

Color Accuracy: Chromatic Adaptation and Spectral Relighting

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Abstract

The application of color-difference measures to evaluate the accuracy of image capture for collections is common practice. For example, the FADGI* imaging guidelines express acceptable tolerances in terms of the ΔE_{00} value. The color-accuracy evaluation assesses the extent to which the delivered image represents the desired color encoding of the object or scene. This is usually done with standard test targets, and the color encoding will depend on the selected color image space. Since different image color spaces are defined with different illuminants, it is common practice to transform the color coordinates between those for different illuminants. We can think of these transforms as approximations of complete recalculations that would be based on spectral reflectance data and visual color-matching functions. We address one such common transform in the context of the FADGI* 19264 test target.

Introduction

It is now common to use color-difference measures to evaluate the accuracy of image capture for collections. For example, the FADGI imaging guidelines [1,2] express acceptable tolerances in terms of the ΔE_{00} . Figure 1 outlines the common approach, using a reference object (test target) with known, measured color characteristics. Note that the known color coordinates (in this case, CIELAB values) are supplied and used by the analysis software. Color-accuracy evaluation addresses the degree to which the delivered image represents the desired color-encoding of the object or scene.

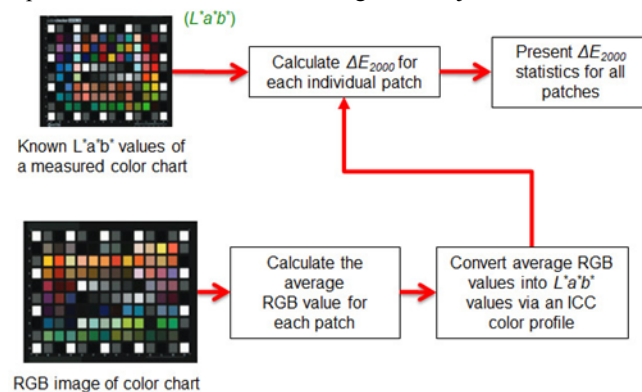


Figure 1: Evaluation of image capture color using reference chart [Ref. 3]

Since different image color spaces are defined with specific illuminants, it is common practice to transform the aim color coordinates between those for different illuminants. For example, if images are encoded in AdobeRGB pixel values, the CIE D65 illuminant is used. To evaluate the accuracy of the image capture, the aim CIELAB values should be based on the D65 illuminant. In

some cases, tolerance values are expressed in terms of a different illuminant, such as D50, used in ProPhotoRGB, and color-management environments using ICC color profiles. Figure 2 shows the relative spectral power distributions for both of these standard illuminants, and an example LED source. [4] Several image color spaces and their corresponding illuminants are,

- ProPhoto, ECIRGBv2, ICC Profile Connection D50
- Adobe RGB (1998), sRGB, Display P3 D65
- DCI-P3 6300 K

The CIELAB color space is intended to describe the visual (color) appearance of illuminated objects, but it is used in a somewhat different way when evaluating the accuracy of image capture systems. The image values for regions of a color test chart are transformed from their RGB image color space to a corresponding set of CIELAB coordinates. In a sense, these values represent the viewed colors that would be displayed by an ideal display or printer. We can describe this as evaluating the accuracy of the camera's color encoding of the test chart. In other words, how well the imaging system encoded the image in the specified image color space/format under a corresponding illuminant.

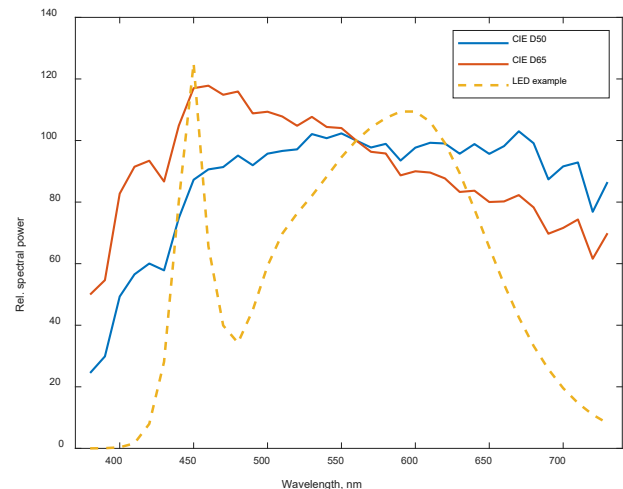


Figure 2: Relative spectral power for CIE standard illuminants and an example LED source (courtesy of the CIE).

Figure 3 shows the FADGI 19264 test target, whose 168 color patches are used to evaluate the color encoding for digital collections. In some cases, these are also used to compute ICC color profiles for image color correction. In addition, there are several elements of this design that are used for the evaluation of other imaging characteristics, such as sharpness and geometric distortion,

* US Federal Agencies Digital Guidelines Initiative [1]

but here we focus on color capture. Figure 4 shows the test target sampling of the CIELAB color space in the a^*-b^* plot, where the hue angle is often visualized. Values for both D50 and D65 illuminants are shown.



Figure 3: FADGI ISO 19264 test target

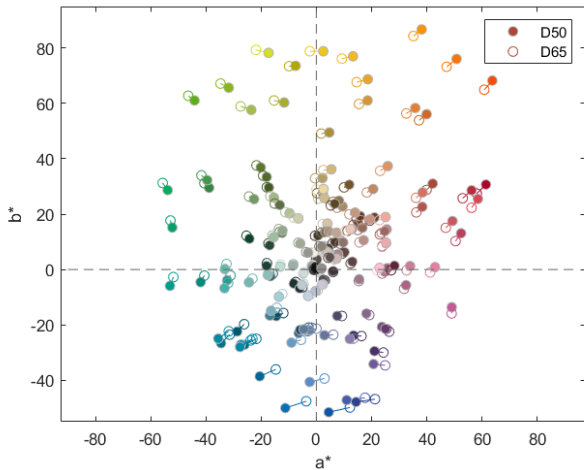


Figure 4: FADGI target color-patch sampling in CIELAB a^*-b^*

CIELAB coordinates are computed from visual tristimulus values, so they explicitly include the illuminant spectral power distribution (SPD). This means that both the computed test image values and ideal (aim) values should be expressed with the same illumination. This is true, regardless of the actual physical light source used to capture the target and collection material. A file image (and tagged) color space implies a particular standard illuminant. For color measurements and situations where we have the object (target patch) spectral reflectance data, we can recalculate the CIELAB

coordinates. This is the ideal situation and defines the ‘ground truth’ for the aim CIELAB values.

In many practical scenarios, spectral reflectance data are unavailable. Instead, only tristimulus values (XYZ) or derived quantities such as CIELAB coordinates are known. In such cases, the transformation between illuminants must be approximated using chromatic adaptation transforms (CATs), such as the Bradford transform. The simplified, or linear, version of this transform is used in ICC profiles. For detailed comparison of various CATs using several object data sets, see Ref. [5].

CATs provide mappings between color representations under different illuminants that preserve perceptual relationships for a wide range of natural object reflectance. This mapping is necessarily approximate because the transformation from spectral reflectance to tristimulus values is many-to-one. We can think of these transformations as approximations to complete recalculations based on spectral reflectance data and visual color-matching functions.

Color Accuracy under FADGI Guidelines

Evaluation of color (encoding) under FADGI Guidelines, as outlined in Fig. 1, is done by comparing the results for the color patches of test targets, such as that shown in Fig. 3. Table 1 lists the maximum allowable color differences (test-aim), expressed as ΔE_{00} values: average, and 90th percentile. It is in the context of these values that we now examine the approximations introduced by CATs used in both color management and target-based system evaluation.

<i>Performance Level</i>	<i>2*</i>	<i>3*</i>	<i>4*</i>
<i>Bound Volumes: Rare & Special Collections</i>			
Average color accuracy	5	3.5	2
90th Percentile	10	7	4
<i>Bound Volumes: General Collections</i>			
Average color accuracy	5	3.5	2
90th Percentile	10	7	4
<i>Unbound Documents: Man. and Rare & Special Collections</i>			
Average color accuracy	5	3.5	2
90th Percentile	10	7	4
<i>Unbound Documents: General Collections</i>			
Average color accuracy	5	3.5	2
90th Percentile	10	7	4
All values are in units of ΔE_{00}			

Table 1: FADGI Guideline upper values for color accuracy for various collection materials [1].

To simplify matters, we focus on the common color transform between D50 and D65 illuminants. These are the two illuminants

that are used for the adapted white in most image file encoding and formats. Since any detailed examination requires spectral reflectance characteristics of the sample object, we will use the 168 colors of the FADGI 19264 test target. We start by computing the tristimulus values and CIELAB coordinates for the CIE D50 illuminant. We then recalculate the corresponding values under D65. Since these are spectral computations, we can take these as the ground truth, computed at 10 nm increments. We can think of these data as the magnitude of the CIELAB changes (signal) that are needed for the evaluation to be done colorimetrically, and consistent with image color encoding.

Linear or Simplified Bradford Transformation

In color-management systems, when transforming between color spaces, CATs are used to provide color correction. Here, we use the simplified Bradford Transformation, recommended by the International Color Consortium (ICC) for Version 4 color profiles. This transform is based on the idea that if we first express our color coordinates as three (visual) tristimulus values, we can then apply weights that are the ratios of the white-point values. These adjusted tristimulus values are then transformed back to the corresponding illumination-adjusted values. This is outlined in Fig. 5.

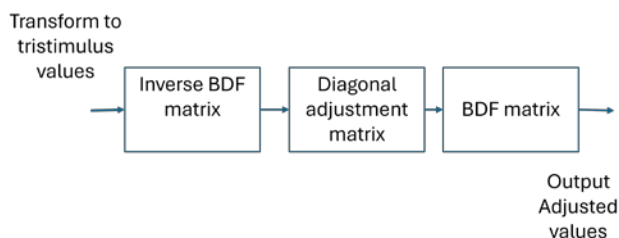


Figure 5: Chromatic adaptation by Simplified Bradford Transform

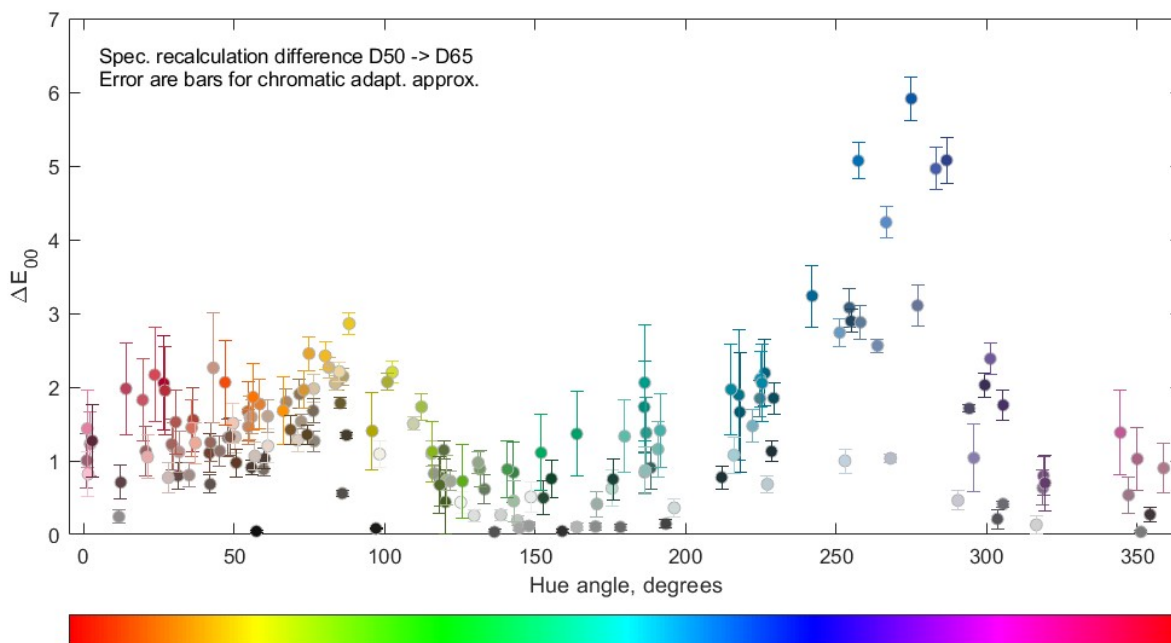


Figure 6: Results of the spectral recalculation between CIE illuminants D50 and D65 (circles), in units of CIE ΔE_{00} . The error bars indicate the differences due to chromatic adaptation approximation.

This was done for the target patch values, and we interpret the resulting values as *estimates* of the recalculated D65 data set. The difference between the results of the Bradford CAT and the (reference) spectral transformation can be seen as an approximation uncertainty, or error.

Figure 6 shows the color difference between the D50 and D65 adapted CIELAB coordinates for the 168 target patches. These are plotted as circles. The color difference between these recalculated (*i.e.*, correct) CIELAB values and the CAT approximation is also shown in the form of error bars. The length of each error bar indicates the magnitude of this difference. The color bar beneath the plot indicates the approximate rendering of the spectral colors, approximating a single wavelength for the hue angles in CIELAB.

If we look more closely at the CAT approximation errors, we can compare them with the allowable tolerances in the FADGI Guidelines in Table 1. Figure 7 shows the approximation errors (differences from the spectrally computed values) for all target patches. The average difference was $0.53 \Delta E_{00}$, and the 90th percentile was $1.04 \Delta E_{00}$.

Since the allowable average color error for all 3-star categories (see Table 1) is $3.5 \Delta E_{00}$, this represents 15% of this margin. For the 90th percentile, the corresponding value is $1.04/7.5 = 14\%$. For more critical collection material (4*), the corresponding values are; 26% (mean) and 30% (90th percentile).

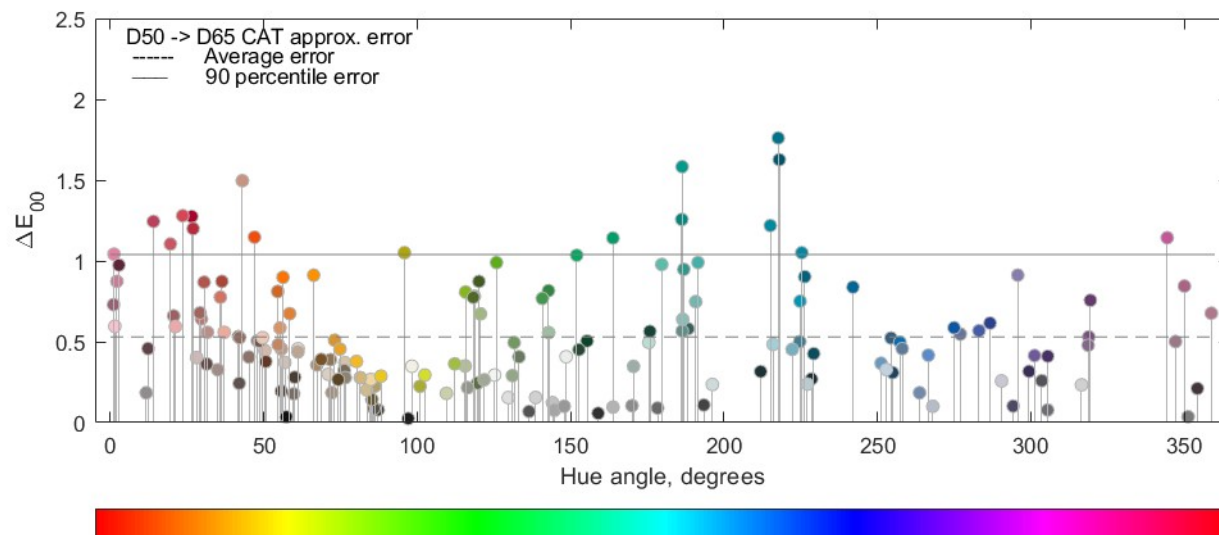


Figure 7: CAT approximation error for all color patches for the FADGI target

Discussion

Ignoring the encoding illuminant, when it is different than that for the aim values, can lead to significant computed color-difference values. These color differences that are introduced can be large enough to fail to meet FADGI guidelines, as listed in Table 1.

The desired color differences after recalculation show high variability, with a range [0, 6], and a mean ΔE_{00} of 1.37. The CAT approximation results show differences [0, 1.8], with a mean of 0.53.

Consider these results in the context of their influence on the system evaluation that follows the FADGI Guidelines. If the target (aim) CIELAB values are available as spectrally computed for the illuminant that is consistent with the image color encoding, then they do not need to be transformed via the CAT. This reduces the uncertainty of the result. While this seems an obvious conclusion, it needs to be stated, as not all evaluation software tools include aim data for all anticipated illuminants.

We have addressed the standard illuminants D50 and D65 here because they are used for the color-encoding used in several image color spaces recommended by the FADGI Guidelines. We should note that this does not mean that non-smooth physical illumination systems, such as LEDs, fall outside of our analysis. Real systems manage color capture by processing image data so that they approximate images captured under, e.g., D50 for ProPhoto RGB. The color accuracy evaluation can proceed as if the data were encoded as tagged under the corresponding CIE illuminant. In which case, the above results hold.

Conclusions

The application of color-difference measures to evaluate the accuracy of image capture for collections is common practice. For the FADGI 19264 test target, we have computed the magnitude of

approximation error introduced by the common simplified Bradford transformation, used in ICC color management. When color capture is evaluated from the image data, e.g. under FADGI guidelines, the differences can be significant. Attention should be paid to the adapted illuminant for any image color space/format.

Acknowledgement

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Author Biographies

Peter Burns is a consultant working in digital image evaluation, system monitoring, and image processing. A frequent presenter, he has experience in several areas of imaging: digital photography, mobile imaging, and cultural heritage, among others.

Don Williams is the founder of Image Science Associates, a digital imaging consulting and software group. Their work focuses on quantitative performance metrics for digital-capture imaging devices and imaging fidelity issues for the cultural heritage community. He has taught short courses for many years and contributes to several imaging standards activities, including FADGI.