# Procedure

# P-2013-001

# Recommended Procedures for the Creation and Use of Digital Camera System Input Device Transforms (IDTs)

The Academy of Motion Picture Arts and Sciences

Science and Technology Council

Academy Color Encoding System (ACES) Project Committee

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Summary: In the Academy Color Encoding System, an Input Device Transform (IDT) processes non-color-rendered RGB image values from a digital camera system's capture of a scene lit by an assumed illumination source (the scene adopted white). The results of this process are white-balanced ACES RGB relative exposure values.

Camera system vendors are recommended to provide two IDTs for each product, one optimized for CIE Illuminant D55 (daylight) and a second optimized for the ISO 7589 Studio Tungsten illuminant. Camera system vendors may optionally provide additional IDTs for common illumination sources such as Hydrargyrum Medium-arc Iodide (HMI) and KinoFlo® lamps.

The main body of this document provides a procedure for the creation and use of an IDT from the measured spectral responsivities of a digital camera system. Appendices provide examples of the use of the procedure, each illustrating a different engineering tradeoff. An additional appendix provides an alternative procedure for IDT creation if the spectral data required for the recommended procedure are unobtainable.

## NOTICES

## Revision History

| Version | Date | Description |
|---|---|---|
| 0.94 | 12/19/2014 | Recommended Procedures for the Creation and Use of Digital Camera System Input Device Transforms (IDTs) |
| 1.0 | 04/24/2015 | Formatting adjustments and typo fixes |
| | 03/29/2016 | Remove version number - to use modification date as UID |
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## Related Academy Documents

| Document Name | Description |
|---|---|
| S-2008-001 | Academy Color Encoding Specification (ACES) |
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# Acknowledgements

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# Introduction

## What an IDT does

In the Academy Color Encoding System (ACES), the Input Device Transform (IDT) converts non-color-rendered RGB image values from a given camera system or other image capture device to ACES RGB relative exposure values.

### Required behaviors

The image data produced by the IDT shall

- In the case of D60 illumination, approximate the ACES RGB relative exposure values that would be produced by the RICD[1],
- Approximate radiometrically linear representations of light reaching the focal plane,
- Contain a nonzero amount of flare as specified in the ACES document,
- Use equal RGB relative exposure values to represent colors that are neutral under the illumination source for which the IDT is designed, and
- Approximate a colorimetric response to the scene for the illumination source for which the IDT is designed, though the native camera system response itself may not be colorimetric.

### Optional behaviors

In addition to the required IDT behaviors, several other behaviors, while not implied by the ACES document, are common enough to deserve mention. At the IDT manufacturers discretion, the image data produced by the IDT may

- Be modified in such a way as to minimize artifacts resulting from camera system clipping, including white balance-specific highlight clipping and recovery.
- Be compensated for differences between the chromaticity of neutrals from the white-balanced camera system and the chromaticity of neutrals in the ACES encoding.

### Recommended illumination source support

The set of IDTs for a given camera system should include IDTs optimized for daylight (CIE Illuminant D55) and tungsten (ISO 7589 Studio Tungsten).

### Optional illumination source support

The set of IDTs may include IDTs for common illumination sources such as Hydrargyrum Medium-arc Iodide (HMI) and KinoFlo® lamps.

### Expectations of IDT input

An IDT is expected to be applied after the following types of initial processing: dark frame subtraction, noise reduction, flat fielding, demosaicing, conversion to a device-specific RGB color space, and/or deblurring. If, for a particular camera system, linearization or white balance takes place prior to one of the abovementioned processes, then that linearization or white balance shall be excluded from the IDT.

### Camera system ‘look; consequences of the IDT

There is no camera-system-independent ‘cookbook’ procedure for producing optimal IDTs. Camera system manufacturers may differ on how to distribute color analysis error across the set of all possible input colors, and may have different philosophies on neutral chromaticity difference compensation.

[1] The spectral sensitivities of the RICD are defined in Annex C of SMPTE ST 2065-1:2008.

Moreover there are an infinite number of possible illumination conditions under which a scene might be captured; even if a manufacturer decided on particular strategies to ameliorate color analysis error and to compensate for the scene neutral chromaticity differing from ACES' neutral chromaticity, 'optimal' capture might require an infinity of IDTs.

To avoid confusion and other problems, the Academy recommends this infinity be reduced to the smallest possible number consistent with best cinematographic practice.

As implied by the 'Recommended illumination source support' section above, this number could be as low as two (a daylight IDT and a tungsten IDT, paralleling film workflows). Some camera systems may also provide finer-grain control of correlated color temperature (interpolating CCT between daylight and tungsten illumination sources, for example), or may handle 'outlier' sources such as HMI or KinoFlo®. The key point of the Academy recommendation is that there be a single differentiating factor between the IDTs offered for a particular digital camera system: the IDT's assumed illumination source.

### Evaluating IDT output

An IDT produces image data that have not been color rendered, and that closely maintain the radiometric relationship of the objects in the captured scene as they existed at the camera focal plane. Image data in this state are well suited for interfacility image exchange, for some sophisticated image operations (e.g. partial or full recovery of highlight detail), for photo-realistic compositing, and for merger with Computer Generated Imagery (CGI) elements.

For critical color evaluation, such image data should be color rendered using the ACES Reference Rendering Transform (RRT), processed by an ACES Output Device Transform (ODT) and viewed using the device and viewing environment specified by the ODT creator.

### Relationship of IDT and Look Modification Transform (LMT)

When a creative choice is made to move the 'look' of the captured imagery away from maximum fidelity to the image existing at the focal plane, this change should be effected not by changing the behavior of the IDT, but by post-processing the IDT output with a Look Modification Transform (LMT) or a set of LMTs.

The on-set relationship of the IDT, any LMT or set of LMTs, the RRT and the ODT for an on-set preview device is shown in Figure 1[2].

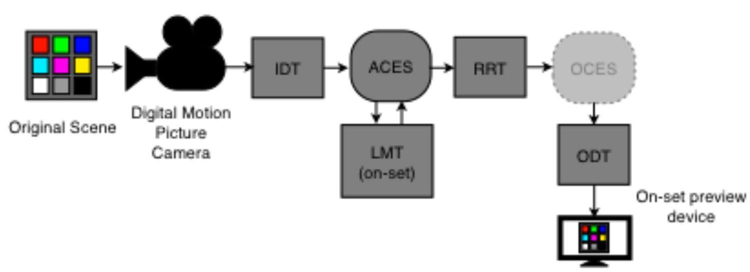


**Figure 1**

Camera system image data are processed by the IDT prior to the application of any LMT or set of LMTs. This means that whether that LMT or set of LMTs is expressed as a Color Transform Language (CTL) program, or as an American Society of Cinematographers Color Decision List (ASC CDL), a 3D LUT provided by the camera vendor, or some combination thereof, the 'look' is being imposed on ACES data.

The LMT or set of LMTs thereafter accompanies the ACES data through postproduction; critical color judgments are made through the concatenation of the 'look' that was established on-set and any additional 'look'

[2] ACES and the Digital Cinema Distribution Master (DCDM) encoding are intended for use as image storage encodings. Although it is possible to use the Output Color Encoding Specification (OCES) encoding for image storage, it is primarily a conceptual encoding, a common 'jumping-off point' for Output Device Transforms (ODTs), and is thus shown in Figure 1 in light rather than in dark gray.

applied in post-production, as shown in Figure 2.

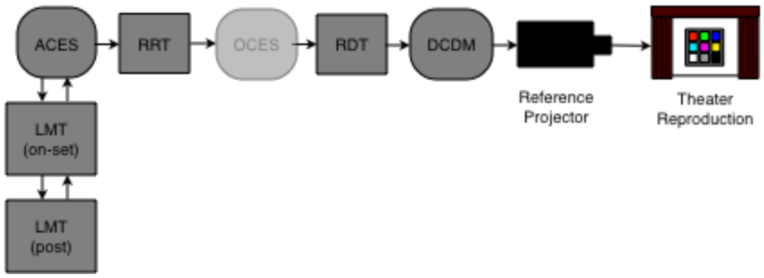


**Figure 2**

Throughout production and postproduction, the ‘look’ established by the cinematographer is carried in parallel with the unmodified ACES data produced by the camera system IDT.

This separation of ‘look’ and unmodified ACES data supports workflows in which the ACES data’s approximation of truly accurate colorimetric capture can greatly aid production, such as when the content will be merged with CGI accurately modeling the physical properties of lights and reflectances in the real or virtual scene. It also separates the tasks of capture and of modeling downstream processes such as the transformation of image data to simulate film-based capture.

Finally, the LMT provides a well-defined point where camera manufacturers can provide emulation of traditional camera system controls, allowing the cinematographer to ‘paint with the camera.’

# How an IDT works

## Structure of an IDT

As detailed above, the required and most common optional responsibilities of an IDT are six-fold: linearization, white balancing, clipping, color analysis, neutral chromaticity difference compensation and encoding as ACES RGB relative exposure values. The first typically requires per-channel functions or 1-dimensional lookup tables (LUTs). The second of these is accomplished by per-channel scaling to the RGB data. The third (clipping) can be done simply or in complex manners that attempt to reconstruct or extrapolate clipped values. The fourth and fifth are accomplished together by the application of a 3x3 signal processing matrix and the sixth is a simple uniform scaling of the matrixed RGB channel data. The final resulting image data are ACES RGB relative exposure values.

This document provides a recommended procedure for the creation of an IDT whose core is a 3x3 matrix that converts normalized white-balanced radiometrically linear RGB code values representing a digital camera system’s capture of a scene to ACES RGB relative exposure values. In doing so, it fulfills the required functions of an IDT and implements several of the optional behaviors (notably clipping and neutral chromaticity difference compensation.) Building the IDT around a single 3x3 matrix has several advantages:

- It follows standard industry practice[3].
- It allows preservation of neutral camera system RGB code values to be enforced mathematically, and chromaticity is invariant with exposure changes.
- It limits the degrees of freedom of the transform, preventing the transform from following the training set colors too closely at the expense of other colors.
- It introduces a smaller amount of color analysis error in its output than would be the case if RICD emulation and neutral chromaticity compensation were separate, individually-optimized transforms.

[3]SMPTE RP 177:1993 (R2003), Derivation of Basic Television Colour Equations

- It is readily invertible, allowing for reconstruction of white-balanced radiometrically linear camera system RGB code values from ACES RGB relative exposure values.
- Its application is simple to understand.

### Linearization

Linearization is constrained to occur between initial acquisition of sensor data and white balance. It is interspersed with operations such as dark current subtraction, pixel defect correction, flat-fielding, and in some cases demosaicing and deblurring. In some camera systems, it may be necessary to incorporate linearization into the IDT; in other camera systems, linearization may be performed prior to the application of the IDT as part of performing those other operations. The result of linearization is an RGB encoding in which RGB channel values are directly and linearly proportional to radiometric energy at the camera focal plane.

### White balancing

The linearized RGB image data are scaled by RGB channel multipliers such that a perfect reflecting diffuser in the scene, illuminated by the scene adopted white, would be encoded with equal RGB channel values.

Although the channel multipliers could conceivably be specified explicitly and independently, it is anticipated that many camera systems will set the channel multipliers providing the white balance when the cinematographer chooses an IDT. The absolute values of the channel multipliers are such that white-balanced linearized RGB image data representing a captured perfect reflecting diffuser illuminated by the scene adopted white would have equal RGB channel values all being unity.

White balance is constrained to occur after linearization and before clipping. In systems where white balancing must precede operations which cannot be done inside the IDT (demosaicing, for example) white balance will need to be done external to and prior to application of the IDT.

### Clipping

The linearized, white-balanced RGB image data are clipped prior to matrix application. This recommended procedure imposes a simple clipping method by which all RGB channel values are clipped to the maximum RGB values imposed or implied by the original camera system encoding.

More ambitious clipping strategies are possible but as these are typically proprietary, and may depend on information being available in a device-dependent way (they may, for example, rely on the ability to examine the values of neighboring pixels), such clipping strategies are not discussed in this document.

### Matrix application

The linearized, white-balanced clipped RGB image data are multiplied by a 3x3 matrix. This matrix implements two functions simultaneously: color analysis, and neutral chromaticity difference compensation.

Color analysis attempts to minimize differences between the spectral responsivities of actual camera sensors and the spectral responsivities of the RICD, a hypothetical colorimetric camera whose spectral sensitivities are exactly expressed as linear transformations of the CIE 1931 colorimetric observer. Such differences can be minimized but not entirely eliminated. The distribution of residual error is an expression of the manufacturer's prioritization of some colors over others, in particular, of 'memory' colors over colors rarely found in digital motion picture production.

Since manufacturers will have different priorities of color preference, there can be no uniquely appropriate weighting system for color error, and the procedure given in this document for IDT manufacture avoids any prioritization entirely: all residual error is weighted equally.

Neutral chromaticity difference compensation reconciles differences between the chromaticity of the scene adopted white and the chromaticity of ACES neutrals (which is the chromaticity of CIE Standard Illuminant D60). Different approaches are possible, variously modeling standard practice in film and in digital still camera (DSC) workflows, among others.

Since manufacturers will have preferences as to one style of neutral chromaticity difference compensation over another, no unique procedure can determine an appropriate 3x3 matrix for implementation. The procedures given in this document will allow for the three cited styles of neutral chromaticity difference compensation and the examples given in Appendix A will show the various styles in use.

Although color analysis and neutral chromaticity difference compensation could be derived and expressed as individual 3x3 matrices then concatenated together for efficiency of application, they are usually derived through a single combined optimization. The procedure described in this document follows this standard practice and co-optimizes the two matrices.

### Overall exposure scaling

The linearized, white-balanced and matrixed values are uniformly scaled such that a spectrally neutral 18% reflector captured under the scene adopted white would map to ACES RGB relative exposure values of [0.18, 0.18, 0.18].

## How an IDT is designed

Parts of the IDT design process are often completely determined by the specifications of the digital camera system. If the camera system's Opto-Electronic Conversion Function (OECF), for example, has a unique inverse, then that inverse will provide the data for the IDT's linearization function. If the camera system's spectral responsivities are known, then for a given scene adopted white there is a unique set of camera system channel multipliers that will implement white balancing. And at the other end of the IDT's internal pipeline, all other IDT elements being designed, the magnitude of the matrixed, clipped, white-balanced, linearized RGB values for a captured 18% spectrally neutral reflector will decide the value of the final overall RGB exposure scalar.

The design of the remaining IDT processes (clipping, minimization of color analysis error and neutral chromaticity difference compensation) all involve engineering decisions and, possibly, proprietary design techniques. This section will briefly describe the design process for the latter two functions.

### Minimization of color analysis error

The color analysis matrix is derived through linear regression of two sets of colorimetric values.

The first set is the camera system's linearized, white-balanced RGB values in response to a set of test stimuli. The second set is the RGB values expected from the Reference Input Capture Device (RICD) for the same set of test stimuli.

The first set can be computed from the measured spectral sensitivities of the camera system and the radiances of a set of training spectra. The second set can be computed from the known spectral sensitivities of the Reference Input Capture Device (RICD) and that same set of training spectra.

The quality and utility of the color analysis delivered by the thus-regressed matrix depends on the degree to which the image capture device's response to light is colorimetric (that is, to the degree the capture devices spectral responsivities can be expressed as linear combinations of the color matching functions of the CIE 1931 Standard Colorimetric Observer), on the degree to which the test stimuli used for determining the IDT (the 'training spectra') represent those found in the actual scene, and on the nature of the distribution of errors in the approximation across those actual scene colors.

Training spectra selection will involve balancing selection of pure spectral colors with the spectra of real-world objects, and of objects measured in isolation vs. objects measured in situ. Error weighting can be done with various degrees of sophistication. Simple repetition of colors in the data set is probably the most straightforward way to weight the results, and this technique is sometimes used to boost the priority of neutrals and other important colors. More sophisticated schemes can examine the type and context, not just the magnitude, of the error. For example, in regions of the color space representing human skin tones, hue accuracy might be given more importance than lightness, but in near-neutral deep shadow, lightness might be given preference over hue.

### Neutral chromaticity difference compensation

The engineering approaches employed when creating an IDT that compensates for the scene adopted white chromaticity differing from that of ACES neutral chromaticity may include:

1. Chromatically adapting the training colors from the scene adopted white chromaticity to the ACES adopted neutral chromaticity. This approach, often used in digital still camera (DSC) design, produces aim colors for the error minimization that have a similar appearance relative to the ACES adopted neutral as the training colors have relative to the scene adopted neutral.
2. Illuminate the training spectral reflectances by a source that is spectrally similar to CIE Standard Illuminant D60 rather than the actual scene illumination source. This approach produces aim colors for the error minimization that attempt to emulate the capture of the scene under CIE Standard Illuminant D60.

## An alternative to recommended IDT design

An alternative to the recommended procedure for IDT creation is provided as a final Appendix to this document. The alternative procedure describes how captured images of test charts under an illumination source (or captured images of an emissive target) can be used to create an IDT. In practice, many camera systems have been calibrated with this method. In uncontrolled environments, however, this alternative procedure is highly susceptible to contamination of the captured test chart data, either by dirt, fading or other irregularities in the test chart materials or by temporal variance in the illumination of the test chart. It also limits the training spectra used to those that can be produced using the test chart. It is strong suggested that when possible, the recommended procedure for IDT creation described in Section 4 of this document should be used.

# 1 Scope and audience

The procedures described in this guide are appropriate for the creation of Input Device Transforms (IDTs) for digital still cameras or digital motion picture camera systems that directly or indirectly provide radiometrically linear focal-plane-referred camera system RGB code values, i.e. that have not been color rendered, and which provide for any dark current subtraction, gain correction (flat fielding), deblurring, and/or noise filtering prior to the application of an IDT.

The procedures provided in this guide are intended for use by camera system manufacturers. Those procedures are not intended for use by Directors of Photography (DPs), nor for on-set technical personnel working under their supervision (e.g. Digital Imaging Technicians (DITs)), as it is expected the camera system manufacturer will provide IDTs for 'standard' capture environments, and that those manufacturer-provided IDTs will have a level of quality difficult to match in the field.

IDT authors are the digital counterparts of film emulsion designers. Authors of LMTs are the digital counterparts of film lab technicians, film color timers, or traditional cinematographers who 'paint with the camera;' as such, LMT authors are recommended to read this document, since their task will be to process the results of transforms developed using the procedures it provides.

# 2 References

The following standards, specifications, articles, presentations, and texts are referenced in this text:

SMPTE ST 2065-1:2012, Academy Color Encoding Specification

ISO 7589:2002, Photography – Illuminants for sensitometry – Specifications for daylight, incandescent tungsten and printer

ISO/TR 17321-2, Graphic technology and photography – Colour characterization of digital still cameras (DSCs) – Part 2: Considerations for determining scene analysis transforms

SMPTE RP 177:1993 (R2003), Derivation of Basic Color Television Equations

# 3 Terms and Definitions

The following terms and definitions are used in this document.

3.1 Academy Color Encoding Specification (ACES)

RGB color encoding for exchange of image data that have not been color rendered, between and throughout production and postproduction, within the Academy Color Encoding System. ACES is specified in SMPTE ST 2065-1.

3.2 ACES RGB relative exposure values

Relative responses to light of the ACES Reference Image Capture Device, determined by the integrated spectral responsivities of its color channels and the spectral radiances of scene stimuli.

3.3 ACES unity neutral

A triplet of ACES RGB relative exposure values all of which have unity magnitude.

3.4 chromatic adaptation

A process by which the visual mechanism adjusts in response to the radiant energy to which the eyes are exposed.

3.5 chromaticity

A property of a color stimulus defined by the ratios of each tristimulus value of the color stimulus to their sum.

3.6 color rendering

The mapping of image data representing the color-space coordinates of the elements of a scene to output-referred image data representing the color-space coordinates of the elements of a reproduction. Color rendering generally consists of one or more of the following: compensating for differences in the input and output viewing conditions, tone scale and gamut mapping to map the scene colors onto the dynamic range and color gamut of the reproduction, and applying preference adjustments.

3.7 color stimulus

Radiant energy such as that produced by an illumination source, by the reflection of light from a reflective object, or by the transmission of light through a transmissive object, or a combination of these.

3.8 focal-plane-referred

A representation of a captured scene that includes any flare light introduced by the cameras optical system.

3.9 Input Device Transform (IDT)

A signal-processing transform that maps an image capture systems representation of an image to ACES RGB relative exposure values.

3.10 memory color

A color sensation derived from memory rather than the immediate perception of a color stimulus.

3.11 radiometric linearity

An attribute of a representation of measured energy in which a change in the amount of measured energy is accompanied by an equal change in the representation of that energy, e.g. a doubling of measured energy is matched by a doubling of the quantity representing that energy.

3.12 Reference Input Capture Device (RICD)

A hypothetical camera, which records an image of a scene directly as ACES RGB relative exposure values.

3.13 re-illumination

An alteration of colors of a captured scene simulating the reflectance of objects in a scene illuminated by an illumination source other than the one under which the scene was captured.

3.14 scene adopted white

A spectral radiance distribution as seen by an image capture or measurement device that is converted to color signals that are considered to be perfectly achromatic and to have an observer adaptive luminance factor of unity; i.e. color signals that are considered to correspond to a perfect white diffuser.

3.15 spectral responsivity

The response of a detection system as a function of wavelength.

3.16 spectral sensitivity

The response of a detector to monochromatic stimuli of equal radiant power.

3.17 white balance

The process of adjusting the RGB signals of an electronic camera system such that equal signals are produced for an object in the scene that is desired to be achromatic

# 4 Recommended procedure for IDT creation

The core of a digital camera system IDT is the 3x3 matrix by which radiometrically linear camera RGB code values are transformed to produce ACES RGB relative exposure values. This procedure describes the derivation of such a matrix.

To have fully followed the recommendations given in this document, IDT authors should provide an IDT for daylight and an IDT for tungsten illumination sources. The daylight illumination source should have the spectral power distribution of CIE Standard Illuminant D55; the tungsten illumination source, ISO 7589 Studio Tungsten.

NOTE: All references to CIE XYZ tristimulus values in this recommendation refer to colorimetric coordinates defined with respect to the CIE 1931 XYZ color space and the CIE 1931 2° Standard Colorimetric Observer.

## 4.1 Selection and Weighting of Training Data

The quality of an IDT constructed as per this recommendation will depend heavily on the diversity and distribution of the set of spectral radiances used in IDT matrix optimization. Training spectra selection should attempt to sample the entire space of real-world scene spectra. Particularly important scene spectra, such as memory color spectra, may be weighted more heavily than colors rarely found in everyday life.

Training spectra should represent in situ stimuli if possible: the training spectrum representing a blade of grass illuminated by sunlight should be representative of that blade of grass in the context of surrounding leaves of grass, rather than in isolation on a laboratory slide, since very few motion pictures feature grass examined under a microscope. Only a small part of the reflected light from a single blade of grass is a first-bounce reflection of sunlight; the larger part of the illumination of a blade of grass in production photography will bounce off of or pass through neighboring blades of grass.

## 4.2 Assumptions and prerequisites

This procedure is appropriate when the IDT manufacturer desires to implement some form of neutral chromaticity difference compensation. It presumes the following information is available to the IDT manufacturer before applying the procedure:

- A set of training spectra against which the IDT matrix will be optimized, expressed either as spectral radiances, or as spectral reflectances which can be multiplied with the spectral power distribution of the scene adopted white to form spectral radiances.
- The spectral power distribution of the scene adopted white.
- A neutral chromaticity difference compensation strategy when the scene adopted white chromaticity differs from that of ACES neutrals.
- A transform from camera system image data code values to three-channel radiometrically linear image data.
- The spectral responsivities of the digital camera system for which the IDT is being created.
- A transform from CIE XYZ colorimetry into an error minimization color space.
- The error metric (cost function) that will be minimized, and any weights that will be applied differentially to the training spectra.

The sampling bounds and sampling interval of the spectra for the scene adopted white, for the RICD spectral responsivities, for the camera system spectral responsivities and for the training spectra are assumed to be the same so that mathematical operations can be performed without ambiguity. In addition, the procedure presumes the IDT author has access to software capable of mathematical operations including vector and matrix algebra, linear regression and minimization with user-defined cost functions.

## 4.3 Symbols

In the table and equations below, lower case italic letters ($m$) represent scalars, lower case bold face letters ($\mathbf{h}$) represent vectors, and upper case bold face letters ($\mathbf{M}$) represent matrices.

| Symbol | Domain | Description |
|---|---|---|
| $m$ | $\Re$ | Number of samples in spectral data. |
| $n$ | $\Re$ | Number of training spectra. |
| $\mathbf{C}$ | $\Re^{m\times 3}$ | Spectral responsivities of camera system (with channel gain differences maintained). |
| $(\mathbf{r}_i)_{i=1}^{n}$ | $\Re^{m}$ | Spectral reflectances of training spectra. |
| $(\mathbf{t}_i)_{i=1}^{n}$ | $\Re^{m}$ | Spectral radiances of training spectra. |
| $(\mathbf{x}_i)_{i=1}^{n}$ | $\Re^{3}$ | CIE XYZ tristimulus values of training spectra. |
| $(\mathbf{d}_i)_{i=1}^{n}$ | $\Re^{3}$ | Native color encoding of the camera system response values of training spectra. |
| $(\mathbf{v}_i)_{i=1}^{n}$ | $\Re^{3}$ | Scaled white-balanced radiometrically linear camera system response values for training spectra. |
| $\mathbf{h}_s$ | $\Re^{m}$ | Spectral power distribution of scene illumination source. |
| $\mathbf{w}_s$ | $\Re^{3}$ | CIE XYZ tristimulus values of the scene illumination source. |
| $\mathbf{h}_w$ | $\Re^{m}$ | Spectral power distribution of scene adopted white. |
| $\mathbf{w}_w$ | $\Re^{3}$ | CIE XYZ tristimulus values of the scene adopted white. |
| $\mathbf{M}$ | $\Re^{3\times 3}$ | Matrix converting ACES RGB relative exposure values to CIE XYZ tristimulus values. |
| $\mathbf{w}$ | $\Re^{3}$ | CIE XYZ tristimulus values of ACES unity neutral. |
| $\mathbf{X}$ | $\Re^{m\times 3}$ | CIE 1931 2° Standard Observer color matching functions. $\mathbf{X}_{\mathrm{Y}}$ is the spectral luminous efficiency function. |
| $\mathbf{b}$ | $\Re^{3}$ | Camera system white balancing and scaling factors. |
| $\mathbf{B}$ | $\Re^{3\times 3}$ | Matrix converting white-balanced scaled camera system RGB response values to ACES RGB relative exposure values. |
| $\mathbf{A}_{Bradford}$ | $\Re^{3\times 3}$ | Bradford matrix for chromatic adaptation, with value $\begin{bmatrix} 0.8950 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix}$ |
| $\mathbf{A}_{CAT02}$ | $\Re^{3\times 3}$ | CAT02 matrix for chromatic adaptation, with value $\begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$ |
| $\mathbf{A}_{re-illum}$ | $\Re^{3\times 3}$ | Example matrix for re-illumination[1], with value $\begin{bmatrix} 1.6160 & -0.3591 & -0.2569 \\ -0.9542 & 1.8731 & 0.0811 \\ 0.0170 & -0.0333 & 1.0163 \end{bmatrix}$ |

[1]Both the contents of this matrix and the method by which it is calculated may be protected by patent(s) including but not limited to U.S. Patent No. 7,298,892 (Inventors: Spaulding, Kevin E.; Woolfe, Geoffrey J.; and Giorgianni, Edward J.).

## 4.4 Functions

In the table and equations below, functions are indicated by a (possibly subscripted) lower case letter or word, followed by comma-separated arguments enclosed in parentheses. Arguments represented by italic lower case letters are scalars, those represented by lower case bold face letters are vectors, and those represented by upper case bold face letters are matrices.

| Function | Domain | Description |
|---|---|---|
| $\mathrm{f}_{\mathrm{CAM}}(\mathbf{x}, \mathbf{w})$ | $\Re^3 \rightarrow \Re^3$ | Return color appearance correlates for tristimulus values $\mathbf{x}$ under adopted white $\mathbf{w}$ suited for measurement of color difference. |
| $\min(\mathbf{v})$ | $\Re^m \rightarrow \Re$ | Return the minimum element of vector $\mathbf{v}$. |
| $\gamma(\mathbf{c})$ | $\Re^3 \rightarrow \Re^3$ | Decode camera image data code values $\mathbf{c}$ to normalized radiometrically linear camera system exposures. |
| $\psi(\mathbf{A}, \mathbf{w})$ | $\Re^3 \rightarrow \Re^3$ | Create a re-illumination matrix which transforms tristimulus values to an alternative color space using matrix $\mathbf{A}$, multiplies transformed values by the reciprocal of transformed white $\mathbf{w}$, and inverse transforms the scaled transformed values to their original color space using the inverse of matrix $\mathbf{A}$. $$\psi(\mathbf{A}, \mathbf{w}) = \mathbf{A}^{-1} \begin{bmatrix} \rho & 0 & 0 \\ 0 & \gamma & 0 \\ 0 & 0 & \beta \end{bmatrix} \mathbf{A}$$ with $$\begin{bmatrix} \rho \\ \gamma \\ \beta \end{bmatrix} = \frac{1}{\mathbf{A}\mathbf{w}}$$ |
| $\phi(\mathbf{A}, \mathbf{w_1}, \mathbf{w_2})$ | $\Re^3 \rightarrow \Re^3$ | Create a chromatic adaptation matrix which transforms tristimulus values to an alternative color space using matrix $\mathbf{A}$, scales transformed values by ratio of transformed white $\mathbf{w_2}$ to transformed white $\mathbf{w_1}$, and inverse transforms the scaled transformed values to their original color space using the inverse of matrix $\mathbf{A}$. $$\phi(\mathbf{A}, \mathbf{w_1}, \mathbf{w_2}) = \mathbf{A}^{-1} \begin{bmatrix} \rho & 0 & 0 \\ 0 & \gamma & 0 \\ 0 & 0 & \beta \end{bmatrix} \mathbf{A}$$ with $$\begin{bmatrix} \rho \\ \gamma \\ \beta \end{bmatrix} = \frac{\mathbf{A}\mathbf{w}_2}{\mathbf{A}\mathbf{w}_1}$$ For equal whites, $\phi$ shall be the identity function: $$\mathbf{w}_1 = \mathbf{w}_2 \Rightarrow \phi(\mathbf{A}, \mathbf{w_1}, \mathbf{w_2}) = \mathbf{I}$$ |
| $\min(\mathbf{v})$ | $\Re^m \rightarrow \Re$ | Return the minimum element of vector $\mathbf{v}$. |
| $\mathrm{clip}(\mathbf{v})$ | $\Re^m \rightarrow \Re^m$ | Clip channel values in vector $\mathbf{v}$ to [1, 1, 1], or extrapolate the channels clipped on capture from the unclipped channels. |

## 4.5 Operations

In the table and equations below, lower case italic letters ($m$) represent scalars, lower case bold face letters ($\mathbf{h}$) represent vectors, and upper case bold face letters ($\mathbf{M}$) represent matrices.

| Operation | Domain | Description |
|---|---|---|
| $\mathbf{v} + \mathbf{w}$ | $\Re^m \to \Re^m$ | Element-wise addition of vectors in $\Re^m$. |
| $\mathbf{v} * \mathbf{w}$ | $\Re^m \to \Re^m$ | Element-wise multiplication of vectors in $\Re^m$. |
| $\mathbf{v}/\mathbf{w}$ | $\Re^m \to \Re^m$ | Element-wise division of vectors in $\Re^m$, $w_i > 0$. |
| $\mathbf{vw}$ | $\Re^m \to \Re$ | Dot product of vectors in $\Re^m$, $\mathbf{vw} = \sum_i^m v_i w_i$. |
| $\mathbf{Mv}$ | $\Re^{nxm}, \Re^m \to \Re^m$ | Matrix-vector multiplication $\mathbf{v} \ni \Re^m$, $\mathbf{M} \ni \Re^{nxm}$. |
| $\mathbf{M}_{\mathrm{T}}$ | $\Re^{nxm} \to \Re^{mxn}$ | Transposition of matrix $\mathbf{M}$. |

## 4.6 Constant symbol values

### 4.6.1 Compute CIE XYZ tristimulus values of the ACES unity neutral

The CIE XYZ tristimulus values $\mathbf{w}$ of the ACES unity neutral will be the same for all IDTs, as the elements involved in its computation do not include scene- or camera-system-specific data; the values are computed by post-multiplication of $\mathbf{M}$ (the ACES RGB to CIE XYZ conversion matrix defined in Section 4.1.1 of the ACES document) by the ACES unity neutral:

$$\mathbf{M} = \begin{bmatrix} 0.9525523959 & 0 & 0.0000936786 \\ 0.3439664498 & 0.7281660966 & -0.0721325464 \\ 0 & 0 & 1.0088251844 \end{bmatrix}$$

$$\mathbf{w} = \mathbf{M} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

## 4.7 Computation

### 4.7.1 Compute (if required) spectral radiances of illuminated training spectral reflectances

When the training colors $\mathbf{t}_i$ are expressed as spectral radiances, they may be used directly in the equations below. When they are expressed as spectral reflectances $\mathbf{r}_i$ under a scene adopted white with spectral power distribution $\mathbf{h}_w$ the resulting spectral radiances are calculated as

$$\mathbf{t}_i = \mathbf{h}_w * \mathbf{r}_i$$

### 4.7.2 Compute CIE XYZ tristimulus values of training colors spectral radiances

The training color CIE XYZ tristimulus values are calculated as

$$\mathbf{x}_i = \mathbf{X}^{\mathrm{T}} \mathbf{t}_i$$

### 4.7.3 Compute CIE XYZ tristimulus values of scene adopted white

The scene adopted white CIE XYZ tristimulus values are calculated as

$$\mathbf{w}_w = \mathbf{X}^{\mathrm{T}} \mathbf{h}_w$$

#### 4.7.4 Adjust training color CIE XYZ tristimulus values to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity

Unless the scene adopted white happens to have the chromaticity of ACES neutrals (which have the chromaticity of CIE Standard Illuminant D60), some transformation is required to map the scaled white-balanced camera system response values that would result from the capture of the scene adopted white to the ACES unity neutral.

The training color CIE XYZ values are transformed to a balancing color space, scaled, then transformed back to CIE XYZ. When this balancing color space is structured around the cone responses of the human visual system (HVS), the scaling transform models chromatic adaptation; when the balancing color space is one of a class of color spaces particularly optimized for color adjustment, the scaling models re-illumination.

Three possible matrices representing a white balance transform are given in this section. The first and second model chromatic adaptation. The third models re-illumination.

##### 4.7.4.1 Alternatives 1 and 2: chromatic adaptation

The training color CIE XYZ values are chromatically adapted such that neutral reflectors illuminated by the scene adopted white are encoded with the chromaticities of ACES neutrals. Two matrices are provided in this document, one defining the Bradford chromatic adaptation transform, and one defining the CAT02 transform.

$\mathbf{x}'_i = \phi(\mathbf{A}_{Bradford}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$ or $\mathbf{x}'_i = \phi(\mathbf{A}_{CAT02}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$

##### 4.7.4.2 Alternative 3: re-illuminate white-balanced ACES RGB relative exposure values for ACES neutral chromaticity

The training color CIE XYZ values are scaled such that the scene adopted white CIE XYZ values are mapped to the ACES unity neutral CIE XYZ values and the white-balanced camera system exposure values are left unchanged.

$\mathbf{x}'_i = \phi(\mathbf{A}_{re-illum}, \mathbf{w}_w)\mathbf{x}_i$

#### 4.7.5 Compute camera system white balance factors

The camera system white balance factors map and normalize the linearized camera system responses corresponding to the capture of a perfect reflecting diffuser illuminated by the scene adopted white to camera system RGB values [1, 1, 1].

$$\mathbf{b} = \frac{1}{\mathbf{C}^{\mathrm{T}}\mathbf{h}_w}$$

#### 4.7.6 Compute white-balanced linearized camera system response values of training colors

The camera system spectral responsivity functions are post-multiplied by the training spectral radiances and scaled by the camera system white balance factors to produce the white-balanced, linearized, and normalized camera system response values for the set of training colors.

$$\mathbf{v}_i = \mathbf{b} * \mathbf{C}^{\mathrm{T}}\mathbf{t}_i$$

#### 4.7.7 Create initial values for the unoptimized IDT matrix entries

The matrix $\mathbf{B}$ is made up of 6 free parameters $(\beta_i)_{i=1}^{6}$.

$$\mathbf{B} = \begin{bmatrix} \beta_1 & \beta_2 & 1-\beta_1-\beta_2 \\ \beta_3 & \beta_4 & 1-\beta_3-\beta_4 \\ \beta_5 & \beta_6 & 1-\beta_5-\beta_6 \end{bmatrix}$$

Although other methods are possible, this document recommends the use of linear regression between the ACES RGB relative exposure values $\mathbf{x}'_i$ calculated in Section 4.7.3 and the white balanced camera system response values for the training colors $\mathbf{v}_i$ determined in Section 4.7.6.

The constraint that each row of matrix entries sums to unity can be formulated into the regression[2] or can be enforced by scaling the parameters obtained from unconstrained regression (although the latter gives only an approximation of the true solution).

#### 4.7.8 Select a cost function for error minimization

The cost function sums the distances between the target values and the transformed camera system response values after both sets of values have been transformed to a suitable color appearance space. The merit function is

$$\chi^2 = \sum_i^n \left\| \mathbf{f}_{\mathrm{CAM}}(\mathbf{x}'_i, \mathbf{w}) - \mathbf{f}_{\mathrm{CAM}}(\mathbf{MBv}_i, \mathbf{w}) \right\|$$

Choices for a suitable color appearance space for $\mathbf{f}_{\mathrm{CAM}}$ include

- Nonlinear, neutral preserving RGB
- CIE L*u*v*
- CIE L*a*b*
- CIECAM

NOTE: Other color spaces may also be used.

NOTE 2: More complex cost functions may also be used to weight the importance of particular training spectra, or to weight particular aspects of the approximation of the RICD's capture of training spectra (hue angle, luminance, colorfulness) more heavily than others, or in other ways chosen by the IDT author.

#### 4.7.9 Find final matrix values minimizing cost function

An iterative algorithm is used to minimize the cost function with respect to the parameters $\beta$. Existing implementations of this IDT calculation use the nonlinear least squares regression from MATLAB's Optimization Toolbox, or the `optim` function in R, or the `FindMinimum` function in Mathematica.

#### 4.7.10 Application

The IDT converts image data to ACES RGB relative exposure values $\mathbf{a}$ as follows:

$$\mathbf{a} = k\mathbf{B}\mathrm{clip}\left(\frac{\mathbf{b} * \gamma(\mathbf{d})}{\min(\mathbf{b})}\right)$$

where $\gamma$, $\mathbf{b}$, $\min()$, clip() and $\mathbf{B}$ are as defined in Sections 4.3 and 4.4; $\mathbf{d}$ is an image data code value vector; and $k$ is the factor that results in a nominally "18% gray" object in the scene producing ACES values [0.18, 0.18, 0.18].

##### 4.7.10.1 Application using CTL

A CTL function taking a normalized linear camera system RGB code value and returning an ACES RGB relative exposure value could be implemented as follows:

[2] Finlayson and Drew: White-point preserving color correction, Proceedings of the Fifth Color Imaging Conference, 1997.

```
// D200 IDT
// D55 illuminant
// camSPECS-measured D200 spec sens
// Woolfe/Spaulding/Giorgianni space for reconciliation of
// scene adopted white chromaticity and ACES neutral chromaticity
// (cf. U.S. Patent No. 7,298,892).

float
min(float a, float b) {
  if (a < b)
    return a;
  else
    return b;
}

float
clip(float v) {
  return min(v, 1.0);
}

void
main
(   input varying float rIn,
    input varying float gIn,
    input varying float bIn,
    input varying float aIn,
    output varying float rOut,
    output varying float gOut,
    output varying float bOut,
    output varying float aOut)
{

const float b[] = { 0.00102373, 0.000570585, 0.000797976 };

const float B[][] = { {  0.674849,    0.231105,  0.0940463 },
                      {  0.0431725,   1.06981,  -0.112982  },
                      {  0.0312748,  -0.151054,  1.11978   } };

const float min_b = min(b[0], min(b[1], b[2]));
const float e_max = 1.0;
const float k     = 1.0;

float clippedRGB[3];
clippedRGB [0] = clip((b[0] * rIn) / (min_b * e_max));
clippedRGB [1] = clip((b[1] * gIn) / (min_b * e_max));
clippedRGB [2] = clip((b[2] * bIn) / (min_b * e_max));

rOut = k * (B[0][0] * clippedRGB[0] + B[0][1] * clippedRGB[1] + B[0][2] * clippedRGB[2]);
gOut = k * (B[1][0] * clippedRGB[0] + B[1][1] * clippedRGB[1] + B[1][2] * clippedRGB[2]);
bOut = k * (B[2][0] * clippedRGB[0] + B[2][1] * clippedRGB[1] + B[2][2] * clippedRGB[2]);

}
```

# Appendix A

(informative)

# Examples of IDT construction

## A.1 IDT Construction for a Linearized Colorimetric Camera System and a D60 Scene Adopted White

This is the simplest case of IDT manufacture. Since the camera system is colorimetric, there is a unique and perfect conversion between the camera system RGB primaries and the ACES RGB primaries. Since the scene adopted white is equal to the encoding white, no neutral chromaticity difference exists, and thus the neutral chromaticity difference compensation matrix is the identity matrix.

The only decision needed from the manufacturer is outside the scope of this recommended procedure: clipping strategy. Therefore procedures Section 4.7.1 through Section 4.7.9 may be followed nearly verbatim, with $\mathbf{x}'_i$ of Section 4.7.4 being replaced by the identity matrix.

### A.1.1 Compute spectral radiances of illuminated training spectral reflectances

$\mathbf{t}_i = \mathbf{h}_w * \mathbf{r}_i$

### A.1.2 Compute CIE XYZ tristimulus values of training spectral reflectances

$\mathbf{x}_i = \mathbf{X}^{\mathrm{T}}\mathbf{t}_i$

### A.1.3 Compute CIE XYZ tristimulus values of scene adopted white

$\mathbf{w}_w = \mathbf{X}^{\mathrm{T}}\mathbf{h}_w$

### A.1.4 Adjust training color CIE XYZ values to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity

$\mathbf{x}'_i = \phi(\mathbf{A}_{Bradford}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$

Note that when the scene adopted white chromaticity is that of CIE Illuminant D60 (and therefore identical to ACES neutral chromaticity) the function $\phi$ will yield an identity matrix, with this equation reducing to

$\mathbf{x}'_i = \mathbf{x}_i$

### A.1.5 Compute camera system white balance factors

$$\mathbf{b} = \frac{1}{\mathbf{C}^{\mathrm{T}}\mathbf{h}_w}$$

### A.1.6 Compute white-balanced linearized camera system response values of training colors

$\mathbf{v}_i = \mathbf{b} * \mathbf{C}^{\mathrm{T}}\mathbf{t}_i$

### A.1.7 Create initial values for the unoptimized IDT matrix entries

$$\mathbf{B} = \begin{bmatrix} \beta_1 & \beta_2 & 1 - \beta_1 - \beta_2 \\ \beta_3 & \beta_4 & 1 - \beta_3 - \beta_4 \\ \beta_5 & \beta_6 & 1 - \beta_5 - \beta_6 \end{bmatrix}$$

### A.1.8 Select a cost function for error minimization

$$\chi^2 = \sum_{i}^{n} \left\| \mathbf{f}_{\mathrm{CAM}}(\mathbf{x}'_i, \mathbf{w}) - \mathbf{f}_{\mathrm{CAM}}(\mathbf{MBv}_i, \mathbf{w}) \right\|$$

### A.1.9 Find final matrix values minimizing cost function

Note that since the camera is colorimetric, the minimized cost function value should be 0, and the final matrix should be the same as would be produced by the matrix calculation.

## A.2 IDT Construction for a Non-Linearized, Non-Colorimetric Camera System and a D60 Scene Adopted White

In this example, the scene adopted white still matches the encoding white, and therefore no neutral chromaticity difference exists. The camera system, however, is non-colorimetric; unlike the camera system described in Section A.1, cost minimization will *not* produce a zero result, implying the presence of color analysis error in the camera system. IDT manufacturers may wish to modify the training spectral reflectances to redistribute color analysis error, e.g. scene neutrals might be repeated in the training spectral reflectances to emphasize their importance

### A.2.1 Compute spectral radiances of illuminated training spectral reflectances

$$\mathbf{t}_i = \mathbf{h}_w * \mathbf{r}_i$$

### A.2.2 Compute CIE XYZ tristimulus values of training spectral reflectances

$$\mathbf{x}_i = \mathbf{X}^{\mathrm{T}}\mathbf{t}_i$$

### A.2.3 Compute CIE XYZ tristimulus values of scene adopted white

$$\mathbf{w}_w = \mathbf{X}^{\mathrm{T}}\mathbf{h}_w$$

### A.2.4 Adjust training color CIE XYZ values to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity

$$\mathbf{x}'_i = \phi(\mathbf{A}_{Bradford}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$$

### A.2.5 Compute camera system white balance factors

$$\mathbf{b} = \frac{1}{\mathbf{C}^{\mathrm{T}}\mathbf{h}_w}$$

### A.2.6 Compute white-balanced linearized camera system response values of training colors

$$\mathbf{v}_i = \mathbf{b} * \mathbf{C}^{\mathrm{T}}\mathbf{t}_i$$

### A.2.7 Create initial values for the unoptimized IDT matrix entries

$$\mathbf{B} = \begin{bmatrix} \beta_1 & \beta_2 & 1-\beta_1-\beta_2 \\ \beta_3 & \beta_4 & 1-\beta_3-\beta_4 \\ \beta_5 & \beta_6 & 1-\beta_5-\beta_6 \end{bmatrix}$$

#### A.2.8 Select a cost function for error minimization

$$\chi^2 = \sum_{i}^{n} \left\| \mathbf{f}_{\mathrm{CAM}}(\mathbf{x}'_i, \mathbf{w}) - \mathbf{f}_{\mathrm{CAM}}(\mathbf{M}\mathbf{B}\mathbf{v}_i, \mathbf{w}) \right\|$$

#### A.2.9 Find final matrix values minimizing cost function

Since the camera is not colorimetric, the minimized cost function value will not be 0 and will be limited by the camera spectral sensitivities, the choice of training spectral reflectances, and choice of color appearance space for $\mathrm{f}_{\mathrm{CAM}}$.

## A.3 IDT Construction for a Non-Colorimetric Camera System, a Tungsten Scene Adopted White, and a Target 'Look' of a Tungsten Capture

In this example, the scene adopted white no longer matches the encoding white, a neutral chromaticity difference exists, and the final result of the IDT construction procedure will need to embody neutral chromaticity difference compensation as well as correct for the non-colorimetric camera system response.

#### A.3.1 Compute spectral radiances of illuminated training spectral reflectances

$$\mathbf{t}_i = \mathbf{h}_w * \mathbf{r}_i$$

#### A.3.2 Compute CIE XYZ tristimulus values of training spectral reflectances

$$\mathbf{x}_i = \mathbf{X}^{\mathrm{T}}\mathbf{t}_i$$

#### A.3.3 Compute CIE XYZ tristimulus values of scene adopted white

$$\mathbf{w}_w = \mathbf{X}^{\mathrm{T}}\mathbf{h}_w$$

#### A.3.4 Adjust training color CIE XYZ values to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity

Since the scene adopted white chromaticity differs from the ACES neutral chromaticity, some sort of transform must map the former to the latter. In this example, since we wish to preserve the appearance of the tungsten-lit scene, we employ a chromatic adaptation transform, employing a Bradford matrix.

$$\mathbf{x}'_i = \phi(\mathbf{A}_{Bradford}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$$

#### A.3.5 Compute camera system white balance factors

$$\mathbf{b} = \frac{1}{\mathbf{C}^{\mathrm{T}}\mathbf{h}_w}$$

#### A.3.6 Compute white-balanced linearized camera system response values of training colors

$$\mathbf{v}_i = \mathbf{b} * \mathbf{C}^{\mathrm{T}}\mathbf{t}_i$$

#### A.3.7 Create initial values for the unoptimized IDT matrix entries

$$\mathbf{B} = \begin{bmatrix} \beta_1 & \beta_2 & 1-\beta_1-\beta_2 \\ \beta_3 & \beta_4 & 1-\beta_3-\beta_4 \\ \beta_5 & \beta_6 & 1-\beta_5-\beta_6 \end{bmatrix}$$

#### A.3.8 Select a cost function for error minimization

$$\chi^2 = \sum_{i}^{n} \left\| \mathbf{f}_{\mathrm{CAM}}(\mathbf{x}_i', \mathbf{w}) - \mathbf{f}_{\mathrm{CAM}}(\mathbf{MBv}_i, \mathbf{w}) \right\|$$

#### A.3.9 Find final matrix values minimizing cost function

Since the camera is not colorimetric, the minimized cost function value will not be 0 and will be limited by the camera spectral sensitivities, the choice training spectral reflectances, choice of transforms used to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity, and choice of color appearance space for $\mathrm{f}_{\mathrm{CAM}}$.

## A.4 IDT Construction for a Non-Colorimetric Camera System, a Tungsten Scene Adopted White, and a Target 'Look' of a D60 Capture

In this example, the scene adopted white no longer matches the encoding white, a neutral chromaticity difference exists, and the final result of the IDT construction procedure will need to embody neutral chromaticity difference compensation as well as correct for the non-colorimetric camera system response.

#### A.4.1 Compute spectral radiances of illuminated training spectral reflectances

$$\mathbf{t}_i = \mathbf{h}_w * \mathbf{r}_i$$

#### A.4.2 Compute CIE XYZ tristimulus values of training spectral reflectances

$$\mathbf{x}_i = \mathbf{X}^{\mathrm{T}}\mathbf{t}_i$$

#### A.4.3 Compute CIE XYZ tristimulus values of scene adopted white

$$\mathbf{w}_w = \mathbf{X}^{\mathrm{T}}\mathbf{h}_w$$

#### A.4.4 Adjust training color CIE XYZ values to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity

Since the scene adopted white chromaticity differs from the ACES neutral chromaticity, some sort of transform must map the former to the latter. In this example, since we wish to generate the appearance of the tungsten-lit scene having instead been captured under CIE Illuminant D60, we employ a transform, that uses a matrix specifically designed for such re-illumination.

$$\mathbf{x}_i' = \psi(\mathbf{A}_{re-illum}, \mathbf{w}_w, \mathbf{w})\mathbf{x}_i$$

#### A.4.5 Compute camera system white balance factors

$$\mathbf{b} = \frac{1}{\mathbf{C}^{\mathrm{T}}\mathbf{h}_w}$$

#### A.4.6 Compute white-balanced linearized camera system response values of training colors

$$\mathbf{v}_i = \mathbf{b} * \mathbf{C}^{\mathrm{T}}\mathbf{t}_i$$

#### A.4.7 Create initial values for the unoptimized IDT matrix entries

$$\mathbf{B} = \begin{bmatrix} \beta_1 & \beta_2 & 1-\beta_1-\beta_2 \\ \beta_3 & \beta_4 & 1-\beta_3-\beta_4 \\ \beta_5 & \beta_6 & 1-\beta_5-\beta_6 \end{bmatrix}$$

#### A.4.8 Select a cost function for error minimization

$$\chi^2 = \sum_i^n \left\| \mathbf{f}_{\mathrm{CAM}}(\mathbf{x}'_i, \mathbf{w}) - \mathbf{f}_{\mathrm{CAM}}(\mathbf{M}\mathbf{B}\mathbf{v}_i, \mathbf{w}) \right\|$$

#### A.4.9 Find final matrix values minimizing cost function

Since the camera is not colorimetric, the minimized cost function value will not be 0 and will be limited by the camera spectral sensitivities, the choice training spectral reflectances, choice of transforms used to compensate for difference between scene adopted white chromaticity and ACES neutral chromaticity, and choice of color appearance space for $\mathrm{f}_{\mathrm{CAM}}$.

# Appendix B

(informative)

# IDT Construction From Captures of Target Materials

If the digital camera system spectral responsivities cannot be obtained from the camera system manufacturer, and the equipment and environment for spectral sensitivity characterization are unavailable, an alternative approach may provide enough data to construct a digital camera system IDT, albeit one with less flexibility and potentially lower quality than direct use of spectral responsivities would provide. With this alternative approach, target patches are captured by both a reference measurement device (such as, for example, a tele-spectroradiometer) and by the digital camera system being characterized. The RICD's documented spectral responsivities are combined with the patches' spectral characteristics to produce the RICD's captured values for those patches, and optimization of those two sets of patchesafter both have been transformed to some error minimization spaceyields the 3x3 matrix at the core of the IDT.

This process can be divided into steps:

1. Spectral or colorimetric measurement of target patches and the target illumination source
2. Calculation of ACES RGB relative exposure values from spectral or colorimetric measurements
3. Digital camera system capture of the target patches under the target illumination source
4. Reconstruction of linear camera exposure values from digital camera system OECF and captured patch values
5. Conversion of reconstructed linear camera exposure and ACES RGB relative exposure values to an error minimization space
6. Linear regression of reconstructed linear camera exposure values and ACES RGB relative exposure values, as converted to the error minimization space, to produce initial values of 3x3 IDT matrix
7. Optimization of the 3x3 IDT matrix
8. Embedding of the optimized 3x3 IDT matrix in an IDT transform

Those steps are discussed in the following sections:

### Spectral measurement of target patches

Telespectroradiometric measurements are preferable to combined spectral reflectance and illumination measurements, especially if the target exhibits fluorescence.

The measurement geometrythe relative position of measurement device or digital camera, sample patch and (for reflective target patches) any illumination source(s)should be rigidly established and maintained. It is critical that this measurement geometry be carried over to target patch capture with the digital camera. If characterization is done on a lab bench, the measurement device and the digital camera should be on the target normal at target center, and the target illumination should be from two opposing directions at 45° to the target normal. The illumination sources must have identical spectral characteristics. The illumination sources should be sufficiently distant from the target so as not to cause a combined illumination variation exceeding $\pm 1\%$ across the target area. Two omni-directional light sources positioned as above, and at a height exceeding four times the largest target dimension, results in a variation within $\pm 1\%$. (If characterization is done onset in daylight conditions then the requirement for opposing directions is dropped.) Neither the target's visibility to the capture device nor the illumination sources' visibility to the target should be in any way obstructed.

The acceptance angle of the measuring instrument, the instrument's position relative to the target patch and the size of the target patch should be such that the edges of the target patch are not being measured: if the patch is recessed in its support, the edges may be shadowed, and moreover the patch center may be more planar than the patch edges. Typical acceptance angles for measuring instruments, when used for this type of capture, range between $^1/_2^\circ$ and $2^\circ$.

Ideally the measurement device or digital camera position would be fixed, the illumination source position and spectral power distribution would be fixed, target patches would be measured individually with the target moved under a mask made from a black material, with mask and target held in a plane perpendicular to the measurement device or digital camera. As with recessed patches, however, this risks shadows being cast into the sampled target area by the target patch mask.

### Calculation of ACES RGB relative exposure values from measurements

The ACES R, G and B relative exposure values are obtained by a two-step process.

1. Compute the dot products of the measured spectral radiance of the target patch (either emitted radiance, or reflected illumination radiance) and the corresponding area-normalized RICD spectral sensitivities given in Annex C of the ACES document.
2. Augment the computed values with the amount of camera flare associated with the RICD, as specified in the ACES document.

### Digital camera capture of the target patches

The considerations of in situ capture, measurement geometry, avoidance of patch edges and use of target patch mask have been covered in a previous section. Digital camera capture requires several other factors be considered:

- The digital camera system data should not be irrevocably modified as part of any color rendering process. Digital camera system output that has been color rendered, typically encoded as video files, often has been internally altered in some spatially and perhaps temporally variant way to suit aesthetic preferences and has lost its relationship to scene radiometry.
- Capture should be at a single exposure level; automatic exposure determination should be disabled. The aperture and exposure time should be established such that clipping of the chart patches is avoided. Usually this can be accomplished when a gray card is captured with ‘normal’ exposure.
- Capture should be with the lens and filter(s) which will be used in production, including filtration for white balance, for reduction of UV, IR or unpolarized light, or for overall reduction of exposure with ND filters.
- Digital camera image compression should be ‘lossless’, or disabled entirely.
- No aesthetic corrections or color-balancing operations should be done between capture and analysis.
- The captured data should be radiometrically linear, whether that linearity be native to the captured image format, or the result of inversion of the native camera system image encoding. If natively linear, there should be at least 10 bits of linear data per RGB component. If linear is the result of an inversion of a log or power function used by the native camera system image encoding data metric, then the data prior to inversion should have at least 8 bits of encoded data per RGB component. The preservation of radiometric linearity can be verified by measurement and capture of a series of spectrally neutral targets.
- If multiple target patches are acquired in a single exposure, the target should occupy the center of the frame and its image on the camera sensor should not extend into regions where lens vignetting or other factors influence transmitted energy relative to that transmitted along the common camera and lens axis.
- The black level should be captured. This allows for estimating and removing the dark current. The black level should be captured with the same exposure settings as used to capture the patches, for example by covering the lens with a lens cap. The black level should be captured immediately after capturing the spatial illumination, as this tends to reduce the black current in defect pixels to levels commonly found in actual production.

- The spatial distribution of the illumination should also be captured. This allows for compensation of uneven illumination and vignetting. This should be captured by replacing the target with a white card, gray card, or similar object having a uniform color and non-specular Binary Reflectance Distribution Function (BRDF). The replacement object must have the same placement as the target, so as not to change the reflected light.
- The captured data for the target patch should be spatially (and if multiple captures are possible, temporally) averaged prior to use. As mentioned above, the averaged pixels should be from target patch center; target patch edges may be in shadow or nonplanar and should be avoided. At least 1,000 pixels, preferably 10,000 pixels, should be included in the computation of the average. The standard error of mean should not exceed 0.1% of the average value.

### Reconstruction of linear camera exposure values from digital camera OECF and captured patch values

The linear data from the prior step describe the response of the camera to light present at the focal plane (that is, at the sensor). These data should be obtained by

1. Averaging any sequences of image data representing multiple captures of a single target patch.
2. Applying the inverse of the Camera system optoelectronic conversion function (OECF) to the camera system values.[1]
3. Correcting for the estimated irregularities in the spatial distribution of the illumination.
4. Subtracting the estimated dark current.

### Conversion of reconstructed linear camera system exposure and ACES RGB relative exposure values to an error minimization space

The reconstructed linear camera system exposure and ACES RGB relative exposure values should be converted to a common error minimization space.

If this common error minimization space depends on the choice of some white tristimulus value, the same CIE XYZ value for white should be used for both sets of conversions.

### Regression of linear camera system exposure values and ACES RGB relative exposure values to produce an optimized 3x3 IDT matrix

Regression of the 3x3 IDT matrix values proceeds in a manner identical to that described in Sections 4.7.7, 4.7.8, and 4.7.9.

### Embedding of the optimized 3x3 IDT matrix in an IDT transform

The optimized 3x3 IDT matrix is embedded in a CTL transform in a manner identically to that described in Section 4.7.10.

[1] Determination of the Camera OECF should follow the procedures given in ISO 14524, Photography – Electronic still-picture cameras – Methods for measuring opto-electronic conversion functions (OECFs).