Accurate ACES Rendering in Systems Using Small 3DLUTs

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Abstract. The ACES color space has unlimited dynamic range, however, it is not so easy to implement ACES workflow keeping high quality on the grading systems currently in use. To this end, we proposed custom Log ACES and High Saturated Log ACES (HSLA) methods. The custom Log ACES can process negative ACES values and can handle high dynamic range. HSLA expands the ACES color space to reduce vacant area and spread real color data area in order to use 3D LUTs more effectively. These two methods drastically improve accuracy of color reproduction even if the post-production system supports less than 33 grid number of 3D LUTs.

Keywords. ACES, 3DLUTs,
Introduction

A new color management process for making of digital motion picture is proposed by AMPAS. The workflow, IIF-ACES, has unlimited scene-referred color space. All Input device image data such as film scanned images, digital camera images and CGI (Computer Generated Imagery) are transformed into ACES. ACES is a connecting color space and all of the motion picture making procedures should be done in ACES. To acquire the output image, the standard transformation RRT (Reference Rendering Transform) and ODT (Output Device transform) are applied to the ACES image.

The transformations of input device RGB to ACES and ACES to output device image have strong non-linear characteristics.

To adopt IIF-ACES workflow, color management software needs to handle such a huge color space image data and needs to calculate such a non-linear transformation accurately.

But many current software such as for grading, editing, VFX only support 1DLUT and 3DLUT for color transformation. Moreover, they can only handle limited integer range image data such as 16bit.

In general, the number of grids of 3DLUT is less than 66. The calculation of the output value is done by linear interpolation of nearest 8 grids. If the 3DLUT transformation has strong non-linear characteristics, the simple linear interpolation can not give accurate answer. IIF-ACES workflow requires using RRT and ODT cascaded 3DLUT, but it has very strong non-linear characteristics because of the difference of math space, input is brightness linear ACES, output is gamma shaped device code value, because of the s-shaped tone scale which compress very bright highlight and very dark shadow.

If the software supports floating point expression 1DLUT which has large number of indices, the transformation from brightness linear ACES into roughly close to output device tone scale can be set into a 1DLUT. In this case, IIF-ACES can be integrated into the software.

But if the software doesn’t support such a 1DLUT, the software cannot handle linear ACES image properly. Moreover, expression for ACES data needs decimal floating point. So the software needs to handle floating point image file format like OpenEXR.

IIF-ACES and its transformations

The IIF-ACES image processing workflow is shown in Fig.1.

![AMPAS-IIF Architecture](image-url)
The film scanned density image data, ADX or Academy Density encoding eXchange, is converted to ACES color space by a Universal Unbuild transformation. The digital camera data is also converted to ACES by an Input Device Transform. Computer graphics is rendered to ACES. Thus, all input image data is converted to scene-referred ACES color space. Even if the input images are acquired from different input devices, the colors of the same object and scene become nearly the same color in ACES color space. This makes easy to edit or compose the image data from different input devices.

RRT is the transformation from scene-referred image to output-referred image data on the ideal output device that has dynamic range of 1:1,000,000. The RRT reproduces “memory colors” such as neutrals, skin, foliage, sky, etc. in a way that follows the reproduction of the film system.

ODT is the transformation from ideal output device to actual output such as Rec709 Television or DCI projector.

Since the ACES is scene brightness linear data and input/output device data usually is not brightness linear data, conversion from input data to ACES and ACES to output device data have non-linear characteristic.

The transformations such as IDT, RRT and ODT are defined in CTL script language and opened to the public from AMPAS-IIF.

The example of these conversion’s characteristic curves are shown in Fig2.

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**Fig.2  Tone transformation between ACES and device code value**

In the case of making a very small grid such as 5 grids 3DLUT of ACES to DCI P3 code value, the grid series are 0.0, 5.0, 10.0, 15.0, and 20.0. The tone characteristic of RRT+ODT has an exponential increase in ACES 0 to 5, but only a gradual increase in ACES 5 to 20. So the accuracy of the 3DLUT deteriorates in ACES 0 to 5. It is necessary to define another scale ACES color space for 3DLUT transformation. It is desirable that the new scale ACES color space to device code value transformation do not have sharp non-linear characteristic.
**Definition of custom Log and its domain**

The output device’s code value is defined to have a nearly proportional relationship to perceived intensity of brightness. The digital camera code value is also defined to have sufficient tone resolution of brightness perception.

The requirements for a new tone scale of ACES color space are:
- The tone scale has nearly proportional relationship to perceived intensity of brightness.
- The scale has sufficient tone resolution of brightness perception.
- The definition is easy to be understood physically.

We propose logarithm scale ACES to satisfy these demand.

Fig.3 shows Log ACES characteristic.

![Graph showing Log ACES characteristic](image)

The left graph shows the tone characteristics of S-Log and LogC code value vs. Log ACES. The right graph shows the tone characteristics of Log ACES vs. DCI P3 code value.

**Fig.3 Tone transformation between Log ACES and device code value**

There is a problem when converting linear ACES to Log ACES. The linear ACES allows minus values and actually, minus values are generated in the IDT calculation. They were created by un-ideal spectral sensitivity of the capturing device or simply by noise of the sensor. Clipping these minus values cause not only image information loss but also image artifacts or noise.

To handle the linear minus ACES values, we propose a the custom Log function.

\[
\begin{align*}
\text{x} &\geq 0: \log_{10}(x+b) \\
\text{x} &< 0: 2\log_{10}(b)-\log_{10}(-x+b)
\end{align*}
\]

\[b=0.0316 \quad \log_{10}(b)=1.5\]

Fig.4 shows the custom Log function. This function can converts all minus ACES values by reversible form.

Next we define the Log ACES domain. The domain definition is important for LUT processing and integer image encoding. We investigated input and output device data domain in the ACES
color space by applying IDT for input device code value and applying inverse of RRT+ODT for output device code value. The result is shown in Fig. 5.

![Fig. 5](image.png)

*Fig. 4 Custom Log curve*

**Table 1. Input and output device data domain.**

<table>
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<tr>
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<td>0</td>
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We defined the domain of -2.1 to 2.3 in Log which correspond to -0.1 to 200 in linear ACES. The domain completely includes S-Log, Log C and DCDM dynamic range, and has enough margin. The resolution for 1 digit in 10 bit integer coding is 0.0043 in Log. This resolution seems enough and reasonable.

Fig. 6 shows the result of image rendering by a cube of 33 grids 3DLUT of IDT and RRT+ODT. The image rendered with CTL is the very accurate result of IIF-ACES rendering. The image rendered with 3DLUT was rendered by using input code value to linear ACES or Custom Log ACES 3DLUT and linear ACES or Custom Log ACES to output code value.

The result with Linear ACES 3DLUT is inaccurate. The image processed in Custom Log ACES is very close to CTL rendering.
Improvement of custom Log ACES color space

We showed the Log scale ACES color space is useful for the system which only supports 3DLUT, but does not supports shaper LUT. But there are systems that only support very small number grids of 3DLUT such as cube of 17 grids. In this case, the accuracy is not enough and the difference from ideal CTL rendering is not acceptable.

Fig7 (a) and (b) shows the result of CTL rendered image and cube of 17 grids 3DLUT. The Gray balance of the 3DLUT rendered image is different from CTL render.

In this case, the input space of 3DLUT is a cubic expression of Custom Log ACES. The cubic space is defined as (R,G,B)=(-2.1,-2.1,-2.1) to (2.3,2.3,2.3) in Custom Log ACES and (-0.1,-0.1,-0.1) to (200,200,200) in linear ACES. The cause of the difference between CTL rendering and the 3DLUT rendering means the Custom Log space is too wide to approximate CTL in cube of 17 grids 3DLUT. The dynamic range of Custom Log can’t reduce any more. But for color direction, the domain might be reduced.

For example, (-2.1,2.3,-2.1) is the edge of the cube. This means the color is something like red = -0.1, green is 200 and blue is -0.1 cd/m². Since the color balance is extremely uneven, this color unlikely exists in the natural world.

We have tried to define the reasonable color space to enhance the accuracy of 3DLUT processing. The necessary domain of the 3DLUT input is the domain that needs to express all output device value. We have investigated the domain by inversion of DCI gamut to Custom Log ACES.
Fig. 8 The gamut in Custom Log ACES to cover all DCI gamut

Fig. 8 shows the color gamut in Custom Log ACES that needed to cover all DCI color when RRT+ODT applied. The color space is three dimensional, but these graphs are the projective. The green square is the Custom Log ACES domain. As you can see in the graph, there are vacancies in the area where red green and blue are unbalanced. As mentioned before, these colors are unlikely to exist, so these areas are useless and wasteful of 3DLUT grid.

To reduce the un-used space, we propose HSLA or High Saturate Log ACES. The HSLA concept involves enhancing the saturation of the Custom Log domain to reduce the vacant area. The HSLA is defined as:

\[
\text{Gray} = \frac{\text{CLogR} + \text{CLogG} + \text{CLogB}}{3}
\]

\[
\text{HSLA}_R = \frac{\text{CLogR} - \text{Gray} \times k}{1-k}
\]

\[
\text{HSLA}_G = \frac{\text{CLogG} - \text{Gray} \times k}{1-k}
\]

\[
\text{HSLA}_B = \frac{\text{CLogB} - \text{Gray} \times k}{1-k}
\]

\[
\text{CLogR}, \text{G}, \text{B} : \text{Custom Log ACES}, \quad k : \text{saturation parameter}
\]

The inverse transformation is:

\[
\text{Gray} = \frac{\text{HSLA}_R + \text{HSLA}_G + \text{HSLA}_B}{3}
\]

\[
\text{CLogR} = \text{HSLA}_R - \frac{(\text{HSLA}_R - \text{Gray}) \times k}{1-k}
\]

\[
\text{CLogG} = \text{HSLA}_G - \frac{(\text{HSLA}_G - \text{Gray}) \times k}{1-k}
\]

\[
\text{CLogB} = \text{HSLA}_B - \frac{(\text{HSLA}_B - \text{Gray}) \times k}{1-k}
\]

Fig. 9 shows the result of HSLA with parameter \( k = 0.5 \). To enhance the saturation, the vacant area is reduced and the waste of 3DLUT grid is also reduced.
Fig. 10 shows the image processing flow for using HSLA color space. The image processing result of 17 grids 3DLut with HSLA color space is shown in Fig. 7(c).

![Image processing flow for using HSLA](image)

Fig. 10 Image processing flow for using HSLA

Fig. 11 shows the difference between CTL script processing and 3DLUT processing. The plots are obtained by applying 3DLUT for 33^3 full range cube and calculated L*a*b* value from output RGB value. By using simple customLog (a), many colors show the dE errors more than 3.0, and average dE is 2.55, not so small value. But using HSLA (b) improves it a lot. Almost all colors show less than 1.0eE and average dE is 0.85.

![Accuracy of 3DLUT processing](image)

(a) without HSLA  
(b) with HSLA

Fig. 11 Accuracy of 3DLUT processing

The HSLA improves 3DLUT grid assignment to an effective area, and the result is an image close to the CTL Render image. This means the accuracy of image processing of IIF-ACES with 3DLUT is improved by the HSLA.

**Application**

We incorporate the HSLA color space in our product IS-100. IS-100 is an on-set look creation system. The system fully adopts the IIF-ACES workflow by using a CTL like GPU script language, shader. The script transformation is completely the same as CTL, so the accuracy is perfect.
The important function of IS-100 is exporting the created look to post production systems such as grading software. Currently, many grading softwares only have 1D LUT and 3D LUT, but not script transformation.

Fig. 12 shows the export function. The IDT and Look Modification Transform is cascaded and transformed into 3D LUT or 1D LUT + 3D LUT in the grading software format. The RRT and ODT are also cascaded and transformed into 3D LUT or 1D LUT + 3D LUT in the grading software format. The input LUT’s output and output LUT’s input color space, which is grading color space, is HSLA.

**Fig.12 IS-100 export function**

The export function creates 1D LUT and 3D LUT with HSLA color space to enhance the conformity between processed image in IS-100 and the grading system.

**Conclusion**

We have explained the method to perform accurate ACES rendering using a 3D LUT that has a small number of lattices. By using the Custom Log ACES, non-linearity of transformation between device RGB and ACES were reduced. Therefore, the accuracy of IIF-ACES calculation with a 3D LUT was improved. For a 3D LUT with small number of lattices, HSLA color space further improved the accuracy of calculation.

The Custom Log ACES and HSLA have been proposed to AMPAS-IIF and discussed for standardization of integer ACES expression.

**Standards**

Academy of Motion Picture Arts and Sciences (AMPAS) Specification S-2008-001, Academy Color Encoding Specification (ACES).
Outline

• About IIF-ACES
• Custom Log ACES Proposal
• Result
• HSLA Proposal
• Result
• Application
• Conclusion
• All input image data are converted into ACES (Academy Color Encoding Specification).
• ACES is a scene referred color space and has unlimited dynamic range.
• Look Modification Transform or Color Grading is applied in ACES.
• ACES image is converted to output referred image by RRT (Reference Rendering Transform) and ODT (Output Rendering Transform).
The Color Transformation Language, or CTL, is a programming language for digital color management.

All transformation defined in IIF-ACES is described in CTL.

Example of CTL (S-Log IDT)

```c
// Slog_to_ACES.ctl

void IDT(
    input varying float rIn, input varying float gIn, input varying float bIn,
    output varying float rOut, output varying float gOut, output varying float bOut
)
{
    /* s-log to Lin */
    float Rraw = (pow(10,(((rIn * 256-16)/219)-0.616596-0.03)/0.432699)-0.037584)*0.9;
    float Graw = (pow(10,(((gIn * 256-16)/219)-0.616596-0.03)/0.432699)-0.037584)*0.9;
    float Braw = (pow(10,(((bIn * 256-16)/219)-0.616596-0.03)/0.432699)-0.037584)*0.9;

    /* raw to ACES matrix */
    float ACESR = ( 0.744847149) * Rraw + ( 0.27237221 ) * Graw + (-0.01721936 ) * Braw;
    float ACESG = (-0.003795515) * Rraw + ( 1.003255292) * Graw + ( 0.000540223) * Braw;
    float ACESB = (-0.07669582 ) * Rraw + ( 0.114265389) * Graw + ( 0.962430431) * Braw;

    rOut = ACESR;
    gOut = ACESG;
    bOut = ACESB;
}

void main(
    input varying float rIn, input varying float gIn, input varying float bIn, input varying float aIn,
    output varying float rOut, output varying float gOut, output varying float bOut, output varying float aOut
)
{
    IDT (rIn, gIn, bIn, rOut, gOut, bOut);
    aOut = 1.0;
}
```
How to implement IIF-ACES

- Current software for grading, editing, VFX cannot handle CTL.
- We need to interpret CTL to 1DLUT and 3DLUT.
IDT, RRT+ODT tone characteristics
Problem of Making 3DLUT

Because of strong non-linear characteristic, to approximate with 3D LUT cause serious error. ACES 1 is 100%. So the error effects important image reproduction area.
Log ACES
How to handle minus?
Custom Log ACES

• Log ACES
  \[ \text{if } x \geq 0.000032: \log_{10}(x) \]
  \[ \text{if } x < 0.000032: -4.5 \text{ (clip)} \]

• Custom Log ACES
  \[ \text{if } x \geq 0: \log_{10}(x+b) \]
  \[ \text{if } x < 0: 2 \log_{10}(b) - \log_{10}(-x+b) \]
  \[ b = 0.0316 \quad \log_{10}(b) = 1.5 \]
Define the Domain

Method for define the reasonable domain of custom Log ACES

• Calculate ACES value correspond to Input and output device Full Range.
• Add some margin.
Custom Log Domain

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ACES in 10 bit

Custom Log ACES value

ACES value
Result of rendering
Problem on using $17^3$ grids 3D LUT
Linear ACES 0 is complete black.
Linear ACES 1 is 100% white.
Bk (-0.1) to Wt (200) is necessary to represent high dynamic image.
But extremely unbalanced color like Rd (-0.1, -0.1, 200) unlikely exist in the natural world.
The color plot is calculated by inversion of DCI gamut to Custom Log ACES. Red square is Custom Log ACES domain.

The green circle area are useless. The 3D LUT grid in these area is wasteful.
High Saturated Log ACES (HSLA)

• Custom Log to HSLA

\[
\begin{align*}
\text{Gray} & = \frac{(C\text{LogR} + C\text{LogG} + C\text{LogB})}{3} \\
\text{HSLA}_R & = \frac{(C\text{LogR} - \text{Gray} \times k)}{(1-k)} \\
\text{HSLA}_G & = \frac{(C\text{LogG} - \text{Gray} \times k)}{(1-k)} \\
\text{HSLA}_B & = \frac{(C\text{LogB} - \text{Gray} \times k)}{(1-k)}
\end{align*}
\]

\text{CLogR,G,B} : \text{Custom Log ACES}
\text{k : saturation parameter}
HSLA colorspace

Useless area are reduced.
Rendering result
Compare accuracy
Image processing flow for using HSLA

Input Image → 3DLUT → IDT → To HSLA → HSLA → De HSLA → RRT/ODT → Output Image
Application

IS-100

• On-set look creation system
• Fully adopts IIF-ACES workflow
• Export Luts for postproduction
Workflow in the Japanese movie ‘the Brain man’

Camera

IS-100
Making Look

On-set Monitor

Recording (ARRI-RAW)

For Daily

Scratch

Final Cut Pro

Develop

LogC

LogC to HSLA

HSLA to Rec 709

Edit

Export 3DLUT

Grading

Pablo

LogC to HSLA

HSLA

HSLA to DCI

Export 3DLUT

HSLA 10bitDPX

VFX

After Effect

HSLA to sRGB (View LUT)

Monitor Calibration

DCI Projector

Export 3DLUT

Monitor Calibration

On-set Monitor

For Daily

Final Cut Pro

HSLA 10bitDPX

VFX

After Effect

Export 3DLUT

Monitor Calibration

On-set Monitor

Recording (ARRI-RAW)
Conclusion

- Custom Log ACES achieve IIF-ACES calculation with 3D LUT.
- HSLA further enhance accuracy of the calculation with small 3D LUT.
- Custom Log ACES and HSLA have been proposed to AMPAS-IIF for standardization of integer ACES.