ACES – The Academy Color Encoding System

A new foundation for motion picture production, mastering, and archiving in the digital age

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Academy of Motion Picture Arts and Sciences

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Background: The Academy

- **Academy of Motion Picture Arts and Sciences**
- **Mission since 1927:**
  To Advance the Art and Sciences of Motion Pictures
- Has engaged in technical activities since its founding, primarily through cooperative research projects
- Represents the interests of the creators of motion pictures
  - Takes on problems that are not commercially feasible
  - Historical role in development of industry standards
Academy-led standards

Fig. 1. Standard Electrical Characteristics for two-way reproducing systems using metal diaphragm, Types I (M, 22, M1, M2, M3) systems. This characteristic for Types I and II systems equipped with metal diaphragm speakers should be adjusted to this Revised Standard Electrical Characteristic.

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Fig. 3. Layout of 35-mm sound film and aperture.

Fig. 4. Standard Electrical Characteristics for two-way reproducing systems using metal diaphragm, Types I (M, 22, M1, M2, M3) systems. This characteristic for Types I and II systems equipped with metal diaphragm speakers should be adjusted to this Revised Standard Electrical Characteristic.

Fig. 5. Standard Electrical Characteristics for two-way reproducing systems using metal diaphragm, Types I (M, 22, M1, M2, M3) systems. This characteristic for Types I and II systems equipped with metal diaphragm speakers should be adjusted to this Revised Standard Electrical Characteristic.
Some history

- Producers-Technicians Joint Committee (1929)
- Research Council of the AMPAS (1932)
- Activities transferred to The Motion Picture Research Center of the Association of Motion Picture Producers (1947-1976)
- Science & Technology Council of the AMPAS (2003–)
The Academy’s Science & Technology Council

- Created by the Academy’s Board of Governors in 2003 in response to the explosion of digital motion picture technology and its impact on the industry
- Created to help ensure that this technology enhances rather than limits or dominates the art form
Sci/Tech Council activities

• Public outreach and education

• History

• Industry-wide projects and collaboration
Sci/Tech Council project: Solid-state lighting

- Incandescent-tungsten lighting, which has been the standard for cinematography, has a smooth spectrum.

- Most LED lighting instruments currently on the market have “spikey” spectra.
• We are witnessing the end of film as a capture and distribution medium
• And yet, we’re still largely using film-preservation practices in archives receiving more and more digital assets
• Two major findings:
  – Every enterprise we spoke with has similar challenges and issues with digital preservation
  – No enterprise yet has a long-term strategy or solution that does not require significant and ongoing capital investment and operational expense
Sci/Tech Council project: ACES

- Academy Color Encoding System
- An architecture and supporting tools for digital motion picture production, mastering and archiving
Film / digital
The “digitalization” of cinema has developed in three overlapping waves:

- **~2010-????**
  - Production: Digital motion-picture cameras

- **~1990-2005**
  - Postproduction: Digital visual effects (CGI), digital editing (Avid), digital sound postproduction, digital intermediate (color grading and conforming)

- **~2005-2015**
  - Distribution: DCI, DCP, digital projection
Film / digital

![Graph showing the relationship between film and digital quality over time.](image-url)
Digital motion-picture cameras
Problems in motion picture mastering

• With the transition from film to digital, we have lost a single standard
  – 35mm intermediate stock was the standard
    – Camera stocks varied, but, even from different manufacturers (Kodak, Fuji), they all printed onto the same interpositive (IP) and internegative (IN) stock, from which all prints could be uniformly made
  – With digital cameras, every manufacturer has its own raw output format, which may even vary from model to model or generation to generation
    – Many variations of “digital negative”
    – No standard format that could preserve everything in the raw capture from any camera
Academy Color Encoding System (ACES)

- **Goal:**
  Create an architecture and supporting tools for digital motion picture production, mastering and archiving
  - Support a variety of workflows (e.g. digital intermediate, VFX, restoration)
  - Support film and digital capture
Milestones in the development of ACES

- 2004: First meeting, “birds-of-a-feather” session at Siggraph 2004
  - Academy File Format Project initiated
- 2005: Problem study, requirements document, white paper
- 2006: Follow-on white paper; Senior Imaging Engineer hired
- 2007: Draft image-encoding specs published for comment, testing
- 2008: Call for Participation issued
  - Introduced at HPA Tech Retreat as the “Image Interchange Framework” (IIF)
  - IIF papers at SMPTE Fall Conference
  - Color-corrector implementations begin
- 2009: Draft encoding specifications finalized; IIF introduced at IBC
Milestones in the development of ACES

- **2010**: SMPTE standards work initiated (first four published in 2012)
- **2011**: Industry trials begin;
  First ACES-compatible products appear at NAB;
  Academy builds state-of-the-art imaging lab, hires two more imaging engineers;
  At least a dozen U.S. TV series and pilots start using ACES
- **2012**: The name “ACES” – which originally referred to only the encoding specification – is adopted as the name for the entire system formerly referred to as “IIF”
Industry-wide collaborative development

- More than 50 leading practitioners, engineers, and scientists
- Leading equipment manufacturers
- Major post-production, VFX, and animation facilities
- Major technical contributions from:
  - Adobe, Arri, Autodesk, Dolby, FilmLight, Fujifilm, ILM, Kodak, Pixar, Sony, and top color-science and imaging experts
What is ACES?

- An image file format
- A color-management system
- An image-interchange framework
Key component: ACES color encoding

- Academy Color Encoding Specification
  - Goal: Define an image format that can:
    - Preserve all the detail captured by any camera
    - Be used as a common format for postproduction processing and interchange
    - Serve as a digital source master for the creation of distribution masters and archiving
**Input Device Transforms (IDT)**

- **Reference Input Capture Device**
  - Idealized camera
  - Outputs ACES data

- **Input Device Transform (IDT)**
  - Specific to a particular camera, converts its output to ACES
On the output side: RRT + ODT

- **Reference Rendering Transform (RRT)**
  - Idealized replacement for print-film emulations
  - Extremely wide gamut and high dynamic range
- **Output Device Transform (ODT)**
  - Tuned for a particular display’s gamut, dynamic range, and transfer function
The Academy Color Encoding System (ACES): Idealized system block diagram
ACES color-encoding criteria

• **Wide color gamut**
  – Encode all possible colors (cover the visible gamut)

• **High dynamic range**
  – Encode full range of film and digital, current and future

• **High-precision representation**
  – No quantizing (contouring)
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Wide gamut: ACES covers all visible colors

- ACES color primaries in perspective
  - Primaries are virtual, but close enough to real RGB to enable their use as a working space

<table>
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<tr>
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<th>CIE y</th>
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<tbody>
<tr>
<td>Red</td>
<td>0.73470</td>
<td>0.26530</td>
</tr>
<tr>
<td>Green</td>
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<td>1.00000</td>
</tr>
<tr>
<td>Blue</td>
<td>0.00010</td>
<td>-0.07700</td>
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Wide color gamut
Wide gamut: ACES covers all visible colors

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Wide Color Gamut

- Simulation – same ACES image converted to different primaries

Rec. 709

UHDTV
ACES color-encoding criteria

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Luminance encoding

• Digital imaging
  – Luminance encoding (tone reproduction, transfer function)

• Output media have limited dynamic ranges
  – Reflection prints: < 100:1
    – That’s okay, that’s about all you can see at any one fixed state of adaptation anyway
  – Film prints: $10^4$:1 for typical print stocks (over $10^5$:1 for Kodak Vision Premier), but typically limited by projector optics, port glass, room surface reflections, exit signs, etc., to roughly 2000:1 or less
  – Digital projection: 2000:1 to 10,000:1, but also limited by room conditions
Camera dynamic range

- Cameras can record a greater dynamic range than projection systems can reproduce
  - Logarithmic representation is useful for photometric measurements
    - Such as luminous intensity (cd = lm/sr), luminance (cd/m²), illuminance (lx = lm/m²), luminous exposure (lx-s), and relative luminance and exposure
    - A “stop” is a factor of 2 (3½ stops ≈ factor of 10)
  - Motion-picture negative film: > 15 stops; digital: currently as much as ~14-15 stops, improving year to year
  - Film, and digital-camera processing and recording formats, together with postproduction processing, compress that dynamic range into the range that can be reproduced at projection, by lowering the contrast of extreme highlights and the deepest shadows
Scene dynamic range

- The dynamic range of the real world is wider still

Moonlight, ISO 800, f8, 240 s  (Relative exposure value: 1:768,000)  Daylight, ISO 800, f8, 1/3200 s

PHOTOS: GEORGE JOBLOVE
• The dynamic range of the real world exceeds that of cameras
  – The cinematographer employs lighting, film or sensor sensitivity, aperture, and filtration to adjust exposure to place middle-grays in the scene around the midpoint of the image-capture system’s dynamic range.
Scene-referred, film-referred, or output-referred?

• **Output-referred**
  – Video: “White” is whatever maximum brightness level is on display
    – Example: 8 bits, 255-0, “white” to “black”
  – Don’t want output-referred, don’t want to be tied to specific display technology and limitations

• **Film-density-referred**
  – Like Cineon, is dependent on film response, limitations

• **Scene-referred is most generic**
A really good solution is just to encode the relative scene luminance or exposure.

Linear scale, directly proportional to luminance or exposure.

Scaled so that 1 represents luminance (or exposure) of 100% diffuse reflector in a properly-exposed image.

- .18 represents “18% gray,” or “middle gray”
- Video levels are defined relative to a reference white; film photographers and cinematographers think in terms of a reference gray.
Numeric representations

• Fixed-point (integer) encoding is a very poor way of encoding values across a wide dynamic range
  – Very roughly speaking, human contrast perception is proportional to luminance; that is, you can discriminate finer differences in luminance at lower luminance levels
  – Thus code values must be “closer together” in the dark end of the luminance scale than in the bright end, and having them just as close in the bright end is wasteful

• Floating-point encoding (“scientific notation”) is much more efficient
ACES uses 16-bit floating-point (half-float) format (IEEE 754-2008 “binary16”)

- **Floating-point is like scientific notation**
- **Decimal examples:**
  - $1.234 \times 10^5$
  - $2.998 \times 10^8$ (c in m/s)
  - $1.803 \times 10^{12}$ (c in fur/ftn)
  - $9.109 \times 10^{-31}$ ($m_e$ in kg)
- **Binary:**
  - $f \times 2^e$
- **16-bit floating point:**
  - 1 bit: sign
  - 5 bits: exponent
  - 10 bits: fraction
ACES dynamic range

- 16-bit floating-point format provides for high dynamic range
  - Magnitude from zero to $2^{16}-32 = 65504$
  - Magnitude as small as $2^{-14} \approx 6.1 \times 10^{-5}$ at full precision

- ACES’ HDR allows all the dynamic range originally captured to be preserved through postproduction, right up to the point of final mastering (and for archiving)
  - Latest digital cameras: 14-15 stops of dynamic range
  - Film: > 15 stops
  - ACES: > 30 stops ($10^{9}:1$) (>12 stops below mid-gray to >18 stops above)
**ACES dynamic range: Example**

**Example: ACES values, exposed for night home interior (100 lux)**

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>65000</td>
<td>65x perfect white diffuser, daylight</td>
</tr>
<tr>
<td>10000</td>
<td>10x perfect white diffuser, daylight</td>
</tr>
<tr>
<td>1000</td>
<td>perfect white diffuser, daylight</td>
</tr>
<tr>
<td>100</td>
<td>perfect white diffuser, skylight or overcast</td>
</tr>
<tr>
<td>10</td>
<td>perfect white diffuser, bright office interior</td>
</tr>
<tr>
<td>1</td>
<td><em>perfect white diffuser, night home interior</em></td>
</tr>
<tr>
<td>0.1</td>
<td>10% gray, night home interior</td>
</tr>
<tr>
<td>0.01</td>
<td>1% black, night home interior</td>
</tr>
<tr>
<td>0.001</td>
<td>$3^{1/3}$ stops down from 1% black, night home interior</td>
</tr>
<tr>
<td>0.0001</td>
<td>$6^{2/3}$ stops down from 1% black, night home interior</td>
</tr>
<tr>
<td>0.00006</td>
<td>$7^{1/3}$ stops down from 1% black, night home interior</td>
</tr>
</tbody>
</table>
“Normal” exposure
ACES – 2 stops under
High-dynamic-range display

Photographed displays

2350:1

> 100,000:1
ACES color-encoding criteria

• **Wide color gamut**
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  – No quantizing (contouring)
Contrast precision: Visual effect of insufficient bits

- 2 bits, $2^2 = 4$ levels
- 4 bits, $2^4 = 16$ levels
- More bits, more levels
Contrast precision: 8 bits are not enough

8 bits, $2^8 = 256$ levels
Contrast precision (Why 10 bits aren’t enough)

![Diagram showing modulation thresholds]

Steps visible

Steps not visible
ACES contrast precision

Full ACES range: 30 stops

1 stop

ACES precision: 1024 steps per stop

.5

1
Recap: ACES color-encoding characteristics

- **Full color gamut**
  - Encodes all possible colors (covers the visible gamut)
- **High dynamic range**
  - 30 stops encoded (much more than film or digital cameras)
- **High-precision**
  - 1024 steps per stop (no quantizing, contouring)

(As defined by SMPTE ST 2065-1)
ACES image container file format

- Constrained version of OpenEXR (SMPTE ST2065-4:2013)
- OpenEXR already in wide use and widely supported
- Was defined to support 16-bit floats
- ACES color encoding
- Includes production metadata
Metadata

• **Required:**
  - `acesImageContainerFlag` (1)
  - `channels` (3, 4, 6, or 8)
  - `chromaticities` (as specified by SMPTE ST 2065-1)
  - `compression` (0)
  - `dataWindow`
  - `displayWindow`
  - `lineOrder`
  - `pixelAspectRatio`
  - `screenWindowCenter`
  - `screenWindowWidth`
Metadata

• **Time-related:**
  - capDate (capture date/time)
  - captureRate
  - expTime (exposure time)
  - framesPerSecond
  - timeCode
  - timecodeRate
  - keyCode
  - utcOffset
  - imageCounter
Metadata

- **Lens and sensor:**
  - lensMake
  - lensModel
  - lensSerialNumber
  - aperture
  - isoSpeed
  - focalLength
  - focus
  - lensAttributes
### Metadata

- **Camera:**
  - `cameraMake`, `cameraModel`, `cameraSerialNumber`, `cameraIdentifier`
  - `cameraFirmwareVersion`
  - `cameraLabel`
  - `latitude`, `longitude`, `altitude`
  - `cameraPosition`, `cameraViewingDirection`, `cameraUpDirection`
  - `imageRotation`
  - `multiView`, `convergenceDistance`, `interocularDistance`
  - `storageMediaSerialNumber`

- **Recorder:**
  - `recorderMake`, `recorderModel`, `recorderSerialNumber`, `recorderFirmwareVersion`
Metadata

• **Miscellaneous:**
  – comments
  – creator
  – `imageDigestMD5`
  – `originalImageFlag`
  – owner
  – `reelName`
  – `UUID`

• *(Custom attributes may also be defined)*
Using ACES in production

- ACES provides components for designing workflows (camera, dailies, editorial, VFX, post, deliverables)
- Many vendors are supporting ACES within their software
- Color management can be implemented directly or through use of lookup tables (LUT’s) in various parts of the workflow
- Coordination among departments to use ACES
Workflow design

- **Camera:**
  - ACES may be a menu option for the output of the video tap (send to a LUT box for proper display with an ACES viewing LUT)
  - Camera-raw convertors may provide ACES file output

- **On-Set:**
  - Preview and playback with ACES viewing LUT
  - Apply ASC CDL in ACES color space
  - Save camera original files (as always)
    - ACES can be created later as the working negative for VFX and color correction, and is then stored as the archival master
Workflow design

• Near-set & Editorial:
  – Manage metadata
  – Apply ASC CDL (in ACES) and use ACES viewing LUT for dailies deliverables
  – “Bake” ACES viewing LUT into proxy images for Editorial
  – Convert camera raw files to ACES .exr format for VFX

• Post:
  – Color-correct in ACES
    – Use ACES viewing LUT for any output viewing
  – Convert camera files to .exr as needed
    (and as late as possible in the production process since they are larger)
  – Use ACES .exr for interchange among facilities, VFX, 3D conversion, etc.
Workflow design

• Film origination:
  – Calibrate scanners and telecines to Academy Printing Density (APD)
  – Output files to 16-bit .dpx Academy Density Encoding (ADX)
  – Convert to ACES OpenEXR as the “digital negative”
Currently in development

- **ACESproxy**
  - For on-set preview, look creation, and color grading via transmission from camera over 10/12-bit interfaces like HD-SDI
  - Send ACESproxy right from cameras to a LUT box
  - Logarithmic encoding, 18 stops of range, 50 steps per stop
  - Not intended for interchange, mastering finals, or archiving – not intended to be recorded!
Current status of ACES

• **ACES is now a SMPTE standard**
  - SMPTE ST 2065-1: Academy Color Encoding Specification (ACES)
  - (Two other standards [2065-2, 2065-3] and an amendment [to 268] relate to how ACES interfaces with film: APD, ADX, DPX for ADX)
  - Soon to be published: SMPTE ST 2065-4: ACES Image Container File Layout (constrained OpenEXR)
  - Currently revising RRT/ODT’s based on feedback, working on metadata issues

• **Widespread adoption by equipment manufacturers, post facilities**

• **Industry trials continue, as ACES is more widely used in production**
Current status of ACES

- Productions that have used ACES
  - PGA-ASC “Image Control Assessment Series”
  - Sony F65 Sample Reel and “El Dorado”
  - 4 TV series
  - 3 restorations
  - 5 D.I.s
  - 20 short-form projects

- ACES awarded Emmy Engineering Award in 2012
Current status of ACES – example of recent success

• **Alamo Bay** [Louis Malle, 1985]
  – Restoration (2013) from original 35-mm negative through ACES workflow
  – Curtis Clark, ASC, Director of Photography:
    “As cinematographer, my original creative intent for color and tonal contrast, along with textural detail of scene content, has been fully realized beyond what was possible when the film was made!”
Summary: The benefits ACES provides

• A digital source master: A standard format that can preserve full fidelity (everything in the raw capture) from any camera

• Uniform, well-defined handling during postproduction, which allows:
  – Precisely-controlled color management
  – Expanded creative choices

• A standard format for archiving
More information

• For more information on ACES:
  oscars.org/aces

• Sign-up for users (volunteers welcome!):
  AcademyACES [at] googlegroups.com

• Questions about this presentation:
  george [at] joblove.com