ICC Profile Creation and Modeling Errors

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Abstract

ICC profiles are a well-established part of color management. There is always interest in how large the color gamut is for a given combination of ink and paper. This color gamut affects practical factors such as how many of the Pantone colors can be simulated using CMYK combinations for a given ink and substrate combination. When converting color imagery in the RGB color space for rendition on a given CMYK device, clipping often occurs. The result of this clipping is that only a certain percentage of the original colors can be colorimetrically reproduced using CMYK combinations. It is also known that the conversion of the resulting CMYK device inking through the profile connection space (PCS) back to original RGB device space can unexpectedly result in a different color than the one that the conversion was started with. This round trip error from the A2B through $L^*a^*b^*$ to the B2A table and back is known, but it is of interest to know how big this round trip error can be. Furthermore, it is interesting to separate out the error due to the inherent modeling technique from any differences caused solely due to gamut mapping. A method of doing so is to run the round trip at least two times; to ensure that all one is measuring is the level of error caused by modeling.

These modeling errors will be demonstrated on well-known ICC-profiles. Three different methods are being evaluated and the results of these methods are shown in this paper.

When profiles are evaluated for their round-trip analysis it is important to use profiles that were made with similar conditions in regards to ink-limiting and the amount of GCR that is being applied. The gamut tag has an obvious influence on the average round-trip DE^*_{ab} error. The i1Pro profile does very well on the round-trip analysis in the far interior of the gamut, not quite as well near the surface, and likely not as well in the bottom of the gamut. The A2B →B2A →A2B round-trip analysis is heavily weighted towards sampling in the bottom of the gamut due to where the

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CMYK grid points map to. The ColorFlow (CE) profile does fairly well in most of the round-trip analysis.

Introduction

ICC profiles have been well established in the graphic arts industry for obtaining more consistent color between input and output devices. The need for ICC profiles arises from the different color spaces that are used by these devices. For example a digital camera captures an image in RGB mode, while the output on press is done in CMYK. The color gamut of CMYK is much smaller than RGB therefore it is necessary to achieve a good representation of the original on the device with the smaller gamut. The conversion from one color space to another takes place through the profile connection space which can either be CIELAB or CIEXYZ.

The conversion from one color space to another is defined through ICC profiles. ICC profiles are based D50 colorimetry. The architecture of an ICC profile allows adjustments to compensate for differences in viewing conditions and color gamut. The color transformation has two elements or stages. The first elements are the stored values of the tables, matricies and per-component curves. The second stage is the transform that takes place by extraction of data points and interpolation of data points. Errors in regards to modeling and calculation can come from the methods of modeling and the computation used in the transform and also from the measurement data that is used to generate the profile.

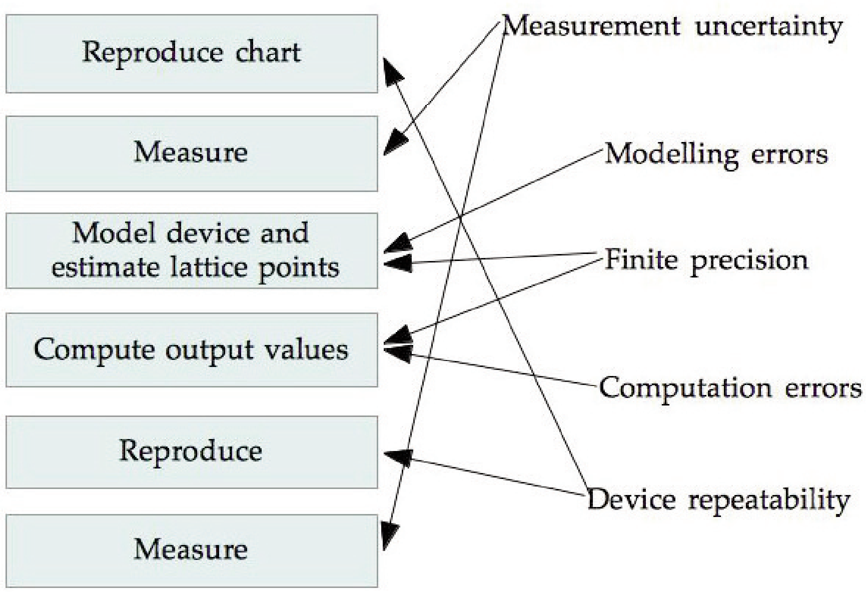

Figure 1: *Workflow for building and evaluating a color transform and possible sources of error*

In any given color reproduction workflow there are a number of possible errors. The following figure is adopted from Green (Green, 2006).

According to this chart first a test chart is printed and measured resulting in device data and their corresponding CIE values. This data is then linearized so that the generated look-up table can be used for more simple interpolation techniques. Each direction of color transform and each rendering intent require a uniform lattice in the input domain. The output values that relate to these input values are estimated. For each color the interpolation will look at surrounding lattice points from the table and calculates the output value. Possible sources of error are the repeatability of the output device, the accuracy and repeatability of the measurement device, the accuracy of the device model and the derived color transform. The accuracy at each calculating stage will also have an influence on the result.

There are four different rendering intents available that can be used in conjunction with ICC profiles. The rendering intents are as specified in ISO 15076-1:" The colorimetric rendering intents operate directly on measured colorimetric values, with correction for chromatic adaptation when the measured values were not obtained relative to the PCS adopted white chromaticity. The other rendering intents (perceptual and saturation) operate on colorimetric values which are adjusted in an as-needed fashion to account for any differences between devices, media, and viewing conditions. (ISO 15076).

An ICC profile can include a A2Bn tag for the transformation from the source color encoding to the profile connection space (PCS) and a B2An tag for the transformation from the PCS to the destination color encoding where n=0, 1 or 2 corresponding to the perceptual, media-relative/absolute colorimetric and saturation rendering intent (Zeng et al., 2009). ICC output profiles contain two sets of tags – one mapping color (profile connection space or PCS) to device coordinates, the other set mapping from device coordinates to PCS. The set mapping PCS to device coordinates are designated as "BToA" (or "B2Ax"), while the set mapping device coordinates to PCS are designated as "AToB" ("A2Bx"). The absolute colorimetric rendering intent (A2B3/B2A3) does not have its own rendering intent tables, but is a combination of the relative colorimetric rendering intent transforms with the media white point included.

What type of color transformation will be done? A forward or A2B transform maps the color data from the device to CIE values. These can be either XYZ or LAB values. The B2A or CIE to device transform uses the output values, which are device values, and translate them back into CIE values.

In proofing applications the image is first converted to the final print process using the B2A transform and is then converted back to the profile connection space with the A2B transformation "in order to convert to the proof with the B2A transform of the proofing system profile."(Green, 2006). The A2B transform can be evaluated by transforming a set of device values for which the CIE values are known (Green, 2006).

A round-trip evaluates the A2B and B2A pair by transforming a set of CIE values into device values and back to CIE values. It is necessary to repeat this process to make sure that the transformed colors are in the gamut of the output space and allow for round-off error (Green, 2006).

An output profile is used mostly in the B2A direction. If one wants to predict the output values that will correspond with input coordinates it is necessary to do a round-trip test. A round-trip test starts with a set of CIE values that are than transformed into device values and than back to CIE values using the forward transform. This test is important for proofing applications. To test just the B2A transform one can use a set of CIE values, convert them to device values, print them out on the specified device and measure them. This method includes all possible errors from device repeatability, to measurement repeatability and numerical transformation errors.

This study will look more at the mathematical errors in relation to the various transformations that are done when a round-trip is being done. The round-trip analysis (RTA) is a type of analysis frequently performed as one of the measures of the quality of an ICC profile, alongside characterization or training data colorimetric fit. The round-trip analysis involves chaining a number of ICC profile transformations in order to see how far-off the results can be.

An important fact about round-trip analysis as an analysis method is that it is only a measure of the invertability of ICC transforms. Invertability as a property is functionally important when desiring to undo a color transform. It is secondarily used as an indicator of the algorithmic quality of a profile, though this is only true for profiles where invertability is a design goal. Strictly speaking, there is no strong requirement for the rendering intent transforms to be mutually invertible in the ICC profile specification. The only comment on invertability is in an Annex suggesting that the transforms "should" as opposed to "shall" be invertible. (ISO 15076-1)

There are some valid arguments for why at least the colorimetric rendering intents ought to be intrinsically invertible, so that the combination of training data colorimetric fit plus invertability of the colorimetric rendering intents (A2B1 & B2A1) together present one facet of the profile's colorimetric quality (Another facet having to do with the profile tables' smoothness in application).

It is important to note that invertability is a property that is only meaningful for in-gamut colors. In mapping from PCS to device coordinates, there are many points which are definable in the B2A transforms' domain which lie far outside of the device's gamut. All such out-of-gamut points are mapped onto in-gamut points (on or within the gamut surface) in the process of mapping PCS to device coordinates, as by definition all device coordinates map in turn to PCS points which are in-gamut. Given such a many-to-one mapping from PCS to device coordinates for the B2A transforms, B2A transforms are inherently mathematically non-invertible. Hence, invertability metrics must be limited to in-gamut points in order to be meaningful.

Experimental & Results

In this study the round-trip errors are being calculated. In contrast to other study two round-trips are being done. During the first round-trip some colors might be outside of the gamut. If this is the case they are mapped to the surface of the gamut and the change in color will be recorded in DE.

Profiles will be generated from the same reference data using different profile generators. This will result in small changes to the overall color transformation and can be called a secondary effect.

The profiles will be evaluated using Matlab. The Matlab code used for the evaluation can be found in the appendix.

This evaluation will look at the grid of values. Three methods will be used for the round-trip analysis.

Method 1

Method 1 involves a single round trip, mapping PCS → device coordinate → PCS through a pair of transforms (B2Ax, then A2Bx). If one starts from a uniformly sampled PCS grid, transforming through the first B2Ax transform, one ends up with approximately 80-90% of the gamut volume points mapped to the gamut surface. For example, for the colour space defined by the Fogra39L characterization data set, approximately 90% of the full $L^*a^*b^*$ input space lies outside the Fogra39L gamut. The ICC profile format allows for $L^*a^*b^*$ domain of $0<L^*<100$, $-128<a^*<+127$, $-128<b^*<+127$.

Running a uniform sampling of $L^*a^*b^*$ points in the full ICC $L^*a^*b^*$ domain through the B2A →A2Bx transform pair means that over 90% of the mapped points will be gamut-mapped to the gamut surface in the first transform, with a resulting high degree of error upon completing the transform.

For example, for Fogra39L, the B2A1→A2B1 transform pair for a uniform 43x43x43 sampling of the ICC $L^*a^*b^*$ domain yields mean dE^*_{ab} = 55.8, max dE*ab = 161.0. (for FOGRA39L_CE.icc)

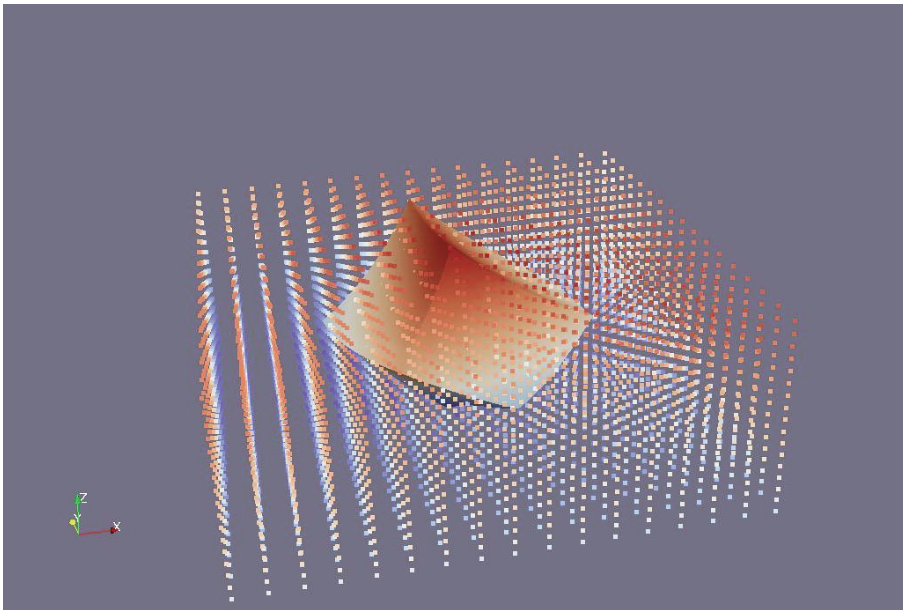

Figure 2: *Color gamut in the full $L^*a^*b^*$ domain*

For a smaller gamut colour space (ifra26L), associated with newspaper printing, the prediction is that a similar assessment would result in higher error, given the same algorithm being used to generate the ICC profile. Indeed, the results are mean dE^*_{ab} = 74.1, max dE^*_{ab} = 179.3.

Clearly, a simple assessment of B2A→A2Bx round-trip is inadequate and misleading.

An alternative couple of methods for an evaluating round-trip analysis yield somewhat more reliable results. Both methods result in round-trip evaluations for in-gamut $L^*a^*b^*$ points only.

Method 2

Method 2 consists of starting with a sampling in device coordinates, then transforming through A2Bx. The resulting set of PCS coordinate points are all guaranteed to be in-gamut. This set can then be run through B2A→A2Bx as in Method 1. The first stage, A2Bx transformation, results in a set of $L^*a^*b^*$ values which are guaranteed to be within the full (non-ink-limited) gamut of the device.

Method 3

Method 3 is a variant of Method 2 wherein the ICC profile's Gamut tag is used as a tool for determining in-gamut sampling points such that only in-gamut points (ICC White paper) are run through the B2A→A2Bx transform pair. The ICC white paper 26 makes reference to $L^*a^*b^* \rightarrow sRGB \rightarrow L^*a^*b^*$ round-trip, where the evaluation is done only on in-gamut points for perceptual rendering. We can see that the Gamut tag is a reasonable predictor by looking at the points which the Gamut tag predicts are in-gamut for Fogra39. This can be seen in figure 3.

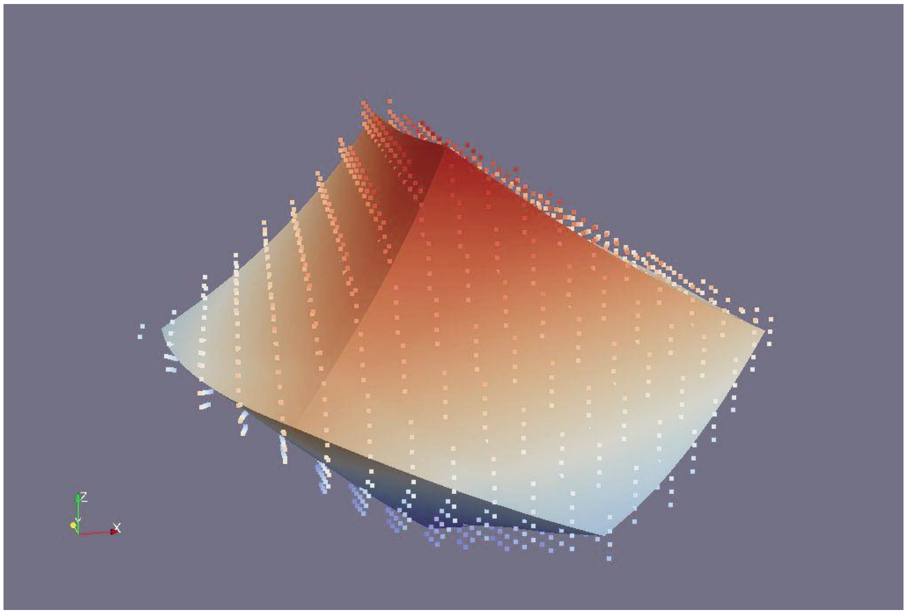

Figure 3: *Analysis of method 3 for Fogra 39L_CE.icc*

For a starting uniform sampling of the FOGRA 39L profile made with ColorFlow in CMYK of 17x17x17x17 grid points using method 2 yields a mean $dE^*_{ab} = 0.2$ and a max $dE^*_{ab} = 4.0$. By contrast method 3 yields a mean $dE^*_{ab} = 0.7$ and a max $dE^*_{ab} = 5.6$. This shows that sampling can have a non-trivial effect on the results, as a uniform device coordinate sampling results in an over-sampling of the bottom of the gamut as compared with the top. However, both results are clearly far different than the result from Method 1, where no suitable gamut restriction had been applied.

The IFRA26L profile made with ColorFlow gave a mean $dE^*ab = 0.3$ and a max $dE^*_{ab} = 3.1$ using method 2 and a mean $dE^*ab = 0.9$ and a max $dE^*ab = 5.7$ using method 3. The results are comparable with the FOGRA39L_CE.icc profile evaluation, despite the big difference in the underlying gamut size. This could be interpreted as saying that these numbers are characteristic of the profile creation algorithm.

Having such low mean dE^*ab-values for the different types of profiles speaks for the quality of the created profiles. Even the max dE^*_{ab} for both profiles are not very high. A comparison of the results of the two methods can be seen in figure 4.

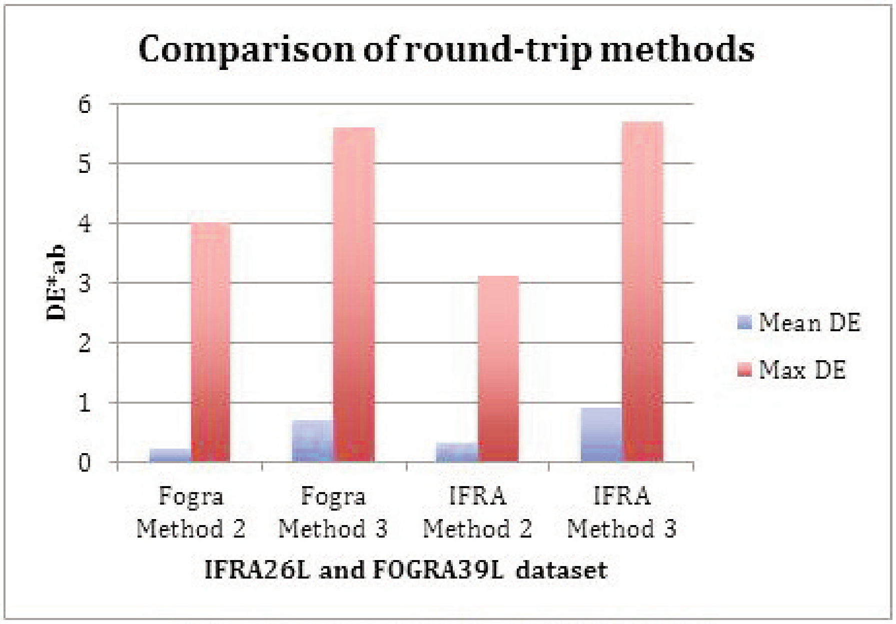

Figure 4: *Comparison of round-trip*

Profile evaluation using different profiling software applications

For this part of the research the reference data set for the FOGRA39L and IFRA26L were used to generate ICC v4 profiles using four different profiling software applications. The software programs used for this evaluation were:

Kodak Colorflow, i1Profiler 1.2 , Monaco Profiler 4.84 and ProfileMaker 5.0.10.

Since the adjustment controls in each software application are slightly different it was tried to keep them all as much as possible the same. The settings from ProfileMaker 5.0.10 were used as reference settings. For the FOGRA39L dataset the "Offset separation" was used with GCR2 . An ink limit of 320 and a maximum black of 95 was automatically selected. The black start was at 0 and the black width was 100. The black point, as set by the software, was C: 90, M: 70, Y: 65, and K: 95. It was tried to have as much as possible the same settings for the three other profiling software applications. The FOGRA 39L dataset used the IT8.7/4 target.

For the IFRA26L reference data the "Newspaper" separation was used with GCR4 automatically selected. The ink limit was 240 and a maximum black of 95 was automatically selected. The black start was at 5 and the black width was 100. The black point, as set by the software, was C: 60, M: 45, Y: 40 and K: 95. As with the FOGRA39L dataset it was tried to keep the same settings for the three other profiling software applications. The IFRA26L dataset used the ECI target.

For both datasets the profile size was set to large and the perceptual rendering intent used paper-colored grey. The gamut mapping was set to classic and not to colorful or chroma plus.

All profiles were inspected using Chromix ColorThink V3.0 to check for the gamut volume and the applied ink limitation. The profiles created from the FOGRA39L dataset had an average gamut volume of 402109 ± 374 and all had an ink limit of 320%. The profiles created from the IFRA26L dataset had an average gamut volume of 87589 ± 278 and an ink limit of 240%.

For the Method 2 analysis (A2B1 → B2A1 → A2B1) for a 17-point grid initial CMYK sampling the results can be seen in table 1 and figure 5.

Software	Mean DE*ab	Max DE*ab
ColorFlow	0.24	4.00
I1Profiler	0.44	6.01
Monaco Profiler	0.99	6.73
ProfileMaker	1.14	8.29

Table 1: *Round-trip errors for ICC profiles using method 2*

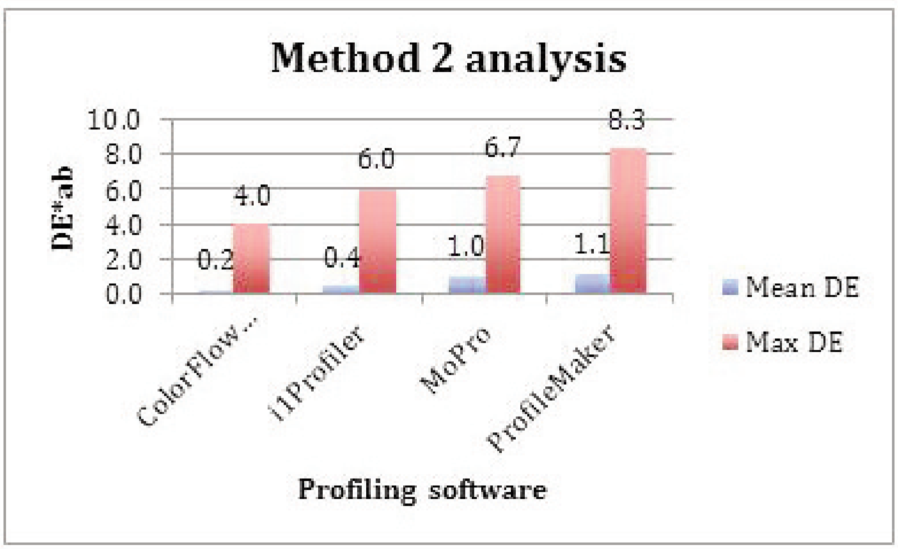

Figure 5: *Graphical view of the round-trip errors shown in table 1.*

From the table and the figure one can see that the average round-trip errors are not that large and even the maximum DE^*_{ab}-values are not very large. In 2005 Sharma (Sharma 2005) evaluated the A2B transform in profiles generated by seven different profiling applications and found an average dE^*_{ab} of 1.61 and a maximum dE^*_{ab} of 20.34.

For the method 3 test, where the 43 grid point $L^*a^*b^*$ sampling is reduced by the gamut tag in each profile. The gamut tag describes which colors are in gamut of the device. Only the colors that are indicated by the gamut tag to be within gamut will be used for the B2A → A2B round-trip. The results from these tests are shown in table 2 and figure 6.

Software	Mean DE*ab	Max DE*ab
ColorFlow	0.66	5.59
I1Profiler	0.07	2.01
Monaco Profiler	0.83	4.04
ProfileMaker	9.20	38.17

Table 2: *Round-trip errors for ICC profiles using method 3 (gamut tag limitation)*

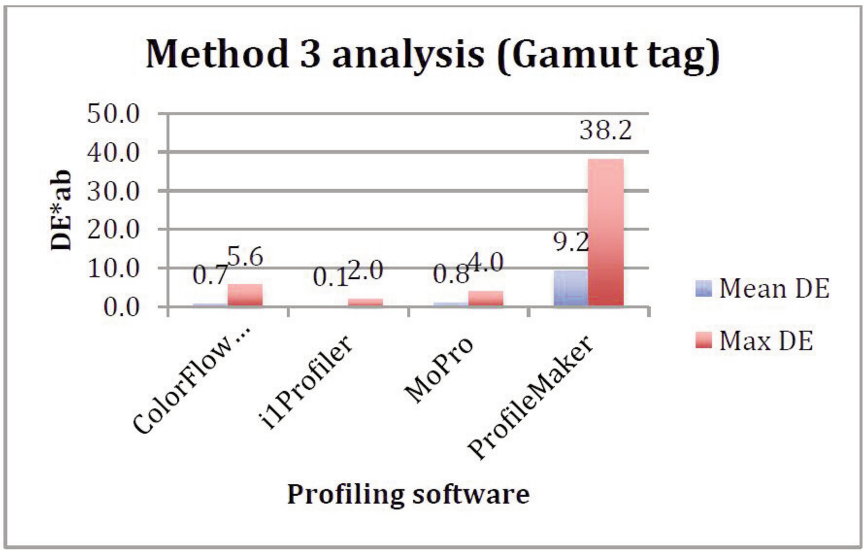

Figure 6: *Graphical view of the round-trip errors shown in table 2*

From figure 6 it can be seen that using only the in-gamut colors, as specified by the gamut tag in the profile, the profile made with the i1Profiler software showed the lowest average DE^*_{ab}-value of 0.07 and the lowest DE^*_{ab}-max of 2.01 for the round-trip analysis. ProfileMaker shows an unusual large DE-value for the average and the maximum. This result has to be analyzed carefully, since this large DE-value stems only from the gamut tag. Comparing these results to the ones shown in figure 4, one might draw the conclusion that the gamut tag might not be done properly when the profile was being created.

A different way of comparing the profiles is by using the gamut tag from one software application and applying it to all the other profiles. This ensures that the same set of $L^*a^*b^*$-values are being used for the analysis. The results in regards to the average and maximum DE-values can be seen in table 3 and figure 7.

Software	Mean DE*ab	Max DE*ab
ColorFlow	0.66	5.59
I1Profiler	0.75	9.55
Monaco Profiler	1.35	10.19
ProfileMaker	1.38	12.08

Table 3: *Round-trip errors for ICC profiles using method 3 (gamut tag limitation, gamut tag from ColorFlow)*

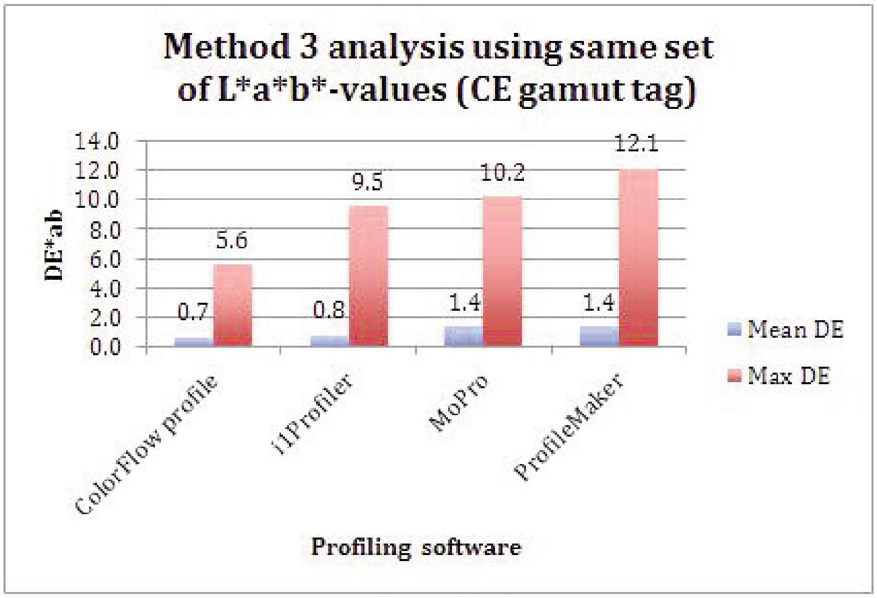

Figure 7: *Graphical view of the round-trip errors shown in table 3*

From table 3 and figure 7 it can be seen that the average DE-values for round-trip errors are not very large when the gamut tag from the ColorFlow profile is being used. The profile created with ProfileMaker shows still the largest maximum DE-value, but not as large as the one shown in figure 5. The newer software applications (ColorFlow and i1Profiler) give the smallest average DE-value for the round-trip analysis indicating the quality of the ICC profile that is generated by these applications.

Another analysis uses the gamut tag from the i1Profiler profile. It needs to be said that a much smaller set of sampling points, 3869 vs. 6640 out of an original 79507 (43^3) of the $L^*a^*b^*$-color space. This is further into the interior of the device gamut. The results from this analysis are shown in table 4 and figure 8.

Software	Mean DE*ab	Max DE*ab
ColorFlow	0.15	2.41
I1Profiler	0.07	2.02
Monaco Profiler	0.77	2.68
ProfileMaker	0.38	3.25

Table 4: *Round-trip errors for ICC profiles using method 3 (gamut tag limitation, gamut tag from i1Profiler)*

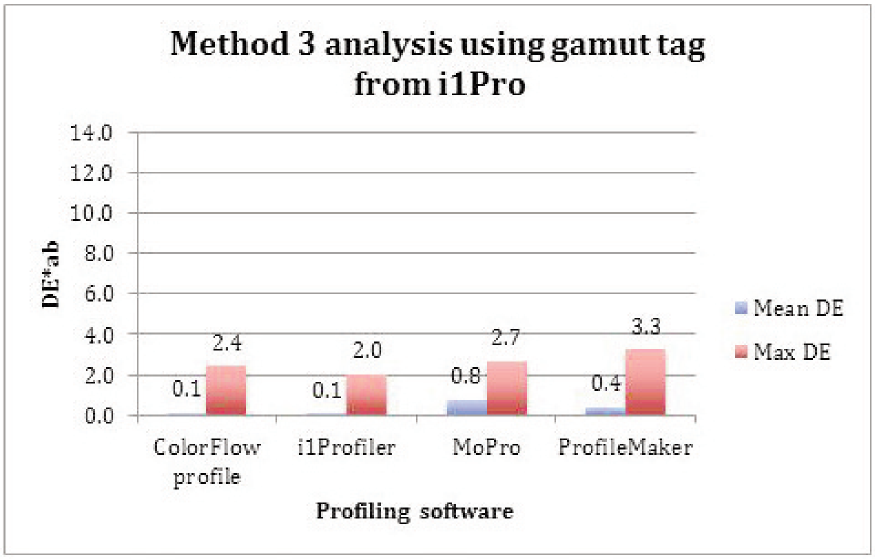

Figure 8: *Graphical view of the round-trip errors shown in table 4*

By using the gamut tag from the i1Profiler profile all profiles have quite a small average DE*ab for the round-trip analysis. This is due to the smaller set of sampling points and that they are more in the interior of the device gamut.

Even with the smaller number of sampling points the profiles created in MonacoProfiler and ProfileMaker still have large max DE-values in comparison to the profiles form ColorFlow and i1Profiler.

Conclusions

When profiles are evaluated for their round-trip analysis it is important to use profiles that were made with similar conditions in regards to ink-limiting and the amount of GCR that is being applied. The gamut tag has an obvious influence on the average round-trip DE*ab error. The i1Pro profile does very well on the round-trip analysis in the far interior of the gamut, not quite as well near the surface, and likely not as well in the bottom of the gamut. The A2B →B2A →A2B round-trip analysis is heavily weighted towards sampling in the bottom of the gamut due to where the

CMYK grid points map to. The ColorFlow (CE) profile does fairly well in most of the round-trip analysis.

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Appendix:

Matlab code used in this research paper:

```
function [errval, dEab, lab, labgam] = calcRT(szProfile, evalType, renderingIntent,
cmykdim, labdim)

% This M-file calculates round-trip error statistics for the profile
% with the file name szProfile.
% Although there is often a desire to reduce fairly complex quality
% statements to unidimensional metrics to facilitate comparisons,
% one must be careful in interpreting the number.
%
% The first metric usually calculated is the aggregated first-order
% statistic of the mean and max dE*ab.  Standard deviation is not
% meaningful as dE*ab is a single-sided quantity.  This function directly
% returns the list of dE*ab values calculated for the sampled L*a*b.
% For our analysis, we'll calculate 3 types of round trip.
% One round trip is the two-step: B2Ax-->A2Bx.  Note we could also
% calculate the A2B-->B2A round trip, but this latter results in us having
% to compare 2 sets of device coordinates, which does not yield a dE type
% of number.  The sample set for the B2Ax-->A2Bx round trip will be a
% simple linearly-spaced grid.
% The second type of evaluation will take an extra stage, going
% A2Bx->B2Ax->A2Bx.  The first stage (A2Bx transformation) results in a set
% of L*a*b* values which are guaranteed to be within the full
% (non-ink-limited) gamut of the device.
% The third evaluation method uses the profile's Gamut tag as an estimator
% to determine which L*a*b* sample points are contained inside and which
% are outside the profile's gamut.  Only the points which the Gamut tag
% indicates are inside the gamut get used for the B2Ax-->A2Bx round trip.

% Parse parameters
if (nargin < 2)
   evalType = 1;
end
if (nargin < 3)
   renderingIntent = 1;
end

if (nargin < 4)
   cmykdim = 17;
end
```

```
if (nargin < 5)
    labdim = 43;
end

evalType = uint8(evalType);
if (evalType < 1)
    evalType = 1;
end

if (evalType > 3)
    evalType = 3;
end

% Start calculation
% Load profile to work with.
pfz = iccread(szProfile);
switch (renderingIntent)
    case 0  % Perceptual
        RIa2b = 'AToB0';
        RIb2a = 'BToA0';
    case 1  % Relative Colorimetric

        RIa2b = 'AToB1';
        RIb2a = 'BToA1';
    case 2  % Saturation

        RIa2b = 'AToB2';
        RIb2a = 'BToA2';
    case 3  % Absolute Colorimetric

        RIa2b = 'AToB3';
        RIb2a = 'BToA3';

    otherwise
        RIa2b = 'AToB0';
        RIb2a = 'BToA0';
end

xfa2b = makecform('clut', pfz, RIa2b);
xfb2a = makecform('clut', pfz, RIb2a);
xfGamut = makecform('clut', pfz, 'Gamut');

% Calculate round trips
switch (evalType)
```

```
    case 1  % B2Ax-->A2Bx, results in Lab-->Lab transform
        disp('B2Ax-->A2Bx');
        labgam = lineargrid([labdim labdim labdim], [0 100.;-128 127;-128 127],
1);
        lab = applycform(applycform(labgam, xfb2a), xfa2b);

    case 2  % A2Bx-->B2Ax-->A2Bx.  Do initial gamut-limiting transform
        disp('A2Bx-->B2Ax-->A2Bx');
        cmykgr = lineargrid([cmykdim cmykdim cmykdim cmykdim], [0 1.;0 1.;0
1.;0 1.], 1);
        labgam = applycform(cmykgr, xfa2b);
        lab = applycform(applycform(labgam, xfb2a), xfa2b);

    case 3  % Now, do gamut restriction using Gamut tag
        disp('B2Ax-->A2Bx with gamut restriction');
        labgr = lineargrid([labdim labdim labdim], [0 100.;-128 127;-128 127], 1);
        labgam = zeros(size(labgr));
        j = 1;
        gam = applycform(labgr, xfGamut);
        for i=1:length(gam)
            if (gam(i) == 0)
                labgam(j,:) = labgr(i,:);
                j = j+1;
            end
        end
        labgam = labgam(1:(j-1),:);
        lab = applycform(applycform(labgam, xfb2a), xfa2b);
    otherwise
        disp('Unknown eval type!');
end

% Finally, calculate error statistics
dEab = vabs(lab - labgam);
errval = [mean(dEab) max(dEab)];
```