Refining ACES Best Practice

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Abstract

ACES is the Academy Color Encoding System established by the Academy of Motion Picture Arts and Science (A.M.P.A.S). Since its introduction (version 1.0 in December 2014), it has been widely used in the film industry. The interaction of four modules makes the system flexible and leaves room for own developments and modifications.

Nevertheless, improvements are possible for various practical applications. This paper analyzes some of the problems frequently encountered in practice in order to identify possible solutions. These include improvements in importing still images, white point conversions problems and test lighting. The results should be applicable in practice and take into account above all the workflow with commercially available software programs.

The goal of this paper is to record the spectral distribution of a GretagMacbeth ColorChecker using a spectrometer and also photography it with different cameras like RED Scarlet M-X, Blackmagic URSA Mini Pro and Canon EOS 5D Mark III under the same lighting conditions. The recorded imagery is then converted to the ACES2065-1 color space. The positions of the patches of the ColorChecker in CIE Yxy color space are then compared to the positions of the patches captured by the spectral device. Using several built-in converters the goal is to match the positions of the spectral data as close as possible

1. Test setup and research tasks

The test took place at the campus of the University of Applied Sciences in Brandenburg in early December 2018 indoors. The research is divided in four parts:

The aim of the first part was to compare recorded spectral data of different lights with the converted positions of the *Macbeth ColorChecker* patches found in the ACES document *TB-2014-004 (S-2008-001)[1]*. A recurring problem is that the individual data sets have different white points, f. i. the *RGB coordinates of the Macbeth ColorChecker [2]* uses the illuminant D50, *RGB coordinates of the Macbeth ColorChecker for ACES2065-1* as in *ACES TB-2014-004 (S-2008-001)* uses *D60,* the camera data mostly uses D65 and the spectral data represents the original light of the scene f. i. 5370 K.

The first task was to investigate how to match the *RGB coordinates of the Macbeth ColorChecker for ACES2065-1* data sets to the spectral data of the different lights without less color deviation as possible. The recorded reference is the *Macbeth ColorChecker (now XRite Color Checker) [3]* (see *figure 1*).
Additional a 100 % perfect diffuser was used to precisely retrieve the 100 % luminance representation *[4]*.


Figure 1. *GretagMacbeth ColorChecker (pocket version) and Identifiers used in the test*

For the illumination we applied three different lights – commonly used in film/tv/video production. They were set to match an illuminant of roughly 6000 K (CIE D60). The spectral data was recorded by a spectrometer *Qmini by rgbphotonics* (see *figure 2*).


Figure 2. *The spectrometer used in this test, the rgbphotonics Qmini [5]*

Light 1 was an Aputure Amaran AL-F7 LED light (see *figure 3*). It consists of two alternating LED rows, one yellowish one white. To diffuse the out-coming light we used the supplied filter for the device.
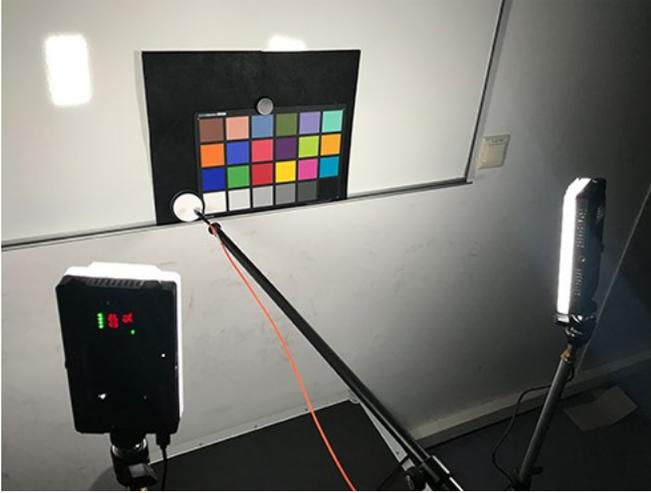
Figure 3. *The Amaran F7 aputure LED light*

Light 2 was a Swit S-2610 LED light (see *figure 4*). We used it as is and chose the maximum color temperature provided by the device.
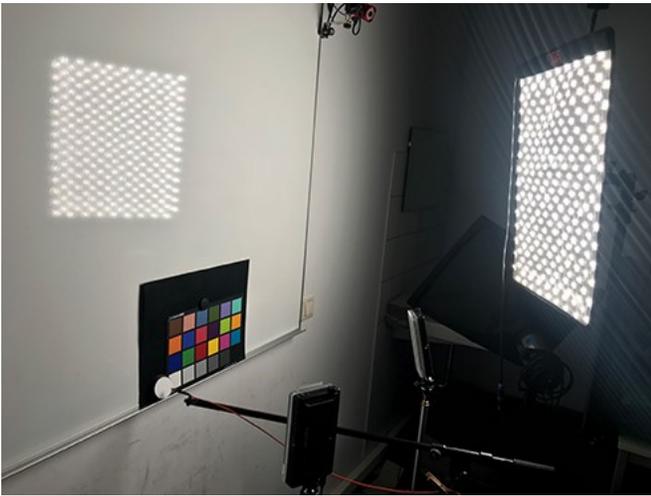
Figure 4. *The Swit S-2610 LED light*

Light 3 was an 800 W Ianiro incandescent light with two Lee 202 Half CTB Filters applied [6] (see *figure 5*).

The three lights did not match the 6000 K CIE illuminant exactly. So as additional reference data along with the spectral data we were using the positions of the Macbeth ColorChecker provided in the ACES document TB-2014-004 (see *Table 1*). We converted the data to the measured white point of every individual light in question using a simple XYZ-scaling inside the CIE XYZ color space to get an idea how the conversion process behaves. With the white point conversion applied, the CIE xy-chromaticity diagram values are retrieved in intention to compare them with the measured spectral data.

Figure 5. *800 W Ianiro incandescent LED light*

Patch	R	G	B
a 1	0.11877	0.08709	0.05895
a 2	0.40003	0.31916	0.23737
a 3	0.18476	0.20398	0.31311
a 4	0.10901	0.13511	0.06493
a 5	0.26684	0.24604	0.40932
a 6	0.32283	0.46208	0.40606
b 1	0.38607	0.22744	0.05777
b 2	0.13822	0.13037	0.33703
b 3	0.30203	0.13752	0.12758
b 4	0.09310	0.06347	0.13525
b 5	0.34877	0.43655	0.10613
b 6	0.48657	0.36686	0.08061
c 1	0.08731	0.07443	0.27274
c 2	0.15366	0.25692	0.09071
c 3	0.21743	0.07070	0.05130
c 4	0.58921	0.53944	0.09157
c 5	0.30904	0.14818	0.27426
c 6	0.14900	0.23377	0.35939
d 1	0.86653	0.86792	0.85818
d 2	0.57356	0.57256	0.57169
d 3	0.35346	0.35337	0.35391
d 4	0.20253	0.20243	0.20287
d 5	0.09467	0.09520	0.09637
d 6	0.03745	0.03766	0.03895
100 White	0.97784	0.97784	0.97784

Table 1. *ACES RGB values of common stimuli as produced by the ACES Reference Input Capture Device [1]*

In the second part we investigated the behavior of Blackmagic cameras. We used the Blackmagic *URSI Mini Pro Camera (see*

figure 6) and recorded the patches of the Macbeth ColorChecker with the light at a color temperature of 5924 K. The aim in this section was to integrate the recently introduced Blackmagic RAW color pipeline into the ACES workflow. In ACES version 1.0.3 there is no Input Device Transform (IDT) for Blackmagic cameras available. So we converted the recorded images to ACES2065-1 using the ACES workflow inside Blackmagic DaVinci Resolve 15 at one hand and two arbitrary linear Workflows using the DaVinci YRGB host color space. We then compared the results of the ACES DaVinci IDT and the linear native conversions to the Macbeth ColorChecker patches recorded by the spectrometer and the converted ACES coordinates.

Figure 6. Blackmagic URSI Mini Pro Camera [7]

The third part addresses the question if the *RED IPP2* color workflow delivers the same results as the *Legacy RED* color workflow. We used the RED Scarlet M-X and recorded the patches of the Macbeth ColorChecker with the same light at a color temperature of 5924 K. Then we compared the results of the IPP2 and Legacy workflow to the Macbeth ColorChecker patches recorded by the spectrometer and the converted ACES coordinates.

The fourth part addresses the question if the already good results researched in our paper *Comparing ACES Input Device Transforms for the Canon EOS 5D Mark III DSLR camera [8]* using the *rawtoaces* converter could be improved by using spectral response data for the Canon EOS Mark III sensor kindly provided by Image Engineering [9]. We recorded the patches of the Macbeth ColorChecker with the same light at a color temperature of 5924 K with the Canon EOS Mark III camera (see figure 8) as still image RAW data. Then we used the rawtoaces converter to convert the imagery to ACES2065-1.

Figure 7. The RED Scarlet M-X [10]

The results of the two methods described in more detail in section 2 were then compared to the Macbeth ColorChecker patches recorded by the spectrometer and the converted ACES coordinates.

Figure 8. The Canon EOS 5D Mark III DSLR camera [11]

2. Test methodology and evaluation settings

The main approach in this test was a practical workflow with as less interchanges as possible. We used the built-in functionality of *The Foundry NukeX v.11.2 [12],* the „*backbone of compositing and image processing pipelines across the motion picture*

industry." [13]. The image processing was done using the built-in *OpenColor IO [14]* system to gain access to the current ACES version 1.0.3. Also custom-made 3x3 color matrices were applied to handle the white balancing.

2.1. Testing the ACES RGB Macbeth ColorChecker conversion

The basic approach was the usage of the spectral data as the basis for the calculations and not to change them. We first tested how the ACES RGB values in *table 1* behave when adjusted to the color temperature of the light.

For the test we used three lights popular in film and video production and adjusted them so that they match the color temperature of 6000 K as close as possible according to the capabilities of the devices.

The lights and the final color temperature the devices were able to produce are listed in *table 2*.

Light	Color temperature / K
Amaran F7 aputure LED light	5924 K
Swit S-2610 LED light	4807 K
Ianiro 800W with 2x ½ blue filter	5370 K

**Table 2**. *Lights and color temperature used in the test*

The CIE Yxy values of the spectral data were recorded using a mobile spectrometer, the *rgbphotonics Qmini* (see *figure 7*). It consisted of the device itself with an USB connection to a desktop computer and an optical fiber cable for the input.

We maintained the same lighting conditions, which was no problem indoor because we used darkening for the windows to avoid mixed light. Every patch was captured individually and the values were stored in a spreadsheet (see *Appendix A*). It has to be pointed out that this process lasted around 10 minutes.

To get access to color of the individual ColorChecker patches described in Table 1 color patches we created the color patches in NukeX accordingly. The working color space of the host converter *NukeX v.11.3.1* was set to ACES2065-1 – the Original ACES Color Space as defined in SMPTE document *ST 2065-1 [15]* (see *figure 9*). To convert from ACES2065-1 to CIE Yxy as the first element of the color conversion we used a 3x3 matrix from ACES2065-1 RGB to CIE XYZ found in *S-2008-001 [16]* (see *formula 1*)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.9525523959 & 0.0000000000 & 0.0000936786 \\ 0.3439664498 & 0.7281660966 & -0.0721325464 \\ 0.0000000000 & 0.0000000000 & 1.0088251844 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

Then another 3x3 color matrix was applied for the white point conversion inside the CIE XYZ color space. We used the additional perfect diffuser as reference for 100 % white (1.0). The matrix was then adjusted in CIE XYZ to match the coordinates of the test light color temperature. The matrix used for every white point conversion is included in the discussion section.
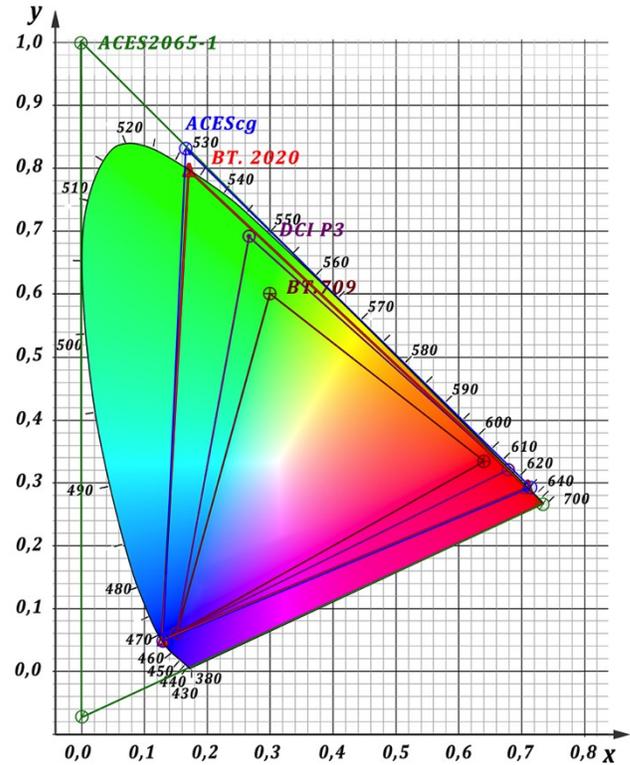
Figure 9. *The ACES2065-1 color space in comparison to other film/tv/video color spaces [17]*

The last step was the conversion from CIE XYZ to CIE Yxy. We used the build-in *Colorspace* node inside NukeX. The CIE Yxy values for the individual color patches were then derived using the Nuke color picker.

The results and color deviation of the individual positions in CIE Yxy compared to the spectral data and the converted ACES RGB values are discussed in section 3.1.

After evaluating the results of the first test we decided to use the *Amaran F7 Aputure* LED light as test light. We used the supplied filter to diffuse the light further and soften out the influence of the two alternate LED rows (white and yellow) and chose a color temperature of 7500 K as indicated by the device. This setting delivered a measured color temperature of 5924 K.

2.2. Testing the Blackmagic URSA mini Pro Camera

For the second task we recorded the test setup with a Blackmagic *URSI Mini Pro Camera* (see *figure 6*). We imported the imagery into Blackmagic *DaVinci Resolve 15.2.2007 [18]* using three different approaches.

The first approach was to use the internal ACES color workflow from DaVinci Resolve with the following settings (see *figure 10*).
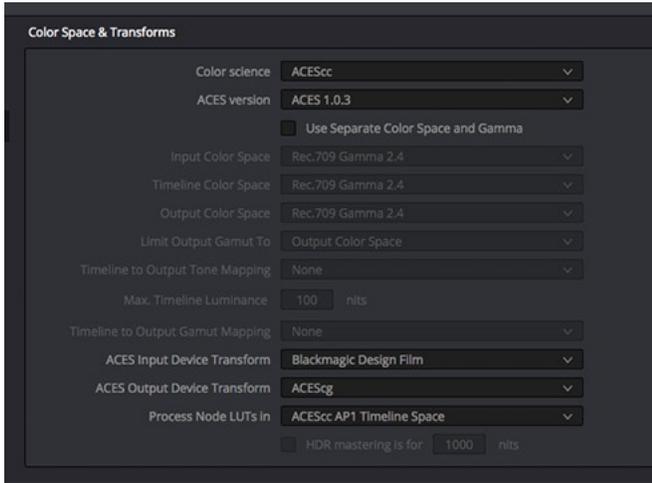

Figure 10. Settings for the ACES workflow in Blackmagic DaVinci Resolve 15

For this setting the central working color space is *ACEScc* a logarithmic color space in the ACES system intended to be used for color correction. The built-in Input Device Transform (IDT) converts the imagery from *Blackmagic Design Film* to ACEScc and the Output Device Transform converts them from ACEScc to ACEScg – a color space in the ACES system intended to be used for Visual Effects (VFX) and Computer Graphics (CG). The image was then exported as an OpenEXR-file with half precision floating point quality.
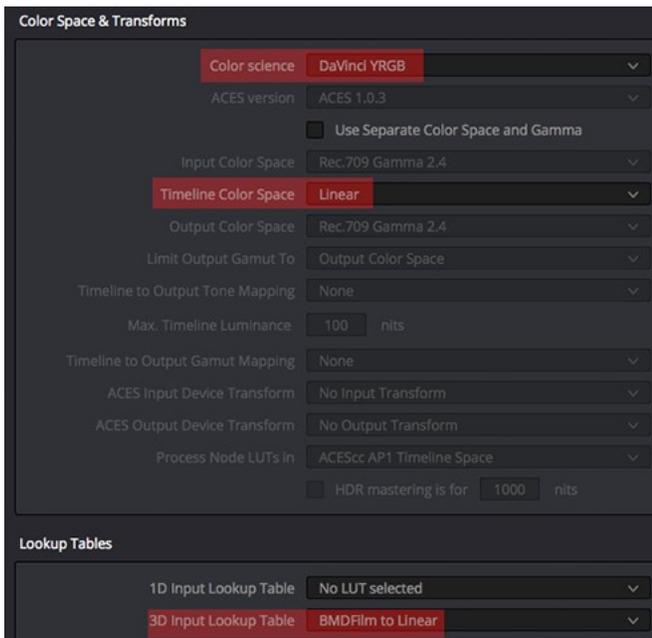

Figure 11. The settings for the second approach

For the second approach we used the native DaVinci YRGB color space. For the Input Device Transform we chose *BMDFilm to Linear* and no changes for the Output Device Transform (see *figure 11)*.

For the third approach we use the native DaVinci YRGB color space. For the Input Device Transform we used the Camera Raw input and chose *Blackmagic Design* as native color space. We chose *Linear* Gamma and no changes for the Output Device Transform (see *figure 12)*.
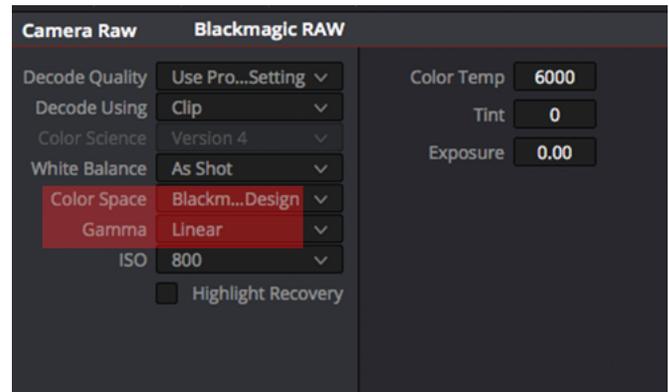
Figure 12. The settings for the third approach

The converted OpenEXR images were then imported into *NukeX11.3v1*. The working color space of the host converter was set to to ACES2065-1. For the first approach the input from ACEScg to ACES2065-1 was handled automatically by the native Nuke import transform (see *figure 13*).
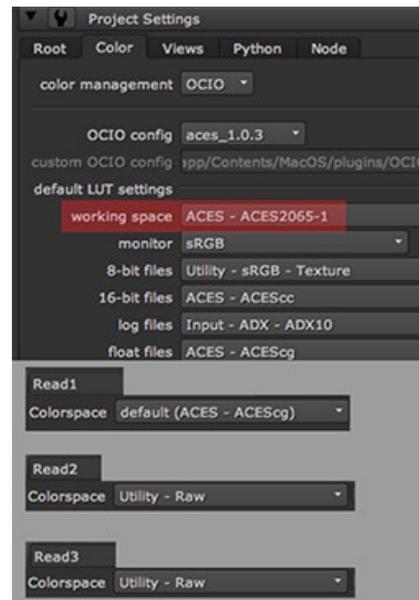
Figure 13. The Nuke import settings for the three approaches

For the second and third approach the inputs from *BlackmagicDesign linear* to ACES2065-1 were handled automatically by the native Nuke import transform (see *figure 13*), where we assumed that *BlackmagicDesign linear* to be equal to

Raw. The following tests were performed to determine whether this assumption is correct. The images then were converted from the ACES2065-1 color spaces to CIE XYZ using formula (1).

Then another 3x3 color matrix was applied for the white point conversion inside the CIE XYZ color space. We used the additional perfect diffuser as reference for 100 % white (1.0). The matrix was then adjusted in CIE XYZ to match the coordinates of the test light color temperature. The matrix used for every white point conversion is included in the discussion section.

The last step was the conversion from CIE XYZ to CIE Yxy. We used the build-in *Colorspace* node inside NukeX. The CIE Yxy values for the individual color patches were then derived using the Nuke color picker (see *figure 14*).

The results and color deviation of the individual positions in CIE Yxy compared to the spectral data and the converted ACES RGB values are discussed in section 3.2.
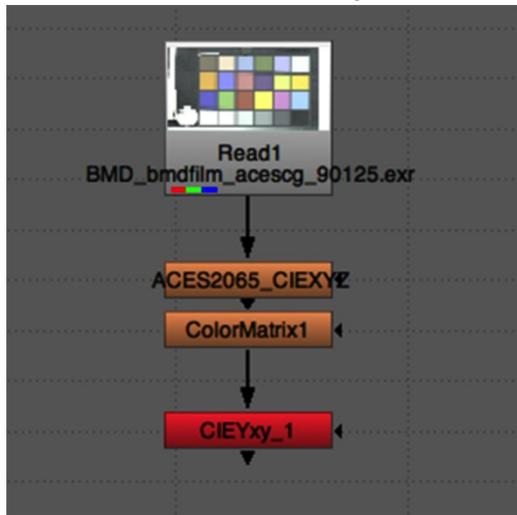

Figure 14. *Arrangement of operators in the Nuke node graph*

2.3. Testing the RED Scarlet-M-X Camera

For the third task we recorded the test setup with a RED *Scarlet-M-X Camera.* The aim of the test was – beside the ability to match the spectral data compared to the other cameras in the test – to find out if there is a different between the recently introduced *RED IPP2* color workflow and the *Legacy* color workflow by the RED company. Another interesting question was the comparison of the results with the result of the test described in our paper *Comparing different ACES Input Device Transforms (IDTs) for the RED Scarlet-X Camera [19]*, where the test environment was plain sunlight of 5700 K.

We import the recorded imagery directly into NukeX without further pre-conversion. The working color space of the host converter was set to ACES2065-1. The input from the RED color system to ACES2065-1 was handled by the implemented OCIO color system inside Nuke. We were also following two approaches, one for RED IPP2 and one for RED Legacy.

For the first approach we chose as Image Pipeline *IPP2* and for the Input Device Transform *Input – RED – REDLog3G10 – REDWideGamutRGB,* which is part of the ACES 1.0.3 system (see *figure 15*).
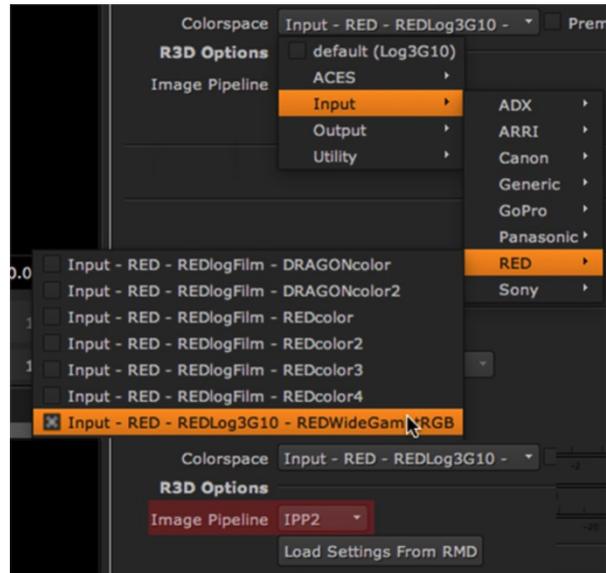

Figure 15. *Import Settings for the RED IPP2 approach*

For the second approach we chose as Image Pipeline *legacy* and for the Input Device Transform *Input – RED – Linear – REDWideGamutRGB,* which is part of the ACES 1.0.3 system (see *figure 16*). Also we chose *HalfFloat ACES linear* to adjust the transfer function.
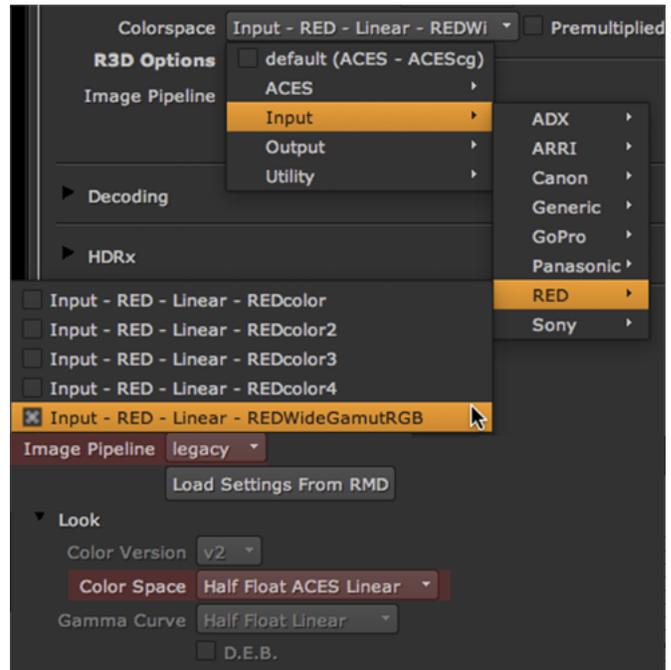

Figure 16. *Import Settings for the RED IPP2 approach*

The images then were converted from the ACES2065-1 color spaces to to CIE XYZ using formula (1).

Then another 3x3 color matrix was applied for the white point conversion inside the CIE XYZ color space. We used the additional perfect diffuser as reference for 100 % white (1.0). The matrix was then adjusted in CIE XYZ to match the coordinates of the test light temperature. The matrix used for every white point conversion is included in the discussion section.

The last step was the conversion from CIE XYZ to CIE Yxy. We uses the build-in *Colorspace* node inside NukeX. The CIE Yxy values for the individual color patches were derived using the Nuke color picker.

The results and color deviation of the individual positions in CIE Yxy compared to the spectral data and the converted ACES RGB values are discussed in section 3.3.

2.4. Testing the Canon EOS 5D Mark III Camera (still images)

For the third task we recorded the test setup with a *Canon EOS 5D Mark III* Camera as a still image. For the conversion to ACES we used the *rawtoaces* software. The aim of the test was – beside the ability to match the spectral data compared to the other cameras in the test – to find out whether there is a difference between the individual mathematical principles in the calculation of the Input Device Transform (IDT).

"The RAW to ACES Utility or ,rawtoaces', is a command line software package that converts digital camera RAW files to ACES container files containing image data encoded according to the Academy Color Encoding Specification (ACES) as specified in [SMPTE 2065-1]" *[20]*. Accordingly to the documentation it can be installed on Linux (Ubuntu, Redhat) and MacOSX.

The processing is controlled by the following options.

```
rawtoaces - convert RAW digital camera files to ACES

Usage:
  rawtoaces file ...
  rawtoaces [options] file
  rawtoaces --help
  rawtoaces --version

IDT options:
  --help          Show this screen
  --version       Show version
  --wb-method [0-4]White balance factor calculation method
                      0=white balance using file metadata
                      1=white balance using user specified
                        illuminant [str]
                      2=Average the whole image for white
                        balance
                      3=Average a grey box for white
                        balance <x y w h>
                      4=Use custom white balance  <r g b g>
                          (default = 0)
  --mat-method [0-2] IDT matrix calculation method
                      0=Calculate matrix from camera spec
                        sens
                      1=Use file metadata color matrix
                      2=Use adobe coeffs included in libraw
                          (default = 0)
                          (default = /usr/local/include
                          rawtoaces/data/camera)
```

```
  --headroom float Set highlight headroom factor
                      (default = 6.0)
  --cameras          Show a list of supported cameras/models
                     by LibRaw
  --valid-illums  Show a list of illuminants
  --valid-cameras Show a list of cameras/models with
                  available spectral sensitivity datasets

Raw conversion options:
  -c float        Set adjust maximum threshold
                      (default = 0.75)
  -C <r b>        Correct chromatic aberration
  -P <file>       Fix the dead pixels listed in this file
  -K <file>       Subtract dark frame (16-bit raw PGM)
  -k <num>        Set the darkness level
  -S <num>        Set the saturation level
  -n <num>        Set threshold for wavelet denoising
  -H [0-9]        Highlight mode (0=clip, 1=unclip,
                  2=blend, 3+=rebuild) (default = 0)
  -t [0-7]        Flip image (0=none, 3=180, 5=90CCW,
                  6=90CW)
  -j              Don't stretch or rotate raw pixels
  -W              Don't automatically brighten the image
  -b <num>        Adjust brightness (default = 1.0)
  -q [0-3]        Set the interpolation quality
  -h              Half-size color image
                  (twice as fast as "-q 0")
  -f              Interpolate RGGB as four colors
  -m <num>        Apply a 3x3 median filter to R-G and B-G
  -s [0..N-1]     Select one raw image from input file
  -G              Use green_matching() filter
  -B <x y w h>    Use cropbox

Benchmarking options:
  -v              Verbose: print progress messages
                  (repeated -v will add verbosity)
  -F              Use FILE I/O instead of streambuf API
  -d              Detailed timing report
  -E              Use mmap()-ed buffer instead of plain
                  FILE I/O
```

We passed the variety of possibilities – above all the white point settings – which will be researched in the future – but concentrated on the IDT options, most of all the *--math-method* .

— mat-method 1

The documentation [20] describes this method as: „Conversion using camera file metadata: In lieu of spectral sensitivity data, camera metadata can be used to convert RAW files to ACES. This includes the camera multiplier white balance gains and any RGB to XYZ matrix included. The RGB to XYZ matrix included in the metadata will be used to calculate the final RGB to ACES matrix used for conversion. The accuracy of this method is dependent on the camera manufacturer writing correct metadata into their RAW files.

The following commands will convert RAW to ACES using the camera file metadata for both white balance and the RGB to XYZ matrix.

$ rawtoaces --mat-method 1 file.raw"

— mat-method 2

The documentation describes this method as: „Conversion using camera data included in LibRaw: libraw includes matrices for a wide range of cameras which may provide a reasonable basis for conversion from RGB to ACES. These matrices were calculated by Adobe and are often referred to as the Adobe coefficients.

To use these built-in matrices the following command may be used .

$ rawtoaces --mat-method 2 file.raw"

— mat-method 0

The documentation describes this method as: „Conversion using spectral sensitivities: If spectral sensitivity data for your camera is included with `rawtoaces` then the following command will convert your RAW file to ACES using that information.

$ rawtoaces --mat-method 0 input.raw"

The camera's sensitivity referred above is practically the filter design of the camera to create the RGB values for each pixel, the response of the camera sensor to the light of the scene. *Figure 17* shows the plotted result of the values included in the file *canon_eos_5d_mark_ii_380_750_5.json* inside the rawtoaces container /data/camera/. In this file the camera color matching functions are provided in the range from 380 nm to 750 nm with sampling every 5 nm.
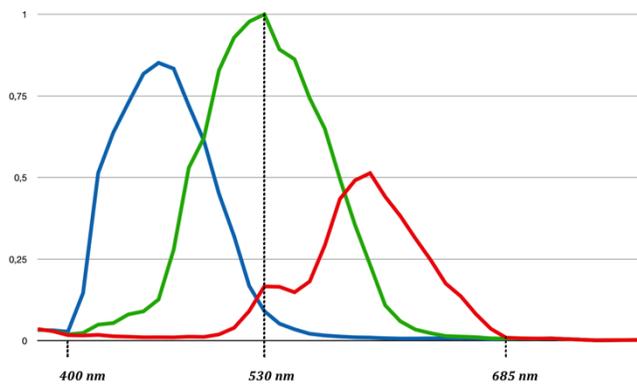
Figure 17. *Spectral sensitivity of the Canon EOS 5D Mark II camera [21]*

The recordings were done with a Canon EOS 5D Mark III which is not enlisted in the valid cameras section. But fortunately we received a data set for the Canon Mark III camera from Image Engineering in Kerpen, Germany *[9]* (see *figure 18*).
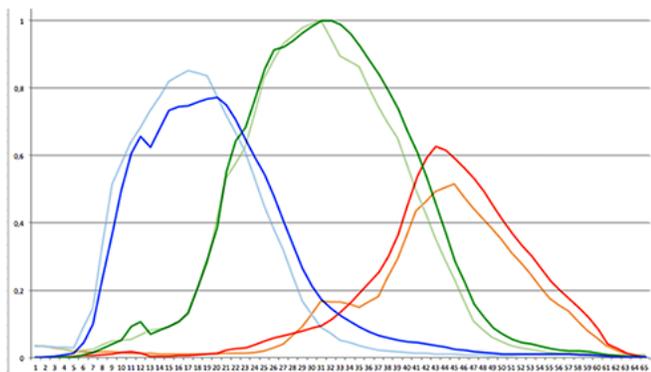
Figure 18. *Spectral sensitivity of the Canon EOS 5D Mark II (thin) and Mark III (solid) camera*

So we tested *rawtoaces math-method 0* vs. *math-method 1* to find out if there is any improvement available. The command line commands are:

$ rawtoaces --mat-method 1 input.raw

for the first approach and

$ rawtoaces --mat-method 0 input.raw

for the second approach.

The converted OpenEXR images were then imported into *NukeX11.3v1*. The working color space of the host converter was set to ACES2065-1. With this setting no color conversion on the input site is necessary.

The images then were converted from the ACES2065-1 color spaces to CIEXYZ using formula (1).

Then another 3x3 color matrix was applied for the white point conversion inside the CIE XYZ color space. We used the additional perfect diffuser as reference for 100 % white (1.0). The matrix was then adjusted in CIE XYZ to match the coordinates of the test light color temperature. The matrix used for every white point conversion is included in the discussion section.

The last step was the conversion from CIE XYZ to CIE Yxy. We used the build-in *Colorspace* node inside NukeX. The CIE Yxy values for the individual color patches were derived using the Nuke color picker.

The results and color deviation of the individual positions in CIE Yxy compared to the spectral data and the converted ACES RGB values are discussed in section 3.4.

3. Discussing the results

In this section we are comparing the converted camera recordings to the ColorChecker patch positions of the spectral recordings and the ACES RGB ColorChecker patch positions. We provide the used 3x3 white point conversion matrix and a table with the deviations in the CIE xy chromaticity diagram. These values are derived by calculating an absolute difference of each the x-values and y-values between the spectral positions and those of the converted images in the CIE xy-chromaticity diagram. Both absolute values are then added to generate the overall deviation. Only simple deviation – i. e. no root-mean-square deviation– has been calculated

3.1. ACES D60 Macbeth ColorChecker positions vs. Spectral Data

We start with the discussion of the ACES RGB ColorChecker positions in comparison to the spectral data. Each of the three lights is calculated individually. To match both data sets we used a white point conversion from ACES D60 to the test color temperature of the perfect diffuser. To match the white point we applied a simple XYZ-scaling to the *perfect reflecting diffuser* components oft the ACES RGB data set.

Light 1 was an *Amaran F7 Aputure* LED light, which produced a color temperature of 5924 K (see *formula 2* for the XYZ-scaling matrix and *table* 3 for the CIE XYZ coordinates of the white point)
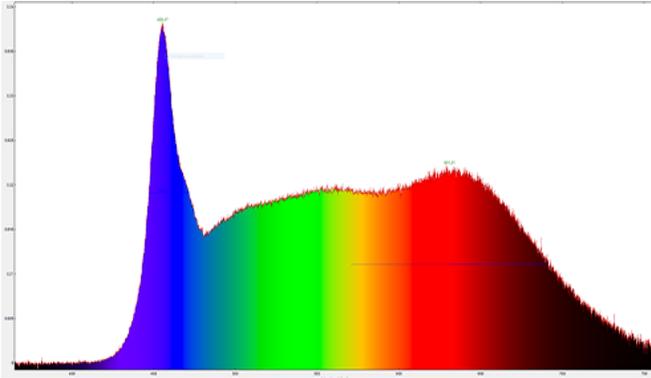
Figure 19. Spectral Power Distribution for light 1 at 5924 K

$$
\begin{bmatrix} X_{5924\,K} \\ Y_{5924\,K} \\ Z_{5924\,K} \end{bmatrix} = \begin{bmatrix} 1.0316 & 0.0000 & 0.0000 \\ 0.0000 & 1.0226 & 0.0000 \\ 0.0000 & 0.0000 & 1.0309 \end{bmatrix} \begin{bmatrix} X_{D60} \\ Y_{D60} \\ Z_{D60} \end{bmatrix} \quad (2)
$$
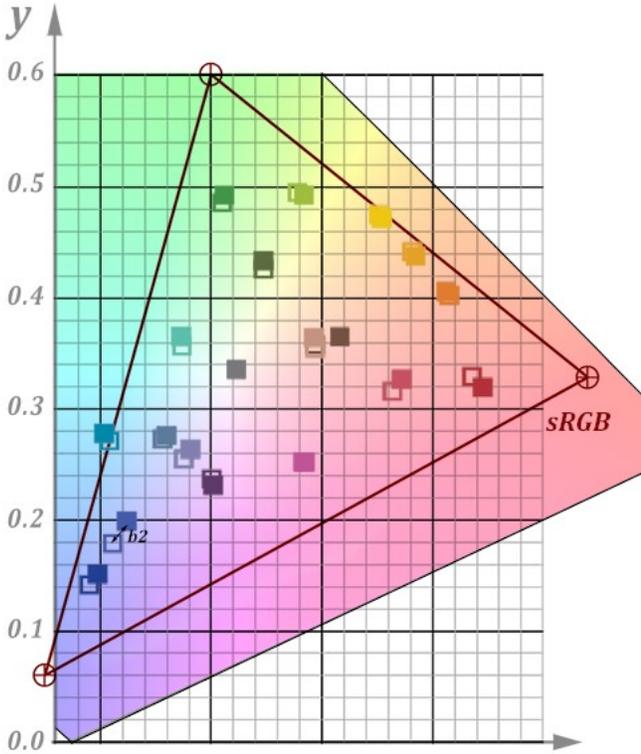
Figure 20. Positions of the converted ACES RGB ColorChecker patches (solid) in comparison to the spectral data positions (hollow) for light 1

	CIE X	CIE X	CIE Y
Amaran F7 Aputure 100% white at 5924 K	96.098	100	101.697

Table 3. CIE XYZ white point coordinates for the first light

Since CIE distinguishes light from illuminant, the *Spectral Power Distribution (SPD)* of the light shown in figure 19 is interesting. What is immediately noticeable is the extreme peak at 451 nm. Here is the maximum of the blue component of the LED system. The following conversions of the ACES data should proof whether this peak has a strong influence on the color distribution.

The temperature difference from 6000 K to 5924 K is very low and produces correspondingly very small color. With one exception (patch #b2 - purplish blue) all ACES patches touch the positions of the spectral data. Also there is no deviation larger then 0.02 in all patches. The overall deviations are noticeable but small (see *table 4*).

	x	y	Σ
Light 1 5924 K	0.1170	0.1300	**0.2470**

Table 4. Differences between spectral data and ACES RGB white point conversion for Light 1.

Light 2 was a *Swit-S2610* LED light, which produced a color temperature of 5924 K (see *formula* 3 for the XYZ-scaling matrix and *table* 5 for the CIE XYZ coordinates of the white point).

$$
\begin{bmatrix} X_{4807\,K} \\ Y_{4807\,K} \\ Z_{4807\,K} \end{bmatrix} = \begin{bmatrix} 1.0664 & 0.0000 & 0.0000 \\ 0.0000 & 1.0226 & 0.0000 \\ 0.0000 & 0.0000 & 0.8541 \end{bmatrix} \begin{bmatrix} X_{D60} \\ Y_{D60} \\ Z_{D60} \end{bmatrix} \quad (3)
$$

	CIE X	CIE X	CIE Y
Swit-S2610 100% white at 4807 K	96.347	100	84.259

Table 5. CIE XYZ white point coordinates for the second light
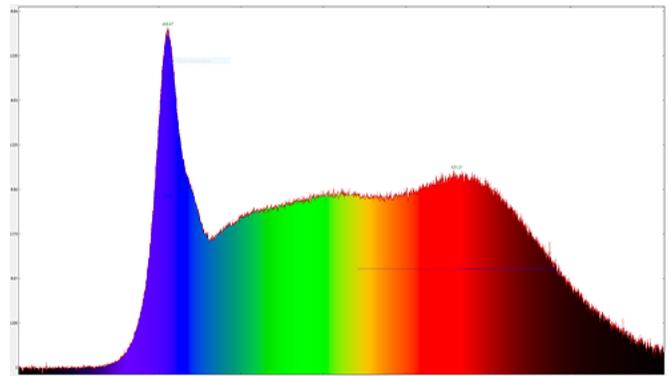
Figure 21. Spectral Power Distribution for light 2 at 4807 K

Since the color temperature difference between 6000 K and 4807 K is considerably higher, the color deviation is larger as for light 1. The patches #a4 –foliage, #b2 - purplish blue, #b4-purple and #c1-blue do not touch the positions of the spectral data. Also there are two deviations larger then 0.02 in the x-direction for patch #b2 and #c1 and one in the y-direction for patch #b4. The overall deviations are therefor larger then for light 1 but still moderate (see *table 6*).
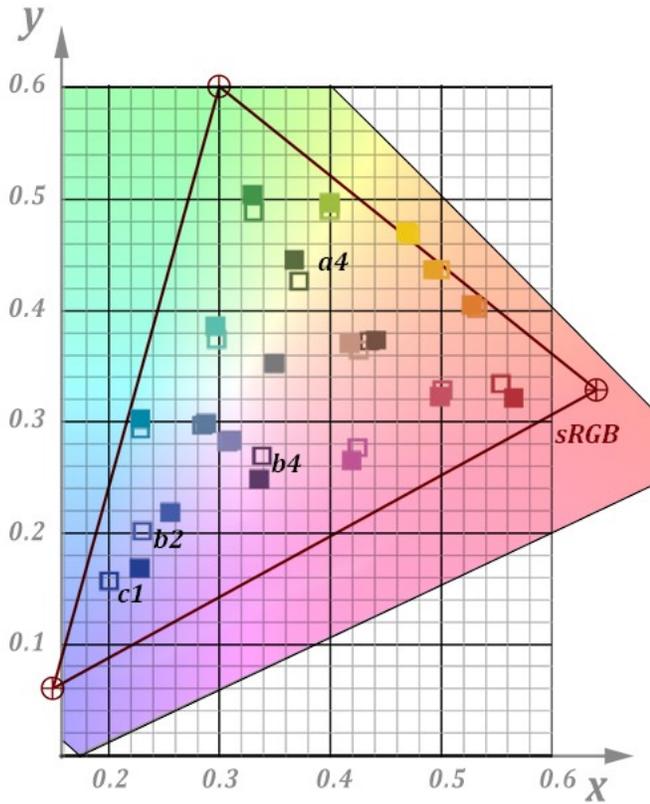
Figure 22. *Positions of the converted ACES RGB ColorChecker patches (solid) in comparison to the spectral data positions (hollow) for light 2*

	x	**y**	**Σ**
Light 2 4807 K	0.1253	0.1653	**0.2905**

Table 6. *Differences between spectral data and ACES RGB white point conversion for light 2*

Light 3 was an *800W Ianiro* light, which produced a color temperature of 5370 K (see *formula* 4 for the XYZ-scaling matrix and *table* 7 for the CIE XYZ coordinates of the white point).

$$\begin{bmatrix} X_{5313} \\ Y_{5313} \\ Z_{5313} \end{bmatrix} = \begin{bmatrix} 1.0057 & 0.0000 & 0.0000 \\ 0.0000 & 1.022 & 0.0000 \\ 0.0000 & 0.0000 & 0.8555 \end{bmatrix} \begin{bmatrix} X_{D60} \\ Y_{D60} \\ Z_{D60} \end{bmatrix} \quad (4)$$

|	**CIE X**	**CIE X**	**CIE Y**
800W Ianiro 100% white at 5370 K	93.687	100	84.399

Table 7. *CIE XYZ white point coordinates for the third light*

The *Spectral Power Distribution (SPD)* of the third light shown in figure 23 is more natural i. e., closer to this of a CIE illuminant because it lacks sharp and steep peaks. It resembles the SPD of an incandescent lamp with an even rise. The relative flat curve section between 500 nm and 650 nm is obtained by adding a blue filter.
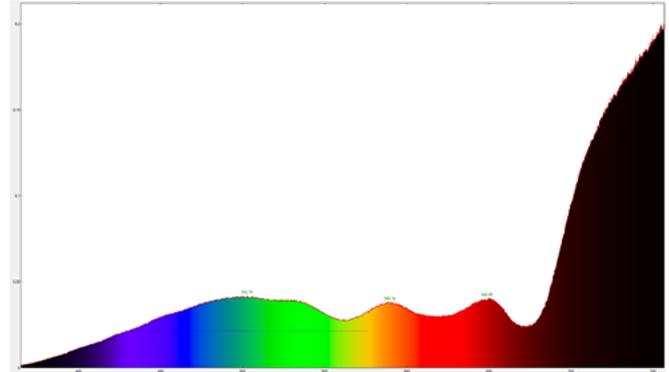
Figure 23. *Spectral Power Distribution for light 3 {31}*

The deviation is also moderate for this light and the distribution in the x-direction is much better then for light 2. Only in the y-direction patch #a4-foliage and patch #b4-purple are more then 0.02 off. The constantly increasing offset in the blue area is apparently due to the greater distance of the white points (see table 9). This behavior corresponds to similar conversion in our other research papers, f. i. *Comparing different ACES Input Device Transforms (IDTs) for the RED Scarlet-X Camera [19]*.

|	**x**	**y**	**Σ**
Light 3 5370 K	0.1347	0.1908	**0.3255**

Table 8. *Differences between spectral data and ACES RGB white point conversion for light 3*

The deviations from *ACES D60 RGB* to the *CIE Yxy* positions of the recorded lights with different color temperatures stay in a moderate error range. Also the distribution of the individual patches inside the CIE Yxy color space is more or less even with a noticeable deviation of rather dark colors like #a4-foliage and #b4-purple. So we can assume our test environment is a reliable source for the following tests.

In Table 9 the deviations of the blue patches #b2-purplish blue and #c1-blue are listed. It is interesting to see that the incandescent-like light 3 delivers – with one exception – better results than the LED light 1 which is closer to the target color temperature. So one can assume that the Spectral Power Distribution of the lights influences the results.

	#c1.x	**#c1.y**	**#b2.x**	**#b2.y**
Light 1 at 5924 K	-0.0076	-0.0092	-0.0128	-0.0199
Light 3 at 5370 K	-0.0133	-0.0089	-0.0111	-0.0018
Light 2 at 4807 K	-0.0266	-0.0124	-0.0250	-0.0173

Table 9. *Deviation of patch #c1 and patch #b2 according to the target color temperature*
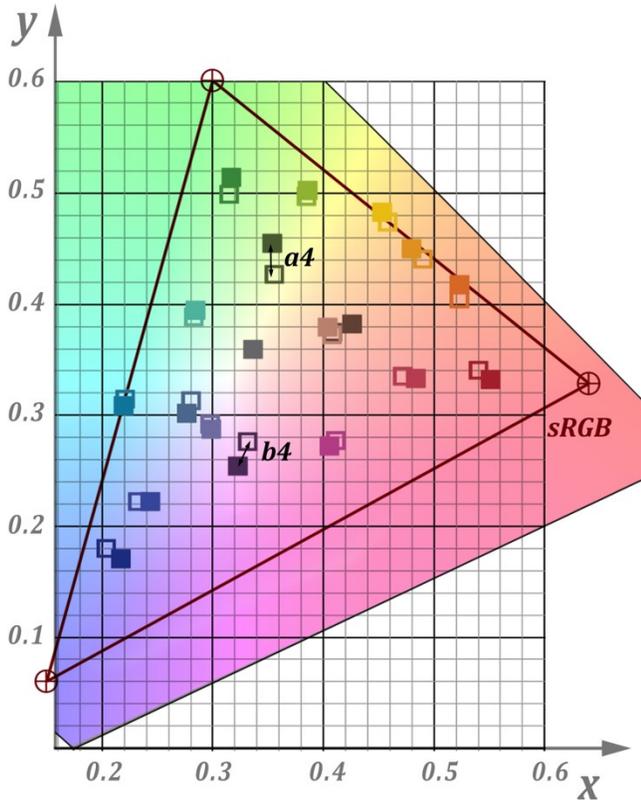
Figure 24. *Positions of the converted ACES RGB ColorChecker patches (solid) in comparison to the spectral data positions (hollow) for light 3*

3.2. Blackmagic Design URSA mini pro Conversions

The second part of the investigation focuses on the recently introduced *BlackmagicRaw* color pipeline. Here three conversion scenarios are compared with the results of the ACES RGB conversion and the recorded spectral data for the first light with a color temperature of 5924 K.

Approach 1 includes the ACES color workflow in DaVinci as described in section 2. See *formula* 5 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 0.4808 & 0.0000 & 0.0000 \\ 0.0000 & 0.4337 & 0.0000 \\ 0.0000 & 0.0000 & 0.4443 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (5)$$
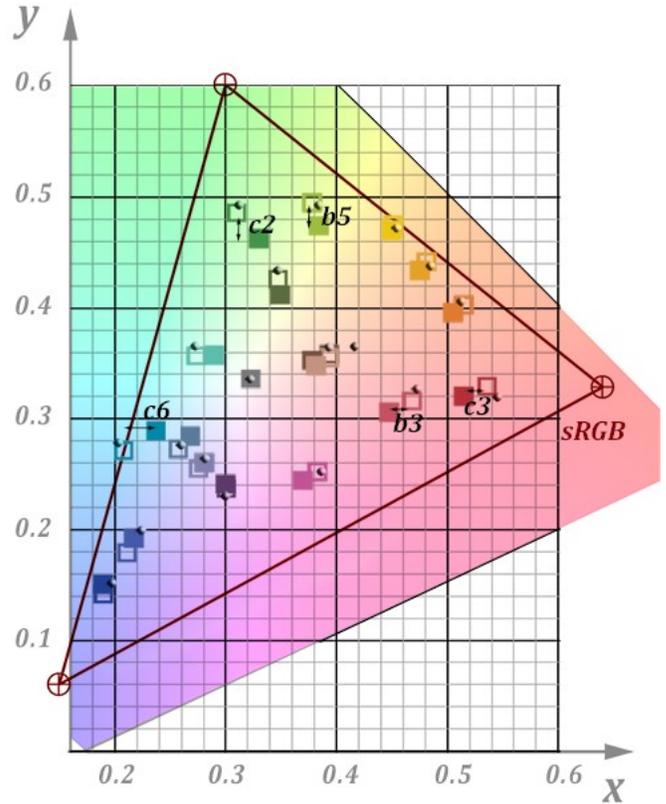
Figure 25. *ColorChecker positions for Blackmagic-ACES workflow (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded)*

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data stay in a small-to-moderate error range. Also the distribution of the individual patches inside the CIE Yxy color space is more or less even with a noticeable deviation by two patches in both x- and y-direction: #c2-green and #c6-cyan. Also the overall error is low compared to other tests. The deviation of the other marked patches is also very low (less then 0.03).

	x	y	∑
BlackmagicDesignRaw ACES Pipeline	0.2113	0.2027	**0.4139**

Table 10. *Differences between spectral data and BlackmagicDesign approach 1*

Approach 2 includes the DaVinci native YRGB color workflow with a linear in- and output as described in section 2. See *formula* 6 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 0.7437 & 0.0000 & 0.0000 \\ 0.0000 & 0.6486 & 0.0000 \\ 0.0000 & 0.0000 & 0.6518 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (6)$$
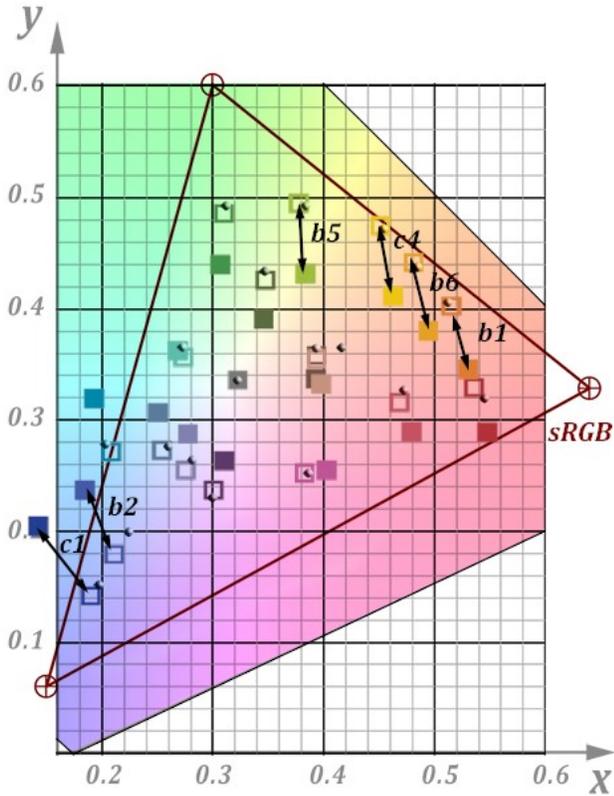
Figure 26. ColorChecker positions for Blackmagic-linear workflow (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded)

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data in this conversion have a considerable offset. This occurs above all in the extreme ranges in the x-direction (yellow-blue). There are several deviations in the x- and y-direction that are larger than 0.05 and even reach values of more than 0.07. The blue cyan patches are also outside the sRGB color space. The selected conversion settings are obviously wrong and the whole systems seams to be rotated in the wrong way. Consequently, the total error is very high.

	x	y	Σ
BlackmagicDesignRaw linear input pipeline	0.2313	0.7186	**0.9499**

Table 11. Differences between spectral data and BlackmagicDesign approach 2

Approach 3 includes the DaVinci native YRGB color workflow with a linear Raw-input and linear output as described in section 2. See *formula* 7 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$
\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 0.5199 & 0.0000 & 0.0000 \\ 0.0000 & 0.4429 & 0.0000 \\ 0.0000 & 0.0000 & 0.4452 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (7)
$$
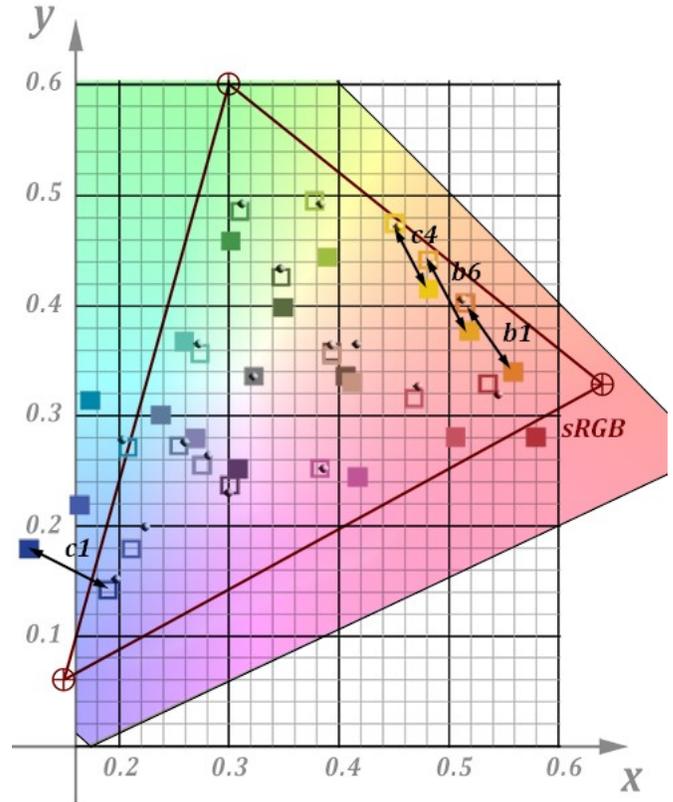
Figure 27. ColorChecker positions for Blackmagic-RAW workflow (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded)

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data in this conversion have a considerable offset as well. This occurs above all in the extreme ranges in the x-direction (yellow-blue). The distribution in the green range is slightly better, but red is also outside the sRGB gamut along with the blue and cyan patches. There are several deviations in the x- and y-direction that are larger than 0.05 and even reach values of more than 0.07. The error distribution is somewhat different to the second approach. While in the second approach the deviations occur mainly in the y-direction, in this conversion they are distributed in both directions (see Appendix B). The selected conversion settings are obviously wrong as well and the whole systems seams also to be rotated in the wrong way. The total error is even higher than in the second approach.

	x	y	Σ
BlackmagicDesignRaw RAW input pipeline	0.4981	0.6418	**1.1399**

**Table 12.** Differences between spectral data and BlackmagicDesign approach 3

The results for the ACES color workflow in DaVinci Resolve 15 using the internal BlackmagicRaw color pipeline are very good. In this way, the URSA pro mini images can be well integrated into an ACES color workflow. The color offset can be tolerated if the requirements for the color workflow are not extraordinarily high.

If the internal DaVinci YRGB color space is used instead, the export to the ACES area is much more difficult. Here a problem occurs, which is mostly observed within a linear workflow. If no output transform takes place, the properties of the host color space (DaVinci YRGB) are inherited by the exported file. Since no input transform is usually applied in the linear workflow, the algorithm interprets the exported parameters (primaries, white point, transfer function) as belonging to ACES, which does not provide a reasonable result. In order to achieve a useful result, an output transform into a corresponding color space (e.g. Rec 2100) would have to be performed, from which the input transform into the ACES color space can then take place, or a transform from DaVinci YRGB directly into ACES should be performed if available. This example shows clearly how predictable a good implemented ACES workflow is.

3.3. RED Scarlet M-X Conversion

The third part of the investigations focuses on the RED Scarlet M-X camera. Here two conversion scenarios are compared with the results of the recorded spectral data for the first light with a color temperature of 5924 K and the converted *ACES RGB* data set.
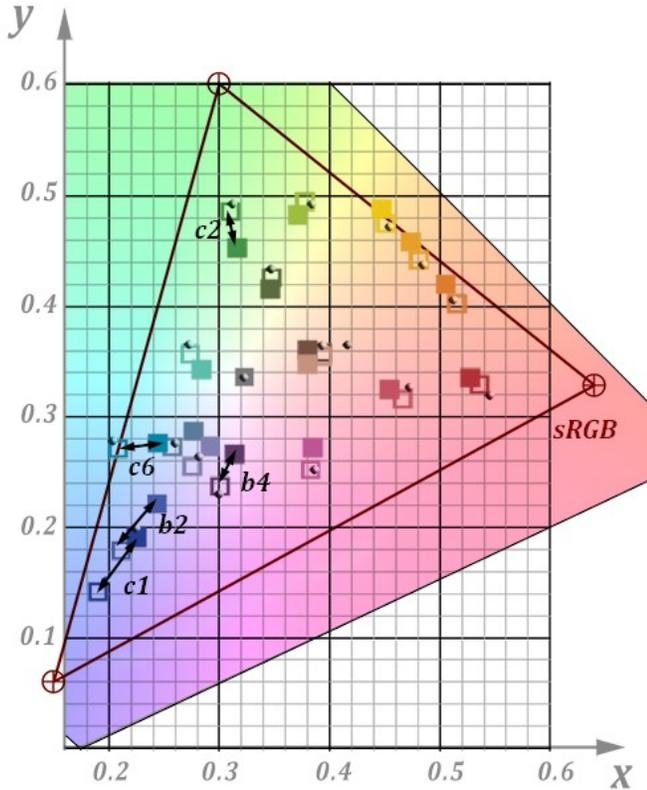
Figure 28. *ColorChecker positions for RED IPP2 and RED Legacy workflow (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded)*

Approach 1 includes the RED IPP2 color workflow as described in section 2. See *formula* 8 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 1.0747 & 0.0000 & 0.0000 \\ 0.0000 & 1.0209 & 0.0000 \\ 0.0000 & 0.0000 & 1.0254 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (8)$$

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data testify to a medium quality. For the IPP2 approach, there are at least two patches (#b2-purplish blue and #c1-blue) which have an offset larger than 0.04 in one direction and larger than 0.03 in the other direction at the same time. Also three other patches with an offset of larger than 0.03 in one direction reduce the quality. The deviation mostly occurs in the blue section of the patches whereas the distribution of the other patches is nice.

	x	y	∑
RED Scarlet M-X IPP2	0.2727	0.3536	**0. 6263**

Table 13. *Differences between spectral data and RED IPP approach*

Approach 2 includes the *RED Legacy* color workflow as described in section 2. See *formula* 9 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 1.0750 & 0.0000 & 0.0000 \\ 0.0000 & 1.0213 & 0.0000 \\ 0.0000 & 0.0000 & 1.0255 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (9)$$

The legacy approach delivers nearly an identical result, so the system is backward compatible. The total error is identical to the IPP2 approach 0(.6263) albeit with small differences in the x and y deviation. The graphic representation would be the same as in *figure 28*.

	x	y	∑
RED Scarlet M-X Legacy	0.2710	0.3553	**0.6263**

Table 14. *Differences between spectral data and RED Legacy approach*

It could be interesting comparing the results in this test with the one in our paper *Comparing different ACES Input Device Transforms (IDTs) for the RED Scarlet-X Camera [23]*. The results are displayed in table 15.

	x	y	∑
IPP2 5924 K Indoors	0.2727	0.3536	**0.6263**
Legacy 5700 K Outdoors	0.2086	0.3327	**0.5412**

Table 15 *Differences between RED IPP2 and a test with a color temperature of 5700 K outdoors*

The relatively high deviations in both tests are mainly concentrated on the blue cyan patches (#b2, #c1, #c6). It can therefore be assumed that the RED IDT provides partially problematic results. However, this could also be due to the outdated

sensor of the test camera. Also the uneven spectral power distribution may contribute to the partially poorer quality.

3.4 Canon EOS D5 Mark III Conversion

Approach 1 includes the rawtoaces *mat-method 1* as described in section 2. See *formula* 10 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$
\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 0.2845 & 0.0000 & 0.0000 \\ 0.0000 & 0.2653 & 0.0000 \\ 0.0000 & 0.0000 & 0.2095 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (10)
$$
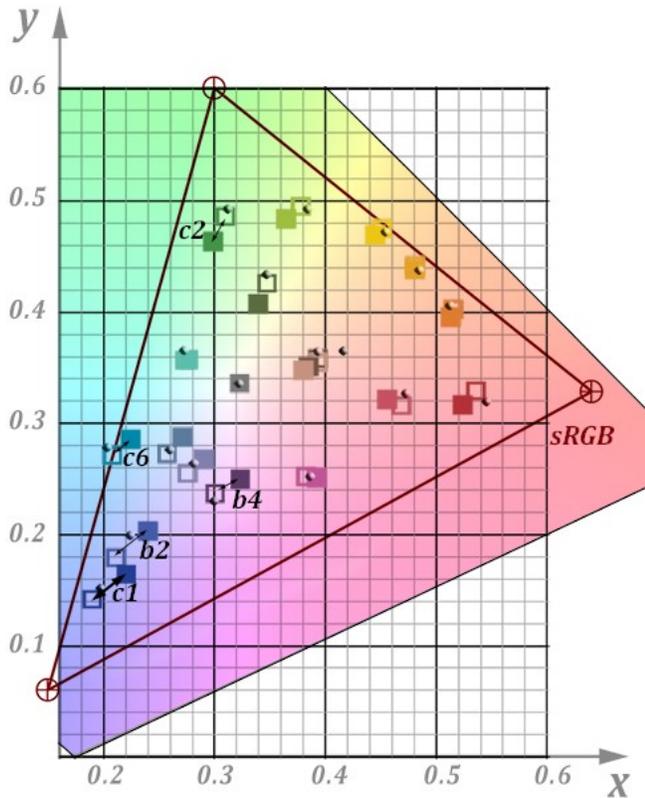
Figure 29. ColorChecker positions for Canon EOS D5 Mark III mat-method 1 (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded

	x	y	Σ
Canon EOS D5 Mark III Mat-Method 1	0.2597	0.2024	**0.4621**

Table 16. Differences between spectral data and Canon EOS D5 Mark III mat-method 1

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data testify to a good quality for the mat-method-1 approach. There is only one patch (#c1-blue), which exceeds the 0.03 error in the x-direction (-0.0303). Then there are four other patches mostly in the blue-cyan-purple region with a deviation larger than 0.02 in one or both directions (#b2-purplish blue). The rest of the patches are distributed very well, above all in the yellow-orange region.

Approach 2 includes the rawtoaces *mat-method 0* as described in section 2. See *formula* 11 for the XYZ-scaling matrix to match the 5924 K white point given in *table 3*.

$$
\begin{bmatrix} X_{5924K} \\ Y_{5924K} \\ Z_{5924K} \end{bmatrix} = \begin{bmatrix} 0.2885 & 0.0000 & 0.0000 \\ 0.0000 & 0.2649 & 0.0000 \\ 0.0000 & 0.0000 & 0.2567 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (11)
$$
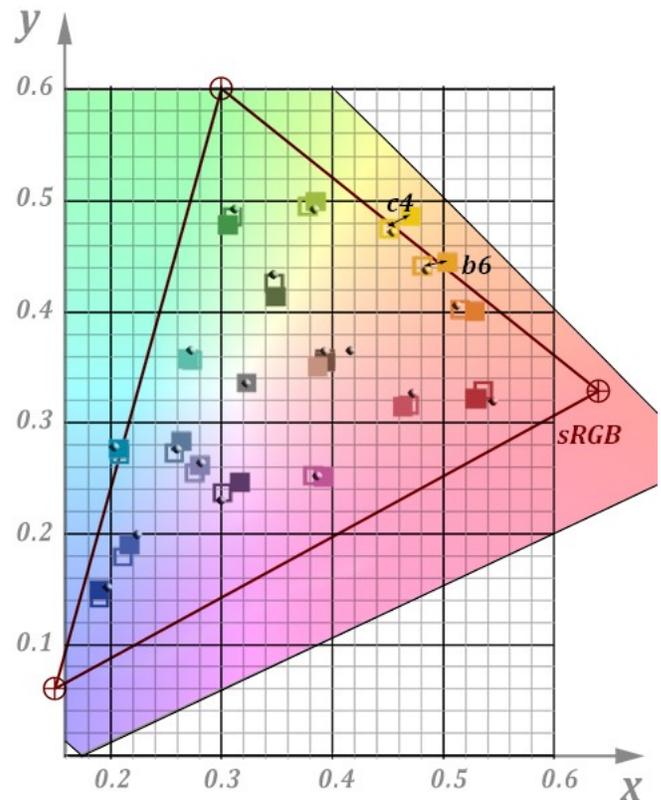
Figure 30. ColorChecker positions for Canon EOS D5 Mark III mat-method 0 (solid) in comparison to the spectral data positions (hollow) and the ACES DATA (shaded

The deviations of the recorded CIE Yxy ColorChecker patch positions to the positions of the recorded spectral data is of an excellent quality for the mat-method-0 approach. The distribution of the patches is even and only two patches (#b6-orange yellow and #c4-orange) have an offset, which is slightly larger than 0.02 (0.0228 and 0.0201). Consequently the total error of 0.2692 is the best in all tests. The deviation in the yellow-orange range may be caused by the uneven spectral power distribution of the light, where the problems in the blue range may be shifted to the corresponding yellow region by adjusting the white point. In comparison to mat-method 1 the quality improvement is huge.

	x	y	Σ
Canon EOS D5 Mark III Mat-Method 0	0.1575	0.1118	**0.2692**

Table 17. Differences between spectral data and Canon EOS D5 Mark III mat-method 0

8. Summary and conclusion

By using the spectral data as a basis for this test and adjusting all camera shots to the white point, the problem arose that the SPD of light had an influence on the measurement results. These deviations were particularly noticeable in the blue-cyan purple range, where the test lighting showed a strong peak due to the LED structure. In order to limit the influence of the unevenness it makes sense to use a light that is spectrally uniform as a basis for the next tests.

The Blackmagic design conversion delivered good results when using the internal ACES workflow in DaVinci Resolve 15. The URSA mini pro camera can be safely integrated into an ACES pipeline if DaVinci Resolve 15 is used as an intermediate step. The total error can be tolerated depending on the quality specifications. The internal YRGB pipeline is more difficult to export at first sight. Further efforts are necessary if the ACES workflow is not to be used. It must be pointed out here that the problems during the export are not due to the reliability of the application but to the selected import-export system, which was used in this test.

The ACES RED IDT delivers the lowest results in the test, which can be mainly due to the older sensors of the camera. The deviations are slightly larger than in other tests [19], which can be due to the uneven SPD of the test lighting.

The best results are obtained by *rawtoaces* conversion using the native spectral distribution (filter design) of the camera (mat-method). Except for minor problems in the yellow-orange range, the distribution of the ColorChecker patches is excellent. The application of spectral sensitivity is definitely the right way forward and another step forward in the design of ACES IDT for still image cameras.

Deviations	x	y	Σ
Blackmagic Design URSA mini pro ACES	0.2113	0.2027	**0.4139**
RED - Scarlet M-X IPP2	0.2727	0.3536	**0.6263**
Canon EOS 5D Mark III rawtoaces mat-method 0	0.1575	0.1118	**0.2692**

Table 18. Deviations between spectral data and color space conversion for the cameras in this test

Figure 31. Recordings of a ColorChecker under the same lighting conditions. top: BMG URSA Mini Pro ACES workflow, middle: RED Scarlet M-X IPP2 workflow, bottom: Canon EOS Mark III Still Image rawtoaces mat-method 0

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Eberhard Hasche received his diploma in electro engineering from the Technical University of Dresden (1976). Afterwards he studied double bass, composition and arranging at Hochschule für Musik „Carl Maria von Weber" in Dresden (state examination 1989). Since 2003 he is professor for audio and video technology at Brandenburg University of Applied Sciences, Germany. He is focused on image compositing (certified Nuke Trainer by The Foundry in 2012). He is member of the Visual Effects Society (VES).

Oliver Karaschewski is graduated as a audio-visual media designer (2007). He received his B. Sc in computer science (2012) and M. Sc. in digital media (2017) from the University of Applied Sciences Brandenburg. He worked as a camera assistant, an event engineer and currently as an academic employee at the University of Applied Sciences Brandenburg, Germany. His work is focused on digital video and photography.

Reiner Creutzburg received his Diploma in Math from the University of Rostock, Germany (1976). Since 1992 he is professor for Applied Informatics at the Brandenburg University of Applied Sciences in Brandenburg. Germany. He is member in the IEEE and SPIE and chairman of the Multimedia on Mobile Device Conference at the Electronic Imaging conferences since 2005.

Appendix A - Calculation Results ACES RGB to Lights

Patch	Spectral-LED light1 (Amaran) x	y		ACES RGB to 5924 K x	y		Spectral-LED light2 (Swit) x	y		ACES RGB to 4807 K x	y		Spectral-Inc. light 3 (Ianiro) x	y
a 1	0.3937	0.3575		0.4163	0.3648		0.4347	0.3731		0.4407	0.3736		0.4077	0.3748
a 2	0.3935	0.3551		0.3927	0.3650		0.4258	0.3647		0.4181	0.3713		0.4078	0.3731
a 3	0.2575	0.2726		0.2590	0.2764		0.2841	0.2967		0.2882	0.2975		0.2802	0.3131
a 4	0.3475	0.4261		0.3468	0.4344		0.3717	0.4271		0.3681	0.4459		0.3561	0.4265
a 5	0.2753	0.2554		0.2805	0.2641		0.3078	0.2820		0.3113	0.2835		0.2980	0.2922
a 6	0.2729	0.3569		0.2718	0.3664		0.2970	0.3751		0.2966	0.3868		0.2830	0.3892
b 1	0.5149	0.4033		0.5124	0.4064		0.5320	0.4016		0.5279	0.4050		0.5232	0.4053
b 2	0.2109	0.1791		0.2237	0.1990		0.2296	0.2017		0.2545	0.2190		0.2323	0.2218
b 3	0.4683	0.3161		0.4720	0.3168		0.5006	0.3288		0.4981	0.3234		0.4722	0.3346
b 4	0.3009	0.2372		0.3027	0.2317		0.3386	0.2694		0.3364	0.2490		0.3319	0.2759
b 5	0.3783	0.4948		0.3837	0.4926		0.4002	0.4898		0.4004	0.4967		0.3853	0.4971
b 6	0.4808	0.4423		0.4779	0.4382		0.4993	0.4366		0.4932	0.4374		0.4904	0.4410
c 1	0.1895	0.1424		0.1970	0.1516		0.2012	0.1570		0.2277	0.1693		0.2040	0.1803
c 2	0.3096	0.4864		0.3119	0.4931		0.3310	0.4888		0.3300	0.5046		0.3150	0.4987
c 3	0.5358	0.3286		0.5445	0.3194		0.5543	0.3342		0.5657	0.3210		0.5395	0.3395
c 4	0.4509	0.4751		0.4536	0.4717		0.4716	0.4681		0.4677	0.4705		0.4576	0.4737
c 5	0.383	0.2524		0.3855	0.2523		0.4249	0.2767		0.4191	0.2654		0.4108	0.2774
c 6	0.2084	0.2705		0.2033	0.2776		0.2293	0.2929		0.2290	0.3025		0.2209	0.3141
Diff. (99%)	0.3227	0.3358		0.3227	0.3358		0.3503	0.3526		0.3503	0.3526		0.3369	0.3596

Patch	ACES RGB to 5370 K x	y		Color Differences Light 1 Spectral –Conv. ACES x	y		Color Differences Light 2 Spectral –Conv. ACES x	y		Color Differences Light 3 Spectral –Conv. ACES x	y
a 1	0.3953	0.3653		-0.0226	-0.0073		-0.0061	-0.0005		-0.0186	-0.0083
a 2	0.3732	0.3481		0.0007	-0.0100		0.0076	-0.0066		0.0040	-0.0072
a 3	0.2459	0.2675		-0.0015	-0.0038		-0.0041	-0.0008		0.0041	0.0108
a 4	0.3335	0.4376		0.0006	-0.0084		0.0036	-0.0188		0.0017	-0.0289
a 5	0.2690	0.2516		-0.0052	-0.0087		-0.0036	-0.0016		-0.0007	0.0037
a 6	0.2541	0.3491		0.0011	-0.0095		0.0003	-0.0118		-0.0014	-0.0061
b 1	0.5058	0.4090		0.0025	-0.0031		0.0041	-0.0035		0.0100	-0.0123
b 2	0.2114	0.1807		-0.0128	-0.0199		-0.0250	-0.0173		-0.0111	-0.0003
b 3	0.4765	0.3095		-0.0038	-0.0008		0.0025	0.0054		-0.0111	0.0018
b 4	0.3021	0.2089		-0.0019	0.0054		0.0022	0.0203		0.0087	0.0221
b 5	0.3612	0.5072		-0.0055	0.0022		-0.0002	-0.0069		-0.0007	-0.0111
b 6	0.4723	0.4529		0.0029	0.0041		0.0061	-0.0009		0.0119	-0.0091
c 1	0.1969	0.1499		-0.0076	-0.0092		-0.0266	-0.0124		-0.0133	0.0089
c 2	0.2856	0.4814		-0.0024	-0.0067		0.0009	-0.0159		-0.0021	-0.0155
c 3	0.5449	0.3176		-0.0088	0.0091		-0.0114	0.0132		-0.0117	0.0078
c 4	0.4386	0.4890		-0.0027	0.0033		0.0039	-0.0025		0.0045	-0.0097
c 5	0.3788	0.2391		-0.0025	0.0000		0.0058	0.0113		0.0061	0.0056
c 6	0.1979	0.2638		0.0051	-0.0072		0.0003	-0.0096		0.0022	0.0078
Diffuser (99%)	0.3128	0.3290		**Sum x,y** 0.1170	0.1300		0.1253	0.1653		0.1347	0.1908
				Total 0.2470			0.2905			0.3255	

Table 19 Positions and deviations of the Macbeth color patches in the CIE xy-chromaticity diagram for the ACES RGB conversions

Appendix B - Calculation Results Blackmagic URSA Mini Pro

	Spectral-LED light1 (Amaran)			DaVinci Resolve 15 ACES Workflow			DaVinci Resolve 15 YRGB linear input			DaVinci Resolve 15 YRGB RAW input		
Patch	x	y		x	y		x	y		x	y	
a 1	0.3937	0.3575		0.37831	0.35276		0.39387	0.33692		0.40631	0.33569	
a 2	0.3935	0.3551		0.38152	0.34782		0.39840	0.33239		0.41198	0.33048	
a 3	0.2575	0.2726		0.26797	0.28399		0.24991	0.30640		0.23831	0.30057	
a 4	0.3475	0.4261		0.34947	0.41183		0.34562	0.39090		0.34896	0.39941	
a 5	0.2753	0.2554		0.28165	0.26593		0.27690	0.28836		0.26905	0.27960	
a 6	0.2729	0.3569		0.28974	0.35776		0.26764	0.36265		0.25842	0.36810	
b 1	0.5149	0.4033		0.50527	0.39635		0.52958	0.34618		0.55913	0.33912	
b 2	0.2109	0.1791		0.21694	0.19248		0.18371	0.23806		0.16373	0.21885	
b 3	0.4683	0.3161		0.44713	0.30583		0.47971	0.28923		0.50573	0.28123	
b 4	0.3009	0.2372		0.30011	0.24074		0.31065	0.26401		0.30822	0.25226	
b 5	0.3783	0.4948		0.38439	0.47448		0.38281	0.43205		0.38998	0.44499	
b 6	0.4808	0.4423		0.47451	0.43394		0.49419	0.37953		0.51878	0.37704	
c 1	0.1895	0.1424		0.18951	0.15095		0.14056	0.20434		0.11792	0.17956	
c 2	0.3096	0.4864		0.32956	0.46347		0.30683	0.44047		0.30232	0.45918	
c 3	0.5358	0.3286		0.51476	0.31982		0.54672	0.28913		0.57907	0.28005	
c 4	0.4509	0.4751		0.44980	0.46998		0.46347	0.41229		0.48246	0.41526	
c 5	0.383	0.2524		0.37029	0.24377		0.40312	0.25502		0.41651	0.24371	
c 6	0.2084	0.2705		0.23711	0.28931		0.19272	0.31888		0.17435	0.31445	
Diff. (99%)	0.3227	0.3358		0.32270	0.33580		0.32270	0.33580		0.32270	0.33580	

	Color Differences Spectral –DaVinci ACES			Color Differences Spect.–DaVinci YRGB linear.			Color Differences Spect.–DaVinci YRGB lin.		
Patch	x	y		x	y		x	y	
a 1	0.0154	0.0047		-0.0002	0.0206		-0.0126	0.0218	
a 2	0.0120	0.0073		-0.0049	0.0227		-0.0185	0.0246	
a 3	-0.0105	-0.0114		0.0076	-0.0338		0.0192	-0.0280	
a 4	-0.0020	0.0143		0.0019	0.0352		-0.0015	0.0267	
a 5	-0.0064	-0.0105		-0.0016	-0.0330		0.0062	-0.0242	
a 6	-0.0168	-0.0009		0.0053	-0.0057		0.0145	-0.0112	
b 1	0.0096	0.0070		-0.0147	0.0571		-0.0442	0.0642	
b 2	-0.0060	-0.0134		0.0272	-0.0590		0.0472	-0.0398	
b 3	0.0212	0.0103		-0.0114	0.0269		-0.0374	0.0349	
b 4	0.0008	-0.0035		-0.0097	-0.0268		-0.0073	-0.0151	
b 5	-0.0061	0.0203		-0.0045	0.0628		-0.0117	0.0498	
b 6	0.0063	0.0084		-0.0134	0.0628		-0.0380	0.0653	
c 1	0.0000	-0.0086		0.0489	-0.0619		0.0716	-0.0372	
c 2	-0.0200	0.0229		0.0028	0.0459		0.0073	0.0272	
c 3	0.0210	0.0088		-0.0109	0.0395		-0.0433	0.0486	
c 4	0.0011	0.0051		-0.0126	0.0628		-0.0316	0.0598	
c 5	0.0127	0.0086		-0.0201	-0.0026		-0.0335	0.0087	
c 6	-0.0287	-0.0188		0.0157	-0.0484		0.0341	-0.0440	
Sum x.y	0.2113	0.2027		0.2313	0.7186		0.4981	0.6418	
Total	0.4139			0.9499			1.1399		

Table 20 Positions and deviations of the Macbeth color patches in the CIE xy-chromaticity diagram for the Blackmagic URSA Mini Pro camera

Appendix C - Calculation Results RED Scarlet M-X

Patch	Spectral-LED light1 (Amaran)			RED IPP2 WideGamutRGB			RED Legacy WideGamutRGB			Color Differences RED IPP2			Color Differences RED legacy	
	x	y		x	y		x	y		x	y		x	y
a 1	0.3937	0.3575		0.3814	0.3609		0.3819	0.3611		0.0124	-0.0034		0.0118	-0.0036
a 2	0.3935	0.3551		0.3809	0.3466		0.3811	0.3469		0.0126	0.0085		0.0124	0.0082
a 3	0.2575	0.2726		0.2767	0.2872		0.2766	0.2871		-0.0192	-0.0146		-0.0191	-0.0145
a 4	0.3475	0.4261		0.3456	0.4158		0.3456	0.4127		0.0019	0.0103		0.0019	0.0134
a 5	0.2753	0.2554		0.2917	0.2729		0.2916	0.2728		-0.0164	-0.0175		-0.0163	-0.0174
a 6	0.2729	0.3569		0.2841	0.3432		0.2843	0.3432		-0.0112	0.0137		-0.0114	0.0137
b 1	0.5149	0.4033		0.5048	0.4201		0.5049	0.4203		0.0102	-0.0168		0.0101	-0.0170
b 2	0.2109	0.1791		0.2437	0.2207		0.2437	0.2208		-0.0328	-0.0416		-0.0328	-0.0417
b 3	0.4683	0.3161		0.4537	0.3255		0.4537	0.3255		0.0146	-0.0094		0.0146	-0.0094
b 4	0.3009	0.2372		0.3145	0.2674		0.3144	0.2673		-0.0136	-0.0302		-0.0135	-0.0301
b 5	0.3783	0.4948		0.3713	0.4833		0.3713	0.4833		0.0070	0.0115		0.0070	0.0115
b 6	0.4808	0.4423		0.4734	0.4595		0.4736	0.4597		0.0074	-0.0172		0.0072	-0.0174
c 1	0.1895	0.1424		0.2253	0.1920		0.2252	0.1920		-0.0358	-0.0496		-0.0357	-0.0496
c 2	0.3096	0.4864		0.3161	0.4527		0.3161	0.4527		-0.0065	0.0337		-0.0065	0.0337
c 3	0.5358	0.3286		0.5274	0.3354		0.5273	0.3353		0.0084	-0.0068		0.0085	-0.0067
c 4	0.4509	0.4751		0.4476	0.4878		0.4475	0.4878		0.0033	-0.0127		0.0034	-0.0127
c 5	0.383	0.2524		0.3853	0.2717		0.3853	0.2717		-0.0023	-0.0193		-0.0023	-0.0193
c 6	0.2084	0.2705		0.2450	0.2762		0.2449	0.2762		-0.0366	-0.0057		-0.0365	-0.0057
Diff. (99%)	0.3227	0.3358		0.3227	0.3358		0.3227	0.3358		0.0000	0.0000		0.0000	0.0000
					Sum x.y					0.2727	0.3536		0.2710	0.3553
					Total					0.6263			0.6263	

Table 21 Positions and deviations of the Macbeth color patches in the CIE xy-chromaticity diagram for the RED Scarlet M-X camera

Appendix D - Calculation Results Canon EOS 5D Mark III

Patch	Spectral-LED light1 (Amaran)			Canon D5 Mark III Mat-method 1			Canon D5 Mark III Mat-method 0			Color Differences Mat-method 1			Color Differences Mat-method 0	
	x	y		x	y		x	y		x	y		x	y
a 1	0.3937	0.3575		0.3854	0.3531		0.39386	0.35540		0.0083	0.0044		-0.0002	0.0021
a 2	0.3935	0.3551		0.3795	0.3480		0.38705	0.35005		0.0140	0.0071		0.0065	0.0051
a 3	0.2575	0.2726		0.2756	0.2884		0.26428	0.28288		-0.0181	-0.0158		-0.0068	-0.0103
a 4	0.3475	0.4261		0.3399	0.4082		0.34886	0.41541		0.0076	0.0180		-0.0014	0.0107
a 5	0.2753	0.2554		0.2910	0.2683		0.28090	0.26236		-0.0157	-0.0129		-0.0056	-0.0070
a 6	0.2729	0.3569		0.2755	0.3572		0.26915	0.35831		-0.0026	-0.0003		0.0037	-0.0014
b 1	0.5149	0.4033		0.5118	0.3963		0.52848	0.40110		0.0031	0.0070		-0.0136	0.0022
b 2	0.2109	0.1791		0.2404	0.2030		0.21723	0.19009		-0.0295	-0.0239		-0.0063	-0.0110
b 3	0.4683	0.3161		0.4561	0.3114		0.46290	0.31427		0.0122	0.0047		0.0054	0.0018
b 4	0.3009	0.2372		0.3242	0.2504		0.31723	0.24586		-0.0233	-0.0132		-0.0163	-0.0087
b 5	0.3783	0.4948		0.3657	0.4838		0.38477	0.50017		0.0126	0.0111		-0.0065	-0.0054
b 6	0.4808	0.4423		0.4811	0.4377		0.50364	0.44467		-0.0003	0.0046		-0.0228	-0.0024
c 1	0.1895	0.1424		0.2198	0.1642		0.19044	0.14777		-0.0303	-0.0218		-0.0009	-0.0054
c 2	0.3096	0.4864		0.2996	0.4634		0.30645	0.47989		0.0100	0.0230		0.0031	0.0065
c 3	0.5358	0.3286		0.5230	0.3160		0.52854	0.32096		0.0128	0.0126		0.0073	0.0076
c 4	0.4509	0.4751		0.4448	0.4749		0.47104	0.48617		0.0061	0.0002		-0.0201	-0.0111
c 5	0.383	0.2524		0.3929	0.2512		0.39158	0.25109		-0.0099	0.0012		-0.0086	0.0013
c 6	0.2084	0.2705		0.2284	0.2860		0.20723	0.27786		-0.0200	-0.0155		0.0012	-0.0074
Diff. (99%)	0.3227	0.3358		0.3227	0.3358		0.3227	0.3358		0.0000	0.0000		0.0000	0.0000
							Sum x.y			0.2597	0.2024		0.1575	0.1118
							Total			0.4621			0.2692	

***Table 22** Positions and deviations of the Macbeth color patches in the CIE xy-chromaticity diagram for the Canon EOS 5D Mark III still image camera*