

Color Rendering Analysis in Nikon D90 Digital Still Camera

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Abstract

The convenient use of digital cameras along with the affordable prices and high image quality allows using them in many fields. The quality of the digital image reproduction would differ based on the camera hardware performance and the applied image color processing. This paper will focus on evaluating the variances of color rendering process of raw image data between in-camera Nikon D90 processing and Adobe Camera Raw (ACR) deferred processing of a Color Checker[®] target image through colorimetric analysis. Results from Color Checker analyses were used as reference data in attempt to reverse-engineer D90 color reproduction with adjustment tools available to ACR processing. ACR processing experiments referred to color measurements and Exchangeable Image File format (Exif) metadata to ultimately reduce average color differences between ACR and D90 processing from $8\Delta E^*_{ab}$ to nearly $2.5\Delta E^*_{ab}$ developing more consistent reproduction between the workflows. This analysis provides digital photo reproduction insights for premedia technicians, photographers, and color scientists.

Keywords: digital camera, color image processing, raw, Adobe Camera Raw, Nikon D90, in-camera processing

1. Introduction

The outcome of digital photography is affected by many complex factors including optical and mechanical conditions during scene capture, electronic color image processing, and final viewing situation (Adams J.*et.al.*, 1998, Guntruk *et.al.*, 2005, Toader, 2013 and Fraser, 2004). A digital camera may capture scenes as standard output-referred data (e.g. D90 JPEG capture), or as raw digital still camera (DSC) data or scene-referred data for deferred image rendering through raw converting applications (e.g. Adobe Camera Raw [ACR]) (Toader, 2013, Fraser, 2004 and Holm *et.al.*, 2002). Additionally, digital photo editors may apply a variety of color transformations using ICC profiles (ICC, 2005 and Green, 2010) and use of Digital Negative (DNG) Camera Profiles (DCP) for raw image processing is also available (Holm *et.al.*, 2002 and Schewe, 2012). Variability between imaging devices and workflow options create challenges for color managing digital photography processes where image states, input, and output device characteristics should be defined and references between “accurate” scene colorimetry and perceptual color appearance should be understood (Toader, 2013, ICC, 2005 and Green, 2010).

Generally, when a digital camera captures in “JPEG mode” its internal image processor produces what the manufacturer designed to be “aesthetically pleasing color” for lossy standard output-referred color space encoding; when a digital camera captures in “RAW mode”, it creates lossless, un-rendered raw data (often as a proprietary image format) for deferred processing with raw converting applications (Fraser, 2004, Schewe, 2012 and Adams R. *et.al.*, 2008). Since there is an economic need for manufacturers to differentiate their products, color reproduction outcome for imaging processors and their various settings can be expected to differ, causing ambiguity and inconsistency for digital color descriptions between workflows (Toader, 2013).

1.1. Digital photography pipeline

The color correction pipeline that influences overall perceived image quality is composed of two modules: illuminant estimation and correction, and color matrix transformation into a standard color space (Bianco *et.al.* 2013 and Ramanath *et.al.* 2005).

ICC defines the scene-to-reproduction perceptual transformation as a “*coordinated combination of color appearance adaptation, preference adjustments, and gamut mapping*” (Green, 2010 and Bianco *et.al.*, 2013). Although color encoding is an unambiguous and standardized process, the gamut-mapping outcome of a perceptual color rendering transformation of the adopted white and adapted scene colorimetry is influenced by reproduction constraints and color preferences (Green, 2010).

In some cases, it is preferred to apply scene- and output medium-specific color renderings, where color space encodings are chosen according to color gamut of the anticipated destination media. In these instances it is necessary to communicate color spaces, image states (as defined in ISO 20028-1) (Green, 2010), reference medium, and viewing conditions in order to correctly reproduce the image appearance. ICC source profiles can be created using standard output-referred data or unrendered and white balanced scene-referred data to communicate “device-state” and “image-state” dependent information about how the graphic to be displayed, processed or printed (ICC, 2005 and Green, 2010).

This paper analyzed the differences between digital photography workflows for a Nikon D90 digital single-lens reflex camera, which uses a proprietary (EXPEED) image/video processor with 90-nanometer complementary metal-oxide-semiconductor (CMOS) sensor technology. The goals of this study were to describe the color reproduction of a Color Checker test target capture through each workflow, to identify variance in digital color descriptions, investigate causes for differences between processing methods, and develop a simulation of D90 processing in Adobe Camera Raw. CIE- and RGB-based metrics were used to investigate color difference between a) D90 camera-processed and ACR-processed images and b) ACR processing with DNG profiles and adjusted ACR settings.

2. Experimental Details

A Nikon D90 was affixed to a LED-lit copy stand. f-number f/5.0, shutter speed 1/30 sec and ISO 200 were selected as the capture settings. The camera was white balanced with an 18% gray card then used to photograph RAW+JPEG (fine) images of a ColorChecker[®] 24 Patch Classic target (Figure 1) in Adobe RGB and sRGB color space. Nikon raw files (NEFs) were processed using default ACR process version 2012 setting where no color adjustments tools were employed and with workflow options matching their JPEG counterparts. All Nikon D90 JPEGs and ACR NEFs were saved as uncompressed TIFF with color profile embedded then characterized with CIE L*a*b*, CIE L*C*h*, and encoded RGB metrics using Adobe Photoshop’s info palette and Babel Color Patch Tool’s extract target. The datasets were compared using color difference equations and correlation charts in Microsoft Excel, color worksheet and 2D L*a*b* diagrams in Chromix Color Think, and Exif metadata was consulted through Exif tool to interpret color differences attributed to each imaging process.



Figure 1 – ColorChecker[®] Classic target

3. Color Image Processing Evaluation

3.1. Default ACR color space comparison

CIEL*a*b* measurements from default ACR Adobe RGB, sRGB and ProPhoto RGB standard output-referred data were compared to examine color variance caused by output-referred encoding (Figure 2) from “original scene capture”.

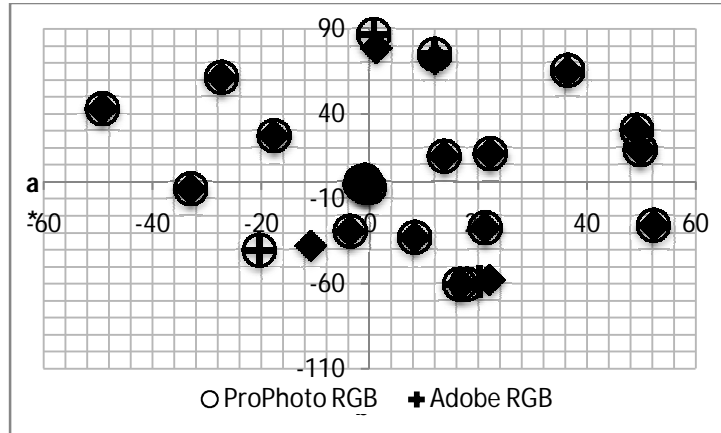


Figure 2 – ACR Process Version 2012 Color Checker chromaticity (a*b*) – Color Space Comparison

The comparisons between NEF processing with different color space encoding reported one Color Checker patch difference (blue) between ProPhoto RGB and Adobe RGB selection and four patches difference (cyan, yellow, orange yellow, blue) between Adobe RGB and sRGB. Similar patches differences were also reported between ProPhoto RGB and sRGB. Generally, NEF processing with larger color gamut space produced more chromatic a* and b* values for colors close to the edge of gamut.

3.2. D90 color space comparison

D90 standard output-referred JPEGs were compared to explore variance within camera processing. D90 only allowed one in-camera encoding per capture so D90 Adobe RGB and sRGB comparisons were evaluated between two separate captures (in contrast to the previous analyses that allowed one raw capture to compare multiple encodings).

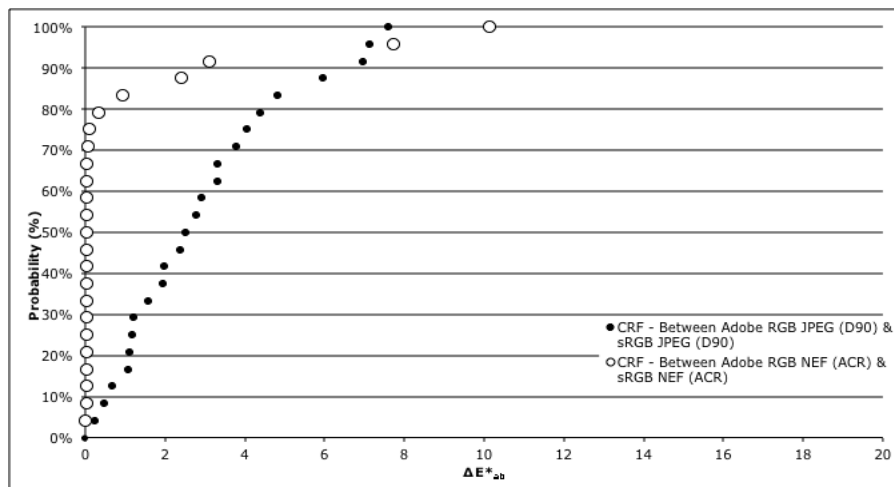


Figure 3a – Cumulative relative frequency – ΔE^*_{ab} between standard output-referred color spaces in D90 & Default ACR process 2012 output

Generally, there were more Color Checker patches with color difference between Adobe RGB JPEG and sRGB JPEG than Adobe RGB NEF and sRGB NEF (Figure 3a). In contrast to default ACR standard output-comparisons, that had color difference in only four patches, there was medium to marked ($\Delta E^*_{ab} > 2$) color difference for most of the color patches between D90 standard output-referred images. This might indicate that D90 employs two different in-camera color processing on each Adobe RGB JPEG and sRGB JPEG images.

Generally, D90 Adobe RGB produced more chromatic patches compared to sRGB (Figure 3b) and there was very close correlation between color difference (ΔE^*_{ab}) and Chroma difference (ΔC^*_{ab}) as demonstrated in Figure 3c.

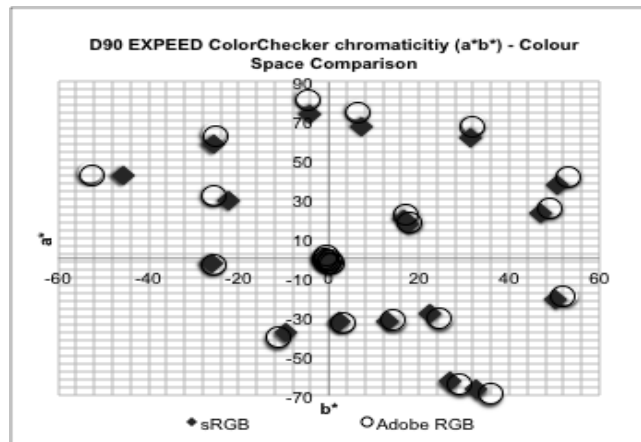


Figure 3b– D90 Color Checker chromaticity (a^*b^*) comparing output color space

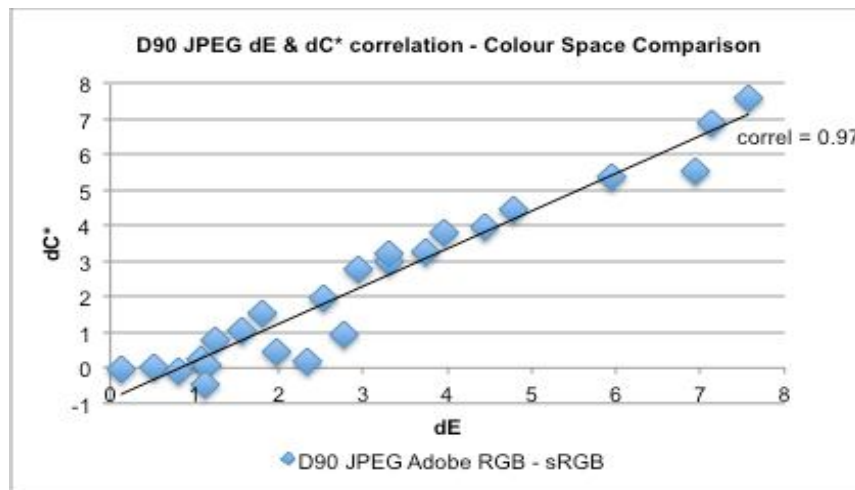


Figure 3c– ΔE^*_{ab} , ΔC^*_{ab} correlation chart comparing Adobe RGB and sRGB JPEG

3.3. D90 EXPEED and default ACR Process Version 2012 comparison

Nikon D90 JPEG and default ACR NEF image sets with same color space were compared, reporting marked color difference ($\Delta E^*_{ab} > 5$) for 20/24 of Color Checker patches in both color space comparisons with average Color Checker difference of about $8.68 \Delta E^*_{ab}$ for Adobe RGB comparison and $7.97 \Delta E^*_{ab}$ in sRGB (Figure 4a). The five colors with less than $5 \Delta E^*_{ab}$ were white, neutral 8, neutral 6.5, yellow green and orange yellow.

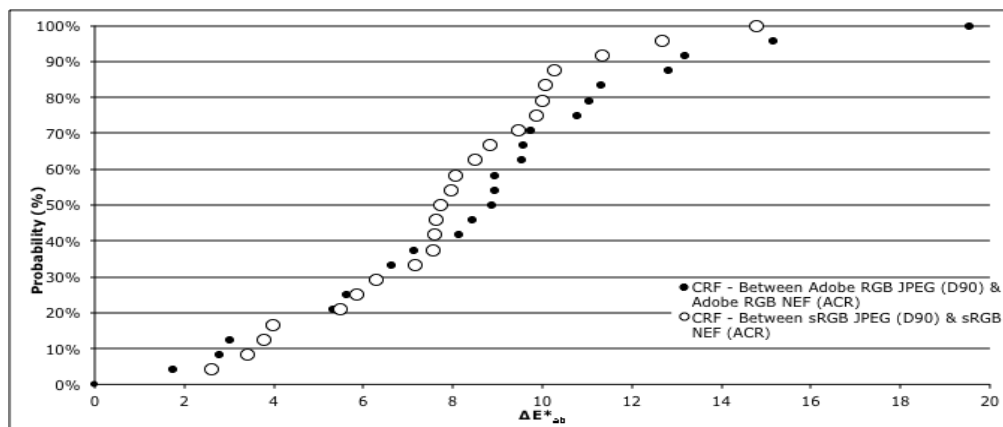


Figure 4a– Cumulative relative frequency – ΔE^*_{ab} between D90 EXPEED processor & default ACR process 2012 in different standard output color spaces

Overall and as shown in Figure 4b, default ACR NEF rendered greater L^* for the five lightest ColorChecker patches (white, yellow, neutral 8, yellow green, orange yellow) and lower L^* for all other tones compared to D90 JPEG resulting in a larger L^* range.

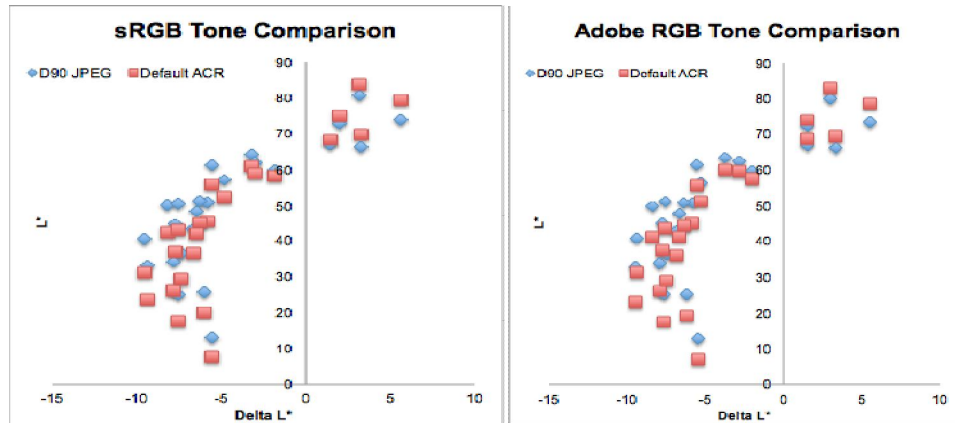


Figure 4b– L^* , ΔL^* diagrams depicted highlight and shadow compression for D90 JPEG compared to default ACR NEF, which generated lighter L^* value for the 5 lightest Color Checker patches and lower L^* values for all other colors compared to D90’s EXPEED processor.

In terms of chromaticity comparisons and specifically in Adobe RGB samples, D90 produced greater C^* green and moderate red, while ACR produced more C^* cyan, and there was nearly $0\Delta C^*_{ab}$ for orange. In sRGB, ACR produced the more C^* green, while D90 produced more C^* orange, and there was very little ΔC^*_{ab} between moderate red and cyan (Figure 4c).

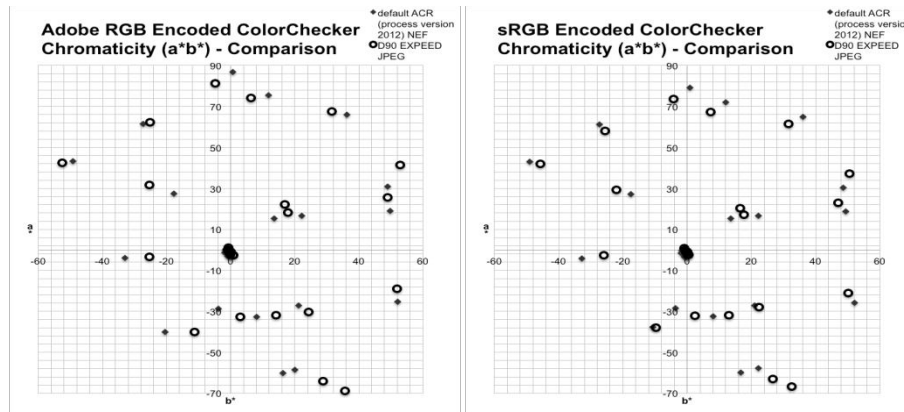


Figure 4c – Chromaticity (a^*b^*) diagrams comparing standard output-referred color space encodings between D90 EXPEED-processed JPEGs and default Camera Raw-processed NEFs.

4. Simulating D90 color reproduction using ACR

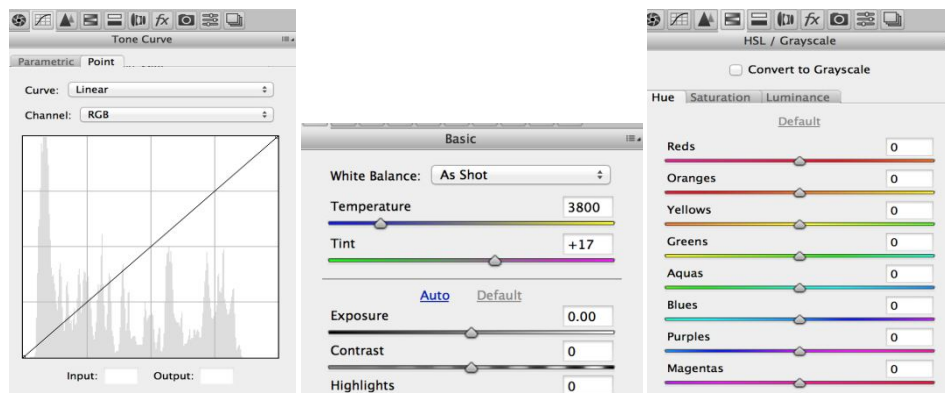


Figure 5–Adobe Camera Raw adjustment tools
(Note: the showing settings in this image dose not reflect the tested models)

A series of experiments tested ACR adjustment tools to calibrate NEF image processing to produce the intermediate color description of D90 standard output-referred patches (Figure 5). Since differences between default ACR versus D90 grayscale patches were affected more by L* lightness difference (tone scale) than a* & b* (grey balance) (Table 1), grayscale adjustments used curve and slider tools to focus on tone scaling without adversely affecting (the rest of the Color Checker’s) hue and saturation. Curve and basic tone sliders were adjusted with reference to RGB data sets, exposure slider was adjusted with reference to Exif metadata, and ACR’s white balance tool was briefly tested. Color adjustments used hue saturation and lightness panel to render specific color patch regions with reference to RGB color space values According to Schewe (Schewe, 2012), DNG Camera Profiles (DCP) can provide linear curves and modify default Camera Raw processing to better match the rendering of a camera model (Bianco *et.al.*, 2013), so Camera Raw NEF processing with DCP was also evaluated.

Table 1: Default ACR minus D90 grayscale L*a*b* difference

sRGB Grayscale Difference (Default ACR – D90)				Adobe RGB Grayscale Difference (Default ACR – D90)			
	ΔL^*	Δa^*	Δb^*		ΔL^*	Δa^*	Δb^*
White	↑ 3.77	↓ -0.09	↓ -0.16	White	↑ 3.00	↓ -0.24	↓ -0.17
Neutral 8	↑ 2.35	↓ -1.14	↑ 0.25	Neutral 8	↑ 1.55	↓ -0.80	↑ 0.07
Neutral 6.5	↓ -3.05	↓ -1.43	↓ -0.64	Neutral 6.5	↓ -3.72	↓ -1.12	↓ -0.43
Neutral 5	↓ -8.00	↓ -0.70	↓ -0.58	Neutral 5	↓ -8.37	↓ -0.84	↓ -0.35
Neutral 3.5	↓ -9.76	↓ -1.00	↓ -1.02	Neutral 3.5	↓ -9.49	↓ -0.85	↓ -0.81
Black	↓ -7.87	↓ -0.72	↓ -1.11	Black	↓ -5.47	↓ -1.01	↓ -0.71
Avg	↓ -3.76	↓ -0.84	↓ -0.54	Avg	↓ -3.75	↓ -0.81	↓ -0.40
Max	↑ 3.77	↓ -0.09	↑ 0.25	Max	↑ 3.00	↓ -0.24	↑ 0.07
Min	↓ -9.76	↓ -1.43	↓ -1.11	Min	↓ -9.49	↓ -1.12	↓ -0.81

5. Simulations Results & Analysis

5.1. Grayscale D90 Simulation – Point Tone Curves

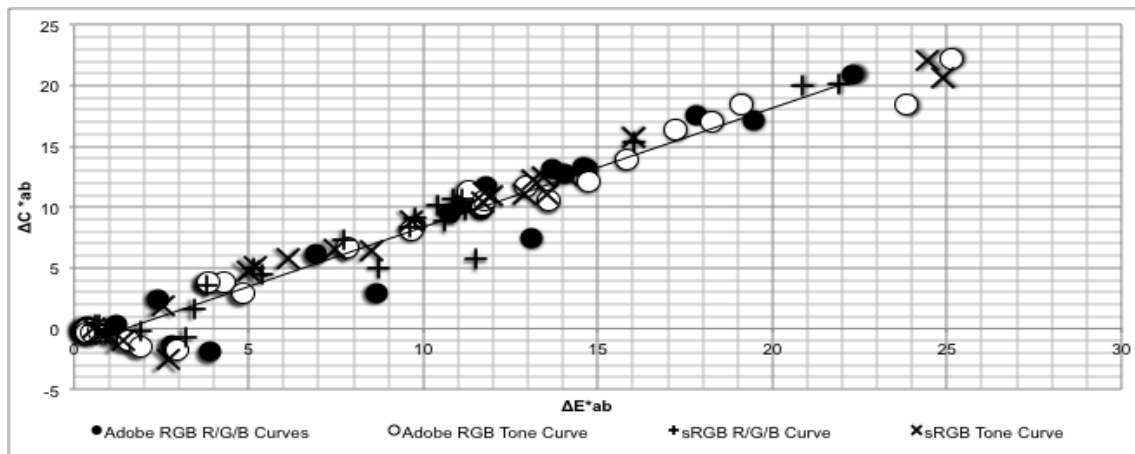


Figure 6– $\Delta E^*_{ab}, \Delta C^*_{ab}$ chart shows a strong correlation between chromaticity and color difference from D90 JPEG colorimetry after parametric tone and separated channel curves.

Overall, 6 point RGB curves or separated R/G/B curves using measured color space values reduced the maximum of ΔL^* from maximum 10 to $2.5\Delta L^*$ between D90 and ACR processing methods. However, 6 point tone curves reduced Chroma through a*b* changes for mostly 21 Color Checker patches, resulting in worsened average Color Checker difference. The resulting color difference had approximately 97% correlation to Chroma difference, suggesting that it could possibly be corrected through later color adjustments (Figure 6). The results yielded $1\Delta E^*_{ab}$ average color difference for grayscale color patches.

5.2. Grayscale D90 Simulation – Exposure +0.20

Exposure +0.2 adjustment was tested according to Exif’s exposure difference metadata. The setting improved ΔE^*_{ab} of 19 patches by boosting shadows and midtones lightness to better match D90 JPEG L* description – the only color that very slightly worsened in ΔL^* was orange in Adobe RGB, which shifted direction from having $-1.97L^*$ to $+2.05L^*$ over D90 description.

The setting worsened ΔL^* and ΔE^*_{ab} for the five lightest colors due to increased L^* values causing overblown highlights. Average grayscale color patch difference and overall average Color Checker difference improved from $5.5\Delta E^*_{ab}$ and $8\Delta E^*_{ab}$ to $5\Delta E^*_{ab}$ and $7\Delta E^*_{ab}$ respectively.

With addition of highlight and shadow adjustments, average grayscale color patch difference improved to $2\Delta E^*_{ab}$ and average Color Checker difference improved to $5\Delta E^*_{ab}$ with varying results based on color space.

5.3. Grayscale D90 Simulation – Neutral 5 R/G/B Curves

Neutral 5 R/G/B curves with basic highlight and shadow slider adjustments consistently yielded small (nearly $1\Delta E^*_{ab}$) average grayscale color difference and improved ($5\Delta E^*_{ab}$) average Color Checker difference. This adjustment setting was preferred over exposure, highlight, and shadow settings, which yielded less effective average color difference results. It was also preferred over more complex settings, which produced comparable but less consistent results due to the product of multiple adjustments and separated tone curves that may improve or worsen overall color difference through changing R/G/B levels.

5.4. Chromatic D90 Simulation



Figure 7a – sRGB JPEG



Figure 7b – sRGB NEF (custom ACR adjustments)

Figure 7– Color Checker target- Process Comparison

Chromatic color adjustments used hue, saturation and lightness adjustments to match color regions based on neutral 5 R/G/B curve settings (Figure 7). The results improved average Color Checker difference to 3.76 average ΔE^*_{ab} for sRGB and 2.91 average ΔE^*_{ab} for Adobe RGB.

Hue, saturation, lightness adjustments had limited capabilities when attempting to render specific color patch descriptions within ACR’s seven specific color regions. For example, in both color spaces, HSL blue adjustments were made according to Color Checker blue patch RGB values, since it is most representative of that color region; however, cyan and blue sky color descriptions were challenging to reproduce since their RGB mixing values were affected by conflicting Chroma direction with other colors that have been adjusted to unmarked color differences (i.e. blue and purple) (Figure 8).

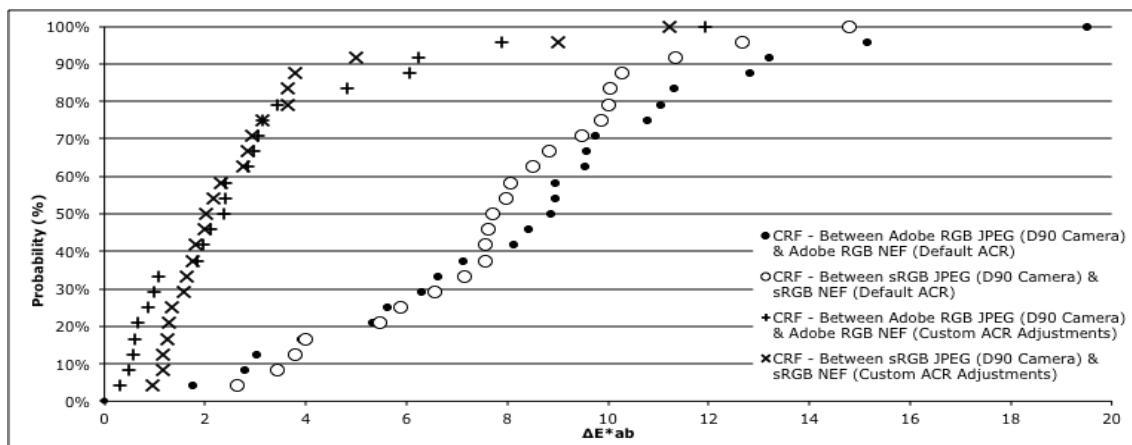


Figure 8 – Cumulative relative frequency between D90 JPEGs and ACR processing showed that ACR adjustments with separated channel curves from neutral 5 Color Checker patch and hue, saturation, lightness yielded an improved color match in both color space encodings.

6. DNG Camera Profiling

As shown in Figure 9, ACR processing with a DNG profile in sRGB shifted 17 Color Checker patches from process version 2012 rendering and shifted 18 Color Checker patches in Adobe RGB.

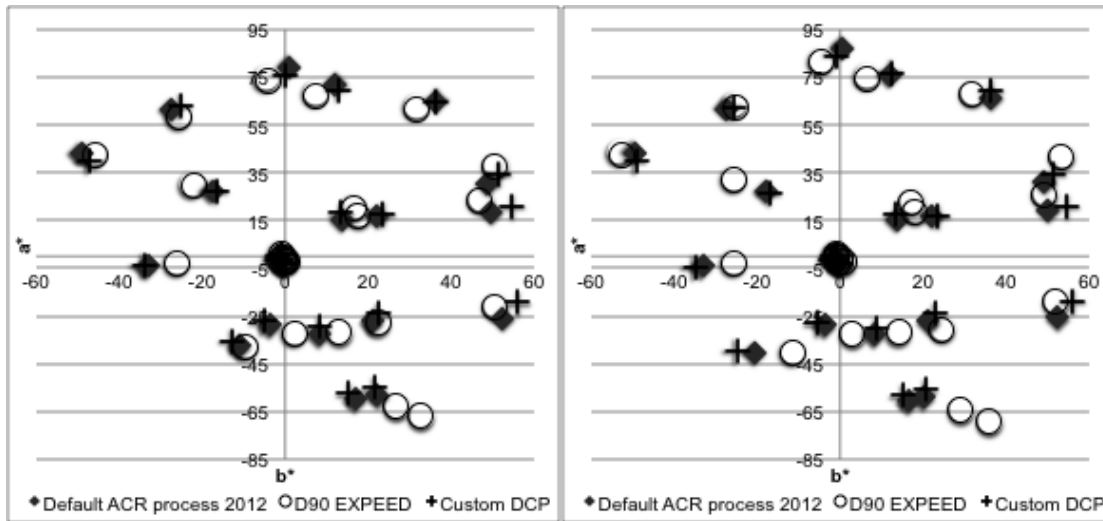


Figure 9a – sRGB

Figure 9b – Adobe RGB

Figure 9–Color Space Chromaticity (a^*b^*) – Process Comparison

The 6 grayscale patches were unaffected by DNG profile application; orange was additionally unaffected in sRGB processing. Overall DNG profile increased L^* for most colors except for bluish green, blue flower, and light skin, which were rendered with very small L^* decreases, and cyan, which was rendered with very small L^* decrease only in sRGB color space.

7. Conclusion

This research showed that D90 JPEG color image processing outcome is significantly different than ACR NEF processing for the two profiles that were examined here.

Adjusting ACR color rendering to match D90 JPEG descriptions had limitations in color mixing, particularly between cyan and blue color regions. “Some... argue that scene-to-picture color rendering should be restricted to in-camera processing and raw processing applications, and correction of color rendering deficiencies limited to image editing applications” (Green, 2010). However and based on the research results, these adjustments have reflected lower overall ΔE^*_{ab} for both tested profiles which create a response to better simulate the internal color image processing in D90 camera.

In our approach we have used the same ACR color rendering model for both sRGB and Adobe RGB profiles to match D90 JPEG processing. Where evaluation results showed that D90 uses different color rendering processing for each profile, we would like to employ two different ACR adjustments for each profile as a future investigation for better simulating the internal color rendering.

Finally, the main objective of this research is to propose an alternative approach to simulate any in-camera processing by using specific sets of ACR adjustments since, each digital camera manufacture has its own “secret sauce” for its in-camera processing and it’s difficult to extract the color rendering algorithm for such cameras.

We showed that someone doesn’t need to have a Nikon camera now to get the look and feel of its in-camera processing as they can apply our rendering model on any raw images from any camera to get the same results as they have been internally processed by Nikon. For instant, suppose that someone was shooting wedding using Nikon digital camera and get the first 50 images to be internally processed and somehow the camera setting changed to NEF. They can use Adobe Camera Raw and our model to make all images look same. In addition, suppose a junior photographer is attending the same wedding and he/she is having a Canon digital camera and was shooting raw images. By using our model they can get the same look and feel of the Nikon’s digital camera that has been using by the assigned wedding photographer.

8. Acknowledgment

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9. References

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