Comparing ACES Input Device Transforms for the Canon EOS 5D Mark III DSLR camera

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Abstract

Color is an important aspect of the camera quality. Above all in a Visual Effects Pipeline (VFX) it is necessary to maintain a linear relationship of the pixel color in the recorded image to the original light of the scene throughout every step in the production pipeline. This means that the plate recorded by the camera is not permitted to be subject of changes in any way („do no harm to the plate"). Unfortunately most of the camera vendors are applying certain functions during the input step to the recorded RAW material, mostly to meet the needs of the display devices at the end of the pipeline. But they also are adding functions to establish a certain look the camera company is associated with.

Maintaining a linear relationship to the light of the scene enables compositing artists and editors to combine imagery of varying sources (mostly cameras of different vendors). The Academy of Motion Picture Arts and Science (AMPAS) established an Academy Color Encoding System (ACES). To achieve a linear relationship to the light of the scene, Input Device Transforms (IDTs) for most of the digital film cameras have been provided recently. Unfortunately, such IDTs are not available for nearly all consumer and DSLR cameras. To add their imagery to the film production pipeline it is desirable to create convenient IDTs for such devices as well.

The goal of this paper is to record the spectral distribution of a GreagMacbeth ColorChecker using a spectrometer and also photography it with a Canon EOS 5D Mark III camera under the same lighting conditions. The RAW image is then converted to ACES color spacers (ACES2065-1 or ACEScg) using industrial approved RAW converters. The positions of the patches of the ColorChecker in CIEYxy color space are then compared to the positions of the patches captured by the spectral device. As a result a tendency could be obtained if the camera can be used inside the AMPAS ACES workflow.

1. The Importance of the Input Device Transform (IDT) in an AMPAS-ACES Workflow

In November 2016 the *Academy of Motion Picture Arts and Sciences (AMPAS)* published version 1.0.3 of their *Academy Color Encoding System (ACES),* which included some significant new developments like the access to the *REDWideGamutRGB* color space. This color system was developed over the last 10 years to unify and simplify the process of interchanging and archiving motion picture images. Beside this general goal it encompasses two recent technical developments in the media industry: the usage of wider color spaces (like BT.2020 for UHDTV) and the movement to high dynamic range content, which has a more dramatic impact on the entire media pipeline. The workflow is based on OpenEXR files with 16 bit half precision floating point accuracy (32 floating point for utility data. It also encompasses a gamut where all colors detect by the human vision system can be encoded. The color encoding system comprises four main elements which are standardized and makes it very convenient f. i. to view high dynamic range content on a low dynamic display using the Reference Rendering Transform (RRT) (see *figure 1*).

Figure 1. *A rough estimation of the ACES RRT*

In this paper we will concentrate on the Input Device Transform (IDT). The goal of an IDT is to convert an image from a certain source, mainly a camera – DSLR and action cameras included – to a unified color space. To ensure that all converted images are looking the same, all transfer functions (gamma, log) and all picture renderings applied by the manufacture company have to be removed. Picture rendering is mostly done to convey the company's preferred idea how a picture may look pleasant. After applying the IDT to all images, they can theoretically be combined without additional color correction – a main goal in modern compositing

For this reason the built-in functionality of an IDT has to ensure that the resulted image maintains a linear relationship to the light of the scene in terms of luminance, which can be achieved by removing the *Opto-Electronic Conversion Function (OECF)* already applied by the camera. Another important part of the functionality of an IDT is to transfer the correct chrominance of the original light. This means, all the company related picture rendering curves have to be removed as well. For this reason an IDT is not a simple color space conversion device and an accurate color representation is an important task.
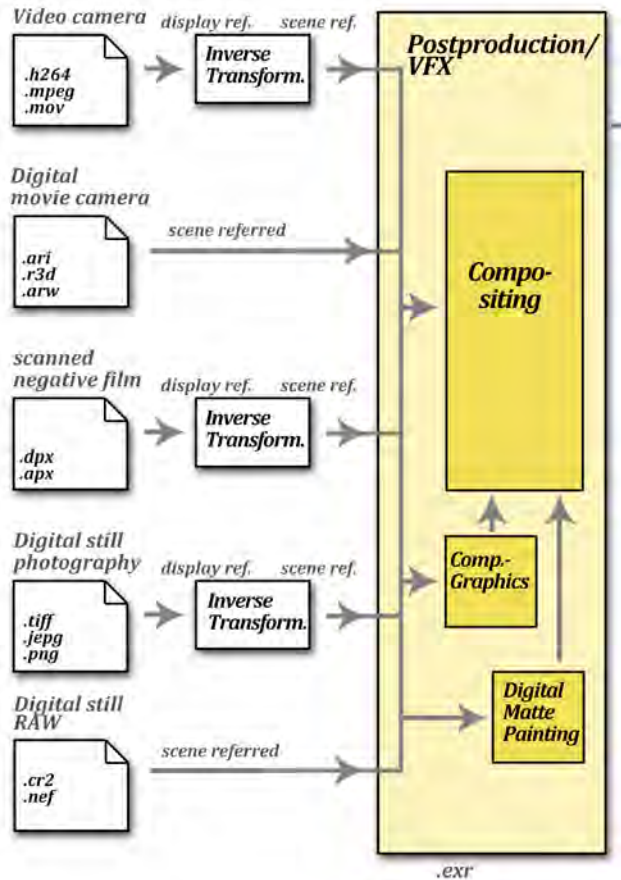
Figure 2. The IDT section of the film color pipeline [1]

IDTs available within the ACES system are representing mostly digital film and moving picture cameras. Some consumer cameras and DSLR cameras with video capability are not included. Neither are still image cameras. The latter are nevertheless important devices for capturing additional imagery. They are used to capture reference images, textures and a representation of the light of the scene, usually done by capturing high dynamic range 360° environment maps.

The aim of this document is to test out if a RAW image captured by a Canon EOS D5 Mark III DSLR camera can be imported into a film pipeline via custom ACES IDTs. Six RAW converter and image processing applications are evaluated by comparing the recording of a ColorChecker (GretagMacbeth) [2] with the spectral data of this chart captured by a spectral capturing device .

Another topic was to verify if a small mobile spectrometer with a laptop can generate sufficiant data. Using such a mobile device is critical for on set capturing inside the film industry.

2. Technical background of Camera (Sensor) RAW

The Camera RAW data is the first appearance of the representation of the light of the scene inside a camera color workflow. It is derived from original light after three filters have been applied to each pixel CCD, an *Optical LowPass Filter (OLPF)* removing high frequency detail to avoid misinterpretation of digital data (folding back low frequencies). The second filter is an *Infrared Blocker* to block near infrared light energy to reach the sensor. The third filter applies the Camera spectral response. It defines the filtering oft he visible light into three LMS (long wave, medium wave, short wave) components mimicking the color reception oft he human eye. The response curves of the filters applied in most (not all) cameras are noticeable different to the color matching functions defined by the CIE [3], by missing the dip in the component $\bar{x}(\lambda)$ with the peak around 440 nm (see *figure 3*). They are also different to the LMS-color response oft he human visual system, by shifting the L-(Red)-curve slightly to the right in the long wave direction for reasons of avoiding correlated noise (see *figure 4)*.
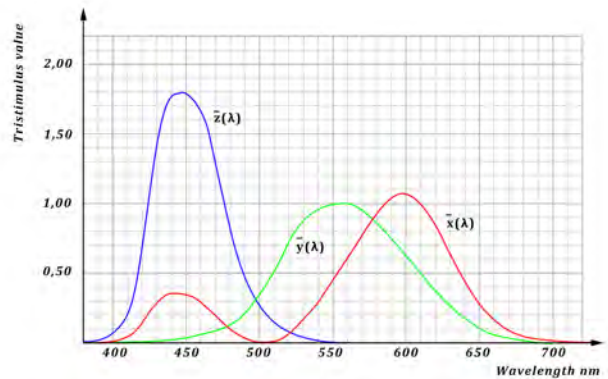

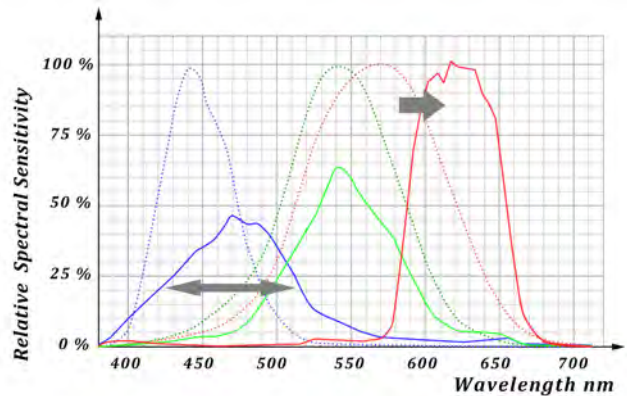**Figure 3.** The CIE standard observer color matching functions [4]

Figure 4. Camera filters (solid lines) compared to the color vision of the human visual system [5]

After passing the filters, color components are available as digital image data. Because of the arrangement of the filters in a 2x2 pixel arrays throughout the sensor there are four color channels generated, two green channel, a red and a blue channel. To create a pleasing image the RAW data is then de-bayered (de-mosaiced), a process where the missing color components of every pixel are calculated using the values of the same channel from surrounding

pixels. After a purification where a compensation for the limitations of the filters is taking place, picture rendering calculations and color transfer functions are applied to establish the pleasant look the camera company is after. Unfortunately the linear relationship to the light of the scene is lost after these steps and a combination of images with different sources (cameras) are nearly impossible.

Another problem in a film pipeline is *high light protection*. Because film cameras and the possibilities in the post production chain can create color values which are considerably higher then the usual 0 to 1 range in standard photography, only floating point file formats can store values above 1.0. Integer file formats from 8 to 16 bit have increased resolution but only in the range of 0 to 1.

Although Sensor RAW data is usually rendered in the range of 0 to 1 it has to be scaled to cover the entire dynamic range of the original recording at some point in post processing. The central value in a film color pipeline is 0.18 because of the floating point nature of the data, where a value of 1.0 (white) is no defined as the highest number like in other media pipelines (television). In a high dynamic range environment white can have different appearances like a shirt, a reflection on a chrome bar or a jet stream. This leads to several problems because some RAW converters are only capable to export the images in TIFF 16 bit integer files, which makes it difficult protecting the highlights from being clipped. Although camera manufacturers are leaving certain headroom for superwhite by not setting the reference white to the highest value, it is not possible to retrieve this value from the RAW data without measuring.

Figure 5. GretagMacbeth ColorChecker (pocket version) and the identifiers used in the test

3. Test setup and methodology

The main approach in this test is a practical workflow with as less interchanges as possible. We used the built-in functionality of *The Foundry NukeX v.11.2[6]*, the „*backbone of compositing and image processing pipelines across the motion picture industry.*" *[7]*. The image processing is done using the built-in *OpenColor IO [8]* 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 if needed.

The test took place at the campus of the University of Applied Sciences in Brandenburg in early December 2017 at noon. The

estimated color temperature was around 5700 K. Four different cameras recorded a ColorChecker chart:

- Canon OS 5D Mark III, (see *figure 6*)
- Blackmagic Design Production Camera
- Blackmagic Design URSI Mini Camera
- RED Scarlet Camera

This paper concentrates on the Canon 5D Mark III camera, the results of the evaluation of the Red Scarlet camera is the topic of the paper: *Comparing different ACES input device transforms (IDTs) for the RED Scarlet-X Camera [6]*. The *Blackmagic Production Camera* and *Blackmagic URSI Mini* Camera are subject of further investigation.

Figure 6. The Canon EOS 5D Mark III DSLR camera [9]

The spectral data were recorded using a mobile Spectrometer, the *rgb photonics Qmini* (see *figure 7*). It consists of the device itself with an USB connection to a laptop and an optical fiber cable for the input..

Figure 7. The spectrometer used in this test, the rgbphotonics Qmini [10]

While ensuring to maintain the same lighting conditions (clouds) 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 5 minutes

The goal for the image conversion process was to keep the recordings as original as possible with no white balance if possible. The output color workspaces by the host converters were either set to *ACES2065-1* – the Original ACES Color Space as defined in SMPTE document *ST 2065-1 [12]* or to *ACEScg* (see *figure* 8). The ACEScg color space is smaller than the all colors encompassing ACES2065-1 color space and intended to be used for processing computer graphics and compositing [13]. The main advantage using this color space is that the primaries are physically plausible and the processing is more traditionally based and user friendly. The file formats were 16 bit integer TIFF or 32 bit floating point OpenEXR depending on the capability of the host software
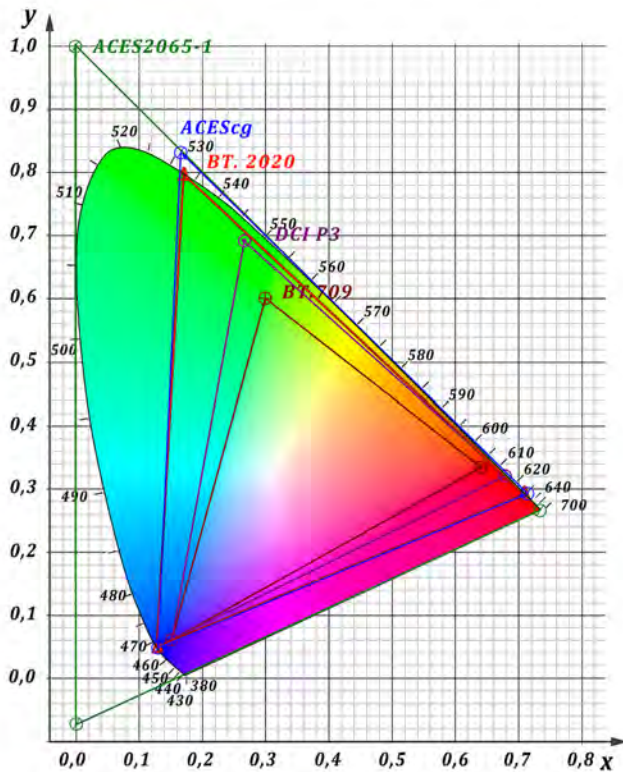

Figure 8. *The ACES2065-1 and ACEScg color space*

The converted imagery was then imported into NukeX11.02. Depending on the color space encoded into the images the correct ACES color space was chosen as the Nuke working color space, either ACES2065-1 or ACEScg. This step was not necessary – the calculations would be the same in either color workspace – but for a clearer workflow we used the appropriate settings. The images then were converted from the ACES color spaces to to CIEXYZ using the following formulas (1) and (2):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.938630938530 & -0.005741920322 & 0.017566898838 \\ 0.338093608618 & 0.727213919163 & -0.065307497978 \\ 0.000723121513 & 0.000818441855 & 1.087516188622 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Formula 1. *ACES2065-1 RGB to CIEXYZ [14]*

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.65223754 & 0.12823614 & 0.16998225 \\ 0.26767218 & 0.67433999 & 0.05798783 \\ -0.00538182 & 0.00136906 & 1.09307051 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Formula 2. *ACEScg RGB to CIEXYZ [14]*

Then another 3x3 color matrix was applied for white balancing inside the CIECXYZ color space when needed. We used patch 19 (#d1) from the Macbeth color chart as reference for 100 % white (1.0). The matrix is adjusted to match the coordinates of the CIE D65 white point in CIE XYZ: 0.95047, 1.00000, 1.08883 *[3]* The matrix used for every white balancing is included in the discussion section.

The selection of patch 19 is not completely correct because the albedo of this patch is indicated as 0,91 in document *RGB coordinates of the Macbeth ColorChecker [11]*. But because the luminance is not subject of this investigation this mismatch can be neglected.

The last step is 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.

4. Evaluation settings

In this section the image conversion settings for the RAW converters, encoded color space, file format and bit depth are listed.

1) Adobe Photoshop CC 2017 - Version 2017.1.1 [15]
Adobe Photoshop is a commercial and proprietary GUI-based raster graphics editor since 1990 with a separate interface to read in RAW material. It is available for Windows, Linux and MacOSX. We used the German version 2017.1.1. The image was imported into its Camera Raw 9.10.1 application and identified as - *Canon EOS 5D Mark III*. The settings were offering a lot of control. We set all controllers to zero and white balance to match the recording so the different results from the converter are only controlled by the *Camera Profile Parameter*. Two different images were exported using the *Adobe Standard* and *Camera Neutral* settings as 16 bit TIFF files with ACEScg linear color space encoded.

2) Serif Affinity Photo 1.6.6 [16]
Affinity Photo is a commercial and proprietary GUI-based raster graphics editor since 2015. It is available for Windows, iOS and MacOSX. We used the German version 1.6.6. The import settings are adjusted in the Develop Assistant. Here all corrections were set to *Take No Action* and the RAW output format was set to *RGB (32 Bit HDR)*. In the presets 32-bit RGB color profile was set to: *ACES CG linear*. Subsequently the image was exported as *OpenEXR 32 bit* linear. No additional white balance had been applied.

3) Blackmagic Design – DaVinci Resolve 14.2 [17]

DaVinci Resolve is a long-term GUI-based color correction and editing tool. Analog roots go back as far as 1982. It is available for Windows, Linux and MacOSX. We used the free version 14.2. In the *Project Settings --> Color Management* page the Color science was set to *ACEScc*, another of the four ACES color spaces intended to be used for color correction. The ACES Input Device Transform was set to *Canon 5D* and the ACES Output Device Transform to *ACEScg*. The image was exported from the Deliver Page as *RGB float (no compression) - OpenEXR* files. No additional white balance had been applied.

(4) Iridient Developer 3.2.1 [18]

Iridient Developer is a commercial and proprietary GUI-based RAW image converter since 2004 available only for Macintosh OS. We used the trial version 3.2.1. The image was imported into the application and automatically detected as *EOS 5D Mark III.* We reset the camera curve in the exposure table to linear. In the color table we selected *IDv320 Canon 5D Mark III Standard* as Input Profile and set the White Balance *As Shot.* Then the image was exported in *ACES CG Linear* color space encoded as 16 bit TIFF integer. Due to the trial version the image contains a watermark, which does not affect the color reading of the intividual color patches.

dcraw v9.27 [19]

dcraw is a command line Open Source RAW photo converter developed by Dave Coffin. It is also used by other image processing applications to read in RAW images. We used version v9.27. The processing is controlled by the following options:

```
raw photo decoder "dcraw" v9.27
by Dave Coffin, dcoffin a cybercom o net

Usage:  dcraw [OPTION]... [FILE]...

-v         Print verbose messages
-c         Write image data to standard output
-e         Extract embedded thumbnail image
-i         Identify files without decoding them
-i -v      Identify files and show metadata
-z         Change file dates to camera timestamp
-w         Use camera white balance, if possible
-a         Average the whole image for white balance
-A <x y w h> Average a grey box for white balance
-r <r g b g> Set custom white balance
+M/-M      Use/don't use an embedded color matrix
-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)
-t [0-7]   Flip image (0=none, 3=180, 5=90CCW, 6=90CW)
-o [0-6]   Output colorspace (raw, sRGB, Adobe, Wide,
           ProPhoto, XYZ, ACES)
-o <file>  Apply output ICC profile from file
-p <file>  Apply camera ICC profile from file or
           "embed"
-d         Document mode (no color, no interpolation)
-D         Document mode without scaling (totally raw)
-j         Don't stretch or rotate raw pixels
-W         Don't automatically brighten the image
-b <num>   Adjust brightness (default = 1.0)
-g <p ts>  Set custom gamma curve (default= 2.222 4.5)
-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 or "all" from each
            file
-6          Write 16-bit instead of 8-bit
-4          Linear 16-bit, same as "-6 -W -g 1 1"
-T          Write TIFF instead of PPM
```

According to [20] we used the *-H 0 clip Highlight mode* and did not apply any white balancing. Other options were *-q 3* for best interpolation quality, *-o 6* to output to ACES color space, and *-4 -T* as Linear 16-bit TIFF images.

```
dcraw –H 0 –o 6 –q3 –4 –T
```

6) ACES rawtoaces 0.1.0 [21]

"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]" [21]. Accordingly to the documentation it can be installed on Linux (Ubunto, Redhat) and MacOSX.

Rawtoaces is a command line tool and handles the conversion to ACES in two ways:

(1) The images are generated using *libraw* by calculating an Image Device Transform (IDT) based on the camera's sensitivity and light source. Currently available at the library are the following cameras:

arri / d21
canon / eos 5d mark ii
canon / powershot s90
canon / xti
nikon / d200
nikon / d5100
nikon / d7000
nikon / d700
nikon / d70
sony / ilce-7rm2
sony / ilce-7sm2

(2) With the other method the images are generated using *libraw* by calculating an RGB to XYZ matrix using information included in *libraw* and metadata found in the RAW file.

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 [21] 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 --wb-method 0 --mat-method 1 file.raw"

— *mat-method 2*

The documentation [21] 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 [21] 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 input.raw"

Although the recordings were done with a Canon EOS 5D Mark III which is not enlisted in the valid cameras section, we used as a test —*mat-method 0* by applying the Canon EOS 5D Mark II spectral data to our Canon EOS 5D Mark III recordings. The results are displayed in the Appendix section as well

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 9* 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. For further research we will generate a camera characterization for the Canon EOS 5D Mark III camera and evaluate the recordings described in this paper using its spectral sensitivity.
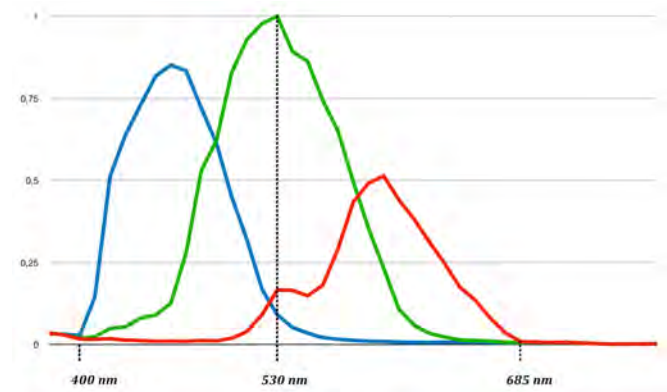
Figure 9. *Spectral sensitivity of the Canon EOS 5D Mark II camera [22]*

5. Discussing the results

In this section we are comparing the ColorChecker patch positions of the spectral recordings with the converted RAW recordings. We provide the used 3x3 white balance matrix and a table with the deviations in the CIE xy chromaticity diagram. The values were 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 values are then added to generate the overall deviation. Only simple deviation calculations are applied.

5.1. Adobe Photoshop CC2017 – CameraRaw 9.10.1

We start with the widely used *Photoshop* application and the results of the conversion retrieved by the included *RAW Converter*. We used white balancing to match the white patch 19 (#d1) to the CIE D65 Illuminant. The matrix is given in *formula 3*.

$$\begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 1.0236 & 0 & 0 \\ 0 & 1.0240 & 0 \\ 0 & 0 & 1.0259 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} \quad (3)$$

Formula 3. *CIE XYZ recorded to CIE D65 simple scaling*

The problem with the converter settings is that only verbal descriptions (Adobe Standard, Camera Neutral, Landscape) are provided, which do not represent any physical quantities. Consequently the deviation is very high (0.920) for *Adobe* Standard and higher (1.2913) for *Camera Neutral*. The patches have offsets to the spectral position that do not follow any pattern. Noticeable deviations appear above all in the patches #b3-moderate red (x 0.0789), #b5-yellow green (y 0.0683), #b2-puplish blue (y 0.0541), #a2-light skin (x 0.0533), and c#5-magenta (x 0.0519).

There may be ways to get closer to the spectral positions, but because the aim of this paper is a practical workflow and ease of use is one main factor in the criteria, we leave it as is. Another drawback is the integer file format, which makes it impossible to transfer high dynamic range content propperly.

Figure 10. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram for Adobe Photoshop in comparison to the spectral data positions (hollow)*

	x	y	Σ
Adobe Standard	0.5201	0.4419	0.9620
Camera Neutral	0.7596	0.5317	1.2913

Table 1. *Differences between spectral data and color space conversion for Adobe Photoshop/CameraRaw*

5.2. Serif Affinity Photo 1.6.6

Affinity Photo calculates the white balance evidently using the meta data and generates an image whose white patch (#d1) inhabits the proper CIE D65 position, so no additional white balance matrix was applied.

The conversion produces a very low deviation of 0.3124 – the best in the test. The positions of the calculated patches are convincing. Only three patches (#a3-blue sky – y 0.0212, #a4-foliage – y 0.0220, and #b3 – x 0.0215) exhibit mediocre deviations. Due to the fact that the output is a 32 bit floating point OpenEXR file, the converter is future proofed and can be inserted in a high dynamic media pipeline. One drawback is the automated character of the conversion process, so certain parameters cannot be accessed – in comparison to *dcraw* and *rawtoaces*.
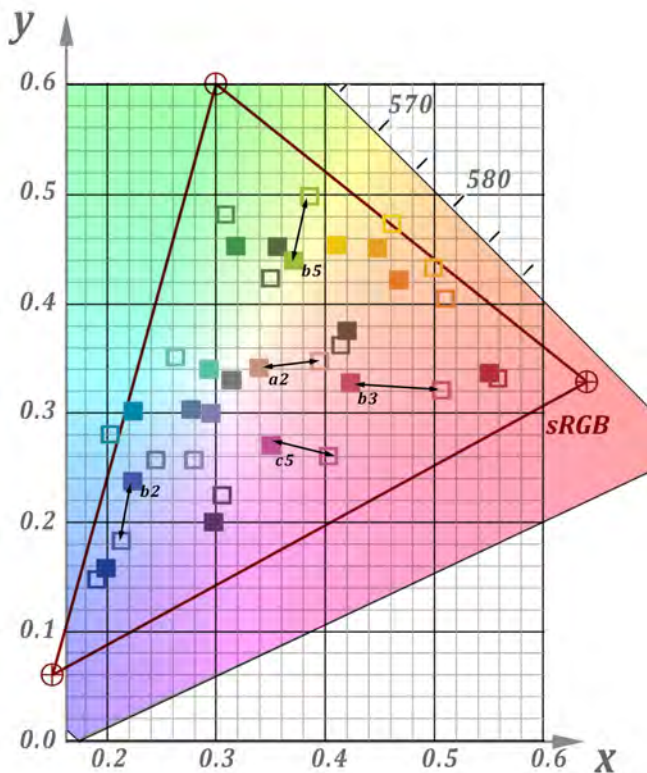
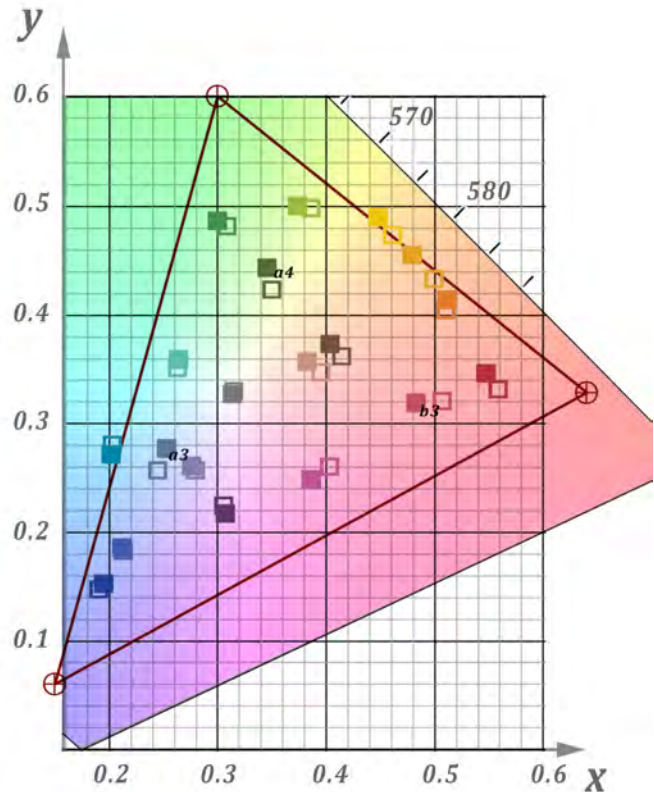**Figure 11**. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram for Affinity Photo in comparison to the spectral data positions (hollow)*

	x	y	Σ
Deviations	0.1417	0.1653	0.3124

5.3. Blackmagic Design – DaVinci Resolve 14.2

Blackmagic Design's *DaVinci Resolve* version 14.2 offers the possibility to choose *ACEScc* as the working color space additionally to its proprietary *DaVinci YRGB* colorspace. This ACES color space offers "a logarithmic encoding of ACES data intended for use in color grading systems whose controls expect a log relationship to relative scene exposures for proper operation" [15]. Using this colorspace *In- and Output Transform Devices* are available.

Interestingly there is an option for a Canon 5D IDT which is not part of the ACES IDTs found in OCIO. We used this IDT and converted the RAW image to ACEScg. The output colors are high dynamic due to the floating point interface. After conversion the ColorChecker patch #d1 has the following values: [RGB = 1.64228, 1.64991, 1.58191]. To correct this, the white balance matrix is the following.

$$
\begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 0.6153 & 0 & 0 \\ 0 & 0.6112 & 0 \\ 0 & 0 & 0.6300 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix}
$$

Formula 4. *CIE XYZ recorded to CIE D65 simple scaling*
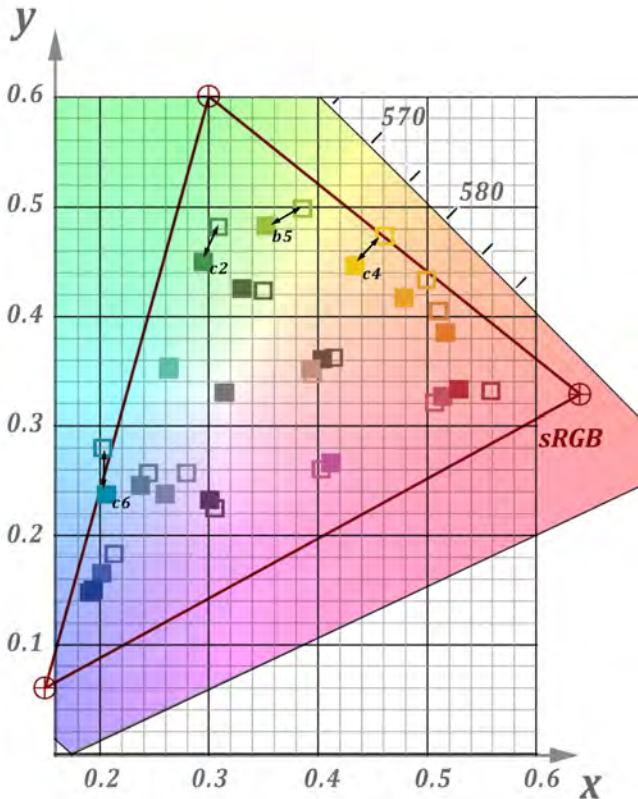
Figure 12. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram for Blackmagic Design DaVinci Resolve in comparison to the spectral data positions (hollow)*

The conversion process generates a deviation of 0.4603, which is mediocre in comparison to the other test examples.

Especially patches in the green/yellow range are somewhat off whereas the blue tones are closer than in the other tests. Patches with higher deviations are #c6-cyan – y 0.0428, #c2-green – y 0.0317 and #b5-yellow green – x 0.0316.

Furthermore there are six other patches with a deviation larger than 0.02, noticeable #c4-yellow. Although the offsets may be tolerable, the implementation of this conversion process into a color pipeline depends on the overall quality settings. For higher standards this conversion may not meet the demands.

	x	y	∑
Deviations	0.2069	0.2534	0.4603

Table 3. *Differences between spectral data and color space conversion for Blackmagic Design DaVinciResolve*

5.4. Iridient Developer 3.2.1

Iridient Developer performs a white balance to CIE D65, so no additional conversion matrix was applied. The converted imagery has a deviation of 0.4169, which is compared to conversions with ACES IDTs for other cameras (see section 6) a good result. The offsets are spread out moderately and compared to DaVinci Resolve – with a deviation also in the 0.4 to 0.5 range – more homogeneous. This are demonstrated by the fact that none of the six patches with a deviation larger than 0.02 does exceed the 0.03 threshold. The patches with the largest offsets are: #b5-yellow green – y 0,0298 and #b3-moderate red – x 0.0272.
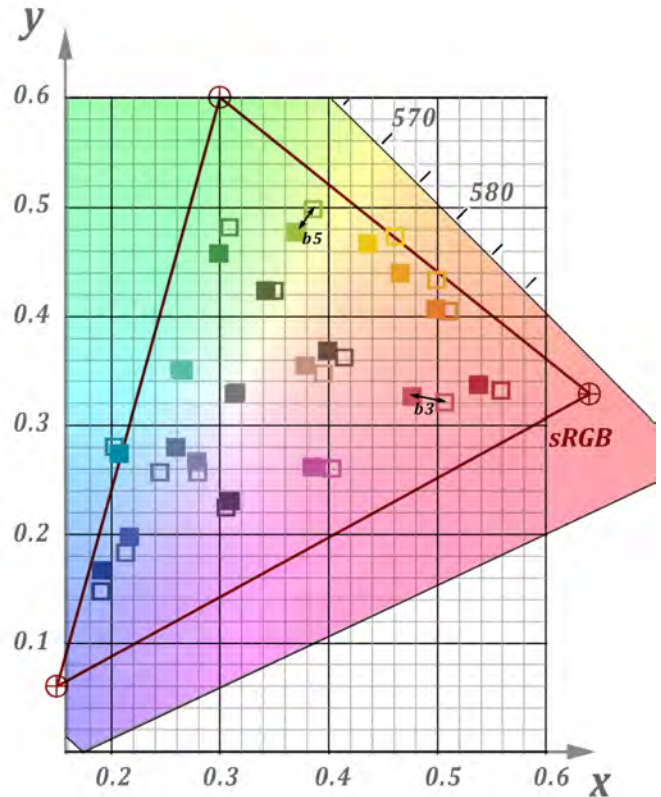
Figure 13. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram for Iridient Developer 3.2.1in comparison to the spectral data positions (hollow)*

One drawback is the export as 16 Bit Integer TIFF file format only, which does not handle highlight protection properly.

	x	y	Σ
Deviations	0.2369	0.1753	0.4159

Table 4. *Differences between spectral data and color space conversion for Iridient Developer*

5.5. dcraw v9.27

The Command line based *dcraw* delivers a conversion result with a slight offset in white balancing, which was corrected with the following matrix.

$$\begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 1.003 & 0 & 0 \\ 0 & 1.008 & 0 \\ 0 & 0 & 1.000 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix}$$

**Formula 5.** *CIE XYZ recorded to CIE D65 simple scaling*

The conversion result is comparable to Affinity Photo. The overall deviation is 0.0318 with a very good spacing. Nearly all patches are touching the positions of the spectral data. The appearance is homogenous with only three patches slightly off: #a3-blue sky – y 0.0301, #a4-foliage – y 0.0272, #c4-yellow – y 0.0205. All other patches have an offset below 0.02.

Figure 14. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram dcraw in comparison to the spectral data positions (hollow)*

The conversion process offers a lot of attributes to further refine the result, an option that is not available within Affinity Photo. But the strongest drawback is, that the export is 16 bit TIFF only, which makes it difficult to meet the needs of a high dynamic color pipeline.

	x	y	Σ
Deviations	0.0997	0.2183	0.3180

Table 5. *Differences between spectral data and color space conversion for dcraw*

5.6. rawtoaceas 0.1.0

Rawtoaces delivers a very bright image, which had to be brought down considerably. This may be due to the fact that in the high dynamic film color pipeline the reference value is a 0.18% grey. We used the following matrix to correct for this:

$$\begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} = \begin{bmatrix} 0.1673 & 0 & 0 \\ 0 & 0.1707 & 0 \\ 0 & 0 & 0.1485 \end{bmatrix} \begin{bmatrix} X_{rec} \\ Y_{rec} \\ Z_{rec} \end{bmatrix} ($$

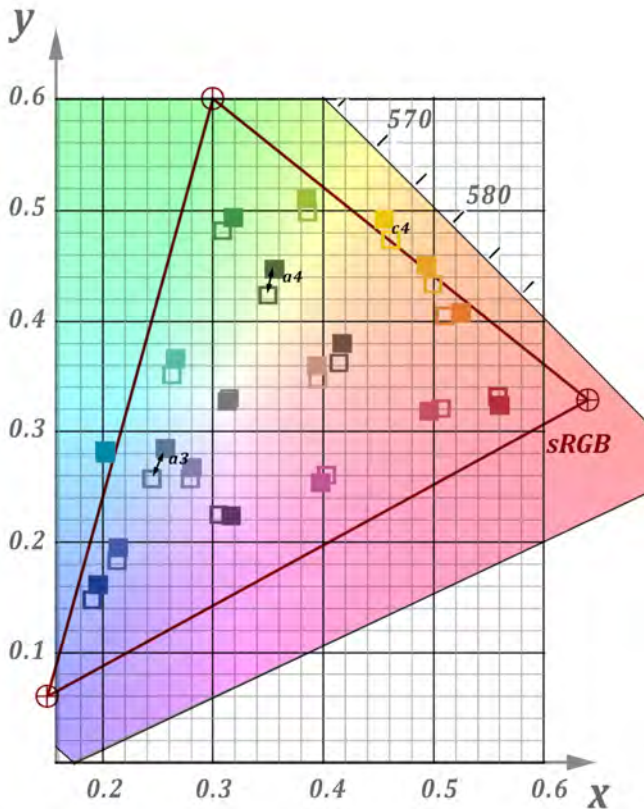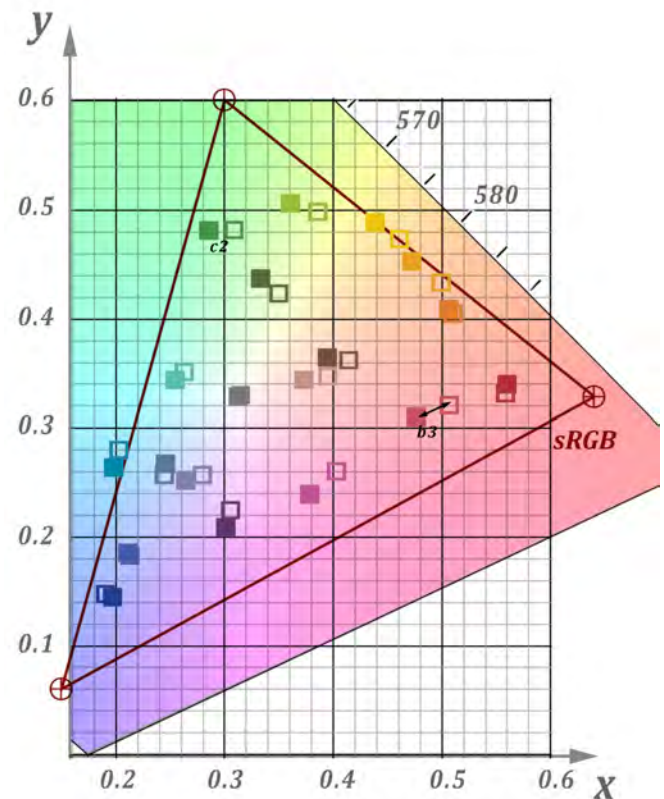**Formula 6.** *CIE XYZ recorded to CIE D65 simple scaling*

Figure 15. *Positions of the ColorChecker patches (solid) in the CIE xy-chromaticity diagram rawtoaces in comparison to the spectral data positions (hollow)*

The deviation for the –mat-method 1 we used, is around 0.4, which is comparable to *Iridient Developer* and *DaVinci Resolve*. There are six patches with offsets between 0.02 and 0.03 for one

axis, but none higher than 0,03. Two patches have a deviation larger than 0.025: #b3-moderate red – x 0.0274, #c2-green – x 0.0259. The overall deviation spacing is better than the two conversion tools mentioned above. It is interesting that in comparison to *dcraw* the offsets in *rawtoaces* are more in the x-direction (horizontally) (6/7) whereas in *dcraw* all patches with offsets larger than 0,02 are in the y-direction (vertically).

	x	y	∑
Deviations	0.2516	0.1566	0.4082

Table 6. Differences between spectral data and color space conversion for rawtoaces

One aspect should be mentioned that makes this conversion tool the most interesting in the test. Beside the ability to put out 32 bit floating point files and the lot of options derived obviously from *dcraw*, the most interesting concept is the ability to use spectral sensitivity data to calculate the conversions. This data can be custom created and inserted into the library and makes it possible to generate camera characterizations to derive spectral sensitivity data not only for the camera but also for the range of lenses that will be used in production along with the camera.

To underline this concept we applied data for the Canon EOS Mark II found in the *rawtoaces* library to the Mark III model. This did not offer convincing results because the chip design is evidently different and produces a significant larger deviation (see *table 7)* than the *–mat-method 1* we used here for comparison, but for further improvement this an interesting concept that we will research in the future.

Deviations for mat-method	x	y	∑
0	0.4436	0.3385	0.7821
1	0.2516	0.1566	0.4082
2	0.2527	0.1645	0.4172

Table 7. Differences between spectral data and color space conversion for the different –mat-methods in rawtoaces

8. Summary and conclusion

The results of the investigation show that it is possible to use the mobile spectrometer to derive data with sufficient quality. One drawback is the time it took to capture the different patches of the Macbeth chart. Here some improvement could help to be used within a robust recording environment (f. i. a film set). The divide between the capabilities of the converters in this test is the capacity to export 32 bit floating point images which makes it possible to include the converter into a high dynamic range media pipeline. Only three converters (*Affinity Photo, BlackmagicDesign DaVinci Resolve, rawtoaces*) are offering this feature. The three converters have different characteristics in color conversion, so it may be useful to compare the results in an RGB color space before the final decision, which converter to use. For future development the *rawtoaces* converter may be a good choice because of the many options it offers, the capability to use camera spectral sensitivity data and a good highlight protection.

In comparison with RED IDTs we researched in [23], the conversion process from RAW to ACES delivered less deviation than the RED ACES IDTs (see *table 8*). In figure 16 two images of the recorded ColorChecker under the same lighting conditions are displayed, the first is the conversion from Canon 5D raw photography using the *rawtoaces* converter, the second a conversion from RED footage using the ACES IDT for REDWideGamutRGB. The image colors are relatively close to each other with some differences in red colors but they can be used together inside a high dynamic pipeline, which proofs, that the usage of ACES IDTs is big leap forward towards a unified color pipeline.

Deviations	x	y	∑
RedWideGamutRGB	0.2086	0.3327	**0.5412**
RedColor41	0.2989	0.2364	**0.5353**
RedDragoncolor22	0.2455	0.2167	**0.4622**
Rec2020	0.2729	0.3140	**0.5869**
			[23]
Adobe Photoshop	0.5201	0.4419	**0.9620**
Affinity Photo	0.1417	0.1653	**0.3124**
Blackmagic Design DaVinci Resolve	0.2069	0.2534	**0.4603**
Iridient Developer	0.2369	0.1753	**0.4159**
dcraw	0.0997	0.2183	**0.3180**
rawtoaces	0.2516	0.1566	**0.4082**

Table 8. Deviations between spectral data and color space conversion for RED ACES IDTs and raw converters

Figure 16. Recordings of a ColorChecker under the same lighting conditions. Top: rawtoaces, bottom: REDWideGamutRGB

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Author Biographies

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).

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Appendix A - Calculation Results

	Photoshop			Affinity Photo			DaVinci Resolve			Iridient Developer			dcraw	
Patch	x	y		x	y		x	y		x	y		x	y
a 1	0.4118	0.3616		0.4206	0.3758		0.4043	0.3612		0.3989	0.3689		0.4167	0.3759
a 2	0.3930	0.3513		0.3397	0.3415		0.3937	0.3517		0.3784	0.3550		0.3942	0.3612
a 3	0.2421	0.2561		0.2773	0.3036		0.2373	0.2461		0.2554	0.2798		0.2568	0.2862
a 4	0.3484	0.4224		0.3568	0.4526		0.3304	0.4258		0.3421	0.4240		0.3553	0.4496
a 5	0.2766	0.2561		0.2955	0.2997		0.2595	0.2388		0.2777	0.2671		0.2819	0.2695
a 6	0.2605	0.3503		0.2938	0.3397		0.2620	0.3541		0.2663	0.3503		0.2684	0.3682
b 1	0.5176	0.4028		0.4677	0.4245		0.5167	0.3806		0.4979	0.4072		0.5236	0.4101
b 2	0.2105	0.1832		0.2436	0.2373		0.2012	0.1657		0.2164	0.1982		0.2144	0.1962
b 3	0.5039	0.3193		0.4250	0.3278		0.5138	0.3265		0.4767	0.3268		0.4948	0.3201
b 4	0.3064	0.2252		0.2980	0.1999		0.3012	0.2323		0.3096	0.2308		0.3168	0.2254
b 5	0.3835	0.5073		0.3711	0.4390		0.3519	0.4832		0.3670	0.4775		0.3846	0.5124
b 6	0.4924	0.4384		0.4483	0.4506		0.4792	0.4107		0.4660	0.4398		0.4922	0.4526
c 1	0.1877	0.1481		0.1900	0.1584		0.1938	0.1503		0.1992	0.1675		0.1960	0.1631
c 2	0.3115	0.4815		0.3180	0.4538		0.2946	0.4498		0.2986	0.4564		0.3062	0.4954
c 3	0.5557	0.3311		0.5505	0.3365		0.5289	0.3324		0.5369	0.3363		0.5592	0.3248
c 4	0.4587	0.4739		0.4103	0.4544		0.4334	0.4461		0.4357	0.4660		0.4534	0.4944
c 5	0.4028	0.2603		0.3509	0.2706		0.4115	0.2658		0.3855	0.2618		0.3986	0.2548
c 6	0.2036	0.2800		0.2239	0.3019		0.2061	0.2372		0.2068	0.2739		0.2021	0.2836
d 1	0.3127	0.3289		0.3135	0.3298		0.3136	0.3299		0.3127	0.3290		0.3127	0.3290

Table 9 Positions of the Macbeth color patches in the CIE xy-chromaticity diagram for the spectral data and the conversions

	rawtoaces									Spectral data converted to D65		
	- - mat-method 1			- - mat-method 2			- - mat-method 0					
Patch	x	y		x	y		x	y		x	y	
a 1	0.3953	0.3653		0.3950	0.3652		0.3881	0.3771		0.4118	0.3616	
a 2	0.3732	0.3481		0.3730	0.3484		0.3694	0.3611		0.3930	0.3513	
a 3	0.2459	0.2675		0.2461	0.2766		0.2665	0.2838		0.2421	0.2561	
a 4	0.3335	0.4376		0.3335	0.4376		0.3420	0.4262		0.3484	0.4224	
a 5	0.2690	0.2516		0.2690	0.2516		0.2834	0.2737		0.2766	0.2561	
a 6	0.2541	0.3491		0.2541	0.3491		0.2763	0.3473		0.2605	0.3503	
b 1	0.5058	0.4090		0.5058	0.4090		0.4848	0.4268		0.5176	0.4028	
b 2	0.2114	0.1807		0.2114	0.1808		0.2365	0.2137		0.2105	0.1832	
b 3	0.4765	0.3095		0.4759	0.3097		0.4511	0.3428		0.5039	0.3193	
b 4	0.3021	0.2089		0.3021	0.2089		0.3071	0.2440		0.3064	0.2252	
b 5	0.3612	0.5072		0.3612	0.5074		0.3672	0.4849		0.3835	0.5073	
b 6	0.4723	0.4529		0.4726	0.4530		0.4556	0.4576		0.4924	0.4384	
c 1	0.1969	0.1499		0.1968	0.1496		0.2241	0.1885		0.1877	0.1481	
c 2	0.2856	0.4814		0.2856	0.4815		0.3065	0.4538		0.3115	0.4815	
c 3	0.5449	0.3176		0.5447	0.3177		0.5097	0.3578		0.5557	0.3311	
c 4	0.4386	0.4890		0.4386	0.4890		0.4292	0.4816		0.4587	0.4739	
c 5	0.3788	0.2391		0.3789	0.2392		0.3691	0.2756		0.4028	0.2603	
c 6	0.1979	0.2638		0.1978	0.2638		0.2300	0.2757		0.2036	0.2800	
d 1	0.3128	0.3290		0.3128	0.3290		0.3132	0.3295		0.3127	0.3289	

Table 10 Positions of the Macbeth color patches in the CIE xy-chromaticity diagram for the rawtoaces conversions

	Photoshop			Affinity Photo			DaVinci Resolve			Iridient Developer			dcraw		
Patch	x	y		x	y		x	y		x	y		x	y	
a 1	0.0088	0.0142		0.0076	0.0120		0.0075	0.0004		0.0129	0.0073		0.0049	0.0143	
a 2	0.0533	0.0098		0.0104	0.0064		0.0007	0.0004		0.0146	0.0037		0.0012	0.0099	
a 3	0.0352	0.0475		0.0102	0.0212		0.0048	0.0100		0.0133	0.0237		0.0147	0.0301	
a 4	0.0084	0.0302		0.0028	0.0220		0.0180	0.0034		0.0063	0.0016		0.0069	0.0272	
a 5	0.0189	0.0436		0.0013	0.0048		0.0171	0.0173		0.0011	0.0110		0.0053	0.0134	
a 6	0.0333	0.0106		0.0032	0.0091		0.0015	0.0038		0.0058	0.0000		0.0079	0.0179	
b 1	0.0499	0.0217		0.0068	0.0111		0.0009	0.0222		0.0197	0.0044		0.0060	0.0073	
b 2	0.0331	0.0541		0.0014	0.0028		0.0093	0.0175		0.0059	0.0150		0.0039	0.0130	
b 3	0.0789	0.0085		0.0215	0.0001		0.0099	0.0072		0.0272	0.0075		0.0091	0.0008	
b 4	0.0084	0.0253		0.0018	0.0076		0.0052	0.0071		0.0032	0.0056		0.0104	0.0002	
b 5	0.0124	0.0683		0.0098	0.0017		0.0316	0.0241		0.0165	0.0298		0.0011	0.0051	
b 6	0.0441	0.0122		0.0134	0.0173		0.0132	0.0277		0.0264	0.0014		0.0002	0.0142	
c 1	0.0023	0.0103		0.0069	0.0043		0.0061	0.0022		0.0115	0.0194		0.0083	0.0150	
c 2	0.0065	0.0277		0.0118	0.0054		0.0169	0.0317		0.0129	0.0251		0.0053	0.0139	
c 3	0.0052	0.0054		0.0081	0.0043		0.0268	0.0013		0.0188	0.0052		0.0035	0.0063	
c 4	0.0484	0.0195		0.0114	0.0159		0.0253	0.0278		0.0230	0.0079		0.0053	0.0205	
c 5	0.0519	0.0103		0.0161	0.0115		0.0087	0.0055		0.0173	0.0015		0.0042	0.0055	
c 6	0.0203	0.0219		0.0020	0.0071		0.0025	0.0428		0.0032	0.0061		0.0015	0.0036	
d 1	0.0008	0.0009		0.0006	0.0007		0.0009	0.0010		0.0000	0.0001		0.0000	0.0001	
Sum x. y	0.5201	0.4419		0.1471	0.1653		0.2069	0.2534		0.2396	0.1763		0.0997	0.2183	
Overall	0.9620			0.3124			0.4603			0.4159			0.3180		

Table 11 Differences between the position of the color space conversions and the positions of spectral data for the individual Macbeth color chart patches

	rawtoaces								
	- - mat-method 1			- - mat-method 2			- - mat-method 0		
Patch	x	y		x	y		x	y	
a 1	0.0165	0.0037		0.0168	0.0036		0.0237	0.0155	
a 2	0.0198	0.0032		0.0200	0.0029		0.0236	0.0098	
a 3	0.0038	0.0114		0.0040	0.0205		0.0244	0.0277	
a 4	0.0149	0.0152		0.0149	0.0152		0.0064	0.0038	
a 5	0.0076	0.0045		0.0076	0.0045		0.0068	0.0176	
a 6	0.0064	0.0012		0.0064	0.0012		0.0158	0.0030	
b 1	0.0118	0.0062		0.0118	0.0062		0.0328	0.0240	
b 2	0.0009	0.0025		0.0009	0.0024		0.0260	0.0305	
b 3	0.0274	0.0098		0.0280	0.0096		0.0528	0.0235	
b 4	0.0043	0.0163		0.0043	0.0163		0.0007	0.0188	
b 5	0.0223	0.0001		0.0223	0.0001		0.0163	0.0224	
b 6	0.0201	0.0145		0.0198	0.0146		0.0368	0.0192	
c 1	0.0092	0.0018		0.0091	0.0015		0.0364	0.0404	
c 2	0.0259	0.0001		0.0259	0.0000		0.0050	0.0277	
c 3	0.0108	0.0135		0.0110	0.0134		0.0460	0.0267	
c 4	0.0201	0.0151		0.0201	0.0151		0.0295	0.0077	
c 5	0.0240	0.0212		0.0239	0.0211		0.0337	0.0153	
c 6	0.0057	0.0162		0.0058	0.0162		0.0264	0.0043	
d 1	0.0001	0.0001		0.0001	0.0001		0.0005	0.0006	
Sum x. y	0.2516	0.1566		0.2527	0.1645		0.4436	0.3385	
Overall	0.4082			0.4172			0.7821		

Table 12 Differences between the position of the rawtoaces color space conversions and the positions of the spectral data for the individual Macbeth color chart patches