Technical Bulletin

TB-2018-001

Derivation of the ACES white point CIE chromaticity coordinates

The Academy of Motion Picture Arts and Sciences

Science and Technology Council

Academy Color Encoding System (ACES) Project

June 15, 2018

Summary: This document describes the derivation of the white point CIE chromaticity coordinates used in various ACES encodings including ACES2065-1, ACEScg, ACESproxy, ACEScc and details of why the chromaticity coordinates were chosen.

NOTICES

Revision History

Date	Description
06/15/2018	Initial Version

Related Academy Documents

Document Name	Description
S-2013-001	ACESproxy – An Integer Log Encoding of ACES Image Data
TB-2014-004	Informative Notes on SMPTE ST 2065-1 – Academy Color Encoding Specification (ACES)
S-2014-003	ACEScc – A Logarithmic Encoding of ACES Data for use within Color Grading Systems
S-2014-004	ACEScg – A Working Space for CGI Render and Compositing
S-2016-001	ACEScct – A Quasi-Logarithmic Encoding of ACES Data for use within Color Grading Systems
P-2016-001	P-2013-001 – Recommended Procedures for the Creation and Use of Digital Camera System Input Device Transforms (IDTs)

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Introduction

The Academy Color Encoding System is a free, open, device-independent color management and image interchange system that can be applied to almost any current or future workflow. It was developed by hundreds of the industry's top scientists, engineers, and end users, working together under the auspices of the Academy of Motion Picture Arts and Sciences.

The primary color encoding in the Academy Color Encoding System (ACES) is the Academy Color Encoding Specification (ACES2065-1). Academy Color Encoding Specification is standardized in SMPTE ST 2065-1:2012 [1]. As part of the specification, the encoding primaries and white point were specified as CIE xy chromaticity coordinates to allow for the transformation of ACES2065-1 RGB values to and from other color spaces including CIE XYZ. Though the CIE xy chromaticity coordinates of encoding red, green, blue and white primaries are only one factor important to unambiguous color interchange[2], their specification is required for the calculation of a normalized primary matrix used in color space transformations [3]. The white point used in ACES2065-1 was later adopted for use in other ACES encodings such as ACEScg, ACEScc, ACEScct, etc [4]–[6]. For brevity and inclusiveness, the white point used in the various encodings will be referred to as "the ACES white point" throughout the remainder of this document unless more specificity is required.

The derivation of the ACES white point chromaticity coordinates outlined in this document is intended to help technical users of the ACES system calculate transformations to and from the various ACES encodings in as accurate a manner as possible. The white point of the ACES encodings does not limit the choice of sources that may be used to photograph or generate source images, nor does it dictate the white point of the reproduction. Using various techniques beyond the scope of this document, the chromaticity of the reproduction of equal ACES2065-1 red, green and blue values (ACES2065-1 R=G=B) may match the chromaticity of the ACES white point, the display calibration white point, or any other white point preferred for technical or aesthetic reasons

ACES technical documentation is available via ACEScentral.com and oscars.org/aces for product developers wishing to implement ACES concepts and specifications into their products and for workflow/pipeline designers to use ACES concepts and ACES-enabled products for their productions.

1 Scope

This document describes the derivation of the ACES white point CIE chromaticity coordinates and details of why the chromaticity coordinates were chosen. This document includes links to an example Python implementation of the derivation and an iPython notebook intended to help readers reproduce the referenced values.

This document is primarily intended for those interested in understanding the details of the technical specification of ACES and the history of its development. The definition of a color space encoding's white point chromaticity coordinates is one important factor in the definition of a color managed system. The white point used in various ACES encodings does not dictate the creative white point of images created or mastered using the ACES system. It exists to enable accurate conversion to and from the other color encodings such as CIE XYZ. The proper usage of the ACES white point in conversion, mastering, or reproduction are beyond the scope of this document. For example, the proper usage of the ACES white point in encoding scene colorimetry in ACES2065-1 is detailed in P-2013-001 [7].

2 References

[1] "SMPTE ST 2065-1:2012 – Academy Color Encoding Specification (ACES)," Society of Motion Picture and Television Engineers, New York, US, Standard, 2012.

[2] E. J. Giorgianni and T. E. Madden, *Digital Color Management: Encoding Solutions, Second Edition*. Addison-Wesley Longman Publishing Co., Inc., 2008, ISBN: 978-0-470-51244-9.

[3] "SMPTE RP 177-1993 – Derivation of Basic Television Color Equations," Society of Motion Picture and Television Engineers, New York, US, Recommended Procedure, 1993.

[4] "S-2014-004 – ACEScg – A Working Space for CGI Render and Compositing," Academy of Motion Picture Arts and Sciences, Beverly Hills, CA, Academy Standard, Mar. 2016.

[5] "S-2014-003 – ACEScc – A Logarithmic Encoding of ACES Data for use within Color Grading Systems," Academy of Motion Picture Arts and Sciences, Beverly Hills, CA, Academy Standard, Jul. 2016.

[6] "S-2016-001 – ACEScct – A Quasi-Logarithmic Encoding of ACES Data for use within Color Grading Systems," Academy of Motion Picture Arts and Sciences, Beverly Hills, CA, Academy Standard, Sep. 2016.

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3 Derivation of CIE chromaticity coordinates

The CIE xy chromaticity coordinates of the ACES white point are specified in SMPTE ST 2065-1:2012 as $x = 0.32168$ $y = 0.33767$ [1]. The ACES white point chromaticity coordinates are derived using the following procedure:

1. Calculate the CIE Daylight spectral power distribution for a Correlated Color Temperature (CCT) of 6000 K over the wavelength intervals 300 nm to 830 nm in 1 nm increments as specified in CIE 15:2004 Section 3.1 [8]
2. Calculate the CIE 1931 XYZ tristimulus values of the spectral power distribution as specified in CIE 15:2004 Section 7.1 [8]
3. Convert the CIE XYZ values to CIE xy chromaticity coordinates as specified in CIE 15:2004 Section 7.3 [8]
4. Round the CIE xy chromaticity coordinates to 5 decimal places

An implementation of the procedure described above can be found at:
`https://github.com/ampas/aces-dev/tree/master/documents/python/TB-2018-001/aces_wp.py`

4 Discussion

4.1 Comparison of the ACES white point and CIE D_{60}

Frequently, the white point associated with various ACES encodings is said to be 'D_{60}' [9]–[11]. This shorthand notation has sometimes led to confusion for those familiar with the details of how the chromaticity coordinates of the CIE D series illuminants are calculated [12]. The chromaticity coordinates of any CIE D series illuminant can be calculated using the equations found in Section 3 of CIE 15:2004 and reproduced in Equation 1 [8].

$$
\begin{aligned}
y_D &= -3.000x_D^2 + 2.870x_D - 0.275 \\
x_D &= \begin{cases} 0.244063 + 0.09911\dfrac{10^3}{T} + 2.9678\dfrac{10^6}{T^2} - 4.6070\dfrac{10^9}{T^3} & 4{,}000\text{ K} \leq T \leq 7{,}000\text{ K} \\ 0.237040 + 0.24748\dfrac{10^3}{T} + 1.9018\dfrac{10^6}{T^2} - 2.0064\dfrac{10^9}{T^3} & 7{,}000\text{ K} < T \leq 25{,}000\text{ K} \end{cases}
\end{aligned}
$$

Equation 1 – Calculation of CIE xy from CCT for CIE Daylight

The CIE has specified four canonical daylight illuminants (D_{50}, D_{55}, D_{65} and D_{75}) [8]. Contrary to what the names might imply, the correlated color temperature (CCT) values of these four canonical illuminants are not the nominal CCT values of 5000 K, 5500 K, 6500 K, and 7500 K. For instance, CIE D_{65} does not have a CCT of 6500 K but rather a CCT temperature of approximately 6504 K [13]. The exact CCT values differ from the nominal CCT values due to a 1968 revision to c_2, the second radiation constant in Planck's blackbody radiation formula [14]. When the value of c_2 was changed from 0.014380 to 0.014388, it altered the CIE xy location of the Planckian locus for a blackbody. This small change to the Planckian locus' position relative to the chromaticity coordinates of the established CIE daylight locus had the effect of changing the correlated color temperature of the CIE D series illuminants ever so slightly. The precise CCT values for the established canonical CIE D series illuminants can be determined by applying the equation in Equation 2 to the nominal CCT values implied by the illuminant name. The exact CCT values of the canonical daylight illuminants are not whole numbers after the correction factor is applied, but it is common to round their values to the nearest Kelvin. The CCT values of the CIE canonical daylight illuminants before the 1968 change to c_2, after the 1968 change, and rounded to the nearest Kelvin can be found in Table 1.

$$CCT_{new} = CCT \times \frac{1.4388}{1.4380}$$

Equation 2 – Conversion of nominal pre-1968 CCT to post-1968 CCT

CIE D Illuminant	CCT before 1968	CCT current (round to 3 decimal places)	CCT current (round to 0 decimal places)
D_{50}	5000 K	5002.782 K	5003 K
D_{55}	5500 K	5503.060 K	5503 K
D_{65}	6500 K	6503.616 K	6504 K
D_{75}	7500 K	7504.172 K	7504 K

Table 1 – CCT of canonical CIE daylight illuminants [15]

D_{60} is not one of the four CIE canonical daylight illuminants so the exact CCT of such a daylight illuminant could be interpreted to be either approximately 6003 K ($6000 \times \frac{1.4388}{1.4380}$) or 6000 K. Regardless, the ACES white point chromaticity coordinates derived using the method specified in Section 3 differs from both the chromaticity coordinates of CIE daylight with a CCT of 6003 K and CIE daylight with a CCT of 6000 K. The chromaticity coordinates of each, rounded to 5 decimal places, can be found in Table 2. As illustrated in Figure 1, the chromaticity coordinates of the ACES white point do not fall on the daylight locus nor do they match those of any CIE daylight spectral power distribution. The positions of the chromaticity coordinates in CIE Uniform Color Space (u′v′) and the differences from the ACES chromaticity coordinates in Δu′v′ can be found in Table 3.

	CIE x	CIE y
ACES White Point	0.32168	0.33767
CIE Daylight 6000K	0.32169	0.33780
CIE Daylight 6003K	0.32163	0.33774

Table 2 – CIE xy chromaticity coordinates rounded to 5 decimal places [15]

	CIE u'	CIE v'	$\Delta u'v'$
ACES White Point	0.20078	0.47421	0
CIE Daylight 6000K	0.20074	0.47427	0.00008
CIE Daylight 6003K	0.20072	0.47423	0.00007

Table 3 – CIE u′v′ chromaticity coordinates and Δu′v′ from the ACES white point rounded to 5 decimal places [15]

Although the ACES white point chromaticity is not on either the Planckian locus or the daylight locus, the CCT of its chromaticity can still be estimated. There are a number of methods for estimating the CCT of any particular set of chromaticity coordinates [16]–[19]. The results of four popular methods can be found in Table 4. Each of the methods estimates the CCT of the ACES white point to be very close to 6000 K.

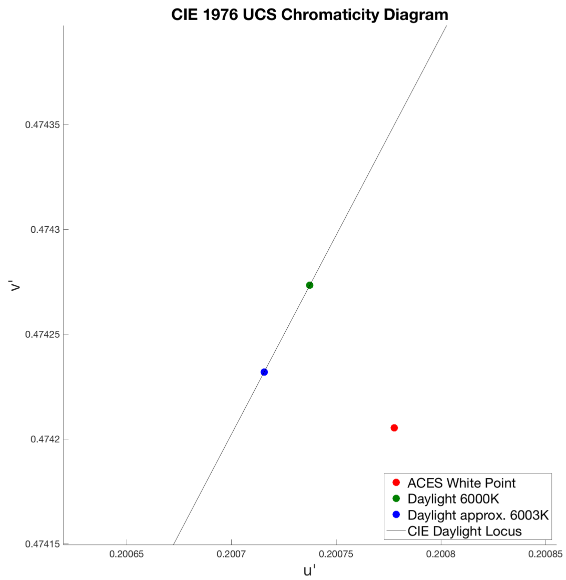

Figure 1 – CIE UCS diagram with chromaticity coordinates

CCT Estimation Method	ACES white point CCT
Robertson	5998.98 K
Hernandez-Andres	5997.26 K
Ohno	6000.04 K
McCamy	6000.41 K

Table 4 – Estimation of the CCT of the ACES white point rounded to 2 decimal places [15]

4.2 Reasons for the "D_{60}-like" white point

The ACES white point was first specified by the Academy's ACES Project Committee in 2008 in Academy Specification S-2008-001. The details in S-2008-001 were later standardized in SMPTE ST 2065-1:2012. Prior to the release of the Academy specification the Project Committee debated various aspects of the ACES2065-1 encoding, including the exact white point, for many months. The choice of the "D_{60}-like" white point was influenced heavily by discussions centered around viewer adaptation, dark surround viewing conditions, "cinematic look", and preference. In the end, the Committee decided to go with a white point that was close to that of a daylight illuminant but also familiar to those with a film heritage. The white point would later be adopted for use in other encodings used in the ACES system. It is important to note that the ACES white point does not dictate the chromaticity of the reproduction neutral axis. Using various techniques beyond the scope of this document the chromaticity of the equal red, green and blue (ACES2065-1 R=G=B) may match the ACES white point, the display calibration white point, or any other white point preferred for technical or aesthetic reasons.

The Committee felt that a white point with a chromaticity similar to that of daylight was appropriate for ACES2065-1. However, the exact CCT of the daylight was in question. Some felt D_{55} was a reasonable choice given its historical use as the design illuminant for daylight color negative films. Others felt D_{65} would be good choice given its use in television and computer graphics as a display calibration white point. Because the exact white point chromaticity would not prohibit users from achieving any reproduction white point, the Committee ultimately decided to use the less common CCT of 6000 K. This choice was based on an experiment to determine the reproduction chromaticity of projected color print film, the relative location of the white point compared to other white points commonly used in digital systems, and the general belief that imagery reproduced with the white point felt aesthetically "cinematic".

The projected color print film experiment involved simulating the exposure of a spectrally non-selective (neutral) gray scale onto color negative film, printing that negative onto a color print film, then projecting the color film onto a motion picture screen with a xenon-based film projector and measuring the colorimetry off the screen. The result of the experiment found that the CIE xy chromaticity coordinates of a projected LAD patch [20], [21] through a film system were approximately $x = 0.32170$ $y = 0.33568$. Figure 2 shows a plot of the CIE $u'v'$ chromaticity coordinates of a scene neutral as reproduced by a film system compared to the CIE daylight locus and the ACES white point. The chromaticity of the film system LAD reproduction was determined to be closest to CIE daylight with the CCT of 6000 K when the differences were calculated in CIE $u'v'$. A summary of the CIE $u'v'$ differences between CIE daylight at various CCTs and the LAD patch chromaticity are summarized in Table 5.

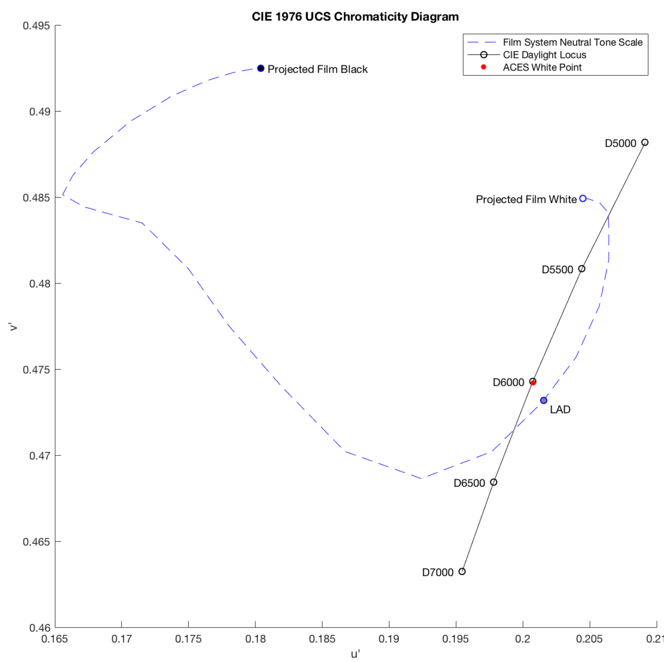

Figure 2 – Film system print-through color reproduction of original scene neutral scale

4.3 Reasons why the ACES white point doesn't match the CIE D_{60} chromaticity coordinates

As discussed in Section 4.2, the ACES white point was chosen to be very close to that of CIE Daylight with a CCT of 6000 K. This raises the question why the CIE chromaticity coordinates of $x = 0.32169$ $y = 0.33780$ were not used. The reasoning is somewhat precautionary; at the time, the exact chromaticity coordinates for the ACES white point were being debated, the ACES Project Committee was concerned about the implications the choice of any particular set of chromaticity coordinates could suggest.

Those new to ACES can often misinterpret the specification of a set of ACES encoding white point chromaticity coordinates as a requirement that the final reproduction neutral axis chromaticity is limited to only that white point chromaticity. However, as pointed out in Section 4.2, the ACES encoding white point does not dictate the chromaticity of the reproduction neutral axis, and regardless of the ACES white point chromaticity, the reproduction neutral axis may match the ACES white point, the display calibration white point, or any other white point preferred for technical or aesthetic reasons. The ACES white point chromaticity coordinates serve to aid in the understanding and, if desired, conversion of the colorimetry of ACES encoded images to any other encoding including those with a different white point.

Just as the implication of the ACES encoding white point on reproduction can be misunderstood, the ACES

Daylight CCT	**$\Delta u'v'$ from LAD chromaticity**
5500 K	0.008183
5600 K	0.006619
5700 K	0.005112
5800 K	0.003676
5900 K	0.002354
6000 K	0.001360
6100 K	0.001448
6200 K	0.002442
6300 K	0.003627
6400 K	0.004836
6500 K	0.006035

Table 5 – CIE Δu′v′ difference between projected LAD patch and CIE Daylight CCT chromaticity coordinates round to 6 decimal places [15]

Project Committee was also concerned that the ACES encoding white point might have unintended implications for image creators. Specifically, the Committee was concerned that the choice of a set of chromaticity coordinates that corresponded to a source with a defined spectral power distribution might be misunderstood to suggest that only that source could be used to illuminate the scene. For example, the Committee was concerned if the ACES white point chromaticity was chosen to match that of CIE Daylight with a CCT of 6000 K then *only* scenes photographed under CIE Daylight with a CCT of 6000 K would be compatible with the ACES system. In reality, ACES does not dictate the source under which movies or television shows can be photographed. ACES Input Transforms handle the re-encoding of camera images to ACES2065-1 and preserve all the technical and artistic intent behind on-set lighting choices.

For these reasons as well as an abundance of caution, the ACES Project Committee decided it would be best to use a set of chromaticity coordinates very near those of CIE Daylight with a CCT of 6000 K but not exactly those of any easily calculated spectral power distribution.