Senior Research

Evaluating a Camera for Archiving Cultural Heritage

Final Report

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Abstract

A characterization of both the color and spatial image quality of a camera was performed in order to find out if the camera is good enough to capture detail in paintings for cultural heritage applications (artwork preservation). The following primary factors that affect color and spatial image quality were characterized: spatial uniformity, tone reproduction, color reproduction accuracy, noise dynamic range, spatial cross-talk, spatial frequency response, color-channel registration and depth of field. In addition, a usability study was performed on Erin P. Murphy's method for characterizing a camera. A Sigma SD9 was found to not be good enough for cultural heritage application. The methods for evaluating a camera are easy; however, there were some difficulties during the experiment. In addition, some improvements to her method should be considered such as more specific guidelines for the values of the criteria and also suggestions could be made as to whether a camera that excels in most areas but fails one or two tests would still be useful

Acknowledgments

The author would like to thank Dr. Roy S. Berns for being my advisor, Lawrence Taplin and David R. Wyble for helping with the experiments and Geoff Franz for helping to edit this thesis.

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Introduction

The goals of this project are to evaluate a camera for cultural heritage applications, specifically artwork preservation, and also to perform a usability study in order to evaluate a method for evaluating a camera and seek to answer the question, "How easy is it to use this method to perform the necessary imaging and then analyze the results?"

The reason art conservators want to preserve artwork is because the artworks are changing over time, especially the color of the painting due to aging and instability in the pigments. Not too many years ago, art conservators preserved the artwork by taking a picture using a film camera because good digital cameras cost tens of thousands of dollars and they did not have the necessary image quality. Now, instead of having to clean the artwork once in a while in order to keep the artwork clean and to make it last longer, it can be measured once and restored digitally without having to use chemicals that might damage the artwork.

Thanks to advancements in technology, art conservators nowadays are using digital cameras to preserve the artwork. They want to use the best camera available in order to get the best possible reproduction. "Digital capture systems have a very efficient workflow compared to traditional methods, based on scanning photographic negatives and transparencies. In addition, the linearity of the initial image capture in digital systems makes it possible to specify the spectral information captured much more accurately than is possible with film system" (Farrell). Cost, accuracy and ease of preservation have greatly improved with the latest digital cameras.

Characterizing the camera is an important step in finding out if the camera is acceptable for cultural heritage application because highly accurate images are needed for artwork preservation. An accurate reproduction of artwork is significant not only for conservation, preservation and restoration, but also for historical purposes (Day, 2003)

If this camera is suitable for museum archives, it will make it easier for museums to preserve their artwork. They do not have to wait to develop the film and they do not have to worry about the properties of the film changing. They can see the image right away and if they do not like it, they can delete it and take more pictures. Besides that, they do not have to make prints of all the images – they can store it in the computer if they wish. Digital cameras also have less noise. Using a digital camera also has fewer steps in the workflow compared to film cameras, since there is no film to be scanned and there is no film to characterize.

Artworks are part of cultural heritage and history. Every country has a unique culture that produces a variety of artwork. By preserving cultural heritage, people will be able to more easily learn about current cultures in the future.

Background

Characterizing a camera is something that is commonly done in order to determine the image quality of the camera. This determines the quality of the output that is produced by the camera. A method for characterizing a camera for cultural heritage was proposed by Erin P. Murphy (Murphy, 2005). Her method involves measuring system spatial uniformity, tone reproduction, color reproduction accuracy, noise, dynamic range, spatial cross-talk, spatial frequency response, color-channel registration, and depth of field. Most of the methods that she used are standards published by the

ANSI (American National Standards Institute), the ISO (International Organization for Standardization), and the IEC (International Electrotechnical Commission). Her method can be applied to a three channel camera as she proposed, or it can be easily adapted to characterize a multi-channel camera.

However, it is unknown how easy or how quick her method is to implement. This paper is primarily a usability study of her methods, and seeks to answer the question, "How easy are her methods to perform the necessary imaging and then analyze the results?" The reasons for a usability study are to refine the method that she proposed and to make it easier for people in the future if somebody wants to use her method.

Image quality is usually divided into two classes: objective image quality and subjective image quality. Objective image quality is evaluated through physical measurements of the image properties; however, subjective image quality is evaluated through judgment by human observers (Frey, 1999). Spatial image quality is composed of the following metrics: system spatial uniformity, image noise, dynamic range, spatial cross talk, spatial frequency response, and depth of field (Murphy, 2005). Ideal system spatial uniformity requires the images to have even illumination and minimal lens falloff. This is measured because it is undesirable to have uneven illumination and lens falloff that cause spatial non-uniformity in the images.

When noise is present in images, it always reduces the signal-to-noise ratio. Because a high signal-to-noise ratio is desirable, noise should be minimized. Measuring noise allows for the signal-to-noise ratio to be calculated. There are four types of image noise that were measured in this experiment: total noise, fixed pattern noise, temporal noise, and black temporal noise. Total noise is the amount of noise in the final image.

Fixed pattern noise is noise that is always consistent in all exposures. Temporal noise is the noise that changes between exposures. Black temporal noise is calculated in order to evaluate the dynamic range of the camera.

Dynamic range is also known as tonal range. Dynamic range is the range of irradiance values that the camera can capture in one image. A large dynamic range preserves details in both the highlights and the shadows. Spatial cross-talk is also known as image flare. Spatial cross-talk happens when an image has a bright pixel surrounded by other bright pixels that should actually be dark.

Spatial frequency response is a detailed description of spatial resolution. The spatial frequency response is measured to determine the ability of the camera to resolve different sized objects in its field of view. Depth of field is the range of object distances that are in acceptable focus. The depth of field changes with the size of the aperture of the lens (f-number) and the object distance. As the aperture diameter decreases, the depth of field increases, and vice versa. Similarly, the further the object is, the greater the depth of field, and vice versa.

Color image quality is composed of following metrics: tone reproduction, color reproduction accuracy, color channel registration and color noise. Tone reproduction is measured and described by the Opto-Electronic Conversion Function (OECF). Tone reproduction is how lightness are reproduced. The OECF is a relationship between input intensity and the corresponding digital count output by the camera. Color reproduction accuracy measures how closely a reproduced color matches the original. For color reproduction accuracy, spectral sensitivity is the most important characteristic of a digital camera (Berns, 2001). Spectral sensitivity was analyzed because spectral sensitivity describes how sensitive the camera is to each wavelength. Ideally, a camera's spectral sensitivity should closely match the human visual system's spectral sensitivity (Berns, 2001). Strictly speaking, a camera's spectral sensitivity should be a linear transformation of the human visual system's spectral sensitivity (Ives, 1915).

Color channel misregistration occurs when a translation error is present. Correct color channel registration happens when the different color channels are correctly aligned on top of one another. Metamerism is a phenomenon in which spectrally different stimuli match to a given observer. There are two kinds of metamerism: illuminant metamerism and observer metamerism. Illuminant metamerism occurs when the pair of objects matches under one light source, but does not match under other light sources. Observer metamerism occurs when the pair of objects matches to one observer, but does not match under other observers (Berns, 2000). The difference in color reproduction between cameras is an example of observer metamerism (Berns, 2000). Color noise is the noise in the color channels.

The following table lists the standards and procedures for evaluating a camera including the test targets for each method.

	Methods	Targets
System Spatial Uniformity	IEC 61966-8 and IEC 61966-9 standards	Gray target
Tone Reproduction	ISO 14524	ISO OECF target
Color Reproduction Accuracy		
• **Spectral Sensitivity**	ISO17321-1 and IEC 61966-9 standards	Integrating sphere in the monochromator
• **Target-based Color Reproduction Accuracy**	ISO 17321-1	- Cobalt blue pigment and Esser - Gretag Macheth ColorChecker, D&H Color Rule and Pigment target charts - Gretag Macbeth ColorChecker DC - Kodak color separation & gray scale and IT8 charts - BCRA target
• **Metamerism**	IEC 61966-2-1 (1999) and IEC 62966-2-1 Amendment 1 (2003)	D& H Color Rule
Noise		
• **Image Noise**	ISO 15739	ISO Noise target
• **Color Noise**	Berns, 2000	Gretag Macbeth ColorChecker
Dynamic Range	ISO 15739	ISO Noise target
Spatial Cross-Talk	IEC 61966-8, 2001	IEC Spatial cross-talk target
Spatial Frequency Response (SFR)	Peter Burns, Slanted-Edge MTF for Digital Camera and Scanner Analysis	ISO Resolution target
Color Channel Registration	Peter Burns and Don Williams, Using Slanted-Edge Analysis for Color Registration Measurement	ISO Resolution target
Depth of Field	Peter Burns, Slanted-Edge MTF for Digital Camera and Scanner Analysis	Depth of field target

Table 1. Experiment methods and targets.

Different types of cultural heritage applications require different types of cameras. For example, a wall-sized mural would require far more resolution than a poster sized portrait. Another example is pointillist paintings which might require a higher resolution than ones painted with large brush strokes. However, it is not the goal of this paper to determine what those requirements are.

Experimental Methods and Results

The method used in this experiment was proposed by Erin P. Murphy. The testing procedure was designed for characterizing both the color and image quality of a digital camera that is used to photograph paintings to create archival quality digital master images for cultural heritage preservation or application (Murphy, 2005). Images of test targets and paintings were captured and then analyzed using a custom written program (MATHLAB) and also by visual analysis. The usability of the method was examined during the experiment.

1. Camera Description and Setup

A Sigma SD9 was characterized in the Munsell Color Science Laboratory. The Sigma SD9 is a digital SLR camera with a Foveon X3 CCD sensor. The X3 sensor can capture three distinct colors (Red Green Blue) at each pixel location. Therefore, the X3 sensor can provide more accurate information about a scene without interpolating color for full color restoration (Rush, 2002). It has a maximum resolution of 2268p x 1512p. The lens that was used is a Sigma 50 mm 1:2.8 macro. There were two Elinchrom Scanlite 1000 Watt Open Face Tungsten Lights with two small Chimera Video Pro Softboxes used for this experiment.

The following figure shows the set up when the targets were imaged.

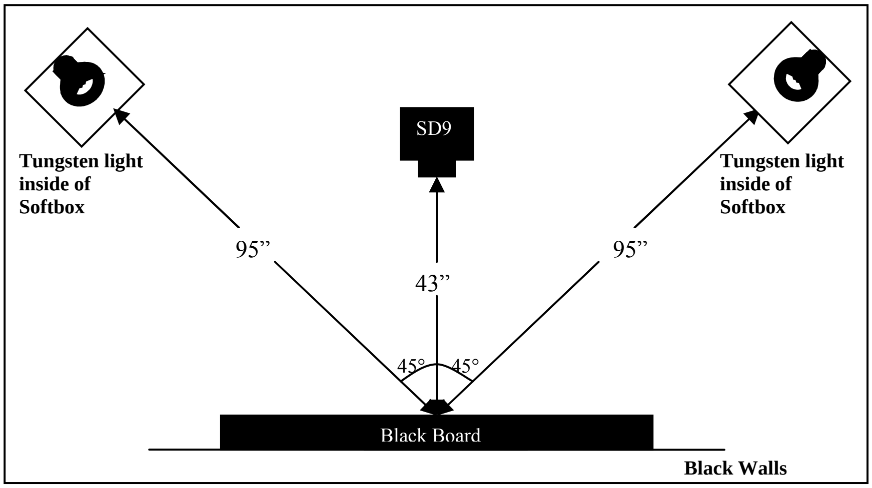


Figure 1. Setup for the all of the targets (top view).

The lights were placed at a 45° angle to the target. The targets and paintings were placed on the blackboard. When the targets and the paintings were imaged, the position of the camera and the lights remained the same, except for the depth of field target and the spectral sensitivity characterization. The lights were moved to reduce the shadow in the image when the depth of field target was captured (Figure 2). The lights were removed and the camera was moved closer to the integrating sphere when the monochromatic light was captured for the spectral sensitivity (Figure 3).

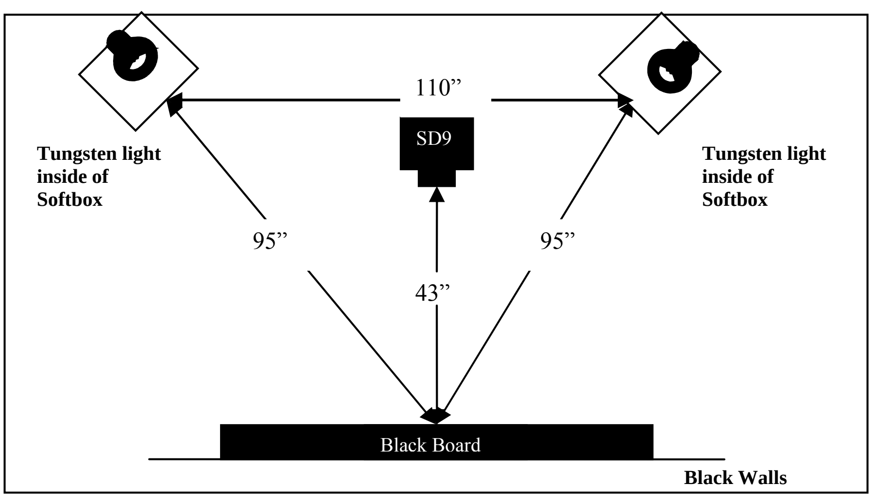


Figure 2. Setup for the depth of field target (top view).

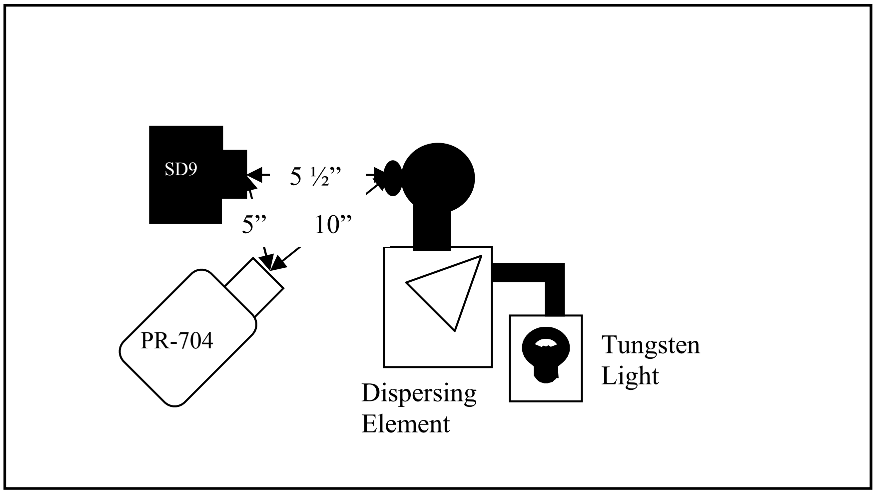


Figure 3. Setup for spectral sensitivity experiment (top view).

The focus was manually adjusted so the images were correctly focused. A white background was used to set the white balance. The exposure level was also adjusted so the images were correctly exposed. The targets and paintings were captured at f/8 for ¼ second. The ISO was set to the lowest setting (ISO 100) in order to reduce noise. The Halon was centered in the scene above each target, and was used to make sure that the exposure level was correct. The digital values in the halon target must be unclipped in order to ensure that the images as a whole were unclipped. The 2-second self-timer was used to capture the targets in order to reduce the effects of vibration. The images were transferred and saved as 16-bit RGB TIFF files.

2. System Spatial Uniformity

Figure 4. Gray card target.

A gray card target was used to evaluate spatial uniformity. The target was imaged twice. An image of the target was captured and then another image was taken with the gray card rotated180°. The two gray card images were averaged for flat fielding. However, only one of the images was used for system spatial uniformity analysis.

The gray target image was divided into 36 (6x6) evenly spaced patches. The Y tristimulus value (luminance factor) data for each of the 36 patches of the gray card target were compared to the mean image Y tristimulus value of all 36 patches together in order to calculate the percent difference between them.

3. Tone Reproduction

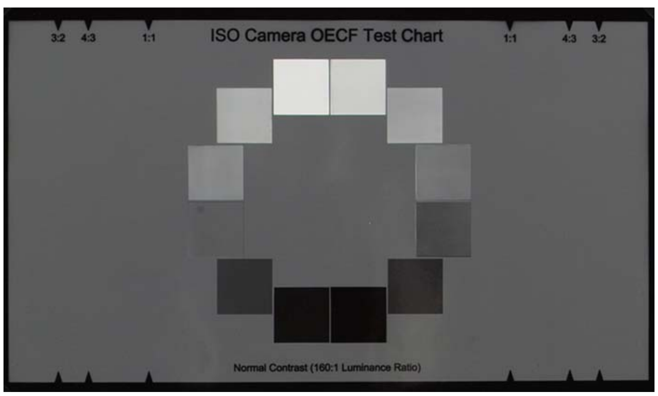


Figure 5. ISO Camera OECF (Opto-Electronic Conversion Function) Test Chart.

An ISO camera chart was used to evaluate the tone reproduction of the camera. The target was imaged three times, once correctly exposed, once 1- stop overexposed, and once 1-stop underexposed, to obtain image data over the full range of possible digital count values. The luminance (cd/m^2) was measured using a PR-704 spectroradiometer for each of the 12 patches including the Halon. The average pixel values for each patch and the Halon were normalized. The values from the under- and over exposed images were rescaled to match the values from the correctly exposed image. Then, the OECF function was fitted to each channel using a cubic spline and summarized by a fitted gamma function. The OECF functions are used to linearize the target images.

4. Color Reproduction Accuracy

Color reproduction accuracy was tested using spectral sensitivity-based and target-based color reproduction accuracy methods. Metamerism was also used as a visual analysis.

4.1. Spectral Sensitivity

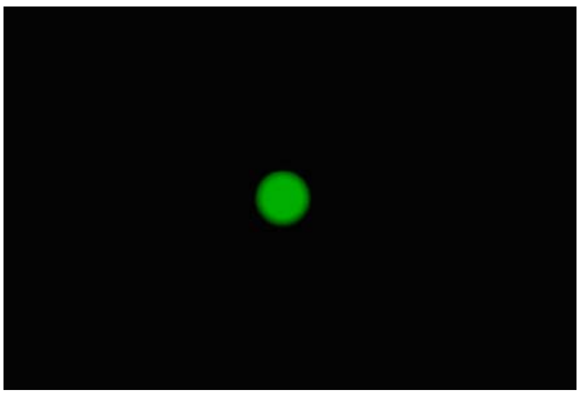


Figure 6. Integrating sphere on monochromator at 550 nm.

A single grating monochromator and PR-704 Spectoradiometer were used to analyze the spectral sensitivity of the camera. The room was darkened in order to measure spectral sensitivity. The light output from the monochromator was dim, therefore the lens was opened all the way. The camera was set to f/1.8, 1/6 second at ISO 100. The integrating sphere in the mocochromator was imaged 36 times from 380 nm to 730 nm in increments of 10 nm. Radiance values were measured with the PR-704 Spectroradiometer after each image was captured.

The averaged RGB digital values of each light output image were linearized by applying the inverse OECF curves (Figure 15) and then plotted against wavelength

(Figure 16, left). The cumulative sum of the radiance was plotted against wavelength (Figure 16, right).

The relative spectral sensitivity was calculated by dividing the linearized digital counts by the radiance at each wavelength. The values were then normalized. The relative spectral sensitivity curves were rotated to fit the CIE 2° observer color matching functions. The goodness of fit of the relative spectral sensitivity of the camera to the standard human observer can be summarized using μ-factor. The μ-factor is how closely a camera's spectral sensitivity matches the human eye's (Lutler-Ives condition).

4.2. Target-based Color Reproduction Accuracy

Figure 7. A target consisting Cobalt Blue and Esser (left) and a target consisting Pigment charts, Macbeth ColorChecker, D&H Color Rule.

Figure 8. ColorChecker DC (left) and Kodak Color Separation & Grayscale and IT8 (right).

Figure 9. BCRA (British Ceramic Research Association) target.

In order to evaluate color reproduction accuracy, five targets that consist of eight color target charts were used. Most of the color target charts are commercial standards and are commonly used to evaluate color reproduction accuracy, such as the Esser, Gretag Macbeth ColorChecker, Kodak Color Separation and Grayscale, IT8 and Gretag Macbeth ColorChecker DC. The other color target charts were picked for various reasons. A cobalt blue pigment was used because cobalt blue reflects a significant amount of light in the longer wavelength part of the visible spectrum and it is harder to reproduce with a digital camera. A Pigment chart was used because a pigment chart is made up using the same color oil paints that were used in the target paintings. The BCRA target was used because it is used as a standard for calibrating spectrophotometers. In order to evaluate color reproduction accuracy, ΔE^*_{ab} and ΔE_{00} color differences were determined between the average image data and the reference of each patch of nine color targets.

4.3. Metamerism

Davidson & Hemmendinger Color Rules were used. The lowest ΔE_{00} match between the alphabetic and numeric strips was calculated.

5. Noise

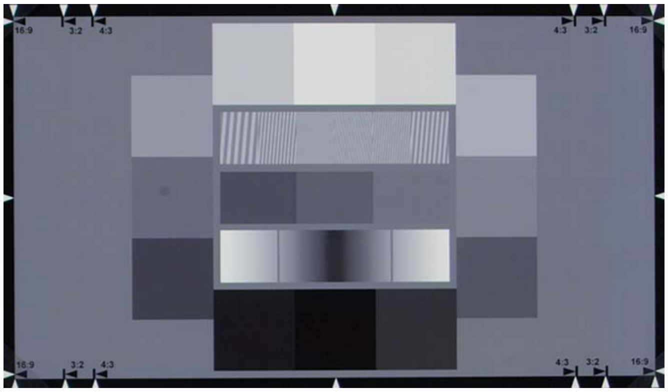


Figure 10. ISO Noise chart.

The ISO Noise chart was capture eight times with the same exposure in order to evaluate image noise.

5.1. Image Noise

The digital counts of the center three patches of the eight images were averaged. The mean digital counts and the measured reflectance values of each patch were used to calculate incremental gain. The middle patch (#13) was used to calculate the total noise, fixed pattern noise and temporal noise. The incremental gain is used to calculate the total noise signal-to-noise ratio. The darkest patch was used to evaluate the black temporal noise, which would be used to determine dynamic range. The total signal-to-noise ratio (SNR) was calculated.

5.2. Color Noise

Gretag MacbethColor Checker was used to determine the percent standard deviation and the mean color difference from the mean, MCDM (Berns, 2000).

The digital counts in the patch in the ColorChecker were averaged and normalized. Then, the standard deviation was divided by the normalized mean and multiplied by 100 to get the percent standard deviation.

The color difference ΔE^*_{ab} and E_{00} were calculated using the CIELAB image in order to determine the MCDM.

6. Dynamic Range

The darkest and second darkest patches of the ISO noise target (Figure 10) were used to calculate dynamic range. The $\log_{10}$ of the luminance ratio was calculated to find the dynamic range density values. Theoretical dynamic range (TDR) is given by equation 1.

$$TDR = \log_{10}(2^n - 1) \qquad (1),$$

where n is the number of bits per channel.

Since the Sigma SD9 camera has 12 bits per channel, the theoretical dynamic range is 3.61 density.

7. Spatial Cross-Talk

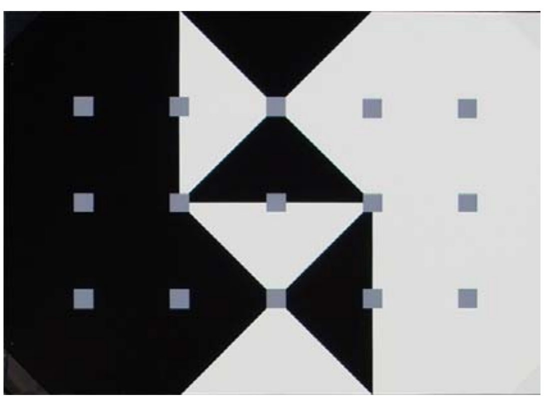


Figure 11. IEC Spatial Cross Talk target.

The IEC Spatial Cross Talk Target was used to evaluate the spatial cross-talk. The target was imaged twice. An image of the target was captured and then another image was taken with the target rotated 180° degrees. The 15 equally spaced squares in the target are used to evaluate the spatial cross-talk. The mean values of each the 15 gray patches in both images were determined. They were linearized by applying the inverse OECF look up table to each channel. Then, the percent relative maximum difference and percent relative standard deviation were calculated.

8. Spatial Frequency Response (SFR)

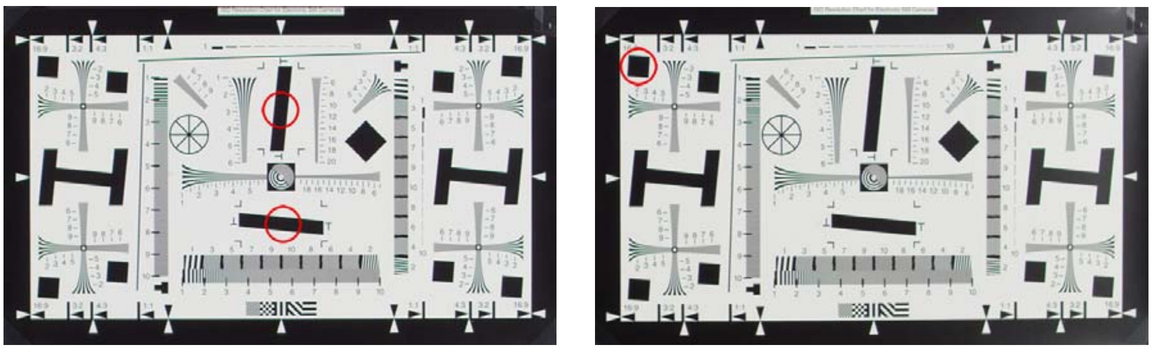


Figure 12. ISO Resolution Chart target.

In order to evaluate SFR, an ISO Camera Resolution Chart was used. The portions of the chart that were used are the black bars and squares that are slanted 5°, which are called knife edge targets.

The srfmat2 MATLAB program was used to evaluate the knife edge targets (Burns, 2000). Then, the normalized SFR curves were plotted. The normalized areas under the SFR curves of each RGB channel from frequencies of 0.0 to 0.5 cycle/pixels were evaluated.

9. Color Channel Registration

An ISO Camera Resolution Chart target was also used to determine the misregistration of the color channel. The same knife edge targets were used. The srfmat2 MATLAB program was used to analyze color channel registration (Burns, 1999).

10. Depth of Field

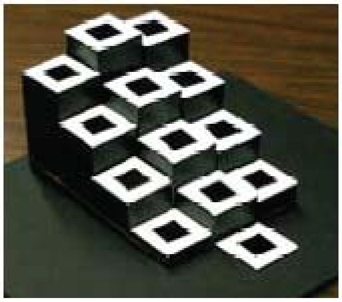


Figure 13. Depth of field target.

A depth of field target was used in this experiment to evaluate the depth of field of the camera. The target consists of 13 columns in 0.5” increments with a SRF square knife edge target on top of each of the columns. The camera was focused on the middle target. The image was analyzed using the srfmat2 program. The image of the target was analyzed in either the horizontal or the vertical direction, whichever has the better spatial frequency response (SRF). Then, the area under the SFR curve of each color channel vs. depth of field distance will be calculated. The theoretical depth of field was also calculated using a depth of field calculator.

11. Summary of the Experiments

1. Make a black background and Halon
2. Put the Halon in the top center of the scene.
3. Measure the custom white balance, adjust the exposure setting and focus point.
4. Make sure the Halon, OECF target and the Macbeth ColorChecker images are not clipped.
5. Start imaging the targets.

Target	Imaging Procedure
Gray target	image 2 times, first 0 and rotate 180
ISO camera OECF target	image 3 times: normal exposure, under and over expose, then measure the luminance of the 12 patches and Halon using the spectroradiometer
Cobalt blue pigment and Esser	image 1 time
Macbeth ColorChecker, D&H Color Rule and Pigment charts	image 1 time
Macbeth ColorChecker DC	image 1 time
Kodak color separation & gray scale and IT8 charts	image 1 time
BCRA target	image 1 time
ISO noise chart	image 8 times, same exposure
Spatial cross talk	image 2 times, capture and the rotate 180
ISO Resolution chart target	image 2 times, first focus in the center and then focus in the top left
fish painting	image 1 time
flower painting	image 1 time
Dark Images	image 5 times with the lens cap on, same exposure
Depth of field	focus on the middle, move the lights to reduce the shadow in the target
*Spectral sensitivity (different exposure setting)	image 36 times, every wavelength between 380 nm to 730 nm with increments 10 nm, then after the image captured, measure the radiance using spectroradiometer

* The room must be darkened, change the exposure setting and focus.

Table 2. Imaging procedure.

After all of the images were captured, the reference methods in the background section were followed. The usability was conducted by timing how long the experiment takes, and also determining how easy were the methods in the experiment.

Results & Discussions

1. System Spatial Uniformity

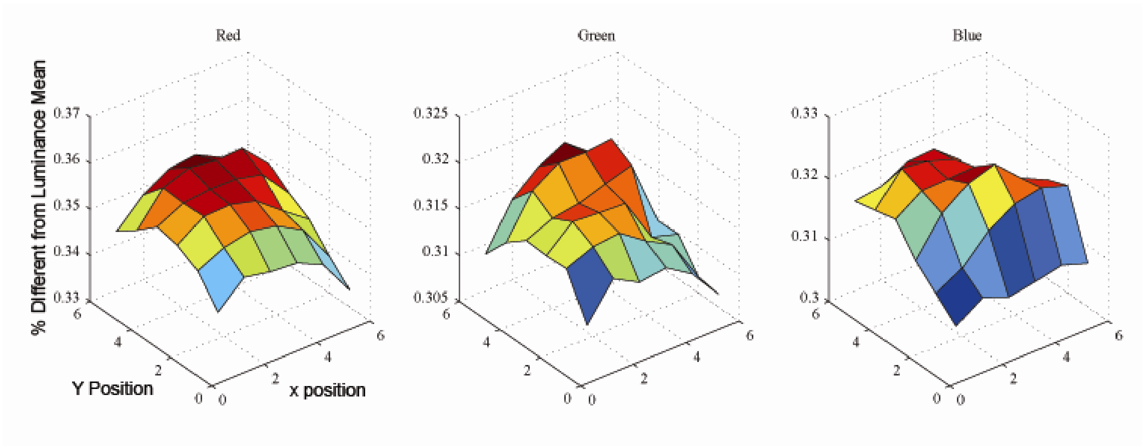


Figure 14. System spatial uniformity surface plot of % difference from luminance (Y) mean of gray card target for RGB channels.

As we can see in figure 14, the camera has a very good spatial uniformity. The desirable percent difference from mean luminance is less than 0.5 %. The highest percent difference that camera has is 0.36 %. Ideal system spatial uniformity would be 0% difference which would be perfectly flat in the graphs.

2. Tone Reproduction

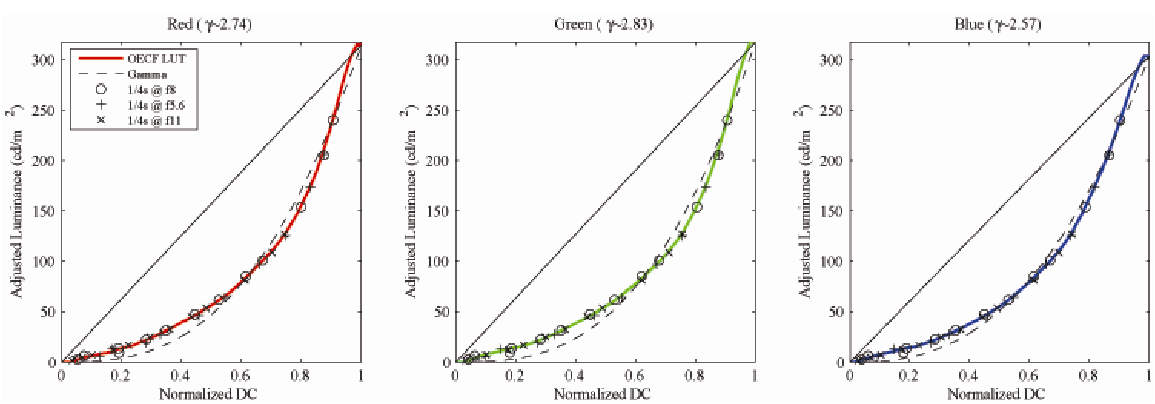


Figure 15. OECF curves for RGB channels.

Figure 15 is the inverse OECF of the camera that describes the relationship between input and output of the camera. The Sigma SD9 non-linearity encodes scene luminance, typical of "prosumer" digital cameras. The γ values were greater than expected, closer to 2.2.

3. Color Reproduction Accuracy

3.1. Spectral Sensitivity

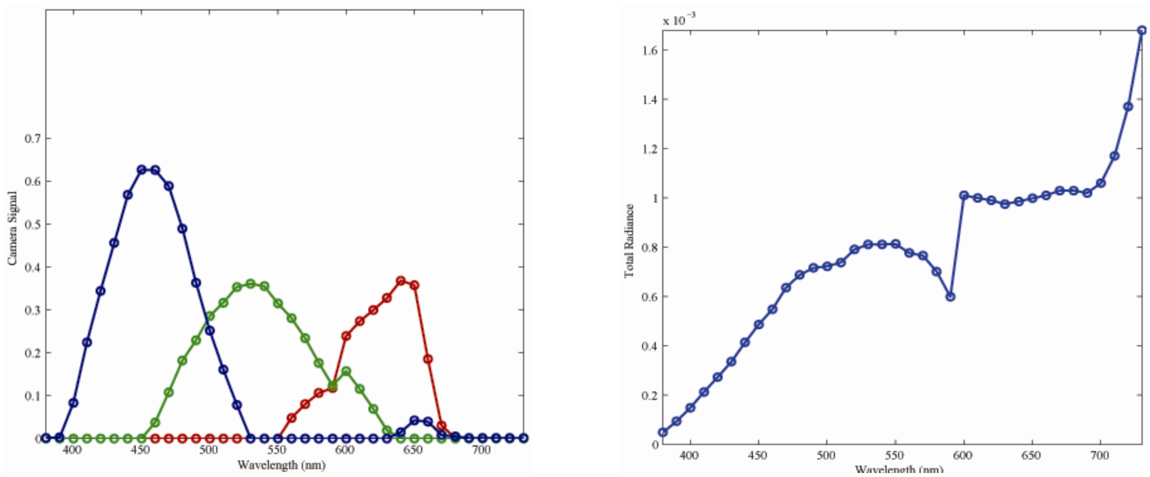


Figure 16. RGB linearized average camera digital count values from the monochromator images vs. wavelength (left), and the sum of the measured spectral radiances vs. wavelength (right).

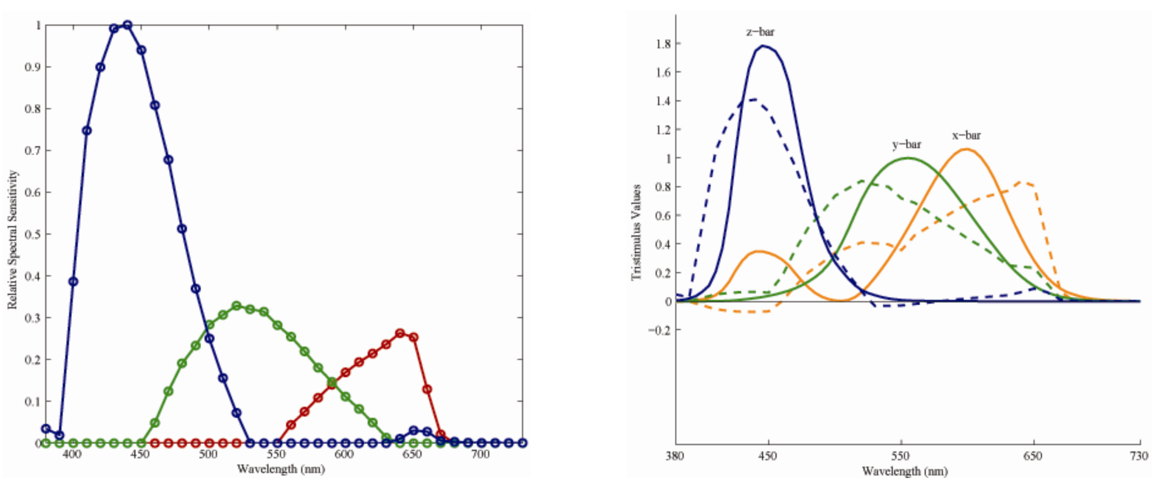


Figure 17. Relative spectral sensitivities vs. wavelength (left), and relative spectral sensitivity vs. wavelength (dotted line) rotated to fit the CIE 2° observer (solid line) (right).

Perfect spectral sensitivity would have a μ-factor equal to 1 and also have relative spectral sensitivites that match the CIE 2° observer. From figure 17 (right), the rotated relative spectral sensitivity of the camera is poor compared with the CIE 2° observer. The spectral sensitivity of the X3 sensor is not similar to the human eye.

Detector	Color Matching Functions	Taking Illuminant	Viewing Illuminant	μ-Factor
Camera	CIE 2° Observer	Tungsten	D50	0.83
		D50		0.85
CIE 2° Observer		Tungsten		0.98

Table 3. μ-factor results with the measurement conditions.

For cultural heritage application, the μ-factor should be at least 0.9 thus, the μ-factor of the Sigma SD9 is lower than a desirable value. The μ-factor of the whole imaging system in this experiment was 0.83. The tungsten lights affect the μ-factor slightly by 0.02.

3.2. Target-based Color Reproduction Accuracy

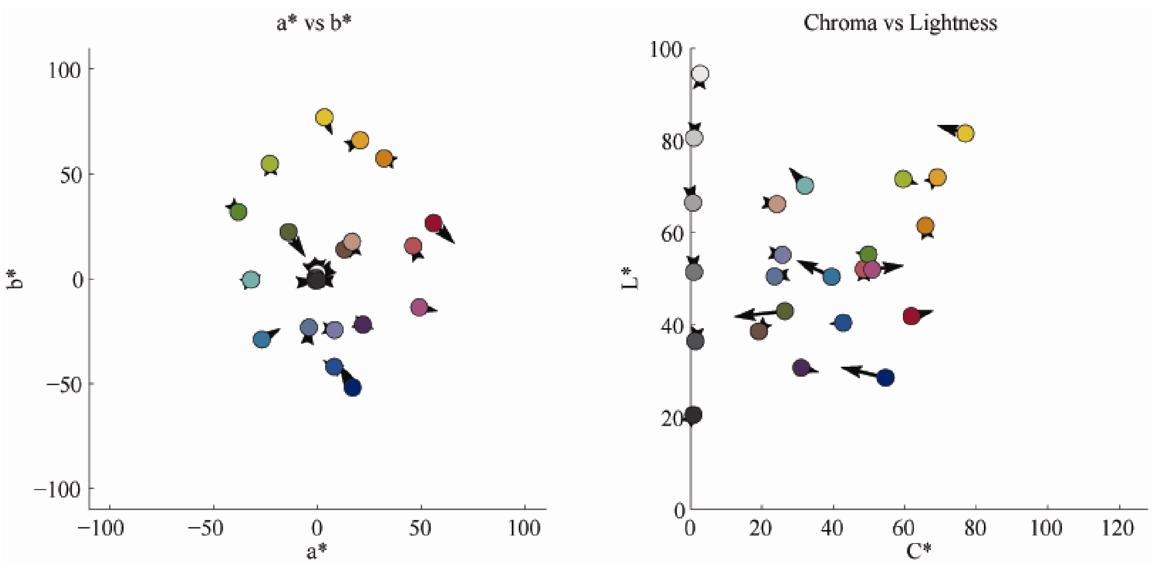


Figure 18. CIELAB a* vs. b* (left) and C^*_{ab} vs. L* (right) error vector plots of the Macbeth ColorChecker between the measured patch data (dot) and the image patch data (point of vector arrow) determined using the second evaluation method with the CCDC as the characterization chart used to build the 3x3 transform.

The CIELAB a* vs. b* plot shows that there is no systematic change in the values. The CIELAB C^*_{ab} vs. L* plot shows that most of the image patch data has less chroma compared to the measured data.

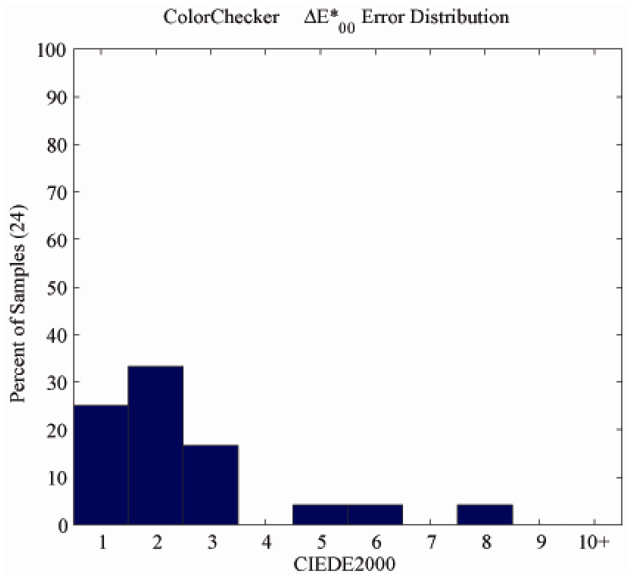


Figure 19. Histogram of the ΔE_{00} distributions of the Macbeth ColorChecker between the measured patch data and the image patch data determined using the second evaluation method with the CCDC as the characterization chart used to build the 3x3 transform.

Color Reproduction Accuracy Chart	ΔE^*_{ab}			ΔE_{00}		
	Mean	Std. Dev.	90th Perc.	Mean	Std. Dev.	90th Perc.
ColorChecker	5.27	4.20	13.09	2.73	1.85	5.74
ColorChecker DC	6.31	6.84	13.28	3.75	2.69	7.36
Esser	7.42	5.23	14.69	3.81	2.22	6.60
Esser Grayscale	3.46	3.12	9.16	3.03	2.23	7.21
BCRA	8.23	8.38	19.49	4.21	3.39	7.98
Blue Pigments	6.23	1.79	8.90	4.50	1.82	6.52
Kodak Color Patch	10.42	9.45	20.91	4.99	2.78	9.79
Kodak Grayscale	4.73	3.03	9.17	3.86	1.92	6.32
IT8	7.68	4.86	14.28	4.99	2.69	8.06
IT8 Grayscale	3.60	1.07	5.30	4.16	0.91	5.55
Pigment Target	13.46	6.35	20.14	7.52	3.75	13.63
Mean	6.98	4.94	13.49	4.32	2.39	7.71

Table 4. Mean, standard deviation and 90^{th} percentile of the ΔE^*_{ab} and E_{00} data between the measured patch data and the image patch data for each color reproduction accuracy chart determined using the second evaluation method with the CCDC as the characterization chart used to build the 3x3 transform.

ΔE_{00} yields a more accurate comparison than ΔE^*_{ab} because it does a better job of describing color perception. It is desirable to have small color differences. For ΔE^*_{ab} the desirable value is less than 2, however 4-6 is acceptable. The color targets have ΔE^*_{ab} values between 3.46 and 12.46, which is too large for artwork preservation.

It is desirable to have very small color difference especially for the Macbeth ColorChecker DC, Macbeth ColorChecker, Cobalt blue pigments and Pigment chart target. The Macbeth ColorChecker had the smallest color difference expected since the target was used to derive the calibration matrix. The camera does not produce the Pigment chart target accurately. The Pigment chart target has the largest color difference of all of the targets. The Sigma SD9 is not good enough for artwork preservations.

3.3. Metamerism

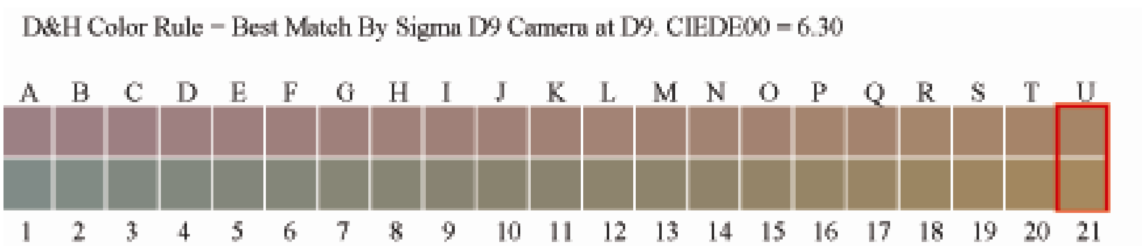


Figure 20. D&H Color Rule camera metameric match (U-21).

	Metameric match	ΔE^*_{ab}		ΔE_{00}	
		Camera	CIE 2° observer	Camera	CIE 2° observer
Camera	U-21	7.52	12.2	6.3	8.5
CIE 2° observer	R-15	9.66	0.42	11.29	0.34

Table 5. D&H Color Rule metameric matches and ΔE*ab and ΔE_{00} color differences of each metameric match as "seen" by the camera and CIE 2° observer under the HMI taking illuminant.

The camera does not "see" the same colors on the D&H color rule as the CIE 2° observer. To the 2° observer, the R and 15 patches look the most similar. However, to the camera, the U and 21 patches look the most similar.

4. Noise

4.1 Image Noise

	Red Channel	Green Channel	Blue Channel	Mean of RGB Channels
Total Average Noise (DC)	292.62	339.66	571.55	401.28
Total Signal to Noise Ratio	48.83	44.62	26.39	39.95
Fixed Pattern Average Noise (DC)	204.35	214.13	250.58	223.02
Fixed Pattern Signal to Noise Ratio	69.92	70.78	60.2	66.97
Temporal Average Noise (DC)	209.45	263.67	513.69	328.94
Temporal Signal to Noise Ratio	68.22	57.48	29.36	51.69
Black Temporal Average Noise (DC)	331.28	271.34	442.5	348.38

Table 6. Image total noise, fixed pattern noise and temporal noise results.

It is desirable to have low average noise and a high signal to noise ratio. The noise is in units of digital counts in a 16 bit image. The total signal to noise ratio is sufficient for artwork preservation.

4.2 Color Noise

ColorChecker Patch	Mean Normalized DC			% Standard Deviation (Norm. DC)			MCDM	
	R	G	B	R	G	B	ΔE*ab	ΔE00
Red	0.45	0.29	0.19	0.93	1.78	7.50	1.25	1.10
Green	0.81	0.63	0.48	0.27	0.79	3.19	1.36	1.06
Blue	0.29	0.47	0.63	1.53	1.03	0.96	0.94	0.68
Cyan	0.36	0.37	0.28	1.08	1.14	3.84	1.19	0.87
Magenta	0.51	0.50	0.71	0.60	0.82	0.74	0.90	0.44
Yellow	0.46	0.78	0.72	0.76	0.51	0.94	1.06	0.65
White	0.87	0.57	0.00	0.46	1.11	0.00	0.91	0.57
Gray	0.00	0.33	0.65	0.00	1.60	0.96	1.11	0.43
Black	0.83	0.41	0.34	0.32	2.15	5.54	1.82	1.08
Mean	0.51	0.48	0.45	0.66	1.21	2.63	1.17	0.76

Table 7. Color noise results of selected patches of the Macbeth ColorChecker.

It is desirable to have a very small % standard deviation and mean color difference from the mean. From the percent standard deviation, the red channel has the least color noise and the blue channel has the most color noise. From the mean color difference from the mean, the magenta patch and white patch have the least color noise and the black patch has the most color noise.

5. Dynamic Range

	Red Channel	Green Channel	Blue Channel	Mean of RGB Channels
ISO Digital Still Camera Dynamic Range (Luminance Ratio)	717.27	904.15	693.18	771.533
ISO Digital Still Camera Dynamic Range (Density)	2.856	2.956	2.841	2.884
Theoretical Dynamic Range (Density)	3.612	3.612	3.612	3.612

Table 8. Dynamic range results.

It is desirable to have a large dynamic range. Murphy did not give a specific number as to how large the dynamic range should be.

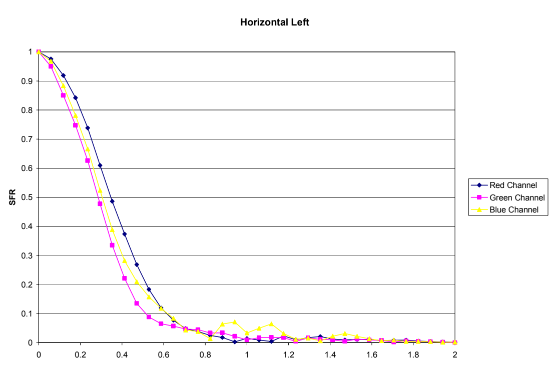
6. Spatial Cross-Talk

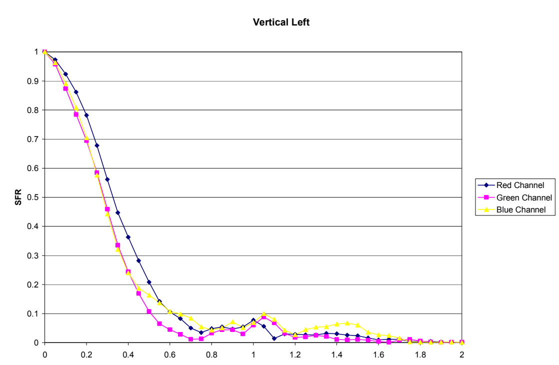
	Red Channel	Green Channel	Blue Channel	Mean of RGB Channels
Mean Linearized Digital Counts	0.18	0.2	0.27	0.22
Relative Maximum Difference (%)	9.15	7.46	9.02	8.54
Relative Standard Deviation (%)	2.81	2.36	2.86	2.68

Table 9. Spatial cross talk results.

It is desirable to have a relative maximum difference as close to 0% as possible. The relative maximum difference of the camera is 8.54%, which is not acceptable for artwork preservation.

7. Spatial Frequency Response (SFR)





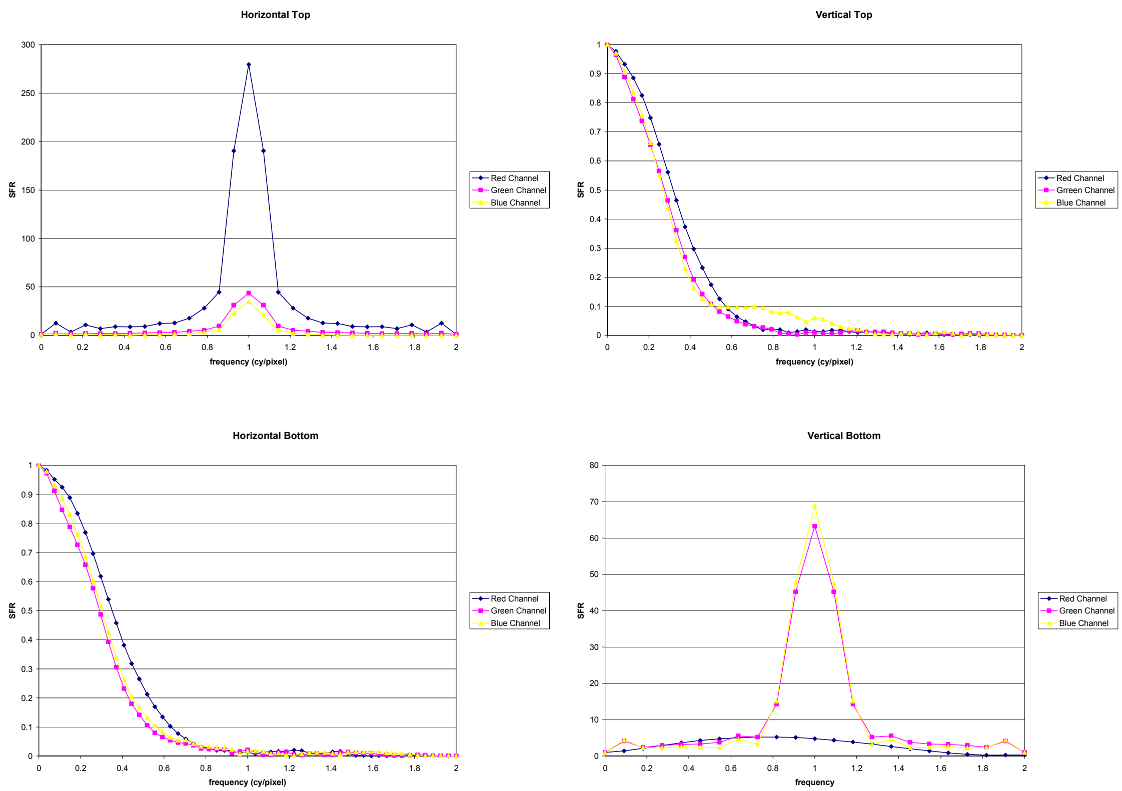


Figure 21. SFR of upper left corner horizontal edge (top left), upper left corner vertical edge (top right), top horizontal edge (middle left), top vertical edge (middle right), bottom horizontal edge (bottom left) and bottom vertical edge (bottom right).

The top horizontal edge and bottom vertical edge should not look like that, the cause is not yet known.

Edge	Area Under SFR Curve from Frequencies of 0.0 to 0.5 cy/pixel			
	Red Channel	Green Channel	Blue Channel	Mean of RGB Channels
Horizontal Left	0.365	0.314	0.335	0.338
Vertical Left	0.354	0.310	0.315	0.326
Horizontal Top	4.401	1.059	0.584	2.014
Vertical Top	0.339	0.298	0.295	0.311
Horizontal Bottom	0.356	0.304	0.318	0.326
Vertical Bottom	1.397	1.537	1.364	1.433
Mean				0.791

Table 10. SFR Area Results.

8. Color Channel Registration

Edge	Misregistration Shift (pixels)		
	Red Channel	Green Channel	Blue Channel
Center Top Horizontal	0.00	0.00	0.07
Center Top Vertical	0.10	0.00	0.33
Center Bottom Horizontal	0.06	0.00	0.06
Center Bottom Vertical	0.16	0.00	0.32
Left Horizontal	0.03	0.00	0.07
Left Vertical	0.10	0.00	0.29
Mean of RGB channels			0.09

Table 11. Color Channel Registration results (Green channel used as reference).

It is desirable to have a color channel misregistration error less than 0.5. The mean of misregistration shift of RGB channels is 0.09 with a maximum of 0.33, which is good enough for cultural heritage application.

9. Depth of Field

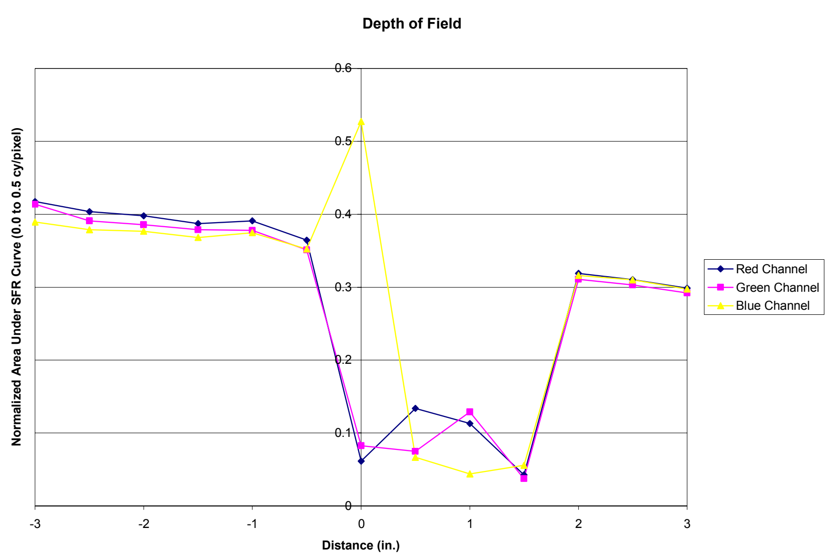


Figure 22. Depth of Field distance vs. area under SFR curve of the horizontal edge.

Near limit of acceptable sharpness	37.4 inch
Far limit of acceptable sharpness	41.8 inch
Total depth of field	4.35 inch
Depth of field in front of subject	2.06 inch (47%)
Depth of field behind subject	2.29 inch (53%)
Hyperfocal distance	686.5 inch
Circle of confusion for selected format	0.018 mm

Table 12. Theoretical depth of field.

The camera does not have a good depth of field because the wide angle was used. Besides that, the sensor type also effect the depth of field of the Sigma SD9.

10. Summary of Results and Discussions

Quality Parameter	Sigma SD9
Tone Reproduction *Mean gamma*	2.71
Color Reproduction Accuracy – Spectral Sensitivity *μ-factor*	0.83
Color Reproduction Accuracy – Target-based *Mean ΔE_{00} 90^{th} percentile of 9 targets*	7.71
Noise – Image *Mean total SNR*	39.95
Noise – Color *Mean MCDM*	0.76
Dynamic Range *Density*	2.88
Spatial Cross-talk *Relative maximum % difference*	8.54
Spatial Frequency Response *Mean under the RGB curves across all 4 edges from frequencies of 0.0 to 0.5 cy/pixel*	0.79
Color Channel Registration *Mean registration shift RGB channels and across 6 edges*	0.09
Depth of Field *Mean under the RGB curves across all 13 edges from frequencies of 0.0 to 0.5 cy/pixel*	0.28

Table 13. Characterization results for ten of the quality parameters.

	Criteria For Cultural Heritage Applications
System Spatial Uniformity	difference from mean luminance less than 0.5%
Tone Reproduction	the gamma of the camera close to 1
Color Reproduction Accuracy	
- Spectral Sensitivity	the relative spectral sensitivity mathes to the CIE 2° observer and the μ-factor at least 0.9
- Target-based Color Reproduction Accuracy	ΔE*ab less than 2, but 4-6 is acceptable
- Metamerism	camera "sees" the same colors as the CIE 2° observer
Noise	
- Image Noise	low average noise and high signal to noise ratio
- Color Noise	small % standard deviation and MCDM
Dynamic Range	large dynamic range
Spatial Cross-Talk	relative maximum difference close to 0%
Spatial Frequency Response (SFR)	large area under SFR curve from frequencies of 0.0 to 0.5 cy/pixel
Color Channel Registration	misregistration error less than 0.5
Depth of Field	As large as possible

Table 14. A summary of the criteria for cultural heritage applications.

Conclusions

The method for evaluating a camera is easy; however, there were a number of difficulties in all of the tests. During the experiment, it is really hard to keep the target flat against the blackboard, and therefore it is hard to make accurate measurements. For the Sigma SD9, this is not a big problem. If the background was made from a black metal and the targets had magnets behind it, the targets would be perfectly flat against the background. Another difficulty is dust in the camera. The tiny dust on the CCD looks like large spots in the final image. It is a good idea to make sure there is no dust before starting this experiment. The other thing that makes the experiment slower is that because the targets were not all the same size because it took a while to center them. It will be nicer if all of the targets are the same size. There are some other improvements to her method that could be made, such as more specific guidelines for the values of the criteria. The desirable values she gives are usually vague, such as "close to 0" and "small." Specific numerical values that are considered acceptable and desirable are needed. Also, suggestions could be made as to whether a camera that excels in most areas but fails one or two tests would still be useful.

The Sigma SD9 camera does not the meet criteria for artwork preservation. The camera needs a lot of improvements in order to be sufficient for cultural heritage applications. Murphy's method is easy to perform but could be improved.

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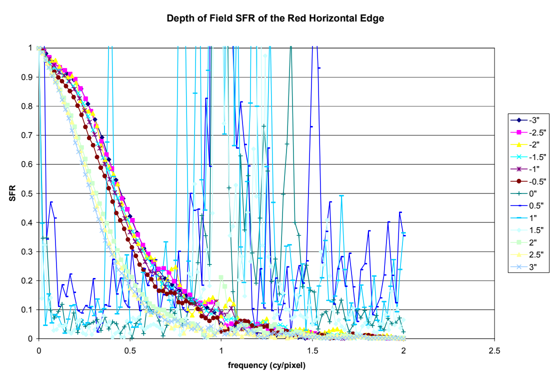
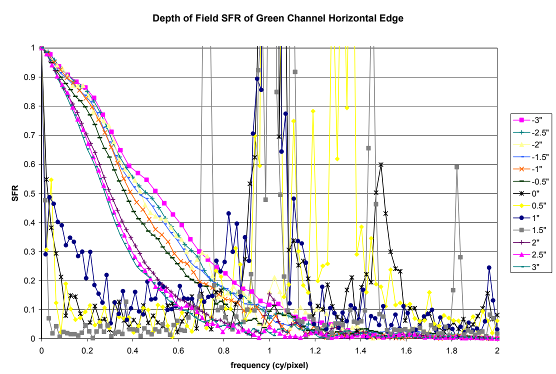
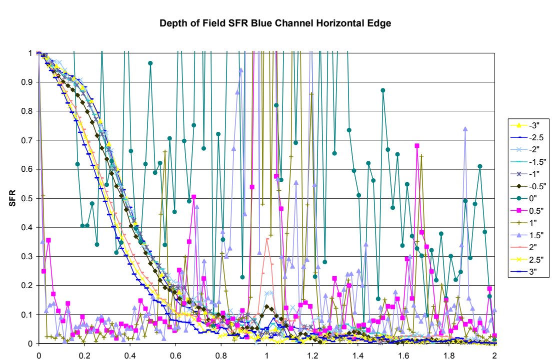
Appendix

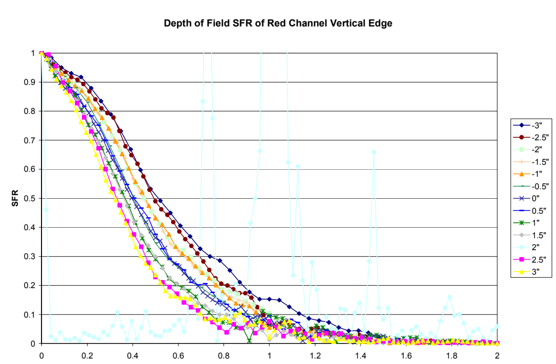
Patch#	Mean DC at 0° R	Mean DC at 0° G	Mean DC at 0° B	Mean DC at 180° R	Mean DC at 180° G	Mean DC at 180° B
1	0.1733	0.1902	0.258	0.1819	0.1983	0.2747
2	0.1857	0.1985	0.2689	0.1782	0.1931	0.275
3	0.1898	0.2029	0.2768	0.1824	0.1956	0.2706
4	0.1907	0.2034	0.2839	0.1741	0.1888	0.2698
5	0.1868	0.1982	0.2833	0.1718	0.1868	0.2625
6	0.1746	0.189	0.2589	0.1819	0.1963	0.2788
7	0.1825	0.1952	0.2676	0.1825	0.1963	0.2791
8	0.1902	0.2018	0.2756	0.1864	0.1981	0.2724
9	0.1878	0.2028	0.2747	0.1793	0.1922	0.2682
10	0.1873	0.2019	0.2825	0.1744	0.1888	0.2581
11	0.1727	0.1885	0.2619	0.1803	0.1941	0.2789
12	0.176	0.1925	0.2686	0.1845	0.2	0.2778
13	0.1864	0.1995	0.2698	0.186	0.1995	0.2697
14	0.1844	0.2014	0.2622	0.1858	0.1988	0.2574
15	0.1874	0.202	0.2776	0.1738	0.1874	0.2549

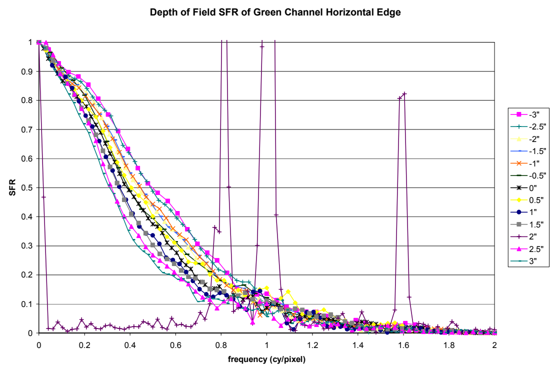
Table 15. Spatial cross-talk linearized normalized mean digital counts of 15 gray patches obtained from images of the target oriented at 0° and 180°.











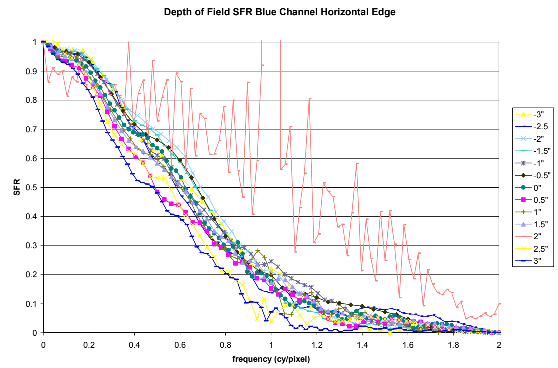


Figure 23. Depth of Field plots for the Horizontal and Vertical Edges. The plots should be smooth and not spiky.

Distance From Center 3" Square (in.)	Area under SFR Curve From Frequencies of 0.0 to 0.5 cy/pixel			
	Red Channel	Green Channel	Blue Channel	Mean of RGB Channels
-3	0.417	0.414	0.389	0.407
-2.5	0.404	0.391	0.379	0.391
-2	0.398	0.386	0.377	0.387
-1.5	0.387	0.379	0.368	0.378
-1	0.391	0.378	0.375	0.381
-0.5	0.364	0.351	0.352	0.356
0	0.061	0.082	0.527	0.224
0.5	0.134	0.075	0.067	0.092
1	0.113	0.129	0.044	0.095
1.5	0.043	0.037	0.056	0.045
2	0.319	0.311	0.316	0.315
2.5	0.310	0.303	0.310	0.308
3	0.298	0.292	0.298	0.296

Table 16. Depth of field areas under the SFR curves (from 0.0 to 0.5 cy/pixel) shown in figure 22 for each distance on the depth of field target for the red, green and blue channels area.