Effects on Digital Image Quality when Photographing Through a Transparent Material Used to Hold or Flatten an Original Object

Paul E. Howell

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EFFECTS ON DIGITAL IMAGE QUALITY WHEN PHOTOGRAPHING THROUGH A TRANSPARENT MATERIAL USED TO HOLD OR FLATTEN AN ORIGINAL OBJECT

by

Paul E. Howell

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Paper Engineering, Chemical Engineering, and Imaging
Advisor: Paul D. Fleming, Ph.D.

Western Michigan University
Kalamazoo, Michigan
December 2009
WE HEREBY APPROVE THE THESIS SUBMITTED BY

Paul E. Howell

ENTITLED Effects on Digital Image Quality When Photographing Through a Transparent Material Used to Hold or Flatten an Original Object

AS PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science

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EFFECTS ON DIGITAL IMAGE QUALITY WHEN PHOTOGRAPHING THROUGH A TRANSPARENT MATERIAL USED TO HOLD OR FLATTEN AN ORIGINAL OBJECT

Paul E. Howell, M.S.
Western Michigan University, 2009

An increasing number of libraries and archives are initiating projects where new and updated technologies make it practical to digitize materials containing color and fine detail. Many of the imaging systems and methods used for this process require that some type of glass or plastic be placed over the original to hold it flat and in the correct position during image capture. The physical properties of a material placed between an original object and the capture system or camera, during digitization, could possibly affect the accuracy of image color and quality being reproduced by the system. This investigation provides an analysis of the possible effects on the process.

This analysis compares the results of image targets captured, with a digital still camera, through various commercially available materials to that of a control target captured without any intermediate material. The accuracy of the color profiling process was evaluated and comparisons made. Image quality and performance analysis, based on standards, was accomplished.

Results of the investigation indicate that with accurately configured equipment and the proper application of an ICC color profile, any effects caused by the introduction of a transparent material between the image capture system and original can be minimized. Specific recommendations on the suitability of the analyzed transparent materials are provided.
ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Paul D. Fleming III, for his encouragement throughout the lengthy period of my studies, and Dr. Abhay Sharma for getting me started in the program. The resources and information they provided in addition to the material covered in required course work have helped me to realize the importance of research as it applies to both my studies and my profession.

I would also like to thank the other members of my final thesis committee, Dr. Susan Steuer and Dr. Alexandra Pekarovicova for their support during the final phases of my studies.

Also, I want to give a special thanks to Miranda Howard for her support, encouragement and assistance in accomplishing a number of the projects and research included in my work.

I would like to posthumously acknowledge Dr. Thomas L. Amos for being a good friend and convincing me that collaboration between the Department of Engineering and The University Libraries would benefit my studies and position in the Libraries.

My sincere appreciation goes to Mr. Don Williams for supplying a current sample copy of his GoldenThread™ system and providing other resources for use in my investigation. His assistance and the time spent discussing image quality and performance metrics and the functioning of the software system was of great value.
Acknowledgments—continued

In accordance with the Society for Imaging Science and Technology copyright agreement, I want to acknowledge the use of material published in the Final Program and Proceedings for “Archiving 2009” held in Arlington, VA., May 4-7, 2009, and presented at the conference.

Finally, I want to express my gratitude and appreciation to my dear wife Susan for her continued support and understanding throughout this lengthy process.

Paul E. Howell
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INTRODUCTION

As the digitization of materials held in archives, libraries and special collections has increased, costs associated with image capture have decreased. This is primarily due to the availability of higher quality and relatively less expensive image capture systems and the continued decrease in the cost of digital storage necessary to maintain the resultant volume of larger and more numerous data files. The initiation of projects, where new equipment and updated technology make it practical to digitize a more varied selection of materials, has led to the inclusion of books and documents containing detailed images and color. In the past, much of the work being done with book scanners and camera-based systems captured only black and white or grayscale images primarily for their content. These newer capabilities provide the ability to capture materials at higher resolutions and in color. With the ability to capture higher quality images in color, it is now possible in many instances, to depict more than just the textual or graphical “content” of a particular item, it also allows to some extent the “context” of the item to be represented.

Many factors need to be taken into account during the image capture process. In addition to resolution requirements, the accuracy of colors in an image and overall image quality need to be considered. To obtain the most consistent and predictable colors, the introduction of color management into the workflow needs to be a requirement. [1] When properly applied, this technology can improve the quality of the captured image by representing the
actual color of the original object with increased accuracy. Recently, the capability to quantify or evaluate the performance of digital imaging equipment and standards for image quality has become available for use by the cultural heritage community in general. [2] The benefits of these technologies can help to improve the overall usability and quality of an image, whether the image is intended for access or preservation. Although a captured image does not always represent the original object exactly, the goal for both access and preservation should be to provide the end user with the most accurate reproduction possible when employing the available technology.

Much of the equipment used in the digitization process, including a variety of book scanning systems, commercial book cradles, and other forms of book holding devices are used to achieve the requirement of properly positioning items during the digitization process. Many of these systems and methods require that some type of transparent material, either glass or plastic, be placed over the item being digitized to hold it flat and in the correct position during image capture. Due to physical properties of the materials placed between the original object and a capture system or camera, there is the possibility of an adverse effect to the accuracy of the color and image quality being reproduced by the system. Of specific interest for this investigation is the photographing (copy photography) of pages from bound books, manuscripts and other documents with the aid of a digital still camera. As there is no readily available information on the specific effects that an intermediate material used in the digitization process has on accurate color management, this investigation provides a basic analysis or test of the
possible effects. The capability and accuracy of profile generating software to correct for these possible effects during the profiling process (generation of camera input profiles), was evaluated. Additionally, a separate set of images was also processed to evaluate any possible effects to overall image quality.

Workflows for digital cameras and the consistent creation of quality images are much more complex than those for other input devices, such as flatbed scanners and slide scanners. In addition to understanding the application of basic color management and the application of color profiles for use with these type systems, consideration must to be given to the effects of lighting balance and intensity, focus, exposure, lens focal length and camera position. Specific requirements, such as image neutralization, [3] and the functioning of specific, and normally proprietary software used in the image capture process, also need to be applied. As previously noted, many of these copy systems use some form of transparent material as a means of positioning the original during image capture. This introduces yet another variable into the already complex number of requirements necessary to digitally reproduce a high quality and color accurate representation of the item being digitized.

Although there are types of glass advertised as being optically clear as compared to ordinary glass, the metal oxides in standard commercially available sheet glass of any type generally impart some tint or color (normally green) to the glass itself. Therefore, the optical properties of the material have the possibility of adversely affecting the actual color and image quality of an original being photographed using the transparent material to hold or flatten it during the digitization process. The color analysis portion of the
investigation is a study of the possible effects associated with capturing images through transparent materials of different properties, with the aim of determining how accurately a generated color profile can compensate for any color shift or difference imparted by the intermediate material. Image capture was performed with both high frequency fluorescent copy lamps, as well as photo strobes, to determine any advantages or disadvantages to the lighting system used. A high quality digital camera optimized for copy photography was used along with standard color calibration targets to create the digital images used in the investigation. International Color Consortium (ICC) profiles were generated and analyzed with commercially available software tools to determine the relative accuracy of their transformation and the resultant color gamut. The analysis compares the results of the images captured through various commercially available materials to that of a control target captured without any intermediate material. Lighting uniformity and intensity were standardized for the sample sets with both systems used. All variables associated with the camera copy system and processes used to capture the images and the profiling processes were minimized to the maximum extent possible. The conclusions derived from the analysis, including the variables noted due to the use of the alternate lighting systems and how the color accuracy of the digitized images were affected, are detailed.

Image quality analysis and methods of evaluating digital cameras and imaging systems have been investigated in various forms for a number of years. International Organization for Standardization (ISO) standards for the OECF - Opto Electronic Conversion Function (ISO 14545) describe factors
such as linearity, sensitivity, tone, neutrality, etc., have been developed. Standards and protocols for measuring SFR - Spatial Frequency Response (ISO 12233, ISO 16067-1, ISO 16067-2, ISO 15524), which describe metrics such as sampling rate, resolution, sharpening and acutance, are also available. 

Other factors, including distortion or noise, can be evaluated using NPS - Noise Power Spectrum tools. The application of these methods can be used to evaluate the imaging performance of equipment and provide a basis for image quality analysis. [4]

The utilization of these methods and interpretation of the metrics have generally been restricted to the scientific and engineering communities and have normally not been taken into account during the image capture process for digitization programs. In many cases, institutions and organizations initiate digitization projects without a comprehensive understanding of the specific capabilities and quality that their selected equipment can provide. Due to a lack of technical expertise and/or education, many digitization programs continue to scan and capture images without consideration for much more than the dots per inch (dpi) output generated. Well-established procedures, such as color management, are not being applied by a large percentage of organizations involved in these activities, [5] let alone image quality analysis or performance monitoring. “Fortunately, there is a gradual awakening to literate imaging through international standards, education, and appropriately prepared imaging specifications.” [6]

In the past, there have not been easy ways for members of the cultural heritage community to apply the standards associated with equipment and image quality analysis and performance. Recently, a small number of
software “suites” that comply with the accepted standards have become commercially available. These products/systems consist of specialized targets and comprehensive software that can be employed to provide “image quality metrics” for evaluating or assessing the performance of the equipment to be used, or for monitoring the quality and consistency of a digitization workflow. After obtaining sample versions of three (3) products currently available for this type analysis, (Certifi Pedigree® from Certifi Media Inc., ImCheck3v1, and GoldenThread™ from Image Science Associates), a review of the functionality and sample tests were performed to determine which would be most applicable for the investigation being made. It was determined that for the subject investigation and equipment being used, the GoldenThread™ system would provide the most comprehensive data for the required test conditions.

The image quality and performance portion of the investigation was conducted to extend and supplement the color analysis study with additional data on imaging performance variances that the selected transparent materials could have on overall image quality requirements. [7] Due to conclusions formulated during the color study, and factors associated with workflow efficiencies and the analysis system, it was determined that only the high frequency fluorescent lighting setup would be used for the image performance investigation. As with the color analysis, target images were captured through the same transparent materials and compared to that of a control target captured without any intermediate material. Uniformity and intensity of the lighting was again standardized to the same configuration as previously used. The effects of variables associated with the camera copy
system and processes used to capture the images were again minimized to the maximum extent possible. The primary difference in the configuration for this portion of the investigation was a change to the lens aperture used for image capture. This was determined “appropriate” to better optimize the data output from the GoldenThread™ software. The conclusions derived from this portion of the analysis and the effects that the use of an intermediate material has on image capture performance are included with those of the color study.

To insure that this investigation would most accurately produce results consistent with normal working conditions and procedures available to the general library and archive community, commonly available materials, equipment and software were used for all tests accomplished for the analysis. The final results provide recommendations as to the suitability of the various transparent materials when they are used to position or flatten pages of a book or document.
PROCEDURES

Equipment and Software Overview

All of the equipment, software and the target used for the color analysis portion of the investigation are generally available through commercial sources. Except for the measurement and comparison of the corrected reference data, all lighting measurements and ICC profile generation were obtained with an i1Pro Spectrophotometer and i1Match software. Comparisons between reference data, images and attached ICC profiles were accomplished with CHROMiX ColorThink 3.0 Pro (referred to as ColorThink). Adobe Photoshop CS4 was used to manipulate images and attach the specific profiles. The availability of the type of equipment and software used to balance lighting and generate profiles should allow the average user to be aware of the requirements for color management and understand the required profiling procedures for this type of image capture.

A GretagMacbeth™ Digital ColorChecker® SG (semi gloss) color reference chart was used as the standard reference target. All color patches of the target were measured using MeasureTool 5.0.8 and the i1Pro mounted in an i1iO Scanning Table. A target reference data file was generated using patch measurement mode and averaging of five samples from each color patch of the target. The reference data were saved in spectral form and used to replace the default target reference file for i1Match and in all applicable comparisons in ColorThink. (For this analysis, the measured reference data differed from the vendor-supplied data by an average of 1.7 ΔE.)
The copy stand setup (Figure 1) for the analysis was a Kaiser rePRO RSP system with Kaiser HFB high frequency fluorescent lamps consisting of two sets of 2 x 55 Watt 5000K lamps. For the photo strobe testing component, the lamps were replaced with two AlienBees B800 flash units mounted on stands, with 32 inch bounce umbrellas providing a “soft white bounce” (the specifications for these units is 320 true wattseconds/144,000 lumen-seconds at 5600K).

The images of the ColorChecker® SG target used in the analysis were captured using a Hasselblad H2 camera body with Hasselblad CF-39MS digital back and Hasselblad HC Macro 120mm lens. All images were captured with an aperture setting (f-stop) of 22. Exposure was initially checked with the aid of a Sekonic Flash Master L-358 light meter.

The proprietary Hasselblad image capture software, Phocus version 1.1.3, was used to operate the camera in a tethered configuration to capture the target images. During the image capture process, all of the software adjustment tools were initially left in a neutral position or deselected. The exceptions to this were the default software settings for “Lens Corrections”, where the RAW processor increases the quality of the native Hasselblad images by providing “digital lens corrections for color aberration, distortion and vignetting”. [8]

For this investigation, three readily available types of transparent material were obtained for analysis. For consistency and sufficient size to completely cover the color target, a 14 by 18 inch sheet as close as possible to .25 inch thick was selected for each. The samples consisted of standard “plate glass”, Starphire® Ultra Clear glass, and Cyro Acrylite® FF Acrylic.
Figure 1. Copy stand setup with camera and target
Image Capture and Color Profiling

Initial setup for each lighting system consisted of using i1Match in the “Advanced” mode to “Check lighting equipment”. The i1Pro was calibrated with the ambient light head and used to balance the specific illumination (continuous or flash) of the target area, as it would be photographed. The relative color temperature and apparent intensity of illumination for each type of lighting is noted with the profile data tables that follow in the analysis section. The ColorChecker® SG target (Figure 2) was then photographed uncovered, and then with each of the transparent materials selected. Additionally, a QPCard 101 v2 was captured in the image area for consistency with each image and the middle gray patch was used to gray balance or neutralize each image with the neutralization tool in Phocus. [9]
With an f-stop of 22 for all samples, the exposure of each image was held as close as possible to obtain a value in the white areas of the target of 210-245 (nominally 230-240), and a value of the black patches below 20 if possible (these values are required by i1Match to successfully create a valid profile in the advanced mode). Minor exposure value (EV) corrections were necessary in the software for some of the basic exposures so that the white and black patches of the target fell into this required range for the profiling procedure. The relative International Standards Organization (ISO) sensitivity rating used for the fluorescent lighting samples was 50, which is the default sensitivity of the charged-coupled device (CCD) sensor and recommended for the highest quality by Hasselblad. [10] The samples captured with photo strobe lighting required an ISO sensitivity rating of 200 to allow for the standardized f-stop of 22 and still maintain the correct exposure for neutralization and proper values in the white and black patches of the target.

After images were captured with the Phocus software, and EV corrections made if necessary, the RAW image files (Hasselblad 3F format) were converted into Tagged Image File Format (TIFF) images that could be processed with the i1Match software. It was important to note the following statement from updated information about the version of the Phocus software being used. “When generating the input file to be used by your profiling tool it’s important to export with an output preset where the profile is set to Source since this means that no ICC transformations will be applied to the data in the file.” [11] This setting is important so that the default input profile, normally Adobe RGB (1998), is not attached to the file changing the source color space data.
Each target image was loaded into i1Match and the actual target area cropped as required. The light source selected was D50, once again for consistency, and the profile was generated (built). The advanced mode of i1Match makes it possible to “modify and fine tune” the profile and requires that a reference picture be loaded. For this step, the original target image was loaded and no modifications were made to the profiles. Verification of this was indicated by the procedure “Summary” indicating no corrections to the profile data had been made. Subsequently, each profile was saved with a descriptive filename.

Because of the requirement to use an ISO rating of 200 for the photo strobe lighting, it was decided at this point to also capture an additional set of target images at ISO 200 with the fluorescent lighting setup. Profiles were generated from these images using the same procedures as with previous samples so that any variances could be noted during the analysis.

Analysis of the data originally acquired revealed a reduction in the relative size of the gamut volume when the targets were captured with fluorescent lighting and a higher ISO sensitivity of 200 rather than the default of 50. Because of this, it was later decided to perform an additional sampling to obtain an idea of the differences across the range of the camera’s capability. Images of the target were captured and processed at f22 with ISO settings of 50, 100, 200, 400, and 800. Subsequently, images were also captured at f8 to provide a reference at the same aperture setting used for the image analysis and performance study. For this portion of the evaluation, there was no intermediate transparent material used, and the samples were acquired with a configuration as close to the original reference target setup as possible.
ICC color profiles were generated for each of the sample targets as previously outlined. It should be noted that the Hasselblad Phocus software had been updated to version 1.2.1 before this portion of the study.

Image Analysis Target Acquisition

The setup for this portion of the investigation was essentially the same as described in the previous section for Image Capture and Color Profiling. The equipment was configured to provide the same field of view and lighting intensity by using the “Advanced” mode of i1Match as with the color study. The Golden Thread Version# DL 1.0 “Device-Level Target” (Figure 3) was then photographed along with the QPCard 101 v2, again to provide consistency between the images captured, so that the middle gray patch could be used to gray balance or neutralize each image as previously described. As stated in the introduction, it was determined that only the high frequency fluorescent lighting setup would be used for the image performance investigation. Due to preliminary experimentation with the GoldenThread™ system and discussion with Mr. Don Williams, [12] founder of Image Science Associates (who provided the software system and target), it was decided that for detailed analysis, an f-stop of 8 would be used for this portion of the investigation. The use of a lens opening closer to the “critical aperture” [13] of the camera system would provide better image definition and help optimize data output from the software used for the evaluation. An ISO sensitivity rating of 50 as previously used for the fluorescent lighting samples was again selected, and the exposure of each image was held as close as possible to the same values used for the profiling procedure.
As can be seen in the figure above, the sample target used with the analysis system was scratched in the upper left corner. This did not affect the quality of the data produced, because the region of interest (ROI) that includes the small gray square could be manually moved away from the
scratch in the software, allowing the generation of proper data values. The Device-Level Target itself is created on high-resolution silver halide paper, with Munsell color patches from X-Rite Corporation, and mounted on an anodized aluminum sheet to maintain flatness and provide protection. [14]

During discussions with Mr. Williams, [12] information was provided that allowed a custom profile for the software system to be created, which better defined the aims and tolerances expected for the copy system being used. The use of this profile did not change any data produced by the software but provided corrected aim points in the data output that allowed better understanding of acceptable tolerances for the equipment configuration being used. Since the primary purpose of the investigation was to determine the effect of using transparent materials in the specific type digitization process, actual quality of the images captured was not the main focus of the analysis.

After the target images were captured with the Phocus software, and the appropriate EV corrections made, the RAW image files were converted, as before, into Tagged Image File Format (TIFF) images that could be processed with the GoldenThread™ system software. For consistency in image processing, these files were also exported using the Hasselblad source profile.

The GoldenThread™ software Analysis Mode was configured for all tests and the custom Test Profile was selected. The Test Image file was selected and manually cropped to insure proper placement of the ROIs after which minor adjustments were made to their placement prior to processing. The resultant data are generated and displayed in the software initially in the Summary tab. There are also output tabs for Tonescale, Color, Resolution, and
Noise. The data are available for viewing in specific graphical screens optimized for the specific function. At the same time the graphical data are exported to a Microsoft Excel spread sheet and the raw data to a Microsoft Access database where they can be used for analysis in a number of different ways. The data files are saved with a name relating to the filename of the original image file.
DATA ANALYSIS

Color Profile Comparison

For the purpose of this investigation, the ColorThink software was used as a basis for data comparisons. All ΔE values are recorded using the ΔE76 standard for profile accuracy. [15] The overall average ΔE values for all 140-sample patches of the ColorChecker® SG chart were used for comparison. The target reference data referred to in the analysis is the same measured spectral data from the file used to generate the ICC profiles for each of the samples.

Initially, each of the profiles were analyzed using the “ColorSmarts Guide” component of ColorThink that recognizes and extracts the reference and measurement data used to generate the profile (when those data are embedded in the profile) and compares these data to evaluate the accuracy of the profile. A report was created for each sample and the average ΔE76 was recorded for each of the samples. Each profile was also opened with the “Profile Inspector” component and the gamut volume recorded. Comparison of the profiles in the “Grapher” for each of the two lighting systems showed little variance between each of the four profiles of each setup. The comparison of fluorescent to photo strobe lighting profiles showed a difference in larger LAB +b values (yellow/orange) for the photo strobe lighting, and larger LAB –a values (green/blue green) for the fluorescent lamps. An example of the ColorThink Grapher display (Figure 4) represents LAB values for the Starphire® glass profiles for both lighting systems.
The ColorThink “Color Worksheet” component was used to compare color values of the patches in each target image file to the values of the original measured reference data file. A report was generated for each comparison providing the overall average ΔE76 values. Two comparisons were made for each image file, one for the basic file as it was converted, with the source Hasselblad RGB color space, [16] and one with the appropriate ICC profile attached/applied for color correction. (Figure 5)
Because ColorThink does not read the reference data file measured in MeasureTool (a color list) in the same order as it interprets the color data from the image file of the ColorChecker® SG target, all of the image files needed to be manipulated before the comparisons could be made and the reports generated. In Photoshop, the Image Rotation functions “90° CW” and “Flip Canvas Horizontal” needed to be applied to each of the images. The images were then saved in the rotated form, both without and with the appropriate ICC profile attached. The Color Worksheet was then manipulated to compare the reference file data to that of these two sets of image files. This was accomplished by using the Target Marquee tool to select the 140 patches of the targets with a “custom” 10 x 14 Target Resolution grid. The Test Feedback reports were then generated for each target comparison providing the average ΔE76 values. (Figure 6)
The following tables (Tables 1-3) list the results from the reports made during the data analysis of the previously discussed comparison procedures. An individual table is shown for each of the lighting system setups (high frequency (HF) fluorescent and photo strobe) and the specific variations of each are annotated. The first two columns list the information extracted from the specific ICC profile generated for the specified target. The third and fourth columns list the comparisons made between the measured reference data file and the image files with source color space (Hasselblad RGB) and with the specific ICC profile applied to either the reference target or target captured with the specific transparent material.
Table 1
Data comparisons for HF fluorescent lighting at ISO 50

<table>
<thead>
<tr>
<th>HF Fluorescent (i1Match / 4900K / 3000 Lux / ΔE76 Average)</th>
<th>f-stop 22 ISO 50</th>
<th>Profile</th>
<th>Gamut Volume</th>
<th>Source Space</th>
<th>Profile Applied</th>
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<tr>
<td>No Glass</td>
<td>2.98</td>
<td>971,522</td>
<td>7.03</td>
<td>3.02</td>
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<tr>
<td>Plate Glass</td>
<td>2.87</td>
<td>983,307</td>
<td>7.11</td>
<td>2.90</td>
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<tr>
<td>Starphire® Glass</td>
<td>3.02</td>
<td>990,278</td>
<td>7.83</td>
<td>3.06</td>
<td></td>
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<tr>
<td>Acrylic Sheet</td>
<td>3.01</td>
<td>986,557</td>
<td>7.59</td>
<td>3.04</td>
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</table>

Table 2
Data comparisons for photo probe lighting at ISO 200

<table>
<thead>
<tr>
<th>Photo Strobe (i1Match / 7800K / 900 Lux / ΔE76 Average)</th>
<th>f-stop 22 ISO 200</th>
<th>Profile</th>
<th>Gamut Volume</th>
<th>Source Space</th>
<th>Profile Applied</th>
</tr>
</thead>
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<tr>
<td>No Glass</td>
<td>2.66</td>
<td>973,539</td>
<td>6.59</td>
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<tr>
<td>Plate Glass</td>
<td>2.76</td>
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<td>Starphire® Glass</td>
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<td>956,482</td>
<td>6.58</td>
<td>2.98</td>
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<tr>
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<td>960,461</td>
<td>6.45</td>
<td>2.76</td>
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Table 3
Data comparisons for HF fluorescent lighting at ISO 200

<table>
<thead>
<tr>
<th>HF Fluorescent (i1Match / 4900K / 3000 Lux / ΔE76 Average)</th>
<th>f-stop 22 ISO 200</th>
<th>Profile</th>
<th>Gamut Volume</th>
<th>Source Space</th>
<th>Profile Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Glass</td>
<td>2.99</td>
<td>916,974</td>
<td>7.23</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>Plate Glass</td>
<td>2.9</td>
<td>923,734</td>
<td>6.90</td>
<td>2.95</td>
<td></td>
</tr>
<tr>
<td>Starphire® Glass</td>
<td>2.86</td>
<td>927,532</td>
<td>6.76</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td>Acrylic Sheet</td>
<td>2.91</td>
<td>920,955</td>
<td>6.96</td>
<td>2.98</td>
<td></td>
</tr>
</tbody>
</table>
Image Color Deviation

After the initial portion of the investigation where the color profile comparison results were analyzed, it was decided that additional data should be evaluated to determine if there were any noticeable deviations or shifts to the colors of corrected images when using an intermediate transparent material. Since only the average ΔE values for the 140 patches of the ColorChecker® SG target were compared as a basis for evaluation the ICC profiles ability to correct for the tint or color of the intermediate materials, additional data from the ColorThink reports were considered. Differences in the maximum and minimum ΔE values between the reference and sample targets could provide an indication of the accuracy of the profiles in transforming the color data. The data in summary table (Table 4) show the maximum and minimum ΔE values for the measured reference data file as compared to the image files with specific ICC profile applied. The standard deviation for the ΔE values from each report is also included.

Table 4

Summary of maximum, minimum and standard deviation ΔE76 values

<table>
<thead>
<tr>
<th>Reference File to Target with Profile Applied</th>
<th>HF Fluorescent ISO 50 Max ΔE76 Min StdDev</th>
<th>Photo Strobe ISO 200 Max ΔE76 Min StdDev</th>
<th>HF Fluorescent ISO 200 Max ΔE76 Min StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Glass</td>
<td>14.72 – 0.26 2.45</td>
<td>10.91 – 0.20 1.96</td>
<td>15.94 – 0.33 2.62</td>
</tr>
<tr>
<td>Plate Glass</td>
<td>14.19 – 0.18 2.40</td>
<td>10.31 – 0.08 1.86</td>
<td>15.25 – 0.24 2.53</td>
</tr>
<tr>
<td>Starphire® Glass</td>
<td>14.45 – 0.20 2.53</td>
<td>10.38 – 0.31 1.96</td>
<td>15.27 – 0.28 2.50</td>
</tr>
<tr>
<td>Acrylic Sheet</td>
<td>14.52 – 0.23 2.46</td>
<td>11.25 – 0.23 1.97</td>
<td>14.67 – 0.30 2.55</td>
</tr>
</tbody>
</table>
As can be seen from the preceding table, and results specific to each lighting type, all maximum, minimum and standard deviation values for the samples are very close to each other. Except for the lower maximum ΔE values recorded for the photo strobe lighting system the data indicate that there are minimal differences in the profile transformations between the target reference data and the color patch values for each of the sample targets with the color profile applied. This would indicate that the generated color profile is performing the same basic color transformations on the reference target as it does to the data of the targets with an intermediate material included in the image capture process.

The ColorThink Color Worksheet was again used to compare the color values of the 140 patches on the reference target with the color profile applied to those of each sample target, also with the appropriate color profile applied. A report was then generated for each comparison providing the overall average and maximum ΔE values for each of the targets captured with the selected intermediate material included. During this comparison process, a sampling was made to assess what colors in the color list had the highest ΔE values. In general, the results indicated that for samples captured with the same lighting system, the colors with the highest values were the same colors for the reference target as those of the targets for the other three image capture setups. However, there were noted differences between samples with the high frequency fluorescent and photo strobe lighting in the specific color patches having the highest variances. This can be attributed to the color gamut difference discovered between the two lighting setups as discussed previously and shown by the Grapher results. (Figure 4)
A summary of the Test Feedback reports for the reference target with ICC profile applied compared to each sample target with the appropriate ICC profile applied, was compiled. (Table 5) As before, analysis indicated very small differences between the color corrected reference target and the sample targets captured with the intermediate materials that also have the appropriate ICC profile applied. It is interesting to note that the values obtained from the photo strobe lighting setup are slightly higher than with the high frequency fluorescent lighting even though the maximum ΔE values for the same setup when compared to the measured reference data file were lower. This would tend to indicate that the use of an intermediate material during the image capture process affects the accuracy of the profiling process more when using photo strobe lighting than it does when high frequency fluorescent lighting is employed.

Table 5

Summary of reference to sample target average and maximum ΔE76 values

<table>
<thead>
<tr>
<th>Reference Target to Sample Target Profile Applied</th>
<th>HF Fluorescent ISO 50 Avg ΔE76 Max</th>
<th>Photo Strobe ISO 200 Avg ΔE76 Max</th>
<th>HF Fluorescent ISO 200 Avg ΔE76 Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Glass</td>
<td>0.72 – 2.58</td>
<td>1.26 – 4.51</td>
<td>0.79 – 2.75</td>
</tr>
<tr>
<td>Starphire® Glass</td>
<td>0.82 – 2.85</td>
<td>1.08 – 3.84</td>
<td>0.84 – 2.84</td>
</tr>
<tr>
<td>Acrylic Sheet</td>
<td>0.80 – 2.52</td>
<td>1.02 – 3.28</td>
<td>0.77 – 3.10</td>
</tr>
</tbody>
</table>
Relative ISO Variance

The additional set of data for the HF fluorescent lamps, captured with a relative ISO of 200, (Table 3) indicate ΔE values in the same range as the other samples. The primary difference is the somewhat smaller gamut volume recorded (<7% difference). This was originally thought to be a factor accounted for by the previously mentioned default sensitivity of ISO 50 for the CCD image sensor, in combination with the lighting method used. Further investigation was made in an attempt to determine what factor or factors could cause the variance in this value. Gamut volume, as represented by the ColorThink Profile Inspector, is defined as a relative measure of cubic LAB values to be used for comparison purposes only. [17] It can also be interpreted as the number of colors the device can resolve within a tolerance of ΔE = \sqrt{3}. [18] After the additional target images were captured and ICC profiles generated for this portion of the evaluation, they were processed with ColorThink Profile Inspector and the gamut volume data recorded for each instance. Initial review of the data showed unexpected and inconsistent variances in the values obtained and suggested that factors other than the ISO values were affecting the results.

The procedures used in processing the RAW images called for neutralizing the image using the middle gray patch on the QPCard 101 v2 captured in the image area. Additionally, minor exposure (EV) corrections were necessary so the white and black patches of the target fell into this required range for the profiling procedure. These exposure corrections were made to keep the white patches as close as possible to values within the range of 230 to 240, so the exposure was maintained at a consistent value for all
targets. As previously discussed, the values of 210-245 for the white patches and values for black patches below 20, if possible, are required by i1Match to successfully create a valid profile in the advanced mode. These exposure values were generally obtained when the gray (RGB) value measured from the QPCard 101 v2, after neutralization, was held to approximately 105.

A review of the imaging processing and export procedures utilizing the Hasselblad Phocus software application revealed a possible factor that could be causing the difference to the gamut volume values. After re-accomplishing the image capture and profiling at f22, the gamut volumes obtained were still inconsistent and showed variances differing somewhat from the first set of additional data. At this point, the settings for exposure and gray values measured from the QPCard 101 v2 were reviewed for all of the RAW files, including those obtained from the original samples of the reference target. It was noted that even very small differences in the exposure values would have an affect on the gamut volume reported by Profile Inspector. There were also some differences in actual gray values saved in the data files in the configuration in which they were exported. Since the ISO sensitivity directly affects exposure values, it can be considered a factor in the gamut volume differences but not the primary cause.

A summary of the gamut volume values obtained from representative samples shows the inconsistent results. (Table 6) It can be seen from the last three rows of data in the table (Original Data) that the gray values were not as consistent for the processing of images during the initial portion of the investigation as during testing for ISO variances, although they provided sufficient values for the targets to be processed and profiles generated in the
advanced mode. Considering these values led to the sampling of two additional targets at an ISO value of 50 (Listed in the table below the ISO of 800) where the relative lower exposure, indicated by the lower gray values, produced color profiles with larger gamut volumes. When taken into account, the variances to gamut volume caused by the small differences in relative exposure are in the range of three to five percent when the overall exposure is maintained close to the selected values. Further evaluation of this characteristic and the encompassing subject is beyond the scope of this investigation, but the observed results (lower relative exposure producing a larger gamut volume) would seem contrary to information presented in other research on the subject of digital cameras and color gamut. [19]

Table 6

Summary of gamut volumes for ISO and exposure analysis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>947,776</td>
<td>105</td>
<td>963,126</td>
<td>104</td>
</tr>
<tr>
<td>100</td>
<td>940,390</td>
<td>105</td>
<td>934,156</td>
<td>106</td>
</tr>
<tr>
<td>200</td>
<td>943,253</td>
<td>105</td>
<td>938,185</td>
<td>106</td>
</tr>
<tr>
<td>400</td>
<td>939,445</td>
<td>105</td>
<td>948,390</td>
<td>105</td>
</tr>
<tr>
<td>800</td>
<td>924,036</td>
<td>106</td>
<td>911,402</td>
<td>106</td>
</tr>
<tr>
<td>50</td>
<td>960,198</td>
<td>98</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>1,002,210</td>
<td>88</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Original Data</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50 HF Fluor.</td>
<td>971,522</td>
<td>95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200 HF Fluor.</td>
<td>916,974</td>
<td>105</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>200 Photo Strobe</td>
<td>973,535</td>
<td>101</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Image Quality and Performance Analysis

With the current availability of standards based systems that can be used to evaluate the performance of digital imaging systems, a more comprehensive analysis of equipment and procedures can be made than with traditional photographic quality assessment techniques. This investigation utilizes a number of standards based image quality metrics and a comparison of the images captured through the transparent materials and control target to assess the possible effects that the materials have on image quality. Data output from the GoldenThread™ software was reviewed for each of the four sample targets that had been processed. The data exported to the Microsoft Excel spreadsheets provided an overview of the quality metrics associated with each individual target. The raw data available in the Microsoft Access database made it possible to compare a number of the metrics between all four of the targets. The capability to export selected information from the database to additional Excel spreadsheets allowed for the creation of the graphical comparisons that follow.

The data produced by the GoldenThread™ software is based on functions of Spatial Frequency Response (SFR), the Opto Electronic Conversion Function (OECF) and Noise Power Spectrum (NPS). The application provides a number of ways to view the data from each of the functions. For example, the Raw SFR curves generated for each of the five regions of the Device-level target are included in the data output to the Excel spreadsheets. (Figure 7) These basic SFR data are used for the registration and various resolution metrics provided by the system, and are based on the 10 “features” of the slanted-edge regions of interest (ROI) on the target. [20]
Figure 7. Example of SFR curves produced by GoldenThread™ at f8

Not all of the detailed information available from the system was included in the analysis of the four targets used for this investigation. The primary areas of concern and basis of analysis are the measures of color registration, resolution, tonescale, uniformity, color, and neutrality and noise. Data were compiled from the database and Excel spreadsheets to allow for the most concise comparison of the specific metrics for each area of analysis. Also, as the primary purpose of this investigation was to assess the variances to imaging quality defined by physical imaging parameters [7] of the selected samples when the digitization process includes the use of a transparent material between the capture system and original, the specific performance variances of the capture equipment itself were not analyzed in depth.
Color Registration

The color registration metric is measured as a function of the slanted-edge ROI on the target as part of the SFR calculation. Also referred to as “color plane registration”, it describes how accurately the color records are stored in register or the degree to which the color planes are coplanar. [21,22] Results are for each of the five ROI with the results given in pixels for both red and blue channels compared against the green channel. [22]

The legend on the right side of the graph (Figure 8) indicates the image data files compared and contain the abbreviation used to designate the specific target, i.e. NG = no glass, PG = plate glass, SF = Starphire® glass, and AC = acrylic. (The abbreviations are applicable to all graphs in this section.)

Figure 8. Color registration differences in pixels
As can be seen in the comparison, there are slight differences between each of the four samples. The aim of this metric was determined to be .3 pixel based on the example for “excellent” listed in the Digital Imaging – Quantitative Performance Guidelines. [23] These samples show very good color registration in that all values have a less than a .12 pixel mismatch, and the largest variance between any two samples is about .05 pixels. This would indicate that the use of an intermediate material in the digitization process would not be a factor affecting the color registration of captured images.

Resolution

Two metric types were analyzed for resolution, a comparison of the average optical resolution or relative resolution and the sampling efficiency. The average optical resolution comparison was based on the 10% SFR values calculated from the targets. This calculation is for both the horizontal and vertical directions for red, green, blue and a weighted neutral [24] for each of the five slanted-edge regions of interest (ROI) on the target. The 10% or 0.1 values of the SFR curves are considered the limiting resolution of a device and translate into the relative resolution used in the comparisons. [25]

The following graph (Figure 9) is a composite of the data obtained from all ROI on each of the four targets. All data are represented, but only the labels for green and neutral are listed due to the size of the graph. The first point indicates the actual sampling frequency or dpi of the captured images, approximately 600 dpi. The next four points show the average optical resolution for both horizontal and vertical directions of the SFR curves, approximately 500 dpi. The CC_V (vertical) and CC_H (horizontal) points for
Figure 9. Resolution comparison for 10% SFR (optical resolution)

the TGT_NG plot compares directly to the SFR curves represented on the graph of spatial frequency response curves for the center ROI on the target as shown in (Figure 7).

Sampling efficiency was also evaluated for each of the four targets. “For the device-level target, Average Optical Resolution is the average of the five locations in both directions for each color.” [26] These results are defined as a percentage and represented on the graphs (Figures 10-13) separately for the control target and each of the transparent materials used. The actual sampling rate for each example is shown as being slightly over 600 dpi. Sampling efficiency, as listed on the left side of the graphs, for all of the targets combined, indicate values in the range of 81.5% to 83.5%. These values are very close for each of the samples evaluated and show that the
Figure 10. Sampling efficiency for target with no intermediate material

Figure 11. Sampling efficiency for target with plate glass
Figure 12. Sampling efficiency for target with Starphire® glass

Figure 13. Sampling efficiency for target with acrylic sheet
introduction of an intermediate material during the image capture process has little effect. The maximum variance of only about two percent across all target conditions and relative values in the same range are evidence that system performance is relatively stable. As a measure of the system performance a sampling efficiency of slightly over 80% would be considered a “normal” performance level aim per the Digital Imaging – Quantitative Performance Guidelines. [23] The aims recommended by these guidelines are still being revised, but provide goals to be considered for overall system performance evaluation.

As previously explained, an f-stop of 8 was used for this portion of the investigation to provide for better image definition and help optimize data output from the software. This function of the digital camera setup might be optimized further with additional experimentation. The use of this configuration with a lens opening closer to the critical aperture of the camera did provide for a higher optical resolution as compared to samples taken during initial testing of the system with an f-stop of 22. Optical resolution and uniformity of sampling efficiency in both the horizontal and vertical direction can be affected by the configuration of the image capture system. This can be seen in (Figure 14) showing the SFR curves produced when the target was captured using an aperture of f22. At this smaller aperture, the SFR curves are much closer and more uniform as compared to the sample shown in (Figure 7) for the target captured at f8. It can also be seen from this example that the 10% value for frequency is only about 400 dpi. The Digital Imaging – Quantitative Performance Guidelines would consider this value, for optical resolution, a “poor” aim point. [23]
Figure 14. Example of SFR curves produced by GoldenThread™ at f22

**Tonescale**

A measure of the tonal reproduction and exposure, the “tonescale analysis” is based on the OECF, an ISO standard of measure for signal encoding. [27] This metric is a measure of the 12 gray density patches on the target. The analysis is a comparison of the differences calculated from the digital values of each of the 12 target patches and a defined aim point (plus and minus five for the active profile). [28] A representation of the values shown as the difference versus density of the patches is illustrated by the graphs for each of the targets in (Figures 15-18). A review of the plots show that all the values fall well within the aim and except for the light patches of
Figure 15. Tonescale difference from aim with no intermediate material

Figure 16. Tonescale difference from aim with plate glass
Figure 17. Tonescale difference from aim with Starphire® glass

Figure 18. Tonescale difference from aim with acrylic sheet
the target captured under Starphire® glass, all values are within the range of plus and minus two, or less than half of the aim. Although the slight variation with the Starphire® glass may indicate a minimal degradation, the aim points for all the samples fall within the “excellent” performance measure provided by the Digital Imaging – Quantitative Performance Guidelines. [29]

Uniformity

“Uniformity is a measure of the difference in Code Value (CV) for identical patches located in different locations in the image.”[30] The graph in (Figure 19) represents a composite of all values calculated for all four targets analyzed. The first five sections are the comparisons of the five features on

Figure 19. Image uniformity comparisons for all sample targets
the target for the center and four corners. The sixth section represents the averages of each color and luminance, and the last indicates maximum difference, which is slightly less than a value of three for all samples. From this data, it appears that the tonal uniformity across the targets sampled is very stable and that little difference can be seen between the control sample and targets with the intermediate material. For this metric, the Digital Imaging – Quantitative Performance Guidelines [23] recommends an aim of zero, so the tolerance values for these samples equate to a performance level of “very good” for this configuration.

**Color**

Because the GoldenThread™ system includes the capability to evaluate color accuracy, this metric was included in the investigation as a second method of identifying any possible inconsistencies in color output from the system when using an intermediate material in the digitization process. X-Rite, Inc. supplies the 18 color patches for the GoldenThread™ target that are the same as on a ColorChecker™ target. The measurements are calculated from RGB digital values to L*a*b* using the ΔE2000 method. [31] Currently, the color space for conversion is limited to a small number of presets, so Adobe RGB was selected. For this comparison, a graph of the combined output showing the maximum ΔE2000 values was generated from the database for all four targets as shown in (Figure 20). There are 30 patches represented in the sample, which include the 18 color patches and 12 density patches (plots 10 through 21 are for density). Once again, there are only small differences between the relative values of the four targets. The maximum
values are lower than the values obtained in the previous section due to the \( \Delta E_{2000} \) calculation. Except for the Starphire\textsuperscript{®} glass plot of patch number 23, all values fall below the specified tolerance for Color Encoding Error of six \( \Delta E_{2000} \) that is considered an “excellent” performance level by the \textit{Digital Imaging – Quantitative Performance Guidelines}. [29]

Neutrality and Noise

There are two additional metrics that the system software is able to produce, both of which are based on the 12 neutral tonescale patches. The neutrality of the patches is a measure of how close the device’s color channels are to one another. [32] The noise metric is a representation of the OECF measurements for each of the patches characterized by the
standard deviation of the root mean square (RMS) counts for each patch. [33]

The data generated by the systems for these metrics is described by the following quote: “For each of the twelve neutral patches, the neutrality and noise are measured and compared to specifications. Neutrality is measured as the difference in average code value between the green channel and the red or blue. Noise is the standard deviation of the code values in these same areas.” [34]

A graph depicting the combined neutrality values for the four targets is shown in (Figure 21). The values displayed are all very close again, with the maximum variance being a difference of only .7 in the negative. The aim point defined in the active system profile was a value of plus or minus four.
The graph representing the noise (total noise) metric in (Figure 21) also shows relative low values compared to active system profile aim of four (4). Even the points for the Starphire® glass that are double the values of the other plots are within the acceptable tolerance for the Digital Imaging – Quantitative Performance Guidelines [29] “excellent” performance level value of less than 2.5. The variance in this metric for the Starphire® glass, along with other minor variances previously noted for the same material, should be taken into consideration in the selection of a transparent material to be used in the digitization process.

Figure 22. Noise comparisons for all sample targets
DISCUSSION

This investigation was initiated to obtain an understanding of the possible effects imparted on the color correction of images captured through a transparent material, such as glass, by a digital camera. The analysis of image quality and performance was subsequently completed using the same materials and configuration, with high frequency fluorescent lighting, as in the color portion of the investigation. Practices involving this method of positioning materials for image capture are common, but in an effort to understand optimal conditions for the highest quality image capture, this specific factor required analysis in greater detail. In addition to the data that were recorded during accomplishment of the procedures described, a number of factors were noted that affected specific results associated with use of the lighting equipment and the transparent materials analyzed.

In configuring the equipment for the color profiling analysis with the two different lighting systems, the high frequency fluorescent lamps proved to be the most easily arranged to obtain the required even and balanced illumination of the target. Ambient light measurements were very consistent and any required adjustments were not difficult to make. Because the target object was continuously illuminated at full intensity, it was much easier to obtain proper object positioning and camera adjustments for framing and focus. Continuous lighting also allows exposure adjustments to be based on a fixed aperture setting, allowing for more control of the depth of field by increasing the length of exposure, and still maintaining an optimal relative
ISO sensitivity value. The use of the high frequency fluorescent lamps also provided for a more consistent configuration with the required changes to exposure and sensitivity during the Image Quality and Performance Analysis portion of the investigation.

The use of the two photo strobes proved to be more complex and a number of factors needed to be resolved before the desired even and balanced lighting was achieved. Initially, an umbrella “soft box” configuration was tried, where the photo strobe light was directed toward the target with translucent material in front of it diffusing the light. This configuration provided more light on the target and color temperature measurements of 6300K were closer to the photo strobes advertised 5600K output than the final configuration. Although it was possible to obtain balanced ambient light readings of the target area, numerous adjustments to the configuration failed to provide sufficient distribution of light to obtain a target image that could be properly processed by i1Match.

At this point, a different configuration was tried where the light from the photo strobe was “bounced” off a white reflective umbrella back to the target area. This configuration provided less actual light to the target area and a measured color temperature of 7800K for the reflected light. After a number of adjustments to the position of the photo strobes, images could be captured that had adequate even lighting and patch densities for the profiling process. Images captured with this configuration also displayed various reflections from the camera and surrounding environment when photographing through the transparent materials and adjustments had to be made. Black foam core board was used to surround the camera lens and block reflections from
reflective materials on the ceiling, thus eliminating these reflections.

Although difficulties were encountered in configuring the tests for photo strobe lighting, results of the ICC profiling provided slightly better ΔE values. For effective results, the use of this type lighting will require additional factors be taken into account. In the specific environment tested, more powerful photo strobes would possibly allow for a broader range of exposure settings. Additionally, the use of four photo strobe lamps should provide more even and consistent illumination of the target area than two lamps as used in the investigation. A reference for this is section 62.2 Illumination of the original, in Applied Photographic Optics. [35]

The data for the image files with the source color space (Hasselblad RGB) indicate relatively consistent and low ΔE values (6-8 ΔE) for all images analyzed. It can also be seen that with the specific equipment used, the ICC profiles generated will provide for a correction of approximately three (3) ΔE or less for each of the targets profiled. Gamut volumes for the first two configurations used are also relatively close (<3.6% difference). Analysis of the TIFF image files show minimal variance between the ΔE values of the profile evaluation and those of the ΔE values calculated from the target image with the profile applied and measured in ColorThink.

Analysis of the additional data available from the reports saved out of the Color Worksheet comparisons provided additional insight into the quality of the generated color profiles and their ability to correct for the tonal variations imparted by the transparent materials used during the capture process. The overall results from this additional analysis indicate minimal variance between the values evaluated for each of the four target samples.
There were differences in the values and colors being affected between the two lighting systems tested, but the color profiles were able to correct for the tonal variations of the transparent materials to acceptable ΔE values for each of the systems. Analysis indicated that the average ΔE values for color corrected images of the targets captured using photo strobe lighting are slightly less when compared to the measured reference data and that the minimum, maximum and standard deviation values are also lower than those of samples captured with the high frequency fluorescent lighting. Of note for this portion of the investigation, is that the average and maximum ΔE comparisons between the actual reference target, and those of targets captured with transparent materials and photo strobe lighting, are higher than comparisons made using high frequency fluorescent lighting. This provides evidence that although the average ΔE values are slightly lower with the photo strobe lighting, the actual profiles being generated may be less consistent than those of the high frequency fluorescent lighting setup. Factors contributing to this difference could include reflections caused by the setup, the difference in color gamut, or the measured color temperature of the lighting. Further investigation of the photo strobe lighting system with more powerful lamps or larger aperture settings may be of interest to evaluate any possible differences in this area.

The data evaluated to determine a possible cause for the variances in the gamut volume, when higher ISO sensitivity values were used, proved to be unique and somewhat inconsistent as described in the analysis section. The overall cause for the observed differences appears to be a function of small exposure value changes to the RAW image before exporting it to a
specified file type, i.e. TIFF. Although additional samples were created where a decrease to the exposure value caused the profile gamut volume to increase, this may not be a consistent or proper way to adjust exposure values for digitization workflows. This portion of the investigation provided information to the possible reasons for the variances, but as described in the analysis section, would appear to be contrary to the determination of a proper exposure. Further investigation into the conditions associated with the specific equipment and software used for the analysis are needed to evaluate and better understand the results produced and determine if any modifications to capture procedures should be made.

The image quality and performance analysis portion of the investigation provided insight into a number of methodologies that can be used to evaluate digitization systems and the “quality” of the images being captured. The three systems evaluated for use in this investigation are all based on standards and provide various forms of data relating to performance metrics. Certifi Pedigree® from Certifi Media Inc., provides a comprehensive suite of tools including both software and targets that can be used to qualify equipment and imaging performance. Evaluation of the version available for testing indicated that it was optimized for large-scale digitization projects with high production rates and could be very effective for projects capturing lower resolution images or for improving the “quality” of images to be processed by optical character recognition. ImCheck3v1 is a free download from Image Science Associates and can produce various forms of data depending on the type target being used (targets can be purchased or obtained from various sources). There are limitations to the types of data
available from this program, but basic metrics can be evaluated to determine equipment or image performance. It provides quality information within its limits, but is not as comprehensive as the GoldenThread™ system used for this investigation.

The performance data produced by the GoldenThread™ system used in the investigation provided a comprehensive set of metrics that were used to evaluate the overall effects of including a transparent material between the capture system and original during the digitization process. The numerous tests performed with the system to determine the optimum conditions needed to produce the data set for analysis, provided an increased awareness of the complexities associated with image capture using a digital still camera. Once a standardized configuration was achieved, the results provided data that could be readily evaluated to confirm and compare the image performance metrics. Except for the optical resolution produced by the system, as configured, all of the metrics analyzed proved to meet the higher quality aim points defined by the guidelines referenced. Continued evaluation and optimization of the system configuration using the information obtained from this investigation will allow the highest quality production to be maintained.
CONCLUSION

Including color management and performance analysis in image capture workflows for materials being digitized with systems and equipment similar to those used in this investigation, is of interest if the most accurate representation of the original item is desired. This analysis provides an indication as to the suitability of three possible materials that could be used to flatten or position pages of a book or document. Within the accuracy and capability of the image capture and testing procedures, the data indicate there are minimal acceptable differences between an uncovered target and one covered with any of the three tested materials. This is provided that the lighting equipment used is correctly adjusted and an ICC color profile is properly generated and attached to the captured image. Results of the data compiled for both the color profiling and the image quality and performance analysis are of interest, due to the fact that the Starphire® Ultra Clear glass generally returned values of the largest variance as compared to the other materials. Although these results were not expected, common assumptions about a “highly transparent” or “ultra clear”, and relatively expensive, material having a lesser effect on color than standard glass when used under conditions similar to this investigation proved to be inaccurate. Although the variances are relatively small, the Starphire® glass also exhibited an effect that caused “noise” spikes for various areas of the target when analyzed for this metric. It should be noted that the ordinary “plate glass”, which generally has a visible green tint, proved to function as well as or slightly better for the
majority of all analyses performed than the other samples. Due to its lower relative cost, and being readily available, it should be considered an optimal material for use in the digitization process. For specific applications, the acrylic sheet could also be a suitable alternative, although increased susceptibility to scratching and attraction of dust need to be taken into account.
REFERENCES


[23] Digital Imaging – Quantitative Performance Guidelines, Draft 0.20, (Still Image Working Group, Categories and Objectives sub-group, October 5, 2009) pg. 4. [Appendix]


[29] Digital Imaging – Quantitative Performance Guidelines, Draft 0.20, (Still Image Working Group, Categories and Objectives sub-group, October 5, 2009) pg. 5. [Appendix]


[33] Digital Imaging – Quantitative Performance Guidelines, Draft 0.20, (Still Image Working Group, Categories and Objectives sub-group, October 5, 2009) pg. 3. [Appendix B]


Appendix

Digital Imaging – Quantitative Performance Guidelines
Digital Imaging – Quantitative Performance Guidelines
Draft 0.20
October 5, 2009

How to Use the Tables

The following are individual measurement criteria that provide the aim point and tolerances for imaging specifications based on a four-tiered performance model. These performance levels can be variably combined with respect to content type and imaging objectives. For instance, a sample specification is shown in Table 1. On the left is the metric name followed on the right by a 1 to 4-star specification code. In italics to the right is a description of the code. The performance level is largely driven by the TOLERANCE (i.e. allowable variability about the AIM). The tighter the tolerance level, the better the performance, and generally, the higher the cost. The "Qualifier" column allows specific user preferences with regard to the aims or tolerance.

Under the Still Image Working Group, there is a Categories and Objectives sub-group. This sub-group is in the process of developing a matrix that will map to the very type of multi-tier model used in the Quantitative Performance Guidelines. The work of this sub-group can be viewed here - http://digitizationguidelines.gov/stillimages/subcommittees.html

This imaging performance guideline model allows for real-world projects where a strict tolerance in one metric does not necessitate strict tolerances across the board. Referencing the system used in this table, a project may require a minimum four-star performance level for color encoding, but may only require a two-star performance level for illuminance non-uniformity.

Two of the listed metrics include notes describing advances we expect to put forth in these areas. But rather than delay this guideline, we’ve included what we consider to be acceptable measures while outlining the advances we expect to develop for future versions.

Finally, because some of the terms included in this table are specialized or subject to alternate interpretations, we have included a glossary in the second tab of the worksheet.
DEFINITIONS AND SUPPORTING INFORMATION FOR TECHNICAL TERMS

**Color Channel Misregistration:** A spatial shift of colors in an imaged object that is otherwise coincident in the object itself. This metric is one form of chromatic aberration. It is measured in both the horizontal and vertical directions and is usually more pronounced near the boundaries or borders of the field of view (FOV). It is sometimes referred to, qualitatively, as color fringing. Color channel misregistration is measured in number of shifted pixels relative to a chosen reference color plane. It is derived from SFR measurements of ISO 12233, 16067-1, and 16067-2 and is an informative annex to the former of these. Reference #1 describes the measurement more fully.¹

**Color Encoding Error:** The perceptual difference (Delta E) between physically measured input colors and their intended rendering to a given color space. The standard definition for this metric comes from The International Commission on Illumination (CIE). This metric can vary considerably depending on the chosen colors under consideration, the particular formula used for calculating color encoding error, and the chosen rendering intent or color space. Since this initiative deals only with digital capture imaging performance and not the actual displayed color reproduction, vis-à-vis a monitor or printer, reference only to the intended encoding is provided.

**Illuminance Non Uniformity:** The extent to which the total lighting effect of a camera or scanner's field of view (e.g. document size) is not uniformly illuminated. This effect includes non uniformity due to lighting of an object as well as the light fall-off (aka, shading or vignetting) within the camera itself. It is measured as a ratio between the maximum and minimum illuminance difference to the average illuminance for a specified object size. This metric is a form of radiometric noise weighted by the color response of the human eye.

**Resolution:** The spatial frequency or sampling frequency associated with a specified SFR level. Limiting resolution is often associated with the 10% SFR level and is a high frequency measure. It can be directly derived from historical Rayleigh resolution criteria. Another mid frequency measure is typically specified at the 50% response level.

**Sampling Frequency:** The reciprocal of the center-to-center distance between closest adjacent pixels. The number of samples per unit distance. Usually specified in terms of dots per inch (dpi) or pixels per inch (ppi) relative to the object being digitized.

**Spatial Frequency Response (SFR):** 1) A descriptor of an imaging system’s ability to maintain the relative contrast of input stimuli of a given spatial frequency. 2) A spatial frequency descriptor of an imaging system’s ability to maintain the relative contrast of features within a given spatial proximity. The metrology protocols for SFR are well

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established and are articulated in several ISO standards. They are ISO 12233, 16067-1, 16067-2, and 15524.

**Tone Response (OECF):** The characteristic behavior of an electronic imaging device to light stimuli. It is presented as a graphical curve plot that associates a camera or scanner's digital response on the vertical axis (i.e., count values) with a known amount of input light stimuli on the horizontal axis (i.e., optical reflectance or density). ISO 14545 is the reference for this standard.

**Total Noise:** The standard deviation, in RMS (Root Mean Square) counts, of a selected region of interest (ROI) for spectrally neutral target patch. The techniques described in ISO 15739 are used for this measurement.

**White Balance Error:** The difference between color channel responses for a range of spectrally neutral input stimuli – sometimes called gray balance or neutral balance. The measurement techniques of ISO 14545 applied to individual color channels are used to perform this measurement.
# Digital Imaging - Quantitative Performance Guidelines

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Level</th>
<th>Qualifier</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Frequency</td>
<td>****</td>
<td>xxx (dpi)</td>
<td>ARO = xxx (dpi)</td>
</tr>
<tr>
<td>Resolution (SFR)</td>
<td>**</td>
<td>native, subpixel, user-defined</td>
<td>Moderately weak correlation for subpixel or non-native sampling resolutions</td>
</tr>
<tr>
<td>Illuminance Non-uniformity</td>
<td>**</td>
<td>A2, A3 (%)</td>
<td>Performance level 2 of 99% FOV, A2 format</td>
</tr>
<tr>
<td>Color Channel Mis-registration</td>
<td>***</td>
<td>A</td>
<td>Performance level 2 of single feature test</td>
</tr>
<tr>
<td>Interpolated Color Quality</td>
<td>***</td>
<td>2.1, 0.64 OCTO</td>
<td>Performance level 2.1, 0.64 OCTO</td>
</tr>
<tr>
<td>White Balance Error</td>
<td>****</td>
<td></td>
<td>Performance level 4</td>
</tr>
<tr>
<td>Total Noise</td>
<td>**</td>
<td></td>
<td>Performance level 2</td>
</tr>
<tr>
<td>Color Encoding Error</td>
<td>****</td>
<td>sRGB, 2009 (ss, sRGB)</td>
<td>Performance level 2 of ssRGB encoding, sRGB at percent, rendering intent, and/or color profile</td>
</tr>
<tr>
<td>Geometric Distortion</td>
<td>TBC</td>
<td>TBC</td>
<td>TBC</td>
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<td></td>
<td>TBC</td>
<td>TBC</td>
<td>TBC</td>
</tr>
</tbody>
</table>

## Key to Performance Measures Charts

- **Excellent**: Archive Model
- **Very good**: Moderate repurpose
- **Normal**: Often
- **Poor**: Web access

## Sampling Frequency

**Performance Level**

- ARO: TOLERANCE
  - ARO: 90% of ARO
- ARO: 72% of ARO
- ARO: 50% of ARO
- ARO: 25% of ARO

## Resolution - Spatial Frequency Response (SFR) - high frequency (note 1)

- For both horizontal and vertical directions equally
- ARO = 20% SFR

**Performance Level**

- ARO = 20% SFR
  - ARO = 20% SFR
- ARO = 20% SFR
- ARO = 20% SFR

## Resolution - Spatial Frequency Response (SFR) - mid-frequency (note 1)

- For both horizontal and vertical directions equally
- ARO = 20% SFR

**Performance Level**

- ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR

## Illuminance Non-uniformity

**Performance Level**

- ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR

## Color Channel Mis-registration

**Performance Level**

- ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR
  - ARO = 20% SFR

### Notes

1. A more unified approach to aim and tolerances for resolution is currently being investigated by specifying the full SFR behavior. While it is recognized that the solution (illustrated here) is a single point derivative of SFR, it is also accepted that more study and agreement is required before introducing full SFR guidelines, especially with respect to sharpening operations. Just as there are performance specification limits for single point resolution metrics in a full DECF description, similarly single point resolution metrics will move to full SFR specification description. Suitable software tools and reporting methods also need to be developed before this can occur.
### Tone Response - (OECF)

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>AIM</th>
<th>TOLERANCE [ 8 \text{ bit equivalent} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>★★★★</td>
<td>0</td>
<td>+/- 3 count levels</td>
</tr>
<tr>
<td>★★★</td>
<td>0</td>
<td>+/- 4 count levels</td>
</tr>
<tr>
<td>★★</td>
<td>0</td>
<td>+/- 5 count levels</td>
</tr>
<tr>
<td>★</td>
<td>0</td>
<td>+/- 6 count levels</td>
</tr>
</tbody>
</table>

### White Balance Error

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>AIM</th>
<th>TOLERANCE [ 8 \text{ bit equivalent} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>★★★★</td>
<td>0</td>
<td>+/- 3 count levels</td>
</tr>
<tr>
<td>★★★</td>
<td>0</td>
<td>+/- 4 count levels</td>
</tr>
<tr>
<td>★★</td>
<td>0</td>
<td>+/- 5 count levels</td>
</tr>
<tr>
<td>★</td>
<td>0</td>
<td>+/- 6 count levels</td>
</tr>
</tbody>
</table>

### Total Noise (note 2)

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>AIM</th>
<th>TOLERANCE [ 8 \text{ bit equivalent} ]</th>
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</thead>
<tbody>
<tr>
<td>★★★★</td>
<td>0.5</td>
<td>&lt; 2.5 count levels (rms)</td>
</tr>
<tr>
<td>★★★</td>
<td>0.5</td>
<td>&lt; 4 count levels (rms)</td>
</tr>
<tr>
<td>★★</td>
<td>0.5</td>
<td>&lt; 5.5 count levels (rms)</td>
</tr>
<tr>
<td>★</td>
<td>0.5</td>
<td>&gt; 7.5 count levels (rms)</td>
</tr>
</tbody>
</table>

### Color Encoding Error (Delta E 2000)

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>AIM</th>
<th>TOLERANCE [ \text{choose option A or B} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>★★★★</td>
<td>0</td>
<td>A: 6 E (Y/20) B: 0.6 E (Y/20)</td>
</tr>
<tr>
<td>★★★</td>
<td>0</td>
<td>&lt; 10 &lt; 5 &lt; 3 &lt; 3</td>
</tr>
<tr>
<td>★★</td>
<td>0</td>
<td>&lt; 10 &lt; 5 &lt; 3 &lt; 3</td>
</tr>
<tr>
<td>★</td>
<td>0</td>
<td>&gt; 10 &gt; 5 &gt; 3 &gt; 3</td>
</tr>
</tbody>
</table>

Note 2 – In the future this section may be complemented or replaced with a signal-to-noise (SNR) section. In theory, SNR is a superior and more robust method for specifying the effects of noise on imaging performance. In practice though, challenges remain on its use in imaging environments. In short, the tools and experience for measuring SNR in fluid conditions are limited at this time.