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Specification

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Academy Color Encoding Specification (ACES)

The Academy of Motion Picture Arts and Sciences

Science and Technology Council

Image Interchange Framework Subcommittee

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Summary: The Academy Color Encoding Specification (ACES) is the common color encoding for the Academy's Image Interchange Framework. The specification defines the ACES RGB color encoding method, the ACES neutral axis, the matrices used for converting ACES values to CIE XYZ values and CIE XYZ values to ACES values, and the ACES floating-point color encoding metric. It describes how ACES RGB colors can be used to capture the creative intent of the cinematographer and relates the encoded colors to other components of the Image Interchange Framework and to imaging system components expecting radiometrically linear inputs.

NOTICES

Revision History

Version	Date	Description
1.0	08/12/2008	Initial Academy Color Encoding Specification
1.0.1	08/05/2011	Minor typographical corrections. Resolutions of diagrams increased. Correction in Annex B equation.

Related A.M.P.A.S Documents

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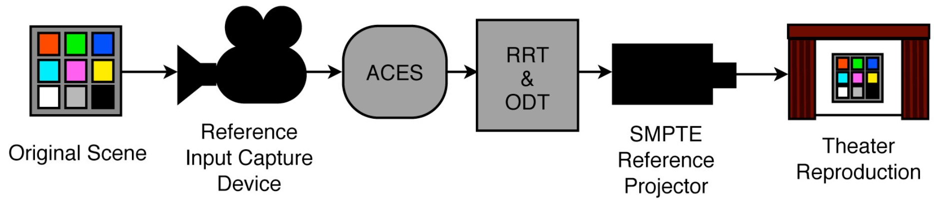
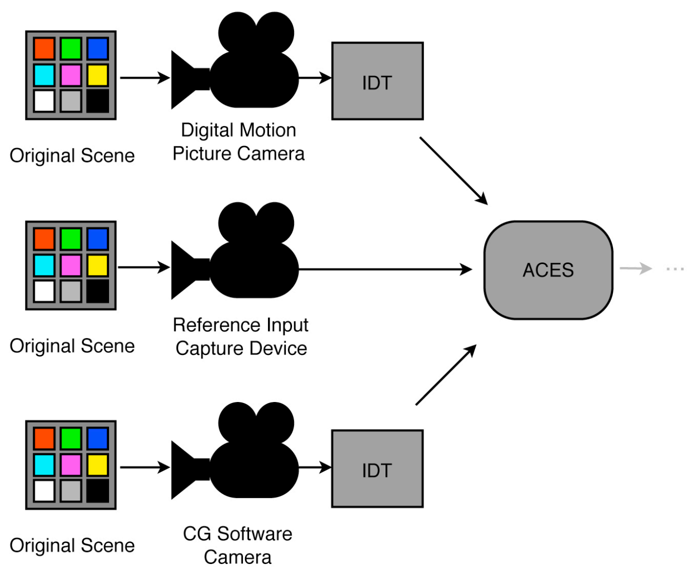
Introduction

The Academy Color Encoding Specification (ACES) defines a digital color image encoding appropriate for both photographed and computer-generated images. It is the common color encoding for the Academy Image Interchange Framework. In the flow of image data from scene capture to theatrical presentation, ACES data encode imagery in a form suitable for creative manipulation. Later points in the workflow provide forms suitable for critical viewing.



Based on the definition of the ACES virtual RGB primaries, and on the color matching functions of the CIE 1931 Standard Colorimetric Observer, ACES derives an ideal recording device against which actual recording devices' behavior can be compared: the Reference Input Capture Device (RICD). As an ideal device, the RICD would be capable of distinguishing and recording all visible colors, and of capturing a luminance range exceeding that of any contemporary or anticipated physical camera. The RICD's purpose is to provide a documented, unambiguous, fixed relationship between scene colors and encoded RGB values. When a real camera records a physical scene, or a virtual camera (i.e. a CGI rendering program) creates an image of a virtual scene, an Input Device Transform (IDT) converts the resulting image data into the ACES RGB relative exposure values the RICD would have recorded of that same subject matter.



ACES images are not directly viewable for final image evaluation, much as film negative or files containing images encoded as printing density are not directly viewable as final images. As an intermediate image representation, ACES images can be examined directly for identification of image orientation, cropping region or sequencing; or examination of the amount of shadow or highlight detail captured; or comparison with other directly viewed ACES images. Such direct viewing cannot be used for final color evaluation. Instead, a Reference Rendering Transform (RRT) and a selected Output Device Transform (ODT) are used to produce a viewable image when that image is presented on the selected output device.

Practical conversion of photographic or synthetic exposures to ACES RGB relative exposure values requires procedures for characterizing the color response of a real or virtual image capture system. These procedures are described in other documents detailing the Image Interchange Framework.

The Image Interchange Framework of which ACES is a part provides theoretical and practical structure for color correction and artistic adjustment. Encoding in ACES does not obsolete creative judgment; rather, it facilitates it.

1 Scope

This document specifies ACES, an RGB color image encoding for exchange of image data that have not been color rendered, between and throughout production and postproduction, within the Academy's Image Interchange Framework.

2 References

The following standards and specifications are referenced in this text.

CIE Publication 15:2004, Colorimetry, Third Edition

CIE Publication 17.4:1987, International lighting vocabulary, Fourth Edition

IEEE DRAFT Standard for Floating-Point Arithmetic P754

ISO 3664:2000, Viewing conditions – Graphic technology and photography

ISO 22028-1:2004, Photography and graphic technology – Extended colour encodings for digital image storage, manipulation and interchange – Part 1: Architecture and requirements

ISO/TS 22028-3:2006, Photography and graphic technology – Extended colour encodings for digital image storage, manipulation and interchange – Part 3: Reference input medium metric RGB colour image encoding (RIMM RGB)

ITU-R BT.709-2, Parameter values for the HDTV standards for production and international programme exchange

SMPTE Recommended Practice RP 177-1993, Derivation of Basic Television Color Equations

SMPTE Recommended Practice RP 431-2-2007, D-Cinema Quality Reference Projector and Environment

3 Terms and Definitions

The following terms and definitions are used in this document.

NOTE Most terms are derived from ISO 22028-1 or ISO 3664.

3.1 Academy Color Encoding Specification (ACES)

an RGB color encoding for exchange of image data that have not been color rendered, between and throughout production and postproduction, within the Academy's Image Interchange Framework.

3.2 Academy Printing Density (APD)

printing density established as part of the Academy Image Interchange Framework, based on print stock and printer characteristics contemporaneous with the establishment of the framework.

3.3 camera flare

unwanted irradiation in the image plane of an optical system, caused by the scattering and reflection of a proportion of the radiation which enters the system.

3.4 capture system noise

positive or negative signal value fluctuations, unmodulated by scene image content, introduced into an image by the image capture system.

3.5 CIE colorimetry

colorimetry whose values are calculated according to the spectral responsitivities of one of the CIE standard observers.

3.6 color component transfer function

single variable, monotonic mathematical function relating to intensity applied individually to one or more color channels of a color space.

3.7 color encoding

generic term for a quantized digital encoding of a color space, encompassing both color space encodings and color image encodings.

3.8 color gamut

enclosed solid in a color space, consisting of all those colors that are either: present in a specific scene, artwork, photograph, photomechanical, or other reproduction; or capable of being created using a particular output device and/or medium.

3.9 color image encoding

digital encoding of the color values for a digital image, including the specification of a color space encoding, together with any information necessary to properly interpret the color values such as the image state and the intended image viewing environment.

3.10 colorimetry

science of measuring color.

3.11 color rendering

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.

3.12 color space

geometric representation of colors in space, usually of three dimensions.

3.13 color space data metric

numerical representation of a color space, including range of values that can be represented and precision with which they can be encoded.

3.14 color space encoding

digital encoding of a color space, including the specification of a digital encoding method, and a color space data metric.

3.15 ERIMM RGB

color image encoding of scene colors, standardized as part of ISO/TS 22028-3:2006.

3.16 image state

attribute of a color image encoding indicating the color rendering state of the image data.

3.17 Input Device Transform (IDT)

signal-processing transform that maps a reference device's representation of an image to a common input color encoding specification. ACES is the common input color encoding used within the Image Interchange Framework.

3.18 Look Modification Transform (LMT)

signal-processing transform that maps an ACES representation of an image to another ACES representation of an image. Zero or more LMTs may be applied to the ACES data prior to their being color rendered by the Reference Rendering Transform.

3.19 observer adaptive white

color stimulus that an observer, adapted to a set of viewing conditions, would judge to be perfectly achromatic and to have a luminance factor of unity.

3.20 Output Color Encoding Space (OCES)

color image encoding used by the Image Interchange Framework to represent images to be displayed on the Reference Display Device (RDD).

3.21 Output Device Transform (ODT)

signal-processing transform that maps an image represented in a common output color encoding to a representation on a reference device of a particular type. OCES is the common output color encoding used within the Image Interchange Framework and is associated with the Reference Display Device (RDD).

3.22 perfect reflecting diffuser

ideal isotropic, nonfluorescent diffuser with a spectral radiance factor equal to unity at each wavelength of interest.

3.23 printing density

optical densities measured according to a set of effective spectral responsitivities defined by the spectral power distribution of a printer light source and the spectral sensitivities of a print medium.

3.24 radiometric linearity

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.

3.25 Reference Display Device (RDD)

ideal output device with an unlimited color gamut and a dynamic range exceeding any current or anticipated real output device.

3.26 Reference Input Capture Device (RICD)

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

3.27 Reference Projector

reference theatrical projector in its controlled viewing environment. The image interchange framework reference projector and associated viewing environment are equivalent to those defined in SMPTE RP 431-2-2007.

3.28 Reference Rendering Transform (RRT)

signal-processing transform that maps an ACES representation of an image to an OCES representation appropriate for viewing on the Reference Display Device.

3.29 relative exposure values

relative responses to light of an image capture system determined by the integrated spectral responsitivities of its color channels and the spectral radiances of scene stimuli.

3.30 RGB unity white point

encoded color with equal R, G and B components, all having value 1.0.

3.31 scaled XYZ color space

color space based upon the CIE 1931 Standard Colorimetric Observer, with X, Y and Z uniformly scaled such that the Y value of a perfect reflecting diffuser is 1.0.

3.32 surround

area adjacent to the border of an image, which, upon viewing the image, may affect the local state of adaptation of the eye. In the context of a scene capture, a ‘normal’ surround is one where the nature of the scene surrounding the view captured does not significantly alter the state of viewer adaptation from that when viewing exclusively the view captured.

3.33 tristimulus value

amounts of the three reference color stimuli, in a given trichromatic system, required to match the color of the stimulus considered.

3.34 viewing conditions

context in which a color stimulus is viewed, producing a color appearance. Typical viewing condition components include viewing flare, surround, absolute luminance and observer adaptive white.

4 Specification

ACES is specified in three successive layers: a color space, a color space encoding, and a color image encoding. This structure meets the requirements for extended-gamut color encodings as given in ISO 22028-1:2004.

The color space relates ACES colors to the relative exposure values which would be obtained from direct capture of the scene by the ACES Reference Input Capture Device (RICD). These relative exposure values are linked to colorimetric coordinates defined with respect to the CIE 1931 XYZ color space and its Standard Colorimetric Observer.

The color encoding specifies the data metric wherein points within this color space are encoded into a digital representation. ACES represents color components as 16-bit floating-point numbers.

The color image encoding provides image state and viewing condition attribute values required for determining visually equivalent colorimetric values when converting between ACES and other color encoding specifications.

The ACES color image encoding is defined as a linear encoding of RICD relative exposure values. The usage of such an encoding in workflows where, for practical or artistic reasons, this linear relationship of scene light to encoded values does not hold is the subject of section 5.6.

4.1 ACES color space

4.1.1 Colorimetric specification

ACES RGB values represent scene colors as measured by a real or virtual capture device. As such, captured values from real devices include both capture system noise and camera flare.

The RICD is defined to be free of capture system noise and to introduce camera flare amounting to 0.5% of the captured values of a perfect reflecting diffuser; the captured values thus augmented by flare are then scaled by a factor S, calculated as follows:

$$S = \frac{0.18000}{0.18000 + 0.00500}$$

NOTE This scale factor S is chosen such that the RICD capture of an ideal gray card (defined here as an isotropic, non-fluorescing, spectrally nonselective reflector with a spectral reflectance equal to 0.18000 at each wavelength of interest) would produce ACES R, G and B relative exposure values each equal to 0.18000.

NOTE 2 Virtual cameras other than the RICD (CGI renderers, for example) may introduce capture system noise, or camera flare, or both, commensurate with that of other elements with which they might wish to achieve input compatibility. Such compatibility may be evaluated by viewing a comparison of the elements' ACES values directly, or as transformed by the RRT and by an ODT for the device used for that evaluation, or both.

4.1.2 Color space chromaticities

ACES RGB values encode color as red, green and blue scene relative exposure values. These ACES RGB values may be converted to CIE colorimetry using the defined ACES RGB primaries. The colorimetry of the ACES RGB primaries (some of which fall outside the spectral locus) is as follows:

	R	G	B	CIE x	CIE y
Red	1.00000	0.00000	0.00000	0.73470	0.26530
Green	0.00000	1.00000	0.00000	0.00000	1.00000
Blue	0.00000	0.00000	1.00000	0.00010	-0.07700

The spectral sensitivities of the RICD, tabulated in Annex C, are derived from these values.

4.1.3 Neutral axis

A color encoded in ACES is considered neutral if its RGB values are equal. The chromaticity coordinates of all such colors are x=0.32168, y=0.33767.

The total absence of light is represented by

$$X_K = 0.00000,\ Y_K = 0.00000,\ Z_K = 0.00000$$

The color space unity white point (with ACES RGB values 1.0, 1.0, 1.0) is the normalized value

$$X_W = 0.95265,\ Y_W = 1.00000,\ Z_W = 1.00883$$

As ACES R, G or B relative exposure values often exceed 1.0, this color space unity white point in no way limits the range of represented colors.

4.1.4 Converting ACES RGB values to CIE XYZ values

ACES R, G, and B tristimulus values are converted to scaled CIE XYZ tristimulus values as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.9525523959 & 0.0000000000 & 0.0000936786 \\ 0.3439664498 & 0.7281660966 & -0.0721325464 \\ 0.0000000000 & 0.0000000000 & 1.0088251844 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

NOTE The above matrix is derived from the color space chromaticity coordinates. These matrices are calculated using the methods provided in section 4 of SMPTE Recommended Practice RP 177-1993 “Derivation of Basic Television Color Equations”.

4.1.5 Converting CIE XYZ values to ACES RGB values

The conversion from scaled CIE XYZ values to ACES RGB values is the inverse of the conversion from ACES RGB values to scaled CIE XYZ values.

CIE XYZ tristimulus values are converted to ACES R, G, and B tristimulus values as follows:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0498110175 & 0.0000000000 & -0.0000974845 \\ -0.4959030231 & 1.3733130458 & 0.0982400361 \\ 0.0000000000 & 0.0000000000 & 0.9912520182 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

NOTE The above matrix is derived from the color space chromaticity coordinates. These matrices are calculated using the methods provided in section 4 of SMPTE Recommended Practice RP 177-1993 “Derivation of Basic Television Color Equations”.

4.2 ACES color space encoding

4.2.1 Color component transfer function

The color component transfer function directly encodes relative exposure values that would be captured from the scene by the RICD as ACES color component values, and is defined as

$$R = E_r,\ G = E_g,\ B = E_b$$

where E_r, E_g and E_b represent relative exposure values that would be captured from the scene by the RICD and R, G and B are the resulting ACES color component values.

4.2.2 Color component value range

The value range for ACES color component values is [-65504.0, +65504.0].

The chromaticity coordinates of the defined ACES RGB primaries form a triangle on the CIE chromaticity diagram. ACES RGB values which express visible colors are represented by points within this triangle.

The set of valid ACES RGB values also includes members whose projection onto the CIE chromaticity diagram falls outside the region representing visible colors. These ACES RGB values include those with one or more negative ACES color component values; they also include those whose color component values are all positive and whose projection onto the chromaticity diagram is within the defined triangle but outside the spectral locus. Such colors should be maintained in anticipation of subsequent processing in ACES, but should be avoided in ACES data passed to the RRT, as their color rendering by that transform may introduce unexpected colors into output imagery.

Values well above 1.0 are expected and should not be clamped except as part of the color correction needed to produce a desired artistic intent.

4.2.3 Color component value encoding

ACES values are encoded as 16-bit floating-point numbers.

This floating-point encoding uses 16 bits per component, with 1 sign bit, 5 bits of exponent, and 10 bits of mantissa (with 1 extra implicit bit of precision), as described in IEEE P754.

Higher-precision floating point values may be used in calculations but the output of the calculation should remain congruent with the above 16-bit half-float representation.

4.3 ACES color image encoding

The appearance of a color stimulus is dependent not only on the stimulus itself but on the environment in which the stimulus is viewed. Color image encodings associate a reference viewing environment with color stimuli, typically by specifying values or value ranges for four attributes of the viewing environment: viewing flare, surround type, luminance level and observer adaptive white. Values or value ranges for these attributes are provided below, so that the color values of other color image encodings can be converted to visually equivalent ACES RGB relative exposure values, or *vice versa*.

4.3.1 Viewing flare

Any flare light in the scene (e.g. atmospheric haze) is considered part of the scene itself. The ACES reference viewing environment is specified to have 0% viewing flare.

NOTE Viewing flare is unrelated to camera flare. Camera flare is specified in section 4.1.1 and discussed in section 5.4.

4.3.2 Surround type

Scene objects are considered to be surrounded by other similarly illuminated scene objects. The ACES reference viewing environment therefore has a ‘normal’ surround.

NOTE Some other publications use the term ‘average surround’ where ACES uses ‘normal surround’. These terms should be considered equivalent.

4.3.3 Luminance level

The luminance level of the ACES reference viewing environment is that of a daylight-illuminated outdoor scene, in which a perfect reflecting diffuser would have a luminance level of at least 1,600 candelas per square meter.

NOTE If the luminance level of the actual scene being photographed differs from the ACES reference viewing environment luminance level specified here, that difference should be preserved as an expression of creative intent.

4.3.4 Observer adaptive white

The ACES reference viewing environment specifies an observer adaptive white whose chromaticity coordinates are equal to those of the RGB unity white point.

NOTE If the observer adaptive white of the actual scene being photographed differs from the ACES reference viewing environment observer adaptive white specified here, that difference should be preserved as an expression of creative intent. A PhotoYCC encoding of the colors of a coldly lit, blue-toned factory interior, for example, should be converted to an ACES encoding of the colors of a coldly lit, blue-toned factory interior, not to an ACES encoding of the colors in a daylight-illuminated outdoor scene. Any creative modifications to the scene color balance would be made by postprocessing the converted data in ACES, not as a part of the conversion to ACES.

5 Usage

5.1 Interpretation of ACES image data

The heart of the Image Interchange Framework is its preservation of creative intent in the interpretation of ACES data. Cinematographers accustomed to the nonlinear characteristic curves of film can continue to light the set as they always have, and the film system's compression of shadow and highlight detail into ‘toe’ and ‘shoulder’ can be maintained in the conversion of scanned film content to ACES data[1]. Visual effects professionals creating image elements in a radiometrically linear space can bring their data into ACES and achieve input compatibility, as can users of digital motion picture cameras.

Input compatibility is achieved by a combination of Input Device Transform (IDT) and Look Modification Transform (LMT). An IDT is specific to a particular input path into ACES; an LMT applies to the data once they are in ACES. This architecture supports the preservation of the particular characteristics of the capture medium or mechanism, by allowing a clean separation of media-specific and media-independent creative decisions if so desired.

In some cases an actual scene may not embody the ‘look’ that the director or cinematographer is trying to convey. In other cases the scene may embody the desired look, but the exposure value capture processes employed may function imperfectly. And in many cases the desired ‘look’ for the content may change during the production to accommodate refinements in creative vision.

Finally when legacy materials are involved (be they archived film, analog tape, or digital records without benefit of accompanying production documentation or metadata) precise reconstruction of scene relative exposure values is rarely possible. In such cases importing the legacy materials into ACES draws on both the arts and sciences of motion picture imaging.

[1] In the Image Interchange framework the combination of the RRT and the ODT of a chosen output device supplies the component of the aggregate ‘look’ that, in a film-based system, would be provided by the chosen print stock.

For all these reasons, the ACES definition of the scene is more broad than that traditionally used by instrument manufacturers and by many camera manufacturers. All of the following can be considered to be valid ACES representations of the scene:

- Relative exposure values of the scene, as derived from relative exposure values of a camera and the transformations of those values by an IDT into ACES RGB values.
- Relative exposure values as above, but modified for creative reasons. As an example, a production might choose to shoot 'day for night', capturing an outdoor scene in daylight and then reducing luminance levels and chroma to make it appear the same scene had been shot in the nighttime.
- Relative exposure values as above, but modified for practical reasons, e.g. reasons of economy. As an example, multiple takes of a supposedly noontime outdoor shot might be captured from mid-morning to late afternoon of the same day, to shorten a production schedule. The illuminating daylight will not be constant across the various takes. To match an adjoining shot, the relative exposure values might be modified from the 'true' corresponding relative exposure values of the chosen take to match that of material with which it must intercut. These modified relative exposure values as adjusted to provide consistent color temperature would still be considered to represent the scene.
- Relative exposure values modified as process control. A production capturing images on film might modify relative exposure values to compensate for changes in laboratory chemistry, inadvertently fogged film, or the premature exhaustion of a 'mortgaged' emulsion batch. This type of correction might be accomplished in an IDT, or could be achieved with a Look Modification Transform (LMT). In either case, the modified relative exposure values would be considered valid ACES data.
- Relative exposure values from a medium whose dynamic range was less than that of the scene being imaged, causing captured shadow and highlight detail to be either clipped or compressed. An IDT for such an image capture system cannot recover scene relative exposure values beyond the bounds of what the input medium could hold, and may reasonably deviate from rigid adherence to a goal of recovered scene relative exposure values at the extremes of the represented range. Relative exposure values that could be captured by the medium and recovered by the IDT would be considered to represent the scene in ACES. As the extremes of the medium were reached, the interpretation of the data in ACES might move from 'represents the scene' to 'consequence of the capture system'.
- 'Best estimate' relative exposure values for legacy materials. If vaulted negative is of a stock no longer made and which predates rigorous manufacturer characterization, or the manufacturer of the negative is no longer extant, or the only remnant of the production process is work print or release print and not negative, the restoration process will involve trial and error, and the estimation of scene relative exposures and thus ACES relative exposure values will almost certainly be inexact. This rough estimation can still be considered to have produced ACES scene relative exposure values, but the amount of manual adjustment required to achieve input compatibility with more typical materials might be similar to the amount of manual adjustment required in the contemporary DI process.

5.2 Image state

ACES values are intended to be used throughout the entire image creation pipeline, from element capture to mastered image. As just described, these values may or may not correspond to actual relative exposure values one would obtain from a capture device at the scene.

ACES values do not directly specify intended final color appearance. The image creation pipeline terminates when the ACES image looks as intended on a targeted output device. The final image is viewed by applying the Reference Rendering Transform (RRT) and the Output Device Transform (ODT) appropriate for that type of output device.

Color edits of the ACES values of the image will almost always be required to finalize a desired creative result. The Reference Display Device (RDD) is the ideal device which is the target of the RRT. The ODT for a class of device accommodates differences in gamut and dynamic range between the RDD and the targeted type of device. ACES values may be creatively modified to refine such gamut mapping or to effect other artistic decisions. Such creative modifications are made by viewing the modified data through the RRT and the device type's ODT.

ACES values are not color rendered, as are for example those of the distribution master file used in digital cinema projection systems, or images 'baked' for display on video monitors with standardized characteristics.

5.3 Neutral reflectors, creative intent and process control

As specified in section 4.1.3, neutral colors in ACES have chromaticity values of x=0.32168, y=0.33767. A light source with these chromaticity values (CIE Standard Illuminant D_{60}, for example) or a spectrally neutral object reflecting such a light source, captured by the Reference Input Capture Device (RICD), would be represented by ACES values with equal R, G and B relative exposure values.

A light source in actual motion picture production will almost never have chromaticity values matching those of the ACES neutral axis. As noted in section 4.3, ACES encoding preserves creative intent. Cinematographers have long used neutral reflectors as a way of capturing creative decisions in lighting and exposure, either as a transfer reference (and in the case of film output, a printing reference) for normal lighting and exposure, or as a preservation mechanism for special lighting or special exposures.

ACES values that would have been produced by an RICD capturing an 18% neutral reflector, a perfect reflecting diffuser and a sample ColorChecker® chart illuminated by a CIE Standard Illuminant D_{60} light source are given in Annex B as an aid to IDT developers.

NOTE The use of a spectrally defined light source in the evaluation procedure provided to IDT writers in Annex B should not be taken to imply that use of ACES in the typical motion picture workflow requires spectral calculation (normal ACES operations involve only tristimulus values) or that scenes must be captured under a CIE Standard Illuminant D_{60} source.

5.3.1 Neutral reflectors, normal lighting and normal exposure

When the intent of a production is to have scene objects with neutral reflectance encode with colors whose values are ACES encoded neutrals, and the scene is being captured with a digital camera, that camera will typically be 'white balanced' against some sort of neutral reference. In such cases, this same neutral reference can be used by an Input Device Transform (IDT) to adjust the relationship between the RGB relative exposure values produced by the camera and the ACES relative exposure values which will be encoded, such that the image data captured from the neutral reflector are represented as neutral colors in ACES.

In film-based capture systems where again the creative intent is that neutral-reflectance objects appear neutral, and a neutral reference was captured in the scene, an IDT may provide controls such that the R, G and B printing densities of the scanned film might be adjusted in relative proportion so that they map to ACES neutral relative exposure values. Spectrally neutral (or nearly so) gray cards reflecting 18% of the illuminant are available from film manufacturers. For 'normal' exposure where the light source intensity is matched to the documented nominal exposure for the film stock being used, it may be useful to adjust IDT parameters such that the device values from such a normally-exposed gray card are transformed to the ACES neutral with RGB values R = 0.18000, G = 0.18000, B = 0.18000. The use of printing densities and the functionality of IDTs are discussed in other Image Interchange Framework documents.

NOTE For the specific case of the RICD's capture of a normally-exposed 18% gray card, the captured colorimetry after applying the offset and scaling operations specified in section 4.1.1 will be equal in value to the colorimetry prior to application of those offset and scaling operations. For this captured colorimetry (and only this captured colorimetry) the scaling operation exactly 'undoes' the effect of the offset operation.

5.3.2 Neutral reflectors, special lighting or special exposure

If the creative intent is to light or expose the scene such that neutral objects have a visible color cast, or if the capture device exposure is altered from that documented as its nominal exposure level, a spectrally neutral reflector can be used to capture the chromaticity or intensity of the scene light source.

If the capture mechanism is subject to process variability (as can be the case with film-based systems) an additional capture of the gray card lit only by the nominal light source for the capture system may be used to distinguish the color and intensity expressing creative intent from that contributed by process variation. This second captured image can be used as a neutral reference under normal lighting and exposure, as described in section 5.3.1 above.

Both the image capturing the light source and any image captured for process control are intended as aids to adjustment of any relevant parameters for the IDT through which the imagery is transformed into ACES RGB relative exposure values; neither image can or should be used as a substitute for creative judgment.

5.3.3 Absolute exposure values

ACES exposure values are relative: they are specified in reference to the values that would be captured from a perfect reflecting diffuser. When absolute exposure values are desired (to guide the creation of matching CGI elements, for example), an external measuring device such as a light meter can be used to determine the absolute luminance of a neutral reflector in the scene. In digital capture systems, the camera may produce metadata (typically camera sensitivity, exposure time and aperture) associated with the captured image, from which absolute exposure values can be determined. In either film-based or digital capture systems, an isolated, calibrated light source can be placed in the scene and captured as a reference.

The information thus determined can be carried, either as metadata associated with the image, or in the image itself. An example of the latter would be an image of a metered neutral reference with the meter in frame and meter readings legible by the viewer.

NOTE Equivalent values to those which would be measured from a perfect reflecting diffuser can be obtained by measuring the values of an identically positioned and oriented 18% neutral gray card, then dividing the measured values by 0.18000.

5.4 Capture system noise and camera flare models

Encoding scene colors in ACES retains any noise introduced by the capture system. In a film-based system, capture system noise might come from film grain, or from electronic noise introduced as the film is scanned. Digital cameras may introduce noise either as the sensor captures the scene or in later processing prior to conversion to camera device code values, or both, and the noise thus introduced may be randomly distributed across the image or may be distributed according to some pattern.

Colors encoded in ACES are assumed to contain camera flare: light that was not associated with color stimuli in the photographed environment, but that is associated with the ACES values. Camera flare may be a creative choice (‘flashing’ film), or it may be accidental (unintended reflection and dispersion within the camera optics, or inadvertent exposure to radioactive materials). It may be uniform across the image plane, or concentrated in particular areas (light leak in camera housing).

Unlike some other image encodings representing scene colors (ERIMM RGB, for example), ACES does not ‘correct for flare’ in its encoding of captured colors. This preserves camera flare as an expression of creative intent while introducing only a moderate amount of complexity to the processing of ACES RGB relative exposure values. It also allows any desired adjustments for camera flare to be deferred from production to postproduction, where image data from multiple capture systems are typically brought together.

Unlike capture system noise, which may be represented by both negative and positive offsets from a noise-free value, flare will always be represented by a non-negative offset from a flareless value.

In processing ACES image data, camera flare is considered both in relative and in absolute terms: relative as it pertains to input compatibility and absolute as it pertains to the Reference Rendering Transform (RRT).

5.4.1 Camera flare in relative terms: reconciling inter-camera flare variation

When there is a need to reconcile camera flare levels or distributions between two or more real cameras, or between a real and a virtual camera, each camera can be associated with some model of camera flare, and at least one of those models must provide for adjustment of the level or distribution of flare. The quality of the match in camera flare will depend on the needs of the production, and on the accuracy and precision of the camera flare models in their simulation of the real-world effects responsible for captured flare.

The complexity and variability of a flare model can thus be matched to the application. Examples include:

- no flare: often used by CGI renderers
- constant flare at a fixed level: used by the RICD (as specified in section 4.1.1)
- constant flare at a variable level: used interactively in compositing and in digital intermediate workflows, typically to match the minimum signal level of multiple image capture systems
- complex flare modeling: used when more accurate models of flare are required than can be accommodated by a simple level adjustment; typically driven by camera response measurements or a mathematical model

Virtual cameras typically have very simple models of camera flare. Many CGI renderers model cameras as being flareless capture devices of a virtual scene. The Reference Input Capture Device (RICD) models camera flare as amounting to 0.5% of the values of a captured perfect reflecting diffuser, as specified in section 4.1.1.

The degree of reconciliation between the camera flare levels of two images may be visually judged by viewing the ACES data directly, or by applying the RRT and then an Output Device Transform (ODT) to the color rendered values, or both. In some cases, the degree of reconciliation may be computable as a statistic.

NOTE In workflows where all image elements are produced using a flareless virtual camera (e.g.by a CGI renderer), consideration of camera flare in reconciliation of image elements is, by definition, not required. The flareless images thus produced will, however, still be color rendered by the RRT and be subject to its camera flare assumptions as described in section 5.4.2.

5.4.2 Camera flare in absolute terms: camera flare assumptions of the RRT

The RRT emulates the behavior of the traditional photochemical imaging chain in that it increases contrast and saturation as it processes ACES image data. The RICD's fixed contribution of camera flare (a constant addition of 0.00500 to the scalar product of color stimulus and RICD spectral sensitivity) is the simplest model which, in adding modeled camera flare to the scalar product of the RICD spectral sensitivities and a color stimulus being captured, provides a level of camera flare meeting the 'middle-of-the-road' camera flare expectation of the RRT.

The performance of the RRT when supplied with ACES values from a capture device, or for a set of capture devices whose relative camera flare levels have been reconciled, may be evaluated visually by application of an ODT appropriate for the viewing device, or by statistical analysis of the RRT or ODT output, or both.

NOTE If the RRT is supplied with image data representing a scene without any contribution from camera flare, the result will have higher contrast and possibly higher saturation than the same scene captured with a camera that does introduce camera flare.

5.5 Contemporary materials, data and workflows

5.5.1 Encoding CGI renderer output directly as ACES data

Many modern CGI rendering programs support the writing of files with radiometrically linear RGB values; some also provide for direct CIE XYZ output. If the renderer is producing output-referred imagery that will be viewed directly, and the RGB unity white point of the color encoding of the renderer output has a different chromaticity from that of the ACES RGB unity white point, then the renderer output should be chromatically adapted so that its neutrals are encoded as ACES neutrals.

The appropriate point in the workflow for such chromatic adaptation will vary. Renderers whose synthetic camera models do not include models of capture system noise or camera flare equivalent to those of typical physical cameras might best integrate into an Image Interchange Framework workflow with some or all of the addition of modeled capture system noise, addition of modeled camera flare and chromatic adaptation taking place as a postprocessing step to the render. If this is done, care should be taken that precision is not lost in the connection of the renderer to the postprocessing program(s).

5.5.2 Converting ‘baked’ CGI imagery to ACES data

Stored CGI imagery is typically encoded in one of two ways: either in radiometrically linear RGB as a representation of the scene, or as a representation ‘baked’ for a particular class of display, that is, with foreknowledge of a particular output device type for which its representation has been optimized. In the former case, the contemporary workflow described in section 5.5.1 may be used to convert from the renderer’s output color space to that of ACES.

In the latter case, preprocessing is required to return the stored values to a radiometrically linear representation. Care must be taken in determining the stored representation of black, the stored representation of white and the encoding function used to produce the data stored in the file; in some 8-bit encoding schemes, for example, black is represented by a code value of 16, not 0, and white by a code value of 235, not 255. When these values and the associated encoding function are known, an inversion of the encoding process should yield the original CGI renderer output (excepting those values which might have been clipped by the encoding function), and this reconstituted CGI renderer output can then be processed as described in section 5.5.1.

5.5.3 Converting Cineon or SMPTE RP-180 printing density data to ACES data

Files containing Cineon and SMPTE RP-180 printing density data first should be converted to Academy Printing Density (APD) data, after which the APD data are brought into ACES by an appropriate Input Device Transform (IDT). The definition of Academy Printing Density, recommendations for its use, and its relation to other printing density specifications are provided in a separate Image Interchange Framework document.

5.5.4 Capturing ACES image data from color rendered image data

Files containing image data whch have already been color rendered for some output device can be converted to files containing ACES image data by first determining the colorimetry which would be produced by those data on that output device, and then determining which ACES values would have produced that colorimetry when put through the RRT.

5.5.5 Capturing ACES image data from print film

Print film imagery can be converted to ACES data by scanning the print, computing the projected colorimetry implied by the scanner output, then determining what ACES values would have produced that colorimetry when put through the RRT and ODT for film projection.

Since the luminance range and gamut of the Reference Display Device exceed those of current film or digital projectors, an ODT for those classes of device will likely clip or compress the RRT output, implying that the ODT is many-to-one and not completely reversible. Although most if not all computed colorimetry should fall within the luminance range and color gamut of an ODT for a particular device class, it is possible that unusual print stocks, or ‘normal’ stocks undergoing abnormal processing, could produce projected colorimetry outside of the range of that ODT. Care should be taken to ensure that the inverse path through the ODT is robust in the face of such input data.

5.6 Linearity of ACES image data

The mathematics of digital imaging (color space transformations, compositing, CGI lighting and CGI rendering) often presume to operate on radiometrically linear values. Although ACES values may be treated as being radiometrically linear, conversion of device values to ACES values may or may not preserve linearity with scene radiometry. Creative modification of ACES values through the use of Look Modification Transforms (LMTs) may also alter the linearity of the relationship of those ACES values to scene radiometry.

The RRT imposes a tone curve on the image data it processes, and it presumes that the ACES data being processed are radiometrically linear (except for their inclusion of any capture system noise or camera flare). If an IDT is used to bring captured imagery into ACES in such a way as to wholly or partially preserve the nonlinear relationship between scene radiometry and device values (e.g. if film scans are brought into ACES where by creative choice the film's nonlinear encoding of shadows or highlights is retained) compositors and colorists should be prepared to modify the ACES data such that the concatenation of the medium's tone curve and the RRT's tone curve preserves the creative intent of the photographer when viewed through the RRT and ODT.

Establishing and tracking the degree of fidelity of ACES data to actual scene radiometry is outside the scope of ACES. CGI renderers which accurately model the physical interactions of energy and material may benefit from associated metadata indicating radiometric fidelity (stored as an image header attribute, or by use of a file naming convention, or by storage in an external database) but the maintenance of that metadata is outside the purview of this Specification.

Annex A

(normative)

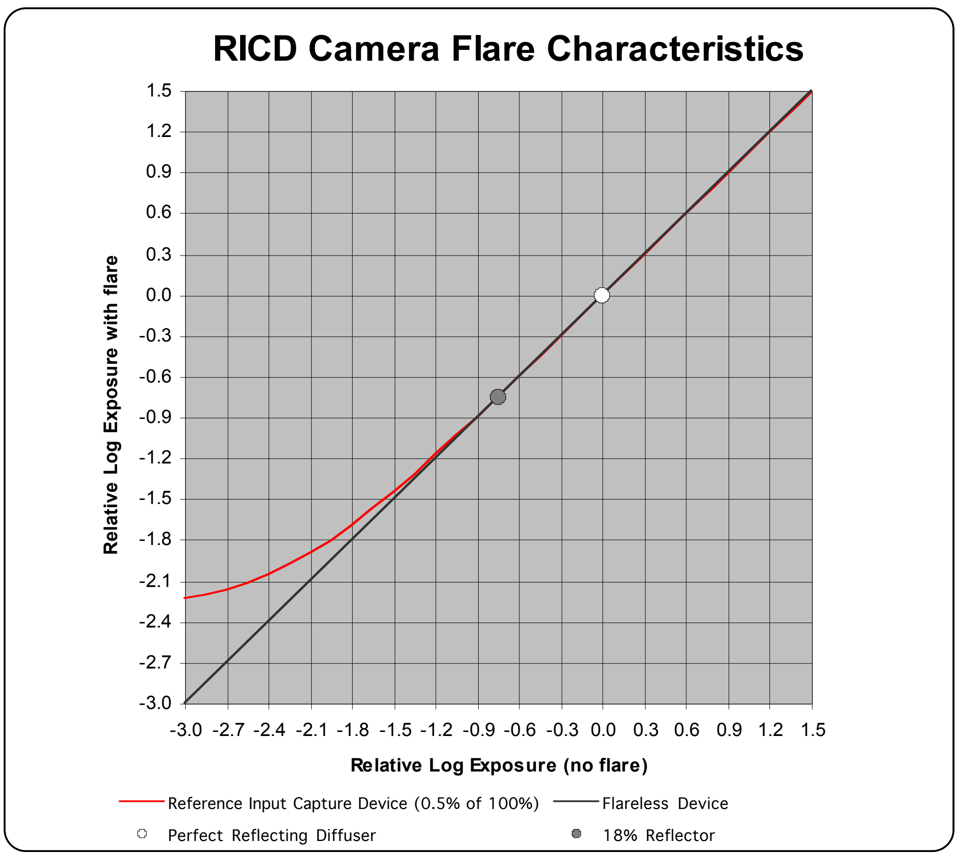
ACES Reference Input Capture Device Noise and Flare Characteristics

The RICD definition specifies in section 4.1.1 that captured camera stimuli are free of capture system noise.

The RICD definition also includes the camera flare model specified in section 4.1.1, which in turn was specified to match the simplest plausible model of camera flare that could be used with the RRT and produce a visually pleasing result.

This camera flare model assumes that captured color stimuli contain an amount of camera flare equal to 0.5% of the relative exposure values of a perfect reflecting diffuser. Moreover, it assumes that this level of camera flare is constant across the image plane and is constant for all values of captured content.

The graph below illustrates the effect of this addition of a constant level of camera flare and subsequent scaling (as specified in section 4.1.1) to the RGB relative exposure values produced by the interaction of a captured spectral stimulus and the RICD's spectral sensitivities (given in Annex C), compared to the values which would have been recorded without applying the RICD's camera flare model, that is, without those addition and scaling operations.



NOTE Though ACES data may be treated as being radiometrically linear (c.f. section 5.6), the relationship between measurements containing camera flare and measurements not containing camera flare is presented here on logarithmic axes to make the difference between the two more visibly evident.

Annex B

(informative)

ACES RGB values of common stimuli as produced by the ACES Reference Input Capture Device

The values that the RICD would produce for a captured set of stimuli are determined by the spectral sensitivities of the RICD (tabulated in Annex C), the RICD capture system noise and camera flare model (described in section 4.1.1), and the spectral power distribution of the stimuli being captured. As an aid to Input Device Transform (IDT) developers, the table below presents the ACES RGB relative exposure values that the RICD would produce for an 18% neutral reflecting diffuser, a perfect reflecting diffuser and a ColorChecker® chart, all illuminated by a CIE Standard Illuminant D_{60} source.

Stimulus	ACES R	ACES G	ACES B
Spectrally non-selective 18% reflecting diffuser	0.18000	0.18000	0.18000
Perfect reflecting diffuser	0.97784	0.97784	0.97784
ColorChecker Dark Skin	0.11877	0.08709	0.05895
ColorChecker Light Skin	0.40003	0.31916	0.23737
ColorChecker Blue Sky	0.18476	0.20398	0.31311
ColorChecker Foliage	0.10901	0.13511	0.06493
ColorChecker Blue Flower	0.26684	0.24604	0.40932
ColorChecker Bluish Green	0.32283	0.46208	0.40606
ColorChecker Orange	0.38607	0.22744	0.05777
ColorChecker Purplish Blue	0.13822	0.13037	0.33703
ColorChecker Moderate Red	0.30203	0.13752	0.12758
ColorChecker Purple	0.09310	0.06347	0.13525
ColorChecker Yellow Green	0.34877	0.43655	0.10613
ColorChecker Orange Yellow	0.48657	0.36686	0.08061
ColorChecker Blue	0.08731	0.07443	0.27274
ColorChecker Green	0.15366	0.25692	0.09071
ColorChecker Red	0.21743	0.07070	0.05130
ColorChecker Yellow	0.58921	0.53944	0.09157
ColorChecker Magenta	0.30904	0.14818	0.27426
ColorChecker Cyan	0.14900	0.23377	0.35939
ColorChecker White	0.86653	0.86792	0.85818
ColorChecker Neutral 8	0.57356	0.57256	0.57169
ColorChecker Neutral 6.5	0.35346	0.35337	0.35391
ColorChecker Neutral 5	0.20253	0.20243	0.20287
ColorChecker Neutral 3.5	0.09467	0.09520	0.09637
ColorChecker Black	0.03745	0.03766	0.03895

The ColorChecker chart was chosen as an example reference for two reasons. First, it is ubiquitous. Second, the spectral reflectances of its samples are such that differences in capture system camera flare behavior make little contribution to differences in captured values. When two digital cameras, for example, capture a ColorChecker chart lit by a daylight illuminant, the differences in their output will be due almost entirely to differences in camera spectral sensitivities.

Calculation of the values above used the following elements:

- the published CIE Standard Illuminant D_{60} spectral power distribution
- the area-normalized RICD spectral sensitivities from Annex C
- red, green and blue scale factors k_r, k_g and k_b which white-balance those area-normalized RICD spectral sensitivities for CIE Standard Illuminant D_{60}
- hypothetical 18% and 100% neutral reflectors
- the measured reflectances of the patches on a particular[2] ColorChecker chart

The scale factors applied to the RICD spectral sensitivity curves are each the reciprocal of the scalar product of that curve and the illuminant. These scale factors k_r, k_g and k_b are calculated as follows:

$$k_r = \frac{1}{I \bullet S_r},\ k_g = \frac{1}{I \bullet S_g},\ k_b = \frac{1}{I \bullet S_b}$$

where I represents the illuminant and S_r, S_g and S_b represent the area-normalized spectral sensitivities from Annex C.

Once these scale factors have been determined, the ACES relative exposure values Er, Eg and Eb are calculated as

$$E_r = k_r \sum_i IRS_{ri}\ ,\ E_g = k_g \sum_i IRS_{gi}\ ,\ E_{br} = k_b \sum_i IRS_{bi}\ ,$$

where (as before) I represents the illuminant and S_r, S_g and S_b represent the area-normalized spectral sensitivities from Annex C, and where R represents the spectral reflectance of the object being captured.

IDT developers wishing to verify their understanding of the calculation are encouraged to compute the ACES RGB relative exposure values for the hypothetical 18% and 100% neutral reflectors and verify their results against the chart above. Since this calculation involves only ideal illuminant spectra, ideal reflectance spectra and ideal spectral sensitivities, the match to the table data for those reflectors should be exact.

If this test is followed by computation of ACES RGB values using the CIE Standard Illuminant D_{60}, the actual measured patch reflectances of the IDT developer's ColorChecker chart, the RICD spectral sensitivities and the RICD camera flare model, the computed differences from the tabulated values above should provide a sense of how that actual ColorChecker chart differs from the ColorChecker chart used in the creation of the table above.

In the likely case that the actual illuminant used with a particular ColorChecker chart is other than CIE Standard Illuminant D_{60}, the IDT developer should generate a new table of RICD capture results, particular to the actual illuminant instead of to CIE Standard Illuminant D_{60}, and to the IDT developer's actual ColorChecker chart. Three new scale factors k_r, k_g and k_b for the area-normalized RICD spectral sensitivity curves from Annex C should be determined, such that under the actual illuminant, the hypothetical 18% neutral reflector would be captured by the RICD with red, green and blue relative exposure values each equal to 0.18000 (including the contribution from and scaling implied by the RICD camera flare model). This white-balances the RICD to a hypothetical gray card under the actual illuminant.

[2] *The Basis of Color Reproduction Engineering (Japanese)*, N. Ohta, 1977, published by the Corona-sha Company of Japan, and subsequently made available on the Internet at http://www.cis.rit.edu/mcsl/online/CIE/MacbethColorChecker.htm.

The contents of the resulting table can thus be compared with the output of the developer's IDT, when that IDT is supplied with the device values from the real camera being characterized, yielding a sense of how the real camera captures colors relative to the ideal behavior embodied by the RICD. Results for multiple cameras of the same type can be computed to assess camera-to-camera variance. When results for different types of cameras are computed, and the scene content to be photographed is known in advance, such calculations may aid the cinematographer in choosing an appropriate type of camera. This is especially true when anticipated use of the captured images requires them to adhere as closely as possible to actual scene colors, as is often the case in visual effects photography.

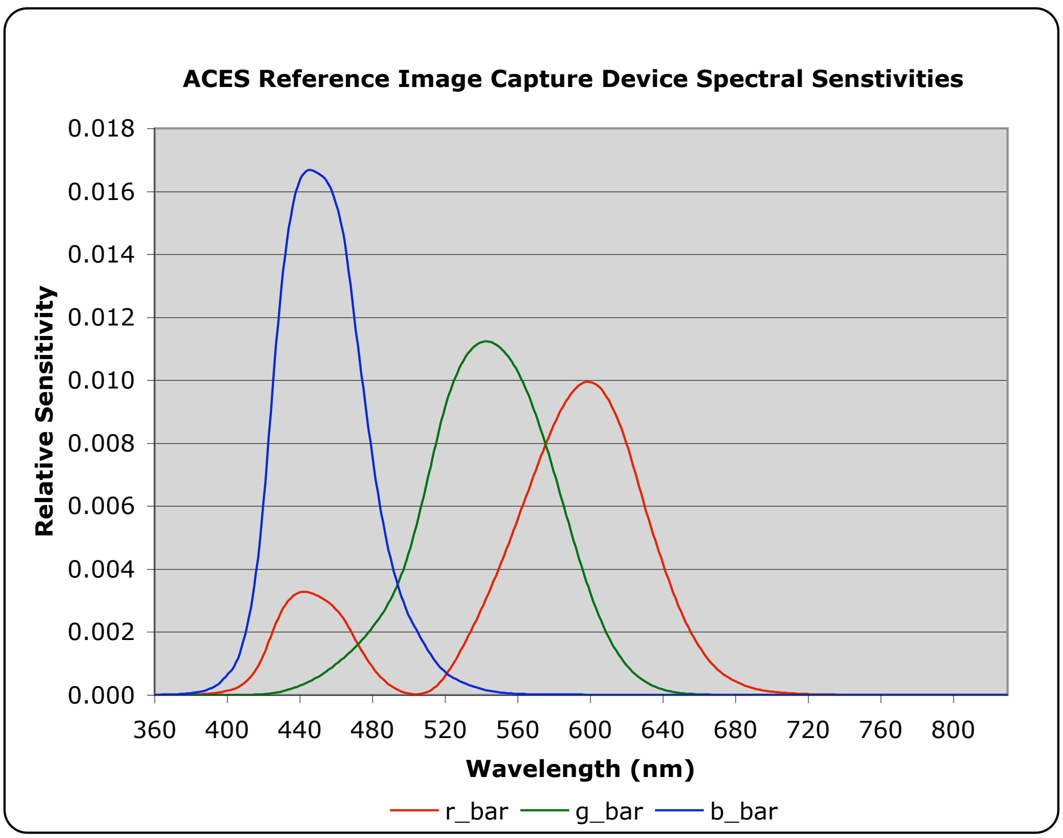
Annex C

(informative)

ACES Reference Input Capture Device spectral sensitivities

The ACES RICD spectral sensitivities are linear combinations of the color matching functions of the CIE 1931 Standard Colorimetric Observer. These spectral sensitivities were chosen such that the RICD captures color exactly as a colorimeter would, but expressed in terms of the ACES RGB primaries instead of the CIE XYZ primaries.

NOTE The RICD spectral sensitivities listed below are area normalized. When calculating the values the RICD would capture for a particular illuminant, separate scaling factors will typically be applied to each of the red, green and blue sensitivities, such that the scalar product of each scaled spectral sensitivity with the captured spectrum of a perfect reflecting diffuser under that particular illuminant would produce values of 1.0. A comparable capture of an 'ideal' 18% gray card (isotropic, non-fluorescing and spectrally nonselective) would produce values of 0.18000 for each scalar product (after the flare addition and the scaling operations specified in section 4.1.1).



wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
360	0.0000012	0.0000000	0.0000057
361	0.0000014	0.0000000	0.0000064
362	0.0000015	0.0000000	0.0000072
363	0.0000017	0.0000000	0.0000080
364	0.0000019	0.0000000	0.0000090
365	0.0000022	0.0000000	0.0000102
366	0.0000024	0.0000000	0.0000114
367	0.0000027	0.0000000	0.0000128
368	0.0000031	0.0000000	0.0000144
369	0.0000035	0.0000000	0.0000162
370	0.0000039	0.0000000	0.0000182
371	0.0000043	0.0000000	0.0000204
372	0.0000049	0.0000000	0.0000228
373	0.0000054	0.0000000	0.0000256
374	0.0000061	0.0000000	0.0000288
375	0.0000069	0.0000000	0.0000326
376	0.0000079	0.0000001	0.0000372
377	0.0000090	0.0000001	0.0000425
378	0.0000102	0.0000001	0.0000483
379	0.0000115	0.0000001	0.0000543
380	0.0000128	0.0000001	0.0000603
381	0.0000141	0.0000001	0.0000663
382	0.0000154	0.0000001	0.0000725
383	0.0000169	0.0000001	0.0000795
384	0.0000187	0.0000001	0.0000881
385	0.0000209	0.0000001	0.0000987
386	0.0000237	0.0000002	0.0001119
387	0.0000271	0.0000002	0.0001278
388	0.0000309	0.0000002	0.0001458
389	0.0000351	0.0000003	0.0001659
390	0.0000397	0.0000003	0.0001876
391	0.0000445	0.0000003	0.0002106
392	0.0000499	0.0000004	0.0002358
393	0.0000559	0.0000005	0.0002646
394	0.0000631	0.0000005	0.0002984
395	0.0000716	0.0000006	0.0003388
596	0.0099180	0.0039465	0.0000091
597	0.0099368	0.0037690	0.0000087
598	0.0099462	0.0035956	0.0000083
599	0.0099472	0.0034261	0.0000079
600	0.0099405	0.0032602	0.0000075
601	0.0099268	0.0030979	0.0000071
602	0.0099054	0.0029397	0.0000068
603	0.0098752	0.0027858	0.0000064
604	0.0098355	0.0026369	0.0000060
605	0.0097852	0.0024933	0.0000056
606	0.0097238	0.0023553	0.0000051
607	0.0096519	0.0022229	0.0000046
608	0.0095705	0.0020958	0.0000041
609	0.0094805	0.0019739	0.0000036
610	0.0093828	0.0018572	0.0000032
611	0.0092776	0.0017455	0.0000029
612	0.0091650	0.0016389	0.0000026
613	0.0090448	0.0015372	0.0000025
614	0.0089172	0.0014404	0.0000024
615	0.0087819	0.0013484	0.0000022
616	0.0086396	0.0012610	0.0000021
617	0.0084904	0.0011783	0.0000021
618	0.0083337	0.0010998	0.0000020
619	0.0081692	0.0010253	0.0000019
620	0.0079963	0.0009547	0.0000018
621	0.0078151	0.0008876	0.0000016
622	0.0076266	0.0008241	0.0000015
623	0.0074323	0.0007641	0.0000013
624	0.0072336	0.0007075	0.0000011
625	0.0070319	0.0006544	0.0000009
626	0.0068278	0.0006045	0.0000008
627	0.0066219	0.0005578	0.0000007
628	0.0064162	0.0005141	0.0000006
629	0.0062122	0.0004733	0.0000005
630	0.0060119	0.0004351	0.0000005
631	0.0058164	0.0003996	0.0000004

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
396	0.0000819	0.0000007	0.0003877
397	0.0000938	0.0000008	0.0004444
398	0.0001068	0.0000009	0.0005063
399	0.0001204	0.0000010	0.0005706
400	0.0001339	0.0000011	0.0006348
401	0.0001469	0.0000012	0.0006968
402	0.0001604	0.0000013	0.0007612
403	0.0001757	0.0000015	0.0008341
404	0.0001941	0.0000017	0.0009219
405	0.0002169	0.0000020	0.0010309
406	0.0002452	0.0000023	0.0011658
407	0.0002786	0.0000027	0.0013256
408	0.0003169	0.0000032	0.0015090
409	0.0003598	0.0000038	0.0017144
410	0.0004070	0.0000044	0.0019403
411	0.0004583	0.0000051	0.0021862
412	0.0005147	0.0000059	0.0024568
413	0.0005773	0.0000069	0.0027577
414	0.0006474	0.0000080	0.0030947
415	0.0007262	0.0000093	0.0034736
416	0.0008134	0.0000109	0.0038937
417	0.0009090	0.0000128	0.0043545
418	0.0010141	0.0000151	0.0048619
419	0.0011297	0.0000181	0.0054216
420	0.0012570	0.0000218	0.0060397
421	0.0013971	0.0000265	0.0067216
422	0.0015472	0.0000320	0.0074534
423	0.0017023	0.0000384	0.0082124
424	0.0018579	0.0000456	0.0089758
425	0.0020090	0.0000537	0.0097205
426	0.0021532	0.0000626	0.0104345
427	0.0022907	0.0000725	0.0111186
428	0.0024207	0.0000833	0.0117700
429	0.0025425	0.0000951	0.0123856
430	0.0026557	0.0001081	0.0129626
431	0.0027590	0.0001221	0.0134962

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
632	0.0056255	0.0003666	0.0000004
633	0.0054382	0.0003359	0.0000003
634	0.0052538	0.0003074	0.0000003
635	0.0050713	0.0002809	0.0000003
636	0.0048907	0.0002562	0.0000003
637	0.0047124	0.0002334	0.0000002
638	0.0045364	0.0002123	0.0000002
639	0.0043628	0.0001928	0.0000002
640	0.0041916	0.0001747	0.0000002
641	0.0040228	0.0001581	0.0000002
642	0.0038566	0.0001428	0.0000002
643	0.0036932	0.0001287	0.0000001
644	0.0035331	0.0001159	0.0000001
645	0.0033765	0.0001043	0.0000001
646	0.0032236	0.0000938	0.0000001
647	0.0030744	0.0000843	0.0000001
648	0.0029294	0.0000757	0.0000000
649	0.0027888	0.0000680	0.0000000
650	0.0026531	0.0000610	0.0000000
651	0.0025225	0.0000546	0.0000000
652	0.0023969	0.0000488	0.0000000
653	0.0022759	0.0000436	0.0000000
654	0.0021592	0.0000389	0.0000000
655	0.0020467	0.0000346	0.0000000
656	0.0019381	0.0000308	0.0000000
657	0.0018335	0.0000274	0.0000000
658	0.0017329	0.0000243	0.0000000
659	0.0016362	0.0000216	0.0000000
660	0.0015432	0.0000192	0.0000000
661	0.0014540	0.0000170	0.0000000
662	0.0013685	0.0000152	0.0000000
663	0.0012867	0.0000135	0.0000000
664	0.0012086	0.0000121	0.0000000
665	0.0011342	0.0000107	0.0000000
666	0.0010635	0.0000095	0.0000000
667	0.0009963	0.0000084	0.0000000

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
432	0.0028521	0.0001372	0.0139842
433	0.0029352	0.0001534	0.0144275
434	0.0030087	0.0001705	0.0148269
435	0.0030728	0.0001886	0.0151831
436	0.0031276	0.0002077	0.0154960
437	0.0031730	0.0002277	0.0157663
438	0.0032096	0.0002486	0.0159962
439	0.0032377	0.0002702	0.0161881
440	0.0032578	0.0002926	0.0163441
441	0.0032702	0.0003156	0.0164656
442	0.0032753	0.0003394	0.0165552
443	0.0032740	0.0003640	0.0166173
444	0.0032672	0.0003897	0.0166563
445	0.0032557	0.0004167	0.0166766
446	0.0032400	0.0004450	0.0166801
447	0.0032202	0.0004745	0.0166682
448	0.0031972	0.0005054	0.0166448
449	0.0031718	0.0005377	0.0166136
450	0.0031448	0.0005713	0.0165785
451	0.0031167	0.0006062	0.0165424
452	0.0030871	0.0006426	0.0165030
453	0.0030553	0.0006803	0.0164553
454	0.0030202	0.0007194	0.0163947
455	0.0029810	0.0007598	0.0163164
456	0.0029373	0.0008017	0.0162178
457	0.0028892	0.0008449	0.0160990
458	0.0028368	0.0008891	0.0159594
459	0.0027804	0.0009342	0.0157985
460	0.0027200	0.0009800	0.0156157
461	0.0026561	0.0010264	0.0154130
462	0.0025883	0.0010734	0.0151874
463	0.0025153	0.0011211	0.0149311
464	0.0024358	0.0011696	0.0146365
465	0.0023486	0.0012190	0.0142957
466	0.0022527	0.0012693	0.0139029
467	0.0021498	0.0013205	0.0134670

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
668	0.0009329	0.0000075	0.0000000
669	0.0008734	0.0000066	0.0000000
670	0.0008179	0.0000058	0.0000000
671	0.0007665	0.0000051	0.0000000
672	0.0007188	0.0000045	0.0000000
673	0.0006745	0.0000040	0.0000000
674	0.0006334	0.0000035	0.0000000
675	0.0005952	0.0000031	0.0000000
676	0.0005597	0.0000027	0.0000000
677	0.0005267	0.0000023	0.0000000
678	0.0004957	0.0000020	0.0000000
679	0.0004662	0.0000017	0.0000000
680	0.0004377	0.0000015	0.0000000
681	0.0004097	0.0000012	0.0000000
682	0.0003825	0.0000010	0.0000000
683	0.0003563	0.0000008	0.0000000
684	0.0003313	0.0000007	0.0000000
685	0.0003079	0.0000005	0.0000000
686	0.0002860	0.0000004	0.0000000
687	0.0002656	0.0000003	0.0000000
688	0.0002465	0.0000003	0.0000000
689	0.0002288	0.0000002	0.0000000
690	0.0002124	0.0000002	0.0000000
691	0.0001973	0.0000001	0.0000000
692	0.0001834	0.0000001	0.0000000
693	0.0001707	0.0000001	0.0000000
694	0.0001590	0.0000001	0.0000000
695	0.0001482	0.0000000	0.0000000
696	0.0001384	0.0000000	0.0000000
697	0.0001294	0.0000000	0.0000000
698	0.0001212	0.0000000	0.0000000
699	0.0001135	0.0000000	0.0000000
700	0.0001063	0.0000000	0.0000000
701	0.0000995	0.0000000	0.0000000
702	0.0000930	0.0000000	0.0000000
703	0.0000869	0.0000000	0.0000000

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$	wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
468	0.0020427	0.0013729	0.0130026	704	0.0000812	0.0000000	0.0000000
469	0.0019343	0.0014269	0.0125242	705	0.0000759	0.0000000	0.0000000
470	0.0018271	0.0014826	0.0120461	706	0.0000710	0.0000000	0.0000000
471	0.0017229	0.0015401	0.0115764	707	0.0000663	0.0000000	0.0000000
472	0.0016210	0.0015995	0.0111124	708	0.0000620	0.0000000	0.0000000
473	0.0015215	0.0016608	0.0106534	709	0.0000580	0.0000000	0.0000000
474	0.0014242	0.0017240	0.0101986	710	0.0000542	0.0000000	0.0000000
475	0.0013289	0.0017891	0.0097472	711	0.0000506	0.0000000	0.0000000
476	0.0012361	0.0018563	0.0093009	712	0.0000473	0.0000000	0.0000000
477	0.0011462	0.0019256	0.0088626	713	0.0000441	0.0000000	0.0000000
478	0.0010593	0.0019967	0.0084333	714	0.0000412	0.0000000	0.0000000
479	0.0009753	0.0020690	0.0080139	715	0.0000385	0.0000000	0.0000000
480	0.0008943	0.0021424	0.0076053	716	0.0000359	0.0000000	0.0000000
481	0.0008163	0.0022166	0.0072084	717	0.0000335	0.0000000	0.0000000
482	0.0007416	0.0022922	0.0068241	718	0.0000312	0.0000000	0.0000000
483	0.0006706	0.0023700	0.0064543	719	0.0000291	0.0000000	0.0000000
484	0.0006038	0.0024507	0.0061006	720	0.0000271	0.0000000	0.0000000
485	0.0005418	0.0025351	0.0057647	721	0.0000253	0.0000000	0.0000000
486	0.0004848	0.0026236	0.0054478	722	0.0000236	0.0000000	0.0000000
487	0.0004326	0.0027165	0.0051493	723	0.0000220	0.0000000	0.0000000
488	0.0003847	0.0028142	0.0048679	724	0.0000206	0.0000000	0.0000000
489	0.0003403	0.0029173	0.0046025	725	0.0000192	0.0000000	0.0000000
490	0.0002992	0.0030263	0.0043519	726	0.0000179	0.0000000	0.0000000
491	0.0002609	0.0031418	0.0041156	727	0.0000167	0.0000000	0.0000000
492	0.0002256	0.0032640	0.0038935	728	0.0000155	0.0000000	0.0000000
493	0.0001933	0.0033928	0.0036849	729	0.0000145	0.0000000	0.0000000
494	0.0001638	0.0035280	0.0034890	730	0.0000135	0.0000000	0.0000000
495	0.0001373	0.0036695	0.0033052	731	0.0000125	0.0000000	0.0000000
496	0.0001135	0.0038168	0.0031327	732	0.0000117	0.0000000	0.0000000
497	0.0000926	0.0039706	0.0029708	733	0.0000108	0.0000000	0.0000000
498	0.0000743	0.0041327	0.0028191	734	0.0000101	0.0000000	0.0000000
499	0.0000587	0.0043045	0.0026772	735	0.0000094	0.0000000	0.0000000
500	0.0000456	0.0044878	0.0025446	736	0.0000087	0.0000000	0.0000000
501	0.0000351	0.0046836	0.0024213	737	0.0000081	0.0000000	0.0000000
502	0.0000273	0.0048904	0.0023059	738	0.0000075	0.0000000	0.0000000
503	0.0000225	0.0051060	0.0021963	739	0.0000070	0.0000000	0.0000000

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
504	0.0000207	0.0053279	0.0020905
505	0.0000223	0.0055539	0.0019861
506	0.0000272	0.0057824	0.0018820
507	0.0000357	0.0060137	0.0017786
508	0.0000483	0.0062484	0.0016767
509	0.0000652	0.0064873	0.0015769
510	0.0000869	0.0067307	0.0014800
511	0.0001136	0.0069786	0.0013859
512	0.0001453	0.0072292	0.0012945
513	0.0001822	0.0074806	0.0012068
514	0.0002244	0.0077310	0.0011233
515	0.0002722	0.0079785	0.0010450
516	0.0003257	0.0082225	0.0009721
517	0.0003847	0.0084618	0.0009043
518	0.0004490	0.0086938	0.0008418
519	0.0005182	0.0089159	0.0007844
520	0.0005920	0.0091254	0.0007320
521	0.0006703	0.0093204	0.0006849
522	0.0007529	0.0095018	0.0006425
523	0.0008398	0.0096712	0.0006040
524	0.0009307	0.0098304	0.0005687
525	0.0010256	0.0099812	0.0005356
526	0.0011245	0.0101242	0.0005043
527	0.0012270	0.0102587	0.0004747
528	0.0013323	0.0103843	0.0004467
529	0.0014398	0.0105006	0.0004200
530	0.0015488	0.0106074	0.0003944
531	0.0016588	0.0107046	0.0003696
532	0.0017700	0.0107925	0.0003455
533	0.0018826	0.0108717	0.0003224
534	0.0019967	0.0109425	0.0003002
535	0.0021126	0.0110054	0.0002792
536	0.0022303	0.0110606	0.0002592
537	0.0023496	0.0111082	0.0002404
538	0.0024705	0.0111480	0.0002225
539	0.0025932	0.0111802	0.0002057

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
740	0.0000065	0.0000000	0.0000000
741	0.0000060	0.0000000	0.0000000
742	0.0000056	0.0000000	0.0000000
743	0.0000052	0.0000000	0.0000000
744	0.0000048	0.0000000	0.0000000
745	0.0000045	0.0000000	0.0000000
746	0.0000041	0.0000000	0.0000000
747	0.0000039	0.0000000	0.0000000
748	0.0000036	0.0000000	0.0000000
749	0.0000033	0.0000000	0.0000000
750	0.0000031	0.0000000	0.0000000
751	0.0000029	0.0000000	0.0000000
752	0.0000027	0.0000000	0.0000000
753	0.0000025	0.0000000	0.0000000
754	0.0000024	0.0000000	0.0000000
755	0.0000022	0.0000000	0.0000000
756	0.0000021	0.0000000	0.0000000
757	0.0000019	0.0000000	0.0000000
758	0.0000018	0.0000000	0.0000000
759	0.0000017	0.0000000	0.0000000
760	0.0000016	0.0000000	0.0000000
761	0.0000015	0.0000000	0.0000000
762	0.0000014	0.0000000	0.0000000
763	0.0000013	0.0000000	0.0000000
764	0.0000012	0.0000000	0.0000000
765	0.0000011	0.0000000	0.0000000
766	0.0000010	0.0000000	0.0000000
767	0.0000010	0.0000000	0.0000000
768	0.0000009	0.0000000	0.0000000
769	0.0000008	0.0000000	0.0000000
770	0.0000008	0.0000000	0.0000000
771	0.0000007	0.0000000	0.0000000
772	0.0000007	0.0000000	0.0000000
773	0.0000006	0.0000000	0.0000000
774	0.0000006	0.0000000	0.0000000
775	0.0000005	0.0000000	0.0000000

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
540	0.0027177	0.0112046	0.0001899
541	0.0028439	0.0112213	0.0001751
542	0.0029720	0.0112306	0.0001613
543	0.0031017	0.0112326	0.0001484
544	0.0032332	0.0112273	0.0001364
545	0.0033662	0.0112149	0.0001254
546	0.0035008	0.0111954	0.0001151
547	0.0036370	0.0111690	0.0001057
548	0.0037750	0.0111362	0.0000971
549	0.0039147	0.0110973	0.0000891
550	0.0040564	0.0110527	0.0000819
551	0.0042000	0.0110022	0.0000752
552	0.0043454	0.0109459	0.0000691
553	0.0044926	0.0108839	0.0000635
554	0.0046415	0.0108161	0.0000584
555	0.0047920	0.0107425	0.0000538
556	0.0049440	0.0106629	0.0000496
557	0.0050975	0.0105773	0.0000458
558	0.0052520	0.0104855	0.0000424
559	0.0054075	0.0103873	0.0000393
560	0.0055636	0.0102827	0.0000365
561	0.0057201	0.0101713	0.0000339
562	0.0058769	0.0100537	0.0000315
563	0.0060339	0.0099302	0.0000294
564	0.0061913	0.0098011	0.0000275
565	0.0063488	0.0096665	0.0000257
566	0.0065063	0.0095268	0.0000242
567	0.0066637	0.0093819	0.0000228
568	0.0068207	0.0092320	0.0000216
569	0.0069769	0.0090771	0.0000206
570	0.0071321	0.0089174	0.0000196
571	0.0072859	0.0087528	0.0000189
572	0.0074383	0.0085837	0.0000182
573	0.0075890	0.0084104	0.0000177
574	0.0077378	0.0082333	0.0000172
575	0.0078845	0.0080525	0.0000168

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
776	0.0000005	0.0000000	0.0000000
777	0.0000005	0.0000000	0.0000000
778	0.0000004	0.0000000	0.0000000
779	0.0000004	0.0000000	0.0000000
780	0.0000004	0.0000000	0.0000000
781	0.0000004	0.0000000	0.0000000
782	0.0000003	0.0000000	0.0000000
783	0.0000003	0.0000000	0.0000000
784	0.0000003	0.0000000	0.0000000
785	0.0000003	0.0000000	0.0000000
786	0.0000003	0.0000000	0.0000000
787	0.0000002	0.0000000	0.0000000
788	0.0000002	0.0000000	0.0000000
789	0.0000002	0.0000000	0.0000000
790	0.0000002	0.0000000	0.0000000
791	0.0000002	0.0000000	0.0000000
792	0.0000002	0.0000000	0.0000000
793	0.0000002	0.0000000	0.0000000
794	0.0000001	0.0000000	0.0000000
795	0.0000001	0.0000000	0.0000000
796	0.0000001	0.0000000	0.0000000
797	0.0000001	0.0000000	0.0000000
798	0.0000001	0.0000000	0.0000000
799	0.0000001	0.0000000	0.0000000
800	0.0000001	0.0000000	0.0000000
801	0.0000001	0.0000000	0.0000000
802	0.0000001	0.0000000	0.0000000
803	0.0000001	0.0000000	0.0000000
804	0.0000001	0.0000000	0.0000000
805	0.0000001	0.0000000	0.0000000
806	0.0000001	0.0000000	0.0000000
807	0.0000001	0.0000000	0.0000000
808	0.0000001	0.0000000	0.0000000
809	0.0000001	0.0000000	0.0000000
810	0.0000000	0.0000000	0.0000000
811	0.0000000	0.0000000	0.0000000

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
576	0.0080289	0.0078685	0.0000165
577	0.0081707	0.0076814	0.0000163
578	0.0083093	0.0074915	0.0000160
579	0.0084443	0.0072987	0.0000157
580	0.0085751	0.0071033	0.0000154
581	0.0087015	0.0069055	0.0000151
582	0.0088231	0.0067057	0.0000146
583	0.0089399	0.0065044	0.0000142
584	0.0090516	0.0063021	0.0000136
585	0.0091582	0.0060993	0.0000131
586	0.0092591	0.0058964	0.0000125
587	0.0093542	0.0056937	0.0000119
588	0.0094435	0.0054917	0.0000113
589	0.0095269	0.0052906	0.0000107
590	0.0096046	0.0050910	0.0000103
591	0.0096765	0.0048931	0.0000100
592	0.0097420	0.0046974	0.0000098
593	0.0098000	0.0045043	0.0000097
594	0.0098494	0.0043144	0.0000096
595	0.0098891	0.0041283	0.0000094

wavelength λ, (nm)	$\bar{r}$	$\bar{g}$	$\bar{b}$
812	0.0000000	0.0000000	0.0000000
813	0.0000000	0.0000000	0.0000000
814	0.0000000	0.0000000	0.0000000
815	0.0000000	0.0000000	0.0000000
816	0.0000000	0.0000000	0.0000000
817	0.0000000	0.0000000	0.0000000
818	0.0000000	0.0000000	0.0000000
819	0.0000000	0.0000000	0.0000000
820	0.0000000	0.0000000	0.0000000
821	0.0000000	0.0000000	0.0000000
822	0.0000000	0.0000000	0.0000000
823	0.0000000	0.0000000	0.0000000
824	0.0000000	0.0000000	0.0000000
825	0.0000000	0.0000000	0.0000000
826	0.0000000	0.0000000	0.0000000
827	0.0000000	0.0000000	0.0000000
828	0.0000000	0.0000000	0.0000000
829	0.0000000	0.0000000	0.0000000
830	0.0000000	0.0000000	0.0000000