Best Practices for Production Line Camera Color Calibration

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Abstract

An important step in the color image processing pipeline for modern digital cameras is the transform from camera response resulting from scene spectral radiance to objective colorimetric or related quantities. Per-camera-module production line calibration of white balance, color shading, color transformation, and other parameters is essential to achieve high yield, high quality, and low cost. Historically, simple color charts have been used for this purpose but due to inherent limitations, the industry is adopting modern spectral approaches which provide greater flexibility and quality. Best practices for production line per-module camera color calibration are overviewed herein.

The Need for Color Calibration

Over the course of the production life of a given make and model of camera module, the color response can vary significantly due to variations in sensor sensitivity, color filter array variation, filter-pixel alignment, optical alignment, and many other factors that are difficult to control economically with a high enough degree of precision to ensure that all modules perform the same. If left uncorrected, this results in color shifts, clipping, and other image quality artifacts. Camera modules that fail image quality standards result in lower yield and increased cost. Typically, however, some level of per-module calibration is performed, at least for white balance and often for color transformation between camera values and the standard color spaces used in well-known color image encodings. Figures 1 and 2 show the difference between class calibration and individual per-module calibration for white balance and color transformation. If a particular module does not have the same characteristics as the average module for which the class calibration was developed, clipping and color shifts become evident.

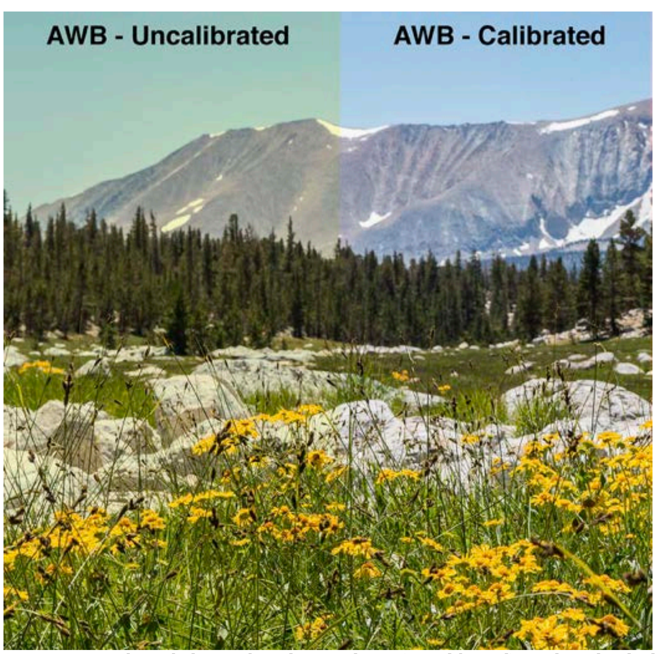

Figure 1: White balance based on class (Uncalibrated) and individual (Calibrated) module calibrations.

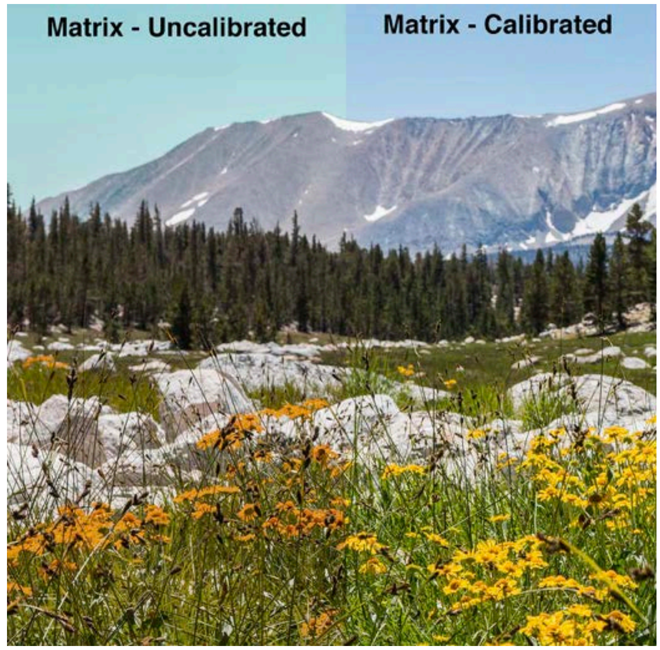

Figure 2: Color correction based on class (Uncalibrated) and individual (Calibrated) module calibrations.

Calibrating the Image Processing Pipeline

Efficient per-module calibration takes advantage of the components of the camera image processing pipeline typically implemented in an image signal processor. While many configurations are possible, a generalized system is shown in Figure 3 and the ISO 17321-1 image-state architecture terminology is used for illustrative purposes herein. While this diagram shows many of the logical steps, typical implementations will combine many of the operations, especially if multidimensional lookup tables are supported.

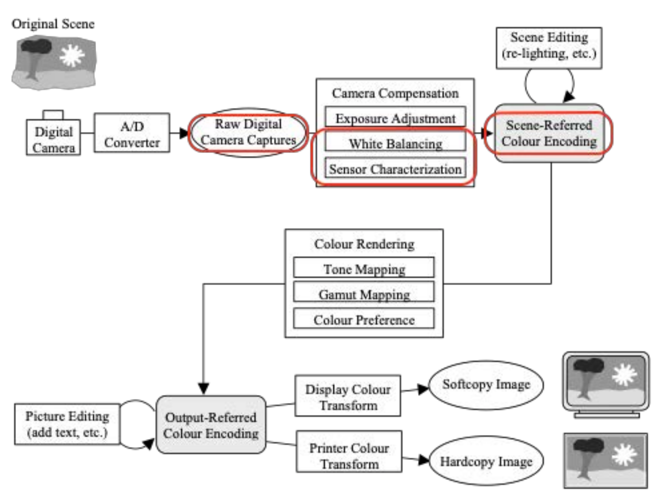

Figure 3: Typical image processing pipeline logical steps, from ISO 17321-1.

Many calibration approaches share common characteristics so calibration to a scene-referred state is described herein. This results in an unambiguous deterministic relationship between the original scene colorimetry and the scene-referred representation.

One commonly used scene-referred representation is CIE tristimulus values XYZ, which are then often linearly transformed to a more convenient (for the purpose of subsequent rendering) set of standard scene-referred values such as RIMM RGB for example. XYZ tristimulus values are computed by integrating (or its linear-algebra-equivalent combination of matrix multiplications) over wavelength the spectral product of a spectral reflectance **s**, a reference illuminant spectral power distribution **l**, and a set of color matching functions **O**. It is commonplace to use vector space arithmetic notation for these kinds of calculations. For example, suppose **S** is a matrix of a set of spectral reflectances whose dimensions are i wavelengths by j spectral samples, that **L** is an i by i diagonal matrix constructed from a reference illuminant spectral power distribution, and **O** is an i by 3 matrix of the set of CIE standard colorimetric observer color matching functions. The resulting set **V** of 3 by j tristimulus values for the set of spectral reflectances **S** is given by:

$\mathbf{V} = \mathbf{O}^t\mathbf{LS}$, scene-referred XYZ tristimulus values (1)

Or, if desired:

$\mathbf{V}' = \mathbf{AO}^t\mathbf{LS}$, scene-referred standard RGB values (2)

Where **A** is a standard conversion between CIE XYZ and the desired set of standard scene-referred RGB values.

Typically, the scene-referred representation is then rendered for application-specific user-preferences as illustrated in Figure 3. It is critical that the per-module-calibration be performed as accurately as possible since the scene-referred step is the logical input to the rest of the color rendering pipeline. Otherwise white balance and color errors will be propagated and amplified by the balance of the rendering process and become potentially visibly objectionable.

In this manner, each camera module can be characterized, and calibration factors for white balance, color transformation, etc. can be determined resulting in optimal input for color rendering. This approach has the additional advantage that upon per-module calibration, only the steps for computing the scene-referred representation need to be updated and the rest of the pipeline remains largely unchanged.

Chart-Based Calibration

The legacy method of determining the white balance factors for a camera is to present a light source that simulates the likely scene illumination and measure the relative camera responses. The white balance factors are computed to apply to each color channel such that equal camera values are achieved for neutral colors under the given illumination. This procedure is repeated for each desired scene white point.

Similarly, the camera color transform may be determined with a color chart whose color coordinates are known for specified illumination, then presenting the chart to the camera under the same illumination, and measuring the camera responses. The camera transform is then computed from the measured camera responses and the known chart color coordinates. This procedure is repeated for each desired scene white point.

This method has several limitations for production line per-module color calibration:

- The entire procedure must be repeated for every likely scene white point which is time-consuming and impractical in a high-speed production environment
- The materials have a limited lifetime and must be replaced and calibrated regularly
- The valid color transform domain is limited to the color gamut of the chart which is generally different from scenes
- The sample set size of color charts are primarily useful only for simple matrix transforms
- The spectral characteristics of natural scenes are quite different from the spectral characteristics of color charts

Figures 4 and 5 show the distribution of color sample chromaticities typical of charts and scenes. The color gamut of charts is considerably smaller than the gamut of typical scenes. The quality of color transformations created from chart data is limited by this smaller gamut and sample set size. The relatively small number of colors available with charts is primarily useful for simple matrix transforms as more accurate transforms require a more comprehensive and dense set of color samples.

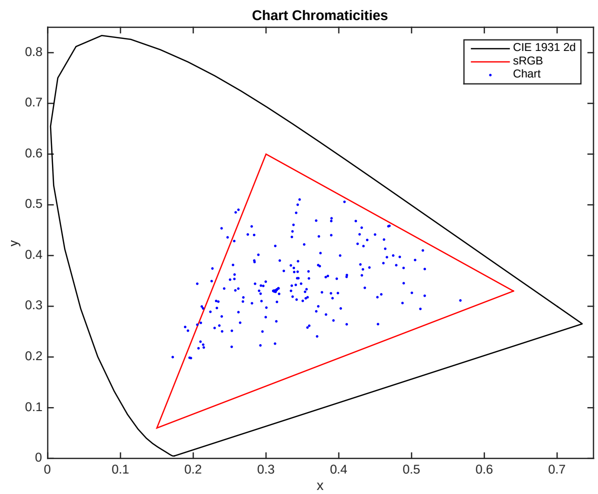

Figure 4: Distribution of color chart sample chromaticities.

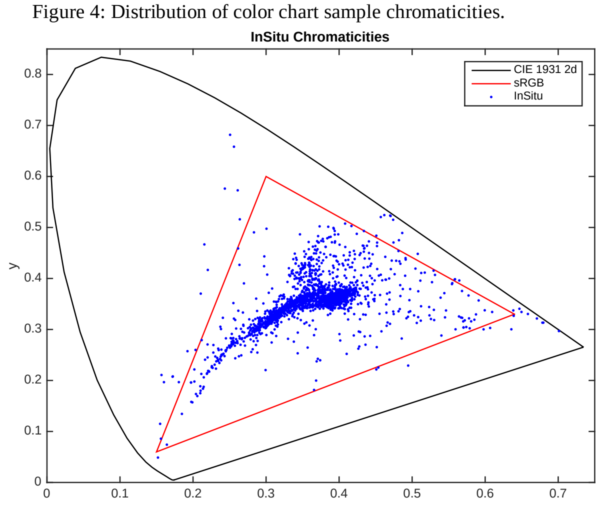

Figure 5: Distribution of natural scene element chromaticities.

Figures 6 and 7 show the first few principal components of the spectral characteristics of the charts and scenes of Figures 4 and 5. This dimensionality-mismatch is particularly important since the spectral sensitivities of most cameras are not linear combinations of human color matching functions. This leads to metameric color errors (and a resultant degradation of image quality) when the color data used to compute the color transform is not a good approximation of the likely scene color content.

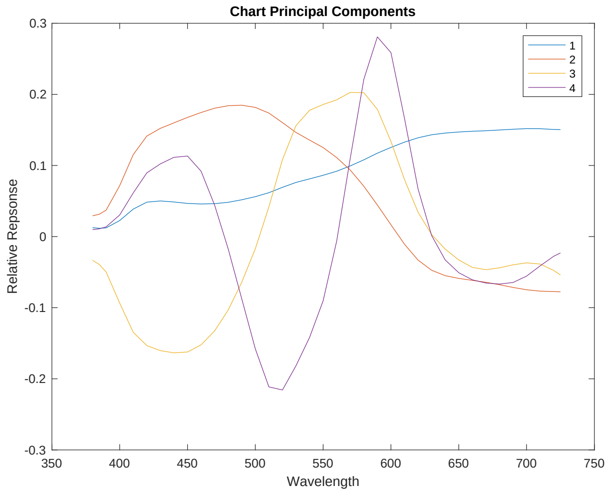

Figure 6: First 4 most significant chart spectra principal components.

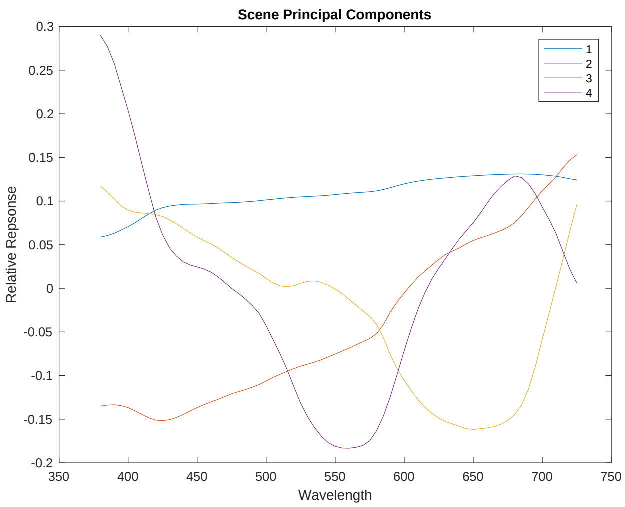

Figure 7: First 4 most significant scene spectra principal components.

For these and other reasons, modern production-line per-camera-module-calibration is migrating from these simple light and chart methods to more comprehensive spectral calibration methods which offer greater quality, flexibility, and speed.

Spectral-Based Calibration

With spectral calibration methods, instead of photographing physical charts, spectral data is collected for sample cameras and likely capture conditions, and the relevant calibration parameters are computed on a per-module basis in production. Spectral calibration produces improved flexibility and image quality over a greater range of capture conditions than can be achieved with charts since white balance and color transformations can be determined for any combination of camera, illumination, and scene spectral data. These computational spectral *characterization* and *calibration* methods are being increasingly adopted and involve the following steps.

Characterization:

- Create a reference database **D** of the spectral sensitivities of a small number of camera modules that are representative of production variation
- Obtain a database **K** of relevant light source spectral power distributions that are representative of the illumination conditions of the likely camera use-cases
- Select a database **S** of training spectral radiances of scene elements representative of the likely camera use-cases

Calibration:

- Present a set of LED spectra **T** to the camera module
- Record camera responses (e.g. RGB) **c** to the LED spectra **T**
- Compute the camera spectral sensitivities **E** from **D**, **T**, and **c**
- Compute white balance factors **G** for all lights from **K** and **E**
- Compute camera transforms **M** for each light from **K**, **S**, **E**

This separates *characterization* from *calibration*. Characterization is done once for a small set of samples of a given make and model of camera module. Production-line calibration is performed on all similar camera modules at high speed.

Camera Spectral Sensitivity Characterization

The spectral sensitivities of an imaging system describe the response to radiation of a given wavelength over the range of all wavelengths which the imaging system can detect. In the case of a typical digital camera, knowledge of the camera spectral sensitivities can be combined with likely scene spectral radiances to compute white balances and camera-specific color transforms.

Typically, ground-truth measurements of spectral sensitivities are measured with a laboratory-grade monochromator. This requires skilled operators to participate in a time-consuming and expensive process utilizing a monochromator with sufficient power throughput to achieve adequate signal to noise levels as the monochromator is stepped through all wavelengths of interest.

Recently, special-purpose monochromators have become available whose illumination, power transmission, and presentation geometry have been optimized for spectral characterization of camera modules, an example of which is shown in Figure 8. While not quite efficient enough for production-line use, it is designed specifically for establishing camera spectral sensitivity databases.

Figure 8: Image Engineering camSpecs express filter-based monochromator designed specifically for camera spectral sensitivity characterization.

For instance, in the case of the Image Engineering camSpecs express, a single photograph of the faceplate filters characterizes the camera spectral sensitivity over the complete visible and near infrared range. Figure 9 shows a database of spectral sensitivity measurements of production camera samples illustrating the need for both white balance calibration due to variation in the heights (integrals) and color transformation calibration due to variation in the shapes. The monochromator is used to measure 30-40 camera modules that are representative of production variation to create the spectral sensitivity database, **D**.

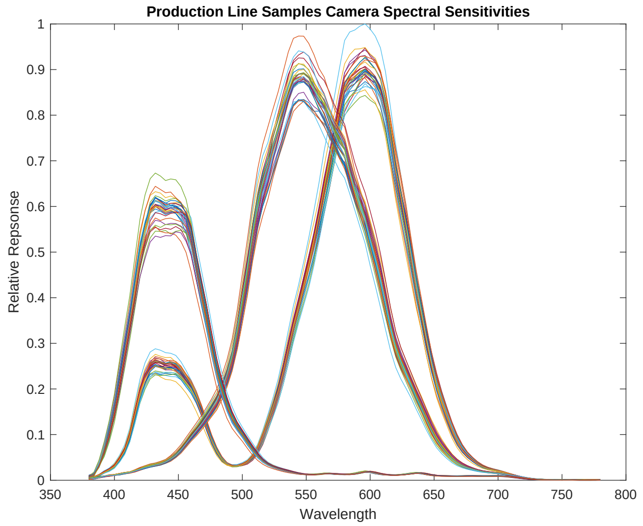

Figure 9: Spectral sensitivity database measurements **D** of 40 production camera modules show the need for white balance and color transform calibrations.

Illumination Spectral Characterization

In order to determine the white balance and color transformation factors, the spectral power distributions of likely scene illuminations must be included. Figure 10 shows typical illuminant spectra.

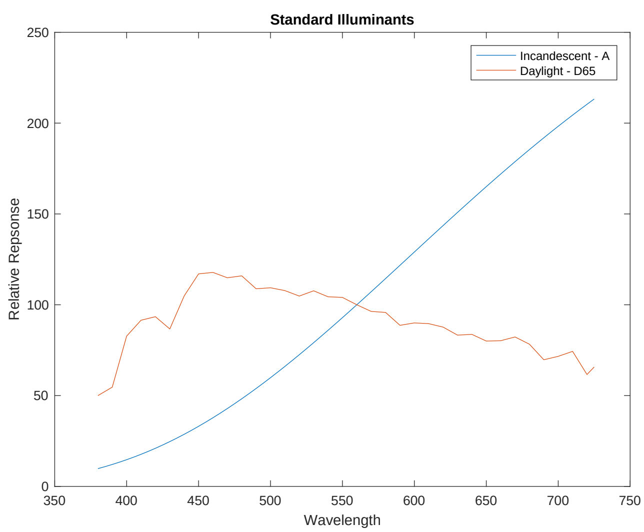

Figure 10: Spectral power distributions for CIE standard illuminants A and D65

Typically, camera processing will identify the class of scene illumination which implies an associated spectral power distribution. Standard illuminant spectral power distributions are available from the CIE and elsewhere. For the set of illumination spectral power distributions of interest **K** and the camera module spectral sensitivities **E**, the set of white balance factors **G** for all of the desired illuminants can be determined for each camera module. By including additional scene spectral training data, the color transforms for each illuminant can be determined for each module.

Scene Spectral Characterization

In order to compute the color transform from camera responses to standard color coordinates such as CIE XYZ for instance, a set of scene spectra is typically assumed. While various sets of spectral databases are widely available, most of these samples are sets of relatively diffuse spectral reflectances measured with a contact spectrophotometer. Consequently, only the surface spectral characteristics are characterized in this manner. Typical camera use cases involve far more diverse illumination modes including transmission, inter-reflection, trans-illumination, etc, under illumination modes varying from diffuse to specular for which surface contact reflectance measurements cannot adequately characterize. Figure 11 shows a scene captured under specular direct illumination while Figure 12 shows the same scene captured under indirect diffuse illumination.

Figure 11: Scene captured under specular illumination.

Figure 12: Scene captured under diffuse illumination.

Figure 13 shows the spectral radiance of the flower (scene elements fa12, fa27). Since the two spectral curves are not parallel to each other, they are different from each other in both luminance and color. This is often the case as many scenes have elements whose illumination produce body as well as surface spectral characteristics. Many colorants have different spectral properties depending on whether they are observed in partially transmissive or in reflective illumination modes.

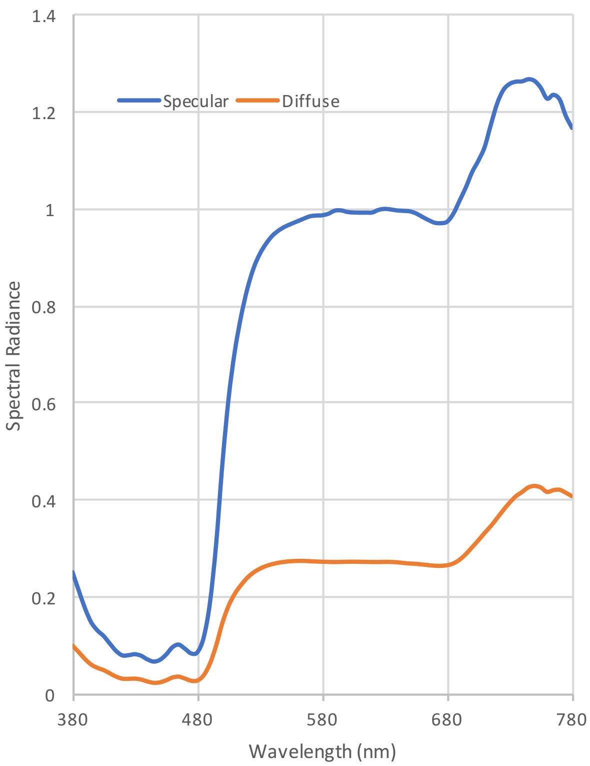

Figure 13: Diffuse and specular spectral radiances for scene element fa12.

Since it optimal to include scene spectral data that closely simulates the likely scene elements and illumination modes that the users are likely to photograph, spectral databases that are measured in-situ are typically the appropriate choice. This is accomplished by placing a telespectraradiometer in the camera position (Figure 14) and measuring the spectral radiance of the scene elements and white tile (Figure 15) under the same illumination. One such database measured in this manner is the Image Engineering InSitu database - a collection of over 2000 scene elements intended for building camera color transforms. While far less comprehensive, another such dataset can be found in ISO17321 and is adequate for evaluating camera color transforms.

Figure 14: Telespectraradiometer at camera position measuring scene elements.

Figure 15: Scene element and white tile measured under the same illumination.

Calibration Device Spectral Characterization

For high-speed production-line color-calibration, it is assumed that a programmable LED-based light source will be used to present a set of known white and color spectra to each camera module. It is essential that the LED source be spatially uniform, temporally stable, include temperature stabilization, use pulse width modulation, and include spectrophotometric self-calibration. Figure 16 shows one such device, the iQ-LED-based Cal 1 from Image Engineering and Figure 17 shows its set of white and color LED spectral power distributions used to create the set of **T**. Additionally, this instrument is also useful for linearity and color shading correction.

Figure 16: Image Engineering Cal-1 programmable LED-based light source.

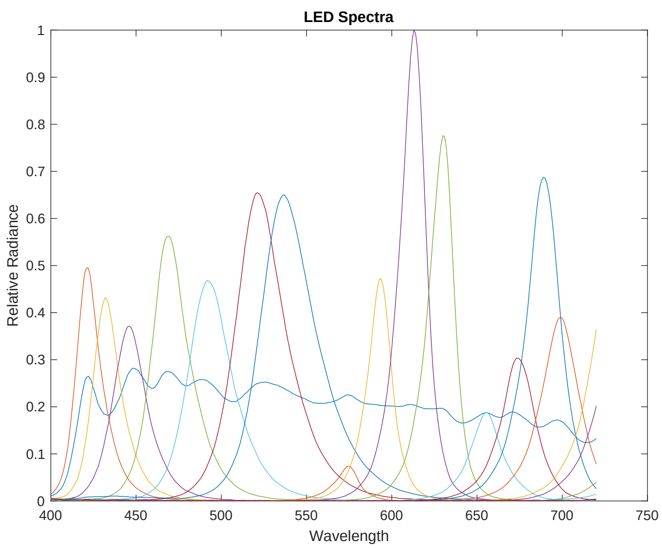

Figure 17: Image Engineering Cal-1 LED spectral power distributions used as **T**.

Production-line Spectral Calibration

The spectral calibration approach assumes that typical production camera module spectral sensitivities have been previously characterized as **D**. To calibrate any given unit in production, a set of spectral radiances from light emitting diodes of well-chosen peak wavelengths and spectral power distributions **T** are presented to the camera and the camera responses are recorded as **c**. The unknown spectral sensitivities for a given production camera module camera **e** are determined by considering the database of representative spectral sensitivities **D** and solving for the spectral sensitivities **e** that, when combined with the light emitting diode spectral power distributions **T**, best reproduce the given camera module responses **c**.

It is assumed that the color sensing behavior of the camera is linear, spatially stationary, and at the time of characterization and calibration that setup and exposure is performed in such a manner that noise is negligible. Furthermore, it is assumed that each color sensing channel is independent of the others thereby allowing separable estimation of each color channel spectral sensitivity.

In the previous Characterization sections, all the necessary elements were gathered: **D** - the database of reference camera spectral sensitivities, **K** – a set of representative scene illumination spectral power distributions, **S** – a set of relevant scene element spectral radiances, and **T** – the spectral power distributions of the LEDs that will be used to calibrate each camera module. Given this data, rapid spectral sensitivity calibration can be performed on each production camera module. From the per-module spectral sensitivity calibration, white balance and color transform calibration can be performed for arbitrary lighting and viewing conditions. The per-module calibration procedure is detailed in the next few steps.

Spectral Sensitivity Calibration

The procedure is comprised of a few simple steps:

1. An integrating sphere with an internal LED module is used to uniformly illuminate a diffusion plate located in an aperture on the surface of the sphere. The LEDs are of known spectral power distributions **T** and are selected such that the set of peak wavelengths cover the visible spectrum.
2. Each LED illuminates the diffusion plate sequentially and the response of the test camera (whose unknown spectral sensitivities **e** are to be determined) to each LED are recorded as the calibration data **c**.
3. The test camera spectral sensitivities **e** are computed in one of several ways that best reproduces the camera responses **c** to the LED spectral power distributions **T** using the spectral sensitivity database, its principal components, or its eigenvectors. This is performed for each color channel separately.

The Eigenvector Analysis (EVA) method applies when the variance in the spectral sensitivity database **D** is large, if the test camera is significantly different from those in the spectral sensitivity database, and if arbitrary constraints are desired on the solution for the unknown spectral sensitivities **e**. The camera response **c** to some presented spectra **T** results from its unknown spectral sensitivities **e** which may be represented as an unknown linear combination **w** of the first few most significant eigenvectors **P** of the spectral sensitivity database **D**:

$\mathbf{e} = \mathbf{w}^t\mathbf{P}^t$ (3)

$\mathbf{c} = \mathbf{w}^t\mathbf{P}^t\mathbf{T}$, the camera response - solving for **w** yields: (4)

$\mathbf{w} = \mathbf{c}^t(\mathbf{P}^t\mathbf{T})^t[(\mathbf{P}^t\mathbf{T})(\mathbf{P}^t\mathbf{T})^t]^{-1}$, therefore by substitution: (5)

$\mathbf{e} = \mathbf{P}(\mathbf{P}^t\mathbf{T}\mathbf{T}^t\mathbf{P})^{-1}\mathbf{P}^t\mathbf{T}\mathbf{c}$ (6)

where **T** is a matrix of the LED spectra presented to the camera whose dimensions are *i* wavelengths by *j* spectral radiance samples. **e** is an *i*-length vector of the spectral sensitivity of the camera for a given color channel. **c** is the resulting vector of camera responses for the given color channel. While it is possible to evaluate equation (6) for **e** directly, its generally desirable to solve equation (4) for **w** first then substitute **w** into equation (3) to obtain the solution for the unknown spectral sensitivities **e**. In this manner, arbitrary constraints can be easily imposed on **w** and **c** such as for positivity or other considerations using generalized numerical optimization. Furthermore, this method has the advantage that the eigenvectors **P** can be examined in advance and regularized or smoothed as desired to ensure reasonable behavior in the computed spectral sensitivities **e**.

The Principal Component Analysis (PCA) method is similar to the EVA method but has increased precision when the variance in the spectral sensitivities database **D** is small as is typically the case for production line calibration and is the preferred method:

$$\mathbf{e} = \mathbf{P}(\mathbf{P}^t\mathbf{T}\mathbf{T}^t\mathbf{P})^{-1}\mathbf{P}^t\mathbf{T}\mathbf{c}+\mathbf{m} \qquad (7)$$

In this method, **D** is first centered by subtracting its mean **m** as a function of wavelength before computing its principal components **P**. This method also presents the opportunity to employ arbitrary constraints since the two-step substitution procedure described in the EVA method also applies to the PCA method.

The Mean Square Error (MSE) method is the simplest and applies in many cases where the variance in the spectral sensitivities database **D** is small and arbitrary constraints are not required:

$$\mathbf{e} = \mathbf{D}^t\mathbf{D}\mathbf{T}(\mathbf{T}^t\mathbf{D}^t\mathbf{D}\mathbf{T}+\mathbf{R})^{-1}\mathbf{c}+\mathbf{m} \qquad (8)$$

In this method, the spectral sensitivities database **D** is first normalized by its mean and variance. The matrix **R** performs regularization, if desired, based on signal-to-noise estimates deduced from the variance in the normalized spectral sensitivities database **D**.

These methods for computing spectral sensitivities depend variably on the camera responses to the LED spectra and therefore may be computed spatially throughout the field-of-view of the camera allowing corrections to be performed on a per-pixel basis if desired – useful for color shading and other corrections. Figure 18 shows typical results with the PCA method and is compared with monochromator-measured spectral sensitivities for a production camera module represented by the database of Figure 9, but not included in the database.

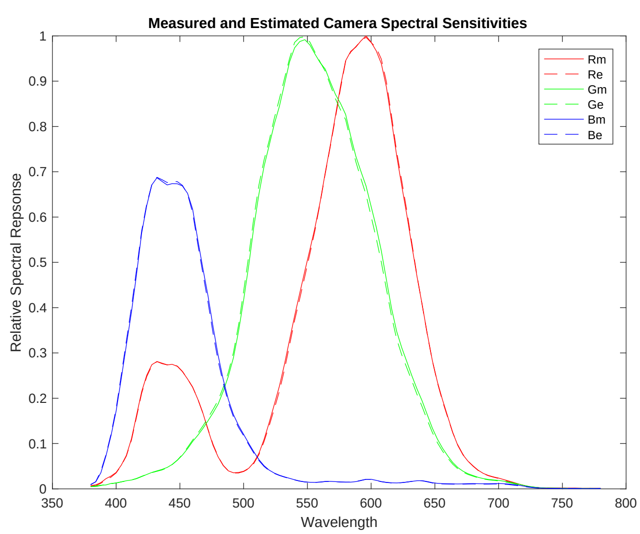

Figure 18: Measured and computed spectral sensitivities using the PCA method.

White Balance Calibration

Since the integral of camera spectral sensitivities vary from module to module as illustrated in Figure 9, its generally necessary to perform white-balance calibration on a per-module basis. Given the full set of spectral sensitivities **E** combined from each of the individual spectral sensitivities **e** computed previously, it is now possible to compute white balance factors **g** for any scene illumination **l** for which spectral power distributions are available:

$$\mathbf{g} = \mathbf{E}^t\mathbf{l} \qquad (9)$$

This is repeated for each of the light sources of interest in the complete set of reference illumination spectral power distributions **K** to create a set of calibrated white balance factors **G** for each camera module.

Color Transform Calibration

Typically, it is necessary to transform camera responses **C** resulting from the scene (e.g. RGB) to some set of standard color coordinates (e.g. CIE XYZ) **V** as inputs to the color rendering pipeline. Since the shape of camera spectral sensitivities vary from module to module as illustrated in Figure 9, its generally necessary to perform color transform calibration on a per-module basis. Given the full set of spectral sensitivities **E**, the set of reference illuminants **K**, and the set of reference scene spectra **S**, it is possible to compute operators **M** that transform between camera responses and standard color coordinates on a per-module basis for any combination of scene illumination and spectral radiances desired. While the color transform **M** can be of many linear or nonlinear forms, illustrated here is a simple linear matrix **M** that transforms between camera response **C** and CIE XYZ **V** in a least-squares sense:

$\mathbf{C} = \mathbf{E}^t\mathbf{L}\mathbf{S}$, the camera responses to scene spectra (10)

$\mathbf{V} = \mathbf{O}^t\mathbf{L}\mathbf{S}$, the tristimulus values of scene spectra (11)

where **L** is a diagonal matrix of a reference illuminant taken from the set of **K** while **O** is the set of CIE standard colorimetric observer color matching functions. The transform **M** from camera response **C** to standard color coordinates **V** is given by:

$\mathbf{V} = \mathbf{M}\mathbf{C}$, **M** transforms from camera to XYZ (12)

and the solution for **M** must be obtained, first by linear estimation:

$$\mathbf{M} = \mathbf{V}\mathbf{C}^t(\mathbf{C}\mathbf{C}^t)^{-1} \qquad (13)$$

then typically followed by nonlinear optimization in a perceptual space (e.g. CIE L*a*b*) or preferably in an appearance space (e.g. CIECAM16 JMh):

$$f_{min} = \arg(\min(\|f(\mathbf{V})-f(\mathbf{MC})\|)) \qquad (14)$$

where f maps to the desired optimization space and the transform **M** is iterated to minimize the cost function f_{min} comprised from the color or appearance errors between the known values f(**V**) and the predicted values f(**MC**). It is generally desirable to reduce the degrees of freedom of the problem by constraining the row sums of **M** to the white point of the illuminant **l** thereby preserving proper white balance.

This is repeated for each of the light sources of interest in the complete set of reference illumination spectral power distributions and any additional scene spectra sets that are representative of other camera scene-modes to create a complete set of calibrated color transforms for each camera module.

Since both scene spectral data and camera spectral sensitivities are available, the color transform need not be limited to low-dimensional linear matrix operators. With this spectral data, it is possible to construct multidimensional lookup tables which offer greater color accuracy as well as precise control over edge-of gamut and out-of-gamut behavior. Additionally, multidimensional lookup tables offer the opportunity to optimize color accuracy as a function of input signal level thereby minimizing camera noise artifacts.

Summary

Production line spectral calibration maximizes camera-module quality while lowering cost. Compared with other calibration approaches, camera modules that might fail quality assurance standards are more likely to pass with spectral calibration. Spectral calibration offers more precise control over white balance, linearity, color shading, and color transform parameters on a per-module or per-pixel basis thereby producing higher yield than with legacy approaches.

The spectral calibration approach assumes spectral characterizations of representative cameras, scenes, and illumination conditions that are performed *a priori*. While in production, each camera-module can be calibrated at high speed using commercially available hardware and software products.

Author Biography

Eric Walowit's interest is in appearance estimation, color management, camera characterization, and digital photography. He is founder (retired) of Color Savvy Systems, a color management company. He currently helps friends and colleagues with interesting color problems and ventures. He graduated from RIT's Image Science program in 1985, concentrating in Color Science. He has authored more than 50 patents, publications, and presentations. Eric is a member of ICC, ISOTC42, CIEJTC10, and IS&T.