Distribution of wavelength inflection points for the four targets. A point is marked for each 10nm band in which an inflection point lies.*

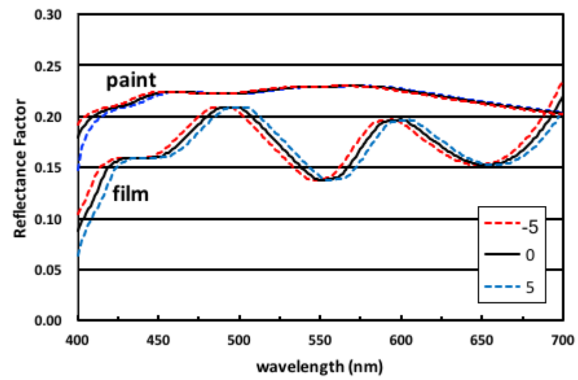

***Figure 5**. Example of the effect of wavelength shift on two neutral colors. Upper lines are for a spectrally flat paint based patch. Lower lines show a film based RGB patch. In both cases the solid black line is the unshifted baseline reflectance.*

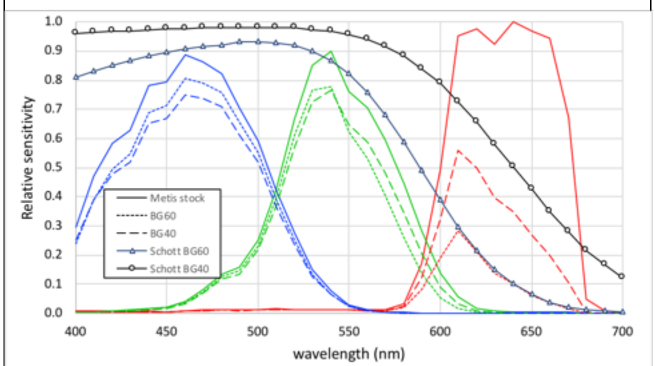

***Figure 6**. Spectral sensitivity tuning of Metis channels. Black lines show the transmittance of the two filters used; dashed colored lines show the effect on the channel sensitivity.*

References

[1] DR Wyble, "Next Generation Camera Calibration Target for Archiving," IS&T Archiving 2017, Riga, Latvia (2017).

[2] MR Pointer, "The Gamut of Real Surface Colors," *Color Res Appl*. **5**, 145–155 (1980).

[3] M Newhall, D Nickerson, DB Judd, "Final report of the O.S.A. subcommittee on spacing of the Munsell colors," *J Opt Soc Am* **33**, 385-418 (1943).

[4] MM Darrodi, G Finlayson, T Goodman, M Mackiewicz, "Reference data set for camera spectral sensitivity estimation," J Opt Soc Am A, Optics, Image Science, and Vision, March 1, 2015, p381-391.

[5] Vora, VR; Trussel, HJ. Measure of Goodness of a Set of Color Scanning Filters. *J Opt Soc Am* A **10**, p8-23 (1991).

[6] Murphy, EP. A Testing Procedure to Characterize Color and Spatial Quality of Digital Cameras Used to Image Cultural Heritage. Masters Thesis, Rochester Institute of Technology (2002).

[7] CIE No. 15.2004, Colorimetry, Commission Internationale de l'Elclairage (2004).

[8] Luo MR, Cui G, Rigg B. The development of the CIE 2000 Colour Difference Formula. *Color Res Appl* **26** 2001;26:340 –350.

[9] These two and other ColorChecker targets are available from X-Rite Incorporated, Grand Rapids MI. www.xrite.com.

[10] The IT8.7/2 is a film based target, available from LaserSoft Imaging, www.silverfast.com.

[11] Berns, RS. Personal communication (2018).

[12] WH Venable Jr., and KL Eckerle, "Didymium Glass Filters for Calibrating the Wavelength Scale of Spectrometers - SRMs 2009," *2010, 2013 and 2014*, NBS Special Publication 260-66 (1979).

[13] Berns, RS; Smith, S. “Analysis of Color Management Default Camera Profiles for Museum Imaging Applications.” IS&T Archiving 2012, Copenhagen, Denmark (2012).

Author Biography

David R. Wyble is the president of Avian Rochester, LLC, which offers traditional and custom color measurements, color consulting, and specialty calibration targets. Wyble was a staff scientist and adjunct professor at Munsell Color Science Laboratory at Rochester Institute of Technology, and technical staff at Xerox. Wyble holds a doctorate from Chiba University, Japan and MS from RIT, both in Color Science. Since 2015 he has been actively consulting on Library of Congress digitization projects.